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Dynamic Analysis of Sigmoid Bidirectional FG Microbeams under Moving Load and Thermal Load: Analytical Laplace Solution

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Abstract: This paper presents for the first time a closed-form solution of the dynamic response of sigmoid bidirectional functionally graded (SBDFG) microbeams under moving harmonic load and thermal environmental conditions. The formulation is established in the context of the modified couple stress theory to integrate the effects of microstructure. On the basis of the elasticity theory, nonclassical governing equations are derived by using Hamilton's principle in combination with the parabolic higher-order shear deformation theory considering the physical neutral plane concept. Sigmoid distribution functions are used to describe the temperature-dependent thermomechanical material of bulk continuums of the beam in both the axial and thickness directions, and the gradation of the material length scale parameter is also considered. Linear and nonlinear temperature profiles are considered to present the environmental thermal loads. The Laplace transform is exploited for the first time to evaluate the closed-form solution of the proposed model for a simply supported (SS) boundary condition. The solution is verified by comparing the predicted fundamental frequency and dynamic response with the previously published results. A parametric study is conducted to explore the impacts of gradient indices in both directions, graded material length scale parameters, thermal loads, and moving speed of the acted load on the dynamic response of microbeams. The results can serve as a principle for evaluating the multi-functional and optimal design of microbeams acted upon by a moving load.

Keywords: closed-form solution; Laplace transform; sigmoid microbeams; dynamic response; moving load; couple stress; thermomechanical

MSC: 74H45

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1. Introduction

Functionally graded material (FGM) is an innovative class of composites with continuous gradation of material through a certain spatial direction, which have enhanced properties rather than traditional composites, such as designability, reduced singular stress interface problems, small stress concentration, lower weight, higher fracture toughness, enhanced thermal properties, high damage resistance, etc. [1]. Due to their unique properties, FGMs are broadly employed in many applications such as electronics, dental implants, and turbines, as well as in aerospace, marine, automotive, military, and nuclear applications [2,3]. Due to the rapid advances in nanotechnology, FGMs nowadays are exploited in micro/nano-electro-mechanical systems (MEMs/NEMs), atomic force microscopes, shape memory alloys, thin film coatings, and transmission systems [4,5]. At nanometer scales, size

effects, which are missing in classical mechanics, often become important and observable and must be considered in the analysis and design of MEMs/NEMs [6]. To consider a size effect, modified continuum models such as nonlocal theories, modified couple stress theory, strain gradient theory, nonlocal strain gradient, doublet mechanics, and surface energy are exploited [7].

Asghari et al. [8] analytically studied the mechanical responses of FG-modified couple stress nanobeams based on first-order shear deformation theory (FOSDT). Şimşek [9] evaluated the critical buckling loads of 2d-FG Timoshenko beams with different boundary conditions via the Ritz method. Nejad et al. [10,11] examined the buckling stability and free vibration of arbitrary 2D-FG thin nonlocal nanobeams by using the generalized differential quadrature method. Mirafzal and Fereidoon [12] investigated the vibration behaviors of temperature-dependent viscoelastic FG nonlocal nanobeams exposed to a 2D-magnetic field under periodic loading. Shafiei et al. [13,14] studied buckling and vibration behaviors of 2D-FG porous tapered modified couple stress nanoscale beams using Euler and Timoshenko beam theories. Rajasekaran and Khaniki [15] illustrated the impact of single/multi-cracked 2D-FG beams on free vibration by using a novel finite element method. Sahmani and Safaei [16,17] investigated the nonlinear vibrations of 2D-FG nonlocal strain gradient micro/nanobeams within the framework of the refined hyperbolic shear deformation beam theory. Tang and Ding [18] studied the nonlinear hygro-thermal dynamics of 2D-FG beams with coupled transverse and longitudinal displacements. Tang et al. [19] presented the asymmetric mode and nonlinear vibration of 2D-FG Euler–Bernoulli beams via the homotopy analysis method. Attia and Mohamed [20] studied the nonlinear vibration characteristics of pre- and postbuckled nonuniform 2D-FGM-modified couple stress microbeams exposed to nonlinear thermal loading.

Barati et al. [21] evaluated the natural frequencies of 2D-FGM nonlocal nanobeam under a magnetic field employed by Maxwell's relations. Ghatage et al. [22] presented a comprehensive review on the modeling and mechanical analysis of multi-directional FG beam, plate, and shell structures. Karami et al. [23] studied the dynamic response of 2D-FG-tapered Timoshenko nonlocal strain gradient nanobeams in a thermal environment by using the numerical generalized differential quadrature method. Zhao et al. [3] examined buckling and postbuckling of FG graphene origami (GOri)-enabled auxetic metallic metamaterial (GOEAM) beams. Guo et al. [24] examined the elastic wave dispersion propagating along the thickness direction in FG-laminated phononic crystal auxetic metamaterials. Zhao et al. [25] proposed data-driven micromechanics models based on molecular dynamic (MD) simulations to predict thermo-elastic properties of vacancy-defective graphene/Cu nanocomposites in different temperature conditions. Daikh et al. [26] studied bending and stress responses of nonlocal strain gradient Quasi-3D FG sandwich nanoplates based on the sigmoid gradation function. Daikh et al. [27] explored the static buckling stability, static deflection, and vibration of an axially temperature-dependent FG-CNTs nanoplate based on higher-order shear deformation. Soni et al. [28] presented an extensive review on FG carbon nanotube-reinforced composite structures, their application, and studies on the mechanical, vibration, thermal, thermo-mechanical, and low-velocity impact responses. Ahmadi [6] exploited the meshless method to examine the dynamic response of 2D-FG nonlocal nanobeams by using FOSDT. Attia and Shanab [29] investigated the size-dependent bending, buckling, and vibration responses of 2D-FG micro/nanoscale beams including the microstructure surface energy-based theory. Zhao et al. [30] presented a comprehensive review on the mechanical analyses of FG graphene platelet-reinforced composite structure. Assie et al. [31] studied the buckling stability of BDFG porous plates resting on an elastic foundation by using unified higher-order shear theories.

Understanding the dynamic motion of nanoparticles is critical for MEMS/NEMS and microfluidics [32]. For example, in biological and colloidal science applications, nanotubes and nanobeams are exploited to transport drug materials into targeted nano-sized molecules to change the behavior of cancer cells [33]. Therefore, understanding the process of mass transport and the dynamic response of micro/nanobeams under such loadings

would be of great importance for optimal designs [34]. Şimşek [35] analytically studied the forced vibration of an elastically connected double-carbon nanotube system (DCNTS) under a moving nanoparticle. Şimşek [36] investigated the forced vibration of a simply supported (SS) single-walled carbon nanotube (SWCNT) under a moving harmonic load, based on nonlocal Euler–Bernoulli beam theory, and showed that dynamic deflection of the SWCNT is strongly affected by the nonlocal parameter, and that its dynamic behavior is also affected by other parameters such as load velocity and excitation frequency. Şimşek [9] developed a mathematical model to examine free and forced vibration of 2D-FG Timoshenko beams under moving loads with the implicit Newmark time integration method. Hosseini and Rahmani [37] adopted the nonlocal elasticity theory to study the dynamic response of SS-FG Euler–Bernoulli nanobeams subjected to a constant moving load. Based on nonlocal elasticity theory, the influences of surface energy and viscoelastic foundation on the steady-state response of Euler–Bernoulli nanobeams in a thermal environment and subjected to a moving concentrated load were examined by Ghadiri et al. [38] using the multiple scales method. In Barati and Shahverdi [39], the forced vibration response of FG nanobeams resting on Winkler–Pasternak foundation and under a uniform harmonic dynamic load was investigated employing a higher-order shear deformation beam theory in the context of nonlocal elasticity theory. In the framework of parabolic shear deformation theory, Zhang and Liu [40] employed the modified couple stress theory to study the vibration response of 2D-FG porous microbeams excited by a moving harmonic load using FEM.

For even and uneven porosity distributions, power law functions were adopted to model the material variation in both thickness and length directions. Liu et al. [41] adopted the modified couple stress theory to explore the effects of thermal rise and moving load on the vibration response of 2D-FG microbeams using FEM. Temperature-dependent material properties were assumed with a power law distribution in both the thickness and length directions. Hosseini et al. [42] presented the influence of the thermal environment on the forced vibration response of FG nonlocal nanobeams under moving load via the Laplace transform method. Abdelrahman et al. [43–45] analyzed the dynamic response of perforated nanobeams and FG nanobeams reinforced by carbon nanotubes under moving load via nonlocal strain gradient. Chung et al. [46] developed a new type of planar transmission line with unique dual-signal path characteristics and ultimately achieved circuit miniaturization. Eltaher et al. [47] exploited bottom-up modeling nano-mechanics theory to illustrate the dynamic response of armchair and zigzag CNTs under a dynamic moving load. Esen et al. [48,49] exploited nonlocal strain gradient theory to present the size scale and microstructure effects on the dynamic response of FG nanobeams reinforced by carbon nanotubes and sigmoid FG nanobeams under moving loads. Thongchom et al. [50] studied the vibration behavior of fluid-conveying hybrid smart CNTs considering slip boundary conditions under a moving nanoparticle. Akbaş et al. [51] studied the dynamic responses of a fiber-reinforced composite Timoshenko beam under a moving load by using the Ritz method.

Based on the literature and our knowledge, the dynamic analysis of sigmoid BDFG microbeams with temperature-dependent materials under moving and thermal loads appears limited. Thus, this article aims to fill this gap analytically by using Laplace transform on a system of variable coefficients for the first time. The effect of microstructure is captured via the modified couple stress. The materials' compositions are changing gradually through thickness and length by sigmoidal functions. The formulation considers the physical neutral axis concept. The nonclassical motion equations are derived. Laplace transform and the Newmark method are employed to evaluate the dynamic deflection of BDFG microbeams under moving loads. The rest of the article is organized as follows. The formulation, constitutive equations, distribution functions, and kinematic relations are presented in Section 2. The variational techniques to derive the equations of motion and the boundary conditions are given in Section 3. Analytical solutions and model validation are presented in Sections 4 and 5, respectively. Numerical and parametric studies to present

the influence of gradation, temperature distribution, and moving velocity on the dynamic response are discussed in Section 6.

2. Theory and Formulation

2.1. Material Constitutions and Distributions

Consider a straight uniform sigmoid bidirectional functionally graded (SBDFG) microbeam with b width, L length, and h thickness, as shown in Figure 1, in a Cartesian system (x_m, y, z_m) that represents the midplane. The beam is excited by a moving load with a constant velocity v. The FG beam is composed of a mixture of ceramic and metallic constituents, where the lowermost ($x = 0$, $z_m = -\frac{h}{2}$) is pure metal "m" and the uppermost ($x = L$, $z_m = \frac{h}{2}$) is pure ceramic "c". The equivalent thermomechanical properties for the bulk continuum of SBDFG at temperature $T(z)$ can be described by a sigmoid function in both directions as [52]:

$$\mathcal{P}_1(x,z,T) = \left\{\mathcal{P}_m(T) + (\mathcal{P}_c(T) - \mathcal{P}_m(T))\left[0.5\left(1+\frac{2z}{h}\right)^{k_z}\right]\left(\frac{x}{L}\right)^{k_x}\right\} \qquad -\frac{h}{2} \le z \le 0 \tag{1}$$

$$\mathcal{P}_2(x,z,T) = \left\{\mathcal{P}_m(T) + (\mathcal{P}_c(T) - \mathcal{P}_m(T))\left[1-0.5\left(1-\frac{2z}{h}\right)^{k_z}\right]\left(\frac{x}{L}\right)^{k_x}\right\} \qquad 0 \le z \le \frac{h}{2} \tag{2}$$

where $\mathcal{P}_m$ and $\mathcal{P}_c$ are the metallic and ceramic constituent properties, respectively. The material property "$\mathcal{P}$" represents the Young's modulus E, Poisson's ratio ν, the mass density ρ, microstructure material length scale parameter (MSLSP) l, and thermal expansion coefficient α. k_x and k_z are the gradient indices in the axial and transverse directions, respectively.

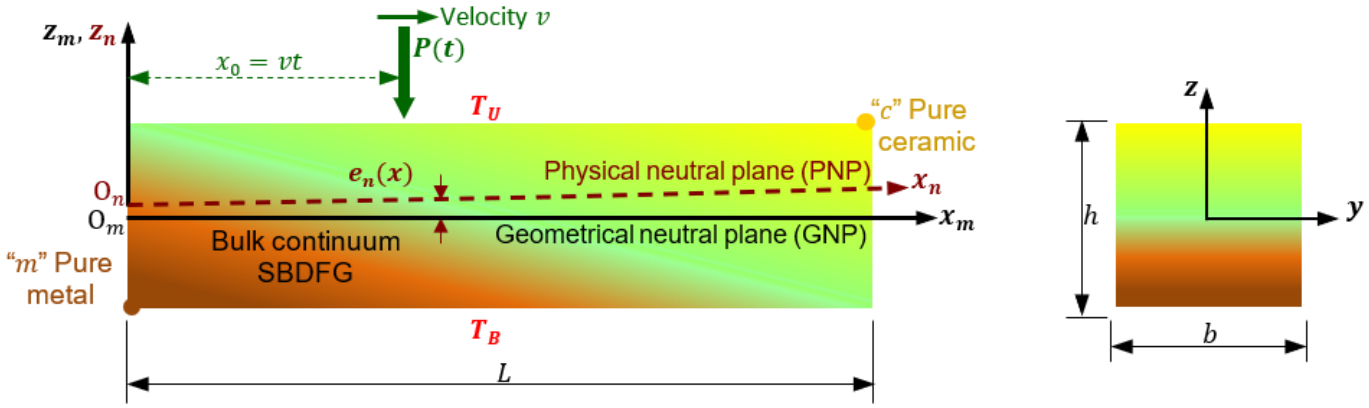


Figure 1. Illustration of a 2D-FG microbeam exposed to a moving load and thermal environment.

Lame's parameters of bulk are:

$$\lambda(x,z) = \frac{E(x,z_m)\,\nu(x,z_m)}{(1+\nu(x,z_m))(1-2\nu(x,z_m))} \qquad \text{and} \qquad \mu(x,z_m) = \frac{E(x,z_m)}{2(1+\nu(x,z_m))} \tag{3}$$

Ignoring the Poisson effect yields, $[\lambda(x,z_m) + 2\mu(x,z_m)] \equiv E(x,z)$, as adopted by [53–55]. In Equations (1)–(3), the axially FG (AFG) and transversely FG (TFG) gradations can be obtained by setting $k_z = 0$ and $k_x = 0$, respectively. A pure metal constituent beam is obtained when $k_x = k_z = 0$. In addition, for $k_z = 1$, the power law distribution function is retained from Equations (1) and (2).

Temperature-dependent (TD) material properties $\mathcal{P}_m$ and $\mathcal{P}_c$ are estimated by [56]:

$$\mathcal{P}_i(T) = \mathcal{P}_0\left[\mathcal{P}_{-1}T^{-1} + 1 + \mathcal{P}_1 T + \mathcal{P}_2 T^2 + \mathcal{P}_3 T^3\right], i = m, c \tag{4}$$

where $\mathcal{P}_{-1}$, $\mathcal{P}_0$, $\mathcal{P}_1$, $\mathcal{P}_2$, and $\mathcal{P}_2$ are temperature-dependent coefficients.

Because of nonsymmetric material properties' gradation of the BDFG beam about its midplane, the geometrical neutral plane (GNP) does not coincide with the physical neutral plane (PNP) [57,58], as shown in Figure 1. The difference between the locations of GNP and PNP is evaluated by [29,59]:

$$e_n(x) = \frac{\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} z_m \left[\lambda^B(x,z_m) + 2\mu^B(x,z_m)\right] dydz_m}{\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} [\lambda^B(x,z_m) + 2\mu^B(x,z_m)] dydz_m}, z_n(x) = z_m - e_n(x) \tag{5}$$

2.2. Kinematics Relation

Based on general shear deformation theory, the displacement field of the BDFG microbeam is presented by [60]:

$$\begin{array}{l} u_x(x,z,t) = u(x) + f(z_n)\frac{\partial w(x,t)}{\partial x} + R(z_n)\phi(x,t) \\ u_y(x,z,t) = 0 \\ u_z(x,z,t) = w(x,t) \end{array} \tag{6}$$

where u and w are the displacement components along the midplane, ϕ is the transverse shear function, and t indicates time. The shear–strain function $R(z_n) = R(z_m) - r_n(x)$, where:

$$r_n(x) = \frac{\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} R(z_m) \left[\lambda^B(x,z_m) + 2\mu^B(x,z_m)\right] dydz_m}{\int_{-\frac{h}{2}}^{\frac{h}{2}} \int_{-\frac{b}{2}}^{\frac{b}{2}} [\lambda^B(x,z_m) + 2\mu^B(x,z_m)] dydz_m} \tag{7}$$

Various beam theories can be derived by proper functions of $f(z_n)$ and $R(z_n)$. The Euler–Bernoulli and Timoshenko beam theories are achieved by setting $f(z_n) = -z_n$, $R(z_m) = 0$ and $f(z_n) = 0$, $R(z_m) = -z_m$, respectively. Adopting the third-order parabolic shear deformable beam theory (PSDBT) [61], we obtain:

$$f(z_n) = -z_n \quad \text{and} \quad R(z_m) = z_m\left(1 - \frac{4z_m^2}{3h^2}\right) \tag{8}$$

2.3. Constitutive Relations

Based on generalized elasticity theory and modified couple stress theory [62], the strain ε, Cauchy stress σ^B, symmetric curvature χ, and the couple stress m are given by [63,64]:

$$\varepsilon = \frac{1}{2}\left[\nabla \mathrm{u} + (\nabla \mathrm{u})^T\right] \tag{9}$$

$$\sigma^B = \lambda^B(x,z_m)\ \mathrm{tr}(\varepsilon) I + 2\mu^B(x,z_m)\ \varepsilon \tag{10}$$

$$\chi = \frac{1}{2}\left[\nabla \theta + (\nabla \theta)^T\right], \ \theta = \frac{1}{2}\mathrm{curl}(\mathrm{u}) \tag{11}$$

$$m = \left[2l^2(x,z_m)\mu^B(x,z_m)\right]\chi \tag{12}$$

where u and θ represent the displacement and rotation vectors, respectively. In this analysis, the gradation of the MLSP in thickness and length directions is considered, as described in Equations (1) and (2). The strain and the symmetric curvature components according to Equations (6), (8), (9) and (11) are:

$$\begin{array}{l} \varepsilon_{xx} = \frac{\partial u}{\partial x} - z_n\frac{\partial^2 w}{\partial^2 x} + R(z_n)\frac{\partial \phi}{\partial x} \\ \gamma_{xz} = \gamma_{zx} = 2\varepsilon_{xz} = \frac{\partial R(z_n)}{\partial z_m}\phi \end{array} \tag{13}$$

$$\begin{aligned}\chi_{xy} = \chi_{yx} &= \frac{1}{2}\left(\frac{1}{2}\frac{\partial R(z_n)}{\partial z_m}\frac{\partial \phi}{\partial x} - \frac{\partial^2 w}{\partial x^2}\right)\\ \chi_{yz} = \chi_{zy} &= \frac{1}{4}\frac{\partial^2 R(z_n)}{\partial z_m^2}\phi\end{aligned} \tag{14}$$

According to Equations (8) and (13), the nonzero components of the classical Cauchy stress tensors including the thermal effects and the deviatoric part of the couple stress tensor are:

$$\sigma_{xx}^B = \mathbb{E}^B(x, z_m, T)\varepsilon_{xx} - \mathbb{E}^{th}(x, z_m, T)\ \varepsilon^{th} \tag{15}$$

$$\sigma_{xz}^B = \mu^B(x, z_m, T)\frac{\partial R(z_n)}{\partial z_m}\ \phi \tag{16}$$

$$m_{yx} = m_{xy} = 2\left[l^2(x, z_m)\ \mu^B(x, z_m)\right]\ \chi_{xy} \tag{17}$$

$$m_{zy} = m_{yz} = 2\left[l^2(x, z_m)\ \mu^B(x, z_m)\right]\ \chi_{zy} \tag{18}$$

where the equivalent elasticity and thermal moduli are [65]:

$$\mathbb{E}^B(x, z_m, T) = \left[\lambda^B(x, z_m, T) + 2\mu^B(x, z_m, T)\right] \tag{19}$$

$$\mathbb{E}^{th}(x, z_m, T) = \left[3\lambda^B(x, z_m, T) + 2\mu^B(x, z_m, T)\right] \tag{20}$$

By ignoring the influence of Poisson's ratio, Equations (19) and (20) can be simplified to:

$$\mathbb{E}^B(x, z_m, T) = \mathbb{E}^{th}(x, z_m, T) = E(x, z_m, T) \tag{21}$$

where $\varepsilon^{th} = \alpha(x, z_m, T)\ \Delta T(z)$, which presents the thermal strain induced by temperature rise ΔT from the ambient temperature T_0, and α is the thermal expansion coefficient.

3. Formulation of Governing Equations

Based on elasticity theory and modified couple stress theory, the total strain energy ($\mathbb{U}$) of the BDFG beam is [66–68]:

$$\mathbb{U} = \frac{1}{2}\int_0^L \int_A \left[\sigma_{ij}\varepsilon_{ij} + m_{ij}\chi_{ij}\right] dA dx \tag{22}$$

where A is the cross-sectional area. Substituting Equations (15)–(18) into Equation (22) produces:

$$\mathbb{U} = \frac{1}{2}\delta\int_0^L \int_A \sigma_{xx}\varepsilon_{xx} + 2\sigma_{xz}\varepsilon_{xz} + 2m_{xy}\chi_{xy} + 2m_{yz}\chi_{yz} dA dx \tag{23}$$

Substituting Equations (15)–(18), the first variation of Equation (23) can be obtained as:

$$\delta\mathbb{U} = \int_0^L \left\{N(x)\frac{\partial \delta u}{\partial x} - [M_c(x) + \Upsilon_1(x)]\frac{\partial^2 \delta w}{\partial x^2} + \left[M_{nc}(x) + \frac{1}{2}\Upsilon_2(x)\right]\frac{\partial \delta\phi}{\partial x} + \left[Q_{nc}(x) + \frac{1}{2}\Upsilon_3(x)\right]\delta\phi\right\} dx dt \tag{24}$$

The classical Cauchy stress and couple stress resultants of the bulk continuum can be obtained as:

$$\begin{Bmatrix} N(x) \\ M_c(x) \\ M_{nc}(x) \end{Bmatrix} \equiv \int_A \sigma_{xx}\begin{Bmatrix} 1 \\ z_n \\ R(z_n) \end{Bmatrix} dA = \begin{bmatrix} A_{xx}(x) & B_{xx}(x) & E_{xx}(x) \\ B_{xx}(x) & D_{xx}(x) & F_{xx}(x) \\ E_{xx}(x) & F_{xx}(x) & H_{xx}(x) \end{bmatrix}\begin{Bmatrix} \frac{\partial u}{\partial x} \\ -\frac{\partial^2 w}{\partial x^2} \\ \frac{\partial \phi}{\partial x} \end{Bmatrix} \tag{25}$$

$$Q_{nc}(x) = \int_A \frac{dR(z_n)}{dz_m}\sigma_{xz} dA \equiv \overline{B}_{xz}(x)\phi \tag{26}$$

$$\begin{Bmatrix} \mathrm{Y}_1(x) \\ \mathrm{Y}_2(x) \\ \mathrm{Y}_3(x) \end{Bmatrix} \equiv \int_A m_{xy} \begin{Bmatrix} 1 \\ \frac{dR(z_n)}{dz} \\ \frac{d^2R(z_n)}{dz^2} \end{Bmatrix} dA = \begin{bmatrix} A_{xz}(x) & 0 & \frac{1}{2}D_{xz}(x) \\ D_{xz}(x) & 0 & \frac{1}{2}B_{xz}(x) \\ 0 & \frac{1}{2}E_{xz}(x) & 0 \end{bmatrix} \begin{Bmatrix} -\frac{\partial^2 w}{\partial x^2} \\ \phi \\ \frac{\partial \phi}{\partial x} \end{Bmatrix} \tag{27}$$

with

$$\begin{Bmatrix} A_{xx}(x) \\ B_{xx}(x) \\ D_{xx}(x) \\ E_{xx}(x) \\ F_{xx}(x) \\ H_{xx}(x) \end{Bmatrix} = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \mathbb{E}(x, z_m, T) \begin{Bmatrix} 1 \\ z_n \\ z_n^2 \\ R(z_n) \\ z_n R(z_n) \\ R^2(z_n) \end{Bmatrix} dzdy \tag{28}$$

$$\overline{B}_{xz}(x) = \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \mu(x, z_m, T) \left(\frac{\partial R(z_n)}{\partial z} \right)^2 dzdy \tag{29}$$

$$\begin{Bmatrix} A_{xz}(x) \\ B_{xz}(x) \\ D_{xz}(x) \\ E_{xz}(x) \end{Bmatrix} \equiv \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \left[l^2(x, z_m)\ \mu(x, z_m, T) \right] \begin{Bmatrix} 1 \\ \left(\frac{\partial R(z_n)}{\partial z} \right)^2 \\ \frac{\partial R(z_n)}{\partial z} \\ \left(\frac{\partial^2 R(z_n)}{\partial z^2} \right)^2 \end{Bmatrix} dzdy \tag{30}$$

Performing the partial integration in Equation (17) with respect to x and t over the time interval $[t_0, t_f]$, the total strain energy first variation can be calculated as:

$$\begin{aligned} \int_{t_0}^{t_f} \delta \mathbb{U} dt \equiv & - \int_{t_0}^{t_f} \int_0^L \left\{ \left[\frac{\partial \boldsymbol{\mathcal{N}}_{xx}(x)}{\partial x} \right] \delta u + \left[\frac{\partial^2 \boldsymbol{\mathcal{M}}_w(x)}{\partial x^2} \right] \delta w + \left[\frac{\partial \boldsymbol{\mathcal{M}}_\phi(x)}{\partial x} - \boldsymbol{\mathcal{Q}}_\phi(x) \right] \delta \phi \right\} dxdt \\ & + \int_{t_0}^{t_f} \left\{ [\boldsymbol{\mathcal{N}}_{xx}(x)] \delta u + \left[\frac{\partial \boldsymbol{\mathcal{M}}_w(x)}{\partial x} \right] \delta w - [\boldsymbol{\mathcal{M}}_w(x)] \frac{\partial \delta w}{\partial x} + [\boldsymbol{\mathcal{M}}_\phi(x)] \delta \phi \right\}_0^L dt \end{aligned} \tag{31}$$

in which the effective stress resultants are defined as

$$\begin{Bmatrix} N^B(x) \\ M_c^B(x) \\ M_{nc}^B(x) \end{Bmatrix} \equiv \int_A \sigma_{xx} \begin{Bmatrix} 1 \\ z_n \\ R(z_n) \end{Bmatrix} dA = \begin{bmatrix} A_{xx}^B(x) & B_{xx}^B(x) & E_{xx}^B(x) \\ B_{xx}^B(x) & D_{xx}^B(x) & F_{xx}^B(x) \\ E_{xx}^B(x) & F_{xx}^B(x) & H_{xx}^B(x) \end{bmatrix} \begin{Bmatrix} \frac{\partial u}{\partial x} \\ -\frac{\partial^2 w}{\partial x^2} \\ \frac{\partial \phi}{\partial x} \end{Bmatrix} \tag{32}$$

$$\begin{Bmatrix} \mathrm{Y}_1^B(x) \\ \mathrm{Y}_2^B(x) \\ \mathrm{Y}_3^B(x) \end{Bmatrix} \equiv \int_A m_{xy} \begin{Bmatrix} 1 \\ \frac{dR(z_n)}{dz} \\ \frac{d^2R(z_n)}{dz^2} \end{Bmatrix} dA = \begin{bmatrix} A_{xz}(x) & 0 & \frac{1}{2}D_{xz}(x) \\ D_{xz}(x) & 0 & \frac{1}{2}B_{xz}(x) \\ 0 & \frac{1}{2}E_{xz}(x) & 0 \end{bmatrix} \begin{Bmatrix} -\frac{\partial^2 w}{\partial x^2} \\ \phi \\ \frac{\partial \phi}{\partial x} \end{Bmatrix} \tag{33}$$

and

$$\begin{Bmatrix} \boldsymbol{\mathcal{N}}(x) \\ \boldsymbol{\mathcal{M}}_c(x) \\ \boldsymbol{\mathcal{M}}_{nc}(x) \end{Bmatrix} = \begin{Bmatrix} \boldsymbol{\mathcal{N}}_{xx}(x) \\ \boldsymbol{\mathcal{M}}_w(x) \\ \boldsymbol{\mathcal{M}}_\phi(x) \end{Bmatrix} \equiv \begin{Bmatrix} N^B(x) \\ M_c^B(x) + \mathrm{Y}_1^B(x) \\ M_{nc}^B(x) + \frac{1}{2}\mathrm{Y}_2^B(x) \end{Bmatrix} = \begin{bmatrix} \mathrm{A}_{11}(x) & \mathrm{B}_{11}(x) & \mathrm{E}_{11}(x) \\ \mathcal{B}_{11}(x) & \mathcal{D}_{11}(x) & \mathcal{F}_{11}(x) \\ \mathcal{E}_{11}(x) & \mathcal{F}_{11}(x) & \mathcal{H}_{11}(x) \end{bmatrix} \begin{Bmatrix} \frac{\partial u}{\partial x} \\ -\frac{\partial^2 w}{\partial x^2} \\ \frac{\partial \phi}{\partial x} \end{Bmatrix} \tag{34}$$

$$\boldsymbol{\mathcal{Q}}(x) = \boldsymbol{\mathcal{Q}}_\phi \equiv Q_{nc}(x) + \frac{1}{2}\mathrm{Y}_3^B(x) = \mathcal{B}_{xz}(x)\phi \tag{35}$$

with

$$\begin{Bmatrix} \mathcal{A}_{11}(x) \\ \mathcal{B}_{11}(x) \\ \mathcal{D}_{11}(x) \\ \mathcal{E}_{11}(x) \\ \mathcal{F}_{11}(x) \\ \mathcal{H}_{11}(x) \\ \mathcal{B}_{xz}(x) \end{Bmatrix} = \begin{Bmatrix} A_{xx}^B(x) \\ B_{xx}^B(x) \\ D_{xx}^B(x) + A_{xz}(x) \\ E_{xx}^B(x) \\ F_{xx}^B(x) + \frac{1}{2}D_{xz}(x) \\ H_{xx}^B(x) + \frac{1}{4}B_{xz}(x) \\ \overline{B}_{xz}(x) + \frac{1}{4}E_{xz}(x) \end{Bmatrix} \tag{36}$$

The kinetic energy of 2D-FG microbeams accounting for the size effect can be expressed as:

$$\begin{aligned}\mathbb{T} \equiv \tfrac{1}{2}\int_0^L \int_A \rho^B(x,z_m,T)\left[\left(\tfrac{\partial u_x}{\partial t}\right)^2+\left(\tfrac{\partial u_z}{\partial t}\right)^2\right]dAdx \\ = \tfrac{1}{2}\int_0^L \Big[\Big(\mathrm{I}_A(x)\tfrac{\partial u}{\partial t}-\mathrm{I}_B(x)\tfrac{\partial^2 w}{\partial x\partial t}+\mathrm{I}_E(x)\tfrac{\partial \phi}{\partial t}\Big)\tfrac{\partial u}{\partial t}+\mathrm{I}_A(x)\Big(\tfrac{\partial w}{\partial t}\Big)\tfrac{\partial w}{\partial t} \\ -\Big(\mathrm{I}_B(x)\tfrac{\partial u}{\partial t}-\mathrm{I}_D(x)\tfrac{\partial^2 w}{\partial x\partial t}+\mathrm{I}_F(x)\tfrac{\partial \phi}{\partial t}\Big)\tfrac{\partial^2 w}{\partial x\partial t}+\Big(\mathrm{I}_E(x)\tfrac{\partial u}{\partial t}-\mathrm{I}_F(x)\tfrac{\partial^2 w}{\partial x\partial t}+\mathrm{I}_H(x)\tfrac{\partial \phi}{\partial t}\Big)\tfrac{\partial \phi}{\partial t}\Big]dxx\end{aligned} \tag{37}$$

where the mass moments of inertia are computed by

$$\begin{Bmatrix}\mathrm{I}_A(x)\\ \mathrm{I}_B(x)\\ \mathrm{I}_D(x)\\ \mathrm{I}_E(x)\\ \mathrm{I}_F(x)\\ \mathrm{I}_H(x)\end{Bmatrix}=\int_{-\frac{b}{2}}^{\frac{b}{2}}\int_{-\frac{h}{2}}^{\frac{h}{2}}\rho^B(x,z_m,T)\begin{Bmatrix}1\\ z_n\\ z_n^2\\ R(z_n)\\ z_nR(z_n)\\ R^2(z_n)\end{Bmatrix}dzdy \tag{38}$$

The first-order variation of the kinetic energy of BDFG microbeam can be expressed by:

$$\delta\mathbb{T}=\int_{t_0}^{t_f}\int_0^L\left[\mathbb{P}_u(x)\frac{\partial\delta u}{\partial t}+\mathbb{P}_w(x)\frac{\partial\delta w}{\partial t}+\mathbb{P}_{w2}(x)\frac{\partial^2\delta w}{\partial x\partial t}+\mathbb{P}_\phi(x)\frac{\partial\delta\phi}{\partial t}\right]dxdt \tag{39}$$

in which the momentums are

$$\begin{Bmatrix}\mathbb{P}_u(x)\\ \mathbb{P}_w(x)\\ \mathbb{P}_{w2}(x)\\ \mathbb{P}_\phi(x)\end{Bmatrix}=\begin{bmatrix}\mathrm{I}_A(x) & 0 & -\mathrm{I}_B(x) & \mathrm{I}_E(x)\\ 0 & \mathrm{I}_A(x) & 0 & 0\\ -\mathrm{I}_B(x) & 0 & \mathrm{I}_D(x) & 0\\ \mathrm{I}_E(x) & 0 & -\mathrm{I}_F(x) & \mathrm{I}_H(x)\end{bmatrix}\begin{Bmatrix}\frac{\partial u}{\partial t}\\ \frac{\partial w}{\partial t}\\ \frac{\partial^2 w}{\partial x\partial t}\\ \frac{\partial\phi}{\partial t}\end{Bmatrix} \tag{40}$$

Proceeding the above integration by parts over the time interval $[t_0,t_f]$ with respect to x and t, and using the zero variation at time boundaries ($t=t_0$ and $t=t_f$), we obtain the following:

$$\begin{aligned}\int_{t_0}^{t_f}\delta\mathbb{T}dt \equiv -\int_{t_0}^{t_f}\int_0^L\left[\left\{\frac{\partial\mathbb{P}_u(x)}{\partial t}\right\}\delta u+\left\{\frac{\partial\mathbb{P}_{w1}(x)}{\partial t}-\frac{\partial^{|}{}_{w2}(x)}{\partial x\partial t}\right\}\delta w+\left\{\frac{\partial\mathbb{P}_\phi(x)}{\partial t}\right\}\delta\phi\right]dxdt+\int_{t_0}^{t_f}\left[\left\{-\frac{\partial\mathbb{P}_{w2}(x)}{\partial t}\right\}\delta w\right]_0^L dt \\ +\int_0^L\left[\{{}^{|}{}_u(x)\}\delta u+\{{}^{|}{}_w(x)\}\delta w+\{{}^{|}{}_{w2}(x)\}\frac{\partial\delta w}{\partial x}+\{{}^{|}{}_\phi(x)\}\delta\phi\right]_{t_0}^{t_f}dx\end{aligned} \tag{41}$$

3.1. Moving Load Formulations

The virtual work carried out by the applied forces on the BDFG beam, including modified couple stress theory, can be expressed as:

$$\delta\mathbb{W}=\int_\Omega(\mathbf{f}\cdot\delta\boldsymbol{u}+\mathbf{f}_c\cdot\delta\boldsymbol{\Theta})d\Omega+\oint_{\partial A}(\bar{\mathbf{t}}\cdot\delta\mathbf{u}+\bar{\mathbf{s}}\cdot\delta\boldsymbol{\Theta})dS \tag{42}$$

where $\mathbf{f}$ is the body force resultant and $\mathbf{f}_c$ is the body couple resultant per unit volume. In the absence of an applied compressive force, assuming the externally applied harmonic load moves with a constant speed, ignoring its inertial effect, a uniform thermal environment is assumed, and employing zero initial conditions, the virtual work in the time interval $[t_0,t_f]$ can be obtained as:

$$\begin{aligned}\int_{t_0}^{t_f}\delta\mathbb{W}dt=\int_0^L\{f_u\delta u+\left[P(x)\delta(x-vt)+q+\frac{\partial}{\partial x}\left(f_c-\frac{1}{2}f_ca_c(x)\right)\right]\delta w-\left(\frac{1}{2}f_ca_c(x)+N_{th}\frac{\partial \mathrm{w}}{\partial \mathrm{x}}\right)\delta\frac{\partial w}{\partial x}+\left(\frac{1}{2}f_ca_c(x)\right)\delta\phi\Big\}dx \\ +\int_{t_0}^{t_f}\left\{\overline{N}\delta u+\left[\overline{V}-\left(f_c-\frac{1}{2}f_ca_c(x)\right)\right]\delta w-(\overline{M}_c+\overline{M}_{nc})\delta\frac{\partial w}{\partial x}-\overline{M}_c\delta\phi\right\}_0^L dtx\end{aligned} \tag{43}$$

where δ is the Dirac delta function, and f_u and q are distributed loads in the x- and z-directions, respectively. f_c represents the y-component of the body couple per unit length along the x-axis. $\overline{N}$ is applied axial force, $\overline{V}$ is applied lateral force, $\overline{M}_c$ is the classical

bending moment, $\overline{M}_{nc}$ is the nonclassical bending moment due to the couple stress, and a_c is defined as:

$$a_c(x) = \int_{-b/2}^{b/2} \int_{-h/2}^{h/2} \frac{\partial R(z_n)}{\partial z} \, dzdy \tag{44}$$

The applied external moving harmonic load is given by:

$$P(x) = P_0 \sin \Omega t \tag{45}$$

in which P_0 and Ω are the amplitude and frequency, respectively, of the applied moving load.

3.2. Thermal Environment Formulations

To consider the impact of the thermal environment on the microbeam, a nonlinear temperature profile can be described by [65]:

$$T(z) = T_0 + \Delta T \left(\frac{Z}{h} + \frac{1}{2} \right)^{\alpha_T} \tag{46}$$

where the temperature difference $\Delta T = T_U - T_0$, and the lower surface temperature is kept constant at $T_B = T_0$.

Based on the power index α_T, two different temperature profiles across the thickness of the beam can be evaluated:

- Linear temperature rise (LTR) for $\alpha_T = 1$
- Nonlinear temperature rise (NTR) for $\alpha_T > 1$

By imposing the thermal influence on the formulation, the force and moment resultants can be evaluated by the integration of Equation (46), which yields:

$$\begin{Bmatrix} \overline{N}^{th}(x) \\ \overline{M}_c^{th}(x) \\ \overline{M}_{nc}^{th}(x) \end{Bmatrix} = \Delta T \int_{-\frac{b}{2}}^{\frac{b}{2}} \int_{-\frac{h}{2}}^{\frac{h}{2}} \mathbb{E}^{th}(x, z_m, T) \alpha(x, z, T) \left(\frac{z_n}{h} + \frac{1}{2} \right)^{\alpha^T} \begin{Bmatrix} 1 \\ z_n \\ \mathrm{R}_n(z) \end{Bmatrix} dzdy \tag{47}$$

In the present work, the nonclassical equilibrium motion and the corresponding nonclassical boundary conditions of 2D-FG microbeams are obtained employing the Hamilton principle:

$$\int_{t_0}^{t_f} (\delta \mathbb{T} - \delta \mathbb{U} + \delta \mathbb{W}) = 0 \tag{48}$$

By substitution Equations (41)–(43) into Equation (48), the governing equations of the 2D-FG temperature-dependent thermomechanical microbeam under moving mass can be evaluated as:

$$\begin{aligned} u : & -\mathrm{I}_A(x) \frac{\partial^2 u}{\partial t^2} + \mathrm{I}_B(x) \frac{\partial^3 w}{\partial x \partial t^2} - \mathrm{I}_E(x) \frac{\partial^2 \phi}{\partial t^2} + \mathcal{A}_{11}(x) \frac{\partial^2 u}{\partial x^2} - \mathcal{B}_{11}(x) \frac{\partial^3 w}{\partial x^3} + \mathcal{E}_{11}(x) \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial \mathcal{A}_{11}(x)}{\partial x} \frac{\partial u}{\partial x} \\ & - \frac{\partial \mathcal{B}_{11}(x)}{\partial x} \frac{\partial^2 w}{\partial x^2} + \frac{\partial \mathcal{E}_{11}(x)}{\partial x} \frac{\partial \phi}{\partial x} + f_u - \frac{\partial N}{\partial x} = 0 \end{aligned} \tag{49}$$

$$\begin{aligned} w : & \left\{ -\mathrm{I}_B(x) \frac{\partial^3 u}{\partial x \partial t^2} - \frac{\partial \mathrm{I}_B(x)}{\partial x} \frac{\partial^2 u}{\partial t^2} + \mathrm{I}_D(x) \frac{\partial^4 w}{\partial x^2 \partial t^2} + \frac{\partial \mathrm{I}_D(x)}{\partial x} \frac{\partial^3 w}{\partial x \partial t^2} - \mathrm{I}_A(x) \frac{\partial^2 w}{\partial t^2} - \mathrm{I}_F(x) \frac{\partial^3 \phi}{\partial x \partial t^2} - \frac{\partial \mathrm{I}_F(x)}{\partial x} \frac{\partial^2 \phi}{\partial t^2} \right\} \\ & + \left\{ \mathcal{B}_{11}(x) \frac{\partial^3 u}{\partial x^3} + 2 \frac{\partial \mathcal{B}_{11}(x)}{\partial x} \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 \mathcal{B}_{11}(x)}{\partial x^2} \frac{\partial u}{\partial x} \right\} \\ & + \left\{ -\mathcal{D}_{11}(x) \frac{\partial^4 w}{\partial x^4} - 2 \frac{\partial \mathcal{D}_{11}(x)}{\partial x} \frac{\partial^3 w}{\partial x^3} + \left\{ -\frac{\partial^2 \mathcal{D}_{11}(x)}{\partial x^2} - \overline{N}^{th}(x) \right\} \frac{\partial^2 w}{\partial x^2} \right\} \\ & + \left\{ \mathcal{F}_{11}(x) \frac{\partial^3 \phi}{\partial x^3} + 2 \frac{\partial \mathcal{F}_{11}(x)}{\partial x} \frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \mathcal{F}_{11}(x)}{\partial x^2} \frac{\partial \phi}{\partial x} \right\} \\ & + \left\{ \mathcal{A}_{11}(x) \frac{\partial^2 u}{\partial x^2} + \frac{\partial \mathcal{A}\mathcal{A}_{11}(x)}{\partial x} \frac{\partial u}{\partial x} + \frac{1}{2} \frac{\partial B_{11}(x)}{\partial x} \frac{\partial^2 w}{\partial x^2} + \frac{1}{2} \frac{\partial^2 B_{11}(x)}{\partial x^2} \frac{\partial w}{\partial x} + \varepsilon_{11}(x) \frac{\partial^2 \phi}{\partial x^2} \right. \\ & \left. + \frac{\partial \varepsilon_{11}(x)}{\partial x} \frac{\partial \phi}{\partial x} \right\} - \frac{\partial^2 \overline{M}_c^{th}(x)}{\partial x^2} + \left\{ P(x) \delta(x - vt) + q + \frac{\partial}{\partial x} \left(f_c - \frac{1}{2} f_c a_c(x) \right) \right\} = 0 \end{aligned} \tag{50}$$

$$\phi:\left\{-\mathrm{I}_E(x)\frac{\partial^2 u}{\partial t^2}+\mathrm{I}_F(x)\frac{\partial^3 w}{\partial x\partial t^2}-\mathrm{I}_H(x)\frac{\partial^2\phi}{\partial t^2}\right\}+\left\{\varepsilon_{11}(x)\frac{\partial^2 u}{\partial x^2}+\frac{\partial\varepsilon_{11}(x)}{\partial x}\frac{\partial u}{\partial x}\right\}$$
$$+\left\{-\mathcal{F}_{11}(x)\frac{\partial^3 w}{\partial x^3}-\frac{\partial\mathcal{F}_{11}(x)}{\partial x}\frac{\partial^2 w}{\partial x^2}\right\}+\left\{\mathcal{H}_{11}(x)\frac{\partial^2\phi}{\partial x^2}+\frac{\partial\mathcal{H}_{11}(x)}{\partial x}\frac{\partial\phi}{\partial x}-\mathcal{B}_{xz}(x)\phi(x)\right\} \quad (51)$$
$$-\left\{\frac{\partial\overline{M}^{th}_{nc}(x)}{\partial x}-\frac{1}{2}f_c a_c(x)\right\}=0$$

with the following boundary conditions:

$$\delta u:\ \textbf{Either}\ u=\widetilde{u}\ \textbf{or}\ \ \mathcal{A}_{11}(x)\frac{\partial u}{\partial x}-\mathcal{B}_{11}(x)\frac{\partial^2 w}{\partial x^2}+\mathcal{E}_{11}(x)\frac{\partial\phi}{\partial x}-\overline{N}=0 \quad (52)$$

$$\delta w:\ \textbf{Either}\ w=\widetilde{w}\textbf{or}\left\{-\mathrm{I}_B(x)\frac{\partial^2 u}{\partial t^2}+\mathrm{I}_D(x)\frac{\partial^3 w}{\partial x\partial t^2}-\mathrm{I}_F(x)\frac{\partial^2\phi}{\partial t^2}\right\}+\left\{\mathcal{B}_{11}(x)\frac{\partial^2 u}{\partial x^2}+\frac{\partial\mathcal{B}_{11}(x)}{\partial x}\frac{\partial u}{\partial x}\right\}$$
$$+\left\{-\mathcal{D}_{11}(x)\frac{\partial^3 w}{\partial x^3}-\frac{\partial\mathcal{D}_{11}(x)}{\partial x}\frac{\partial^2 w}{\partial x^2}-N\frac{\partial w}{\partial x}\right\}+\left\{\mathcal{F}_{11}(x)\frac{\partial^2\phi}{\partial x^2}+\frac{\partial\mathcal{F}_{11}(x)}{\partial x}\frac{\partial\phi}{\partial x}\right\} \quad (53)$$
$$+\left\{\overline{V}-\left(f_c-\frac{1}{2}f_c a_c(x)\right)\right\}=0\mid\alpha$$

$$\delta\phi:\ \textbf{Either}\ \ \phi=\widetilde{\phi}\ \textbf{or}\ \ \mathcal{E}_{11}(x)\frac{\partial u}{\partial x}-\mathcal{F}_{11}(x)\frac{\partial^2 w}{\partial x^2}+\mathcal{H}_{11}(x)\frac{\partial\phi}{\partial x}-\overline{M}_c=0 \quad (54)$$

$$\frac{\partial\delta w}{\partial x}:\ \textbf{Either}\frac{\partial w}{\partial x}=\frac{\overline{\partial w}}{\partial x}\textbf{or}\mathcal{B}_{11}(x)\frac{\partial u}{\partial x}-\mathcal{D}_{11}(x)\frac{\partial^2 w}{\partial x^2}+\mathcal{F}_{11}(x)\frac{\partial\phi}{\partial x}+\left\{\overline{M}_c+\overline{M}_{nc}\right\}=0 \quad (55)$$

4. Analytical Solution

To solve the system of partial differential equations of the SBDFG microbeam excited by a moving load, Equations (49)–(51), Galerkin's decomposition is adopted to reduce this set of equations into a system of ordinary differential equations. In this regard, the dynamic axial, transverse deflection, and the rotation of the SBDFG microbeam are truncated into n-modes as $w(x,t)=\sum_{n=1}^{\infty}W_n(t)\theta_w(x)$, $u(x,t)=\sum_{n=1}^{\infty}U_n(t)\theta_u(x)$, and $\phi(x,t)=\sum_{n=1}^{\infty}\Phi_n(t)\theta_\phi(x)$, in which the θ_w,θ_u, and θ_ϕ denote the appropriate nth mode shapes of the SBDFG beam that satisfies the boundary conditions. $W_n(t)$ is deflection time-dependent for nth mode shapes. In the case of SS boundary conditions, the mode shapes are $\theta_w(x)=\sin(\alpha_n x)$ and $\theta_u(x)=\theta_\phi(x)=\cos(\alpha_n x)$ and $\alpha_n=n\pi/L$. For simplicity, a single-mode Galerkin decomposition is used, $\alpha_n=\alpha=\pi/L$. Multiplying Equations (49)–(51) by $\cos(\alpha x)$ and $\sin(\alpha x)$, we can integrate the obtained equations with respect to x from 0 to L.

By using the general property of the Dirac delta function and its Fourier series $\delta(x,t)=\sum_{n=1}^{\infty}\sin(\alpha_n x)\sin(\alpha_n v_0 t)$, the following set of ODEs is obtained:

$$a_1\ddot{U}_n(t)+a_2U_n(t)+a_3\ddot{W}_n(t)+a_4W_n(t)+a_5\ddot{\Phi}_n(t)+a_6\Phi_n(t)=0 \quad (56)$$

$$b_1\ddot{U}_n(t)+b_2U_n(t)+b_3\ddot{W}_n(t)+b_4W_n(t)+b_5\ddot{\Phi}_n(t)+b_6\Phi_n(t)=F_1\sin(\alpha_n v_0 t) \quad (57)$$

$$c_1\ddot{U}_n(t)+c_2U_n(t)+c_3\ddot{W}_n(t)+c_4W_n(t)+c_5\ddot{\Phi}_n(t)+c_6\Phi_n(t)=0 \quad (58)$$

where the coefficients a_i, b_i, and c_i are defined as $(i=1,\ 2,\ \ldots 6)$

$$\begin{Bmatrix} a_1 & a_2\\ a_3 & a_4\\ a_5 & a_6\end{Bmatrix}=\int_0^L\begin{Bmatrix}-\mathrm{I}_A(x)\theta_u & \mathcal{A}_{11}(x)\theta_u''+\frac{\partial\mathcal{A}\mathcal{A}_{11}(x)}{\partial x}\theta_u'\\ \mathrm{I}_B(x)\theta_w' & -\mathcal{B}_{11}(x)\theta_w'''-\frac{\partial\mathcal{B}_{11}(x)}{\partial x}\theta_w''\\ -\mathrm{I}_E(x)\theta_\phi & \mathcal{E}_{11}(x)\theta_\phi''+\frac{\partial\mathcal{E}_{11}(x)}{\partial x}\theta_\phi'\end{Bmatrix}\cos(\alpha_m x)dx \quad (59)$$

$$\begin{Bmatrix} b_1 & b_2 \\ b_3 & b_4 \\ b_5 & b_6 \end{Bmatrix} = \int_0^L \begin{Bmatrix} -\mathrm{I}_B(x)\theta_u' - \frac{\partial \mathrm{I}_B(x)}{\partial x}\theta_u & \mathcal{B}_{11}(x)\theta_u''' + 2\frac{\partial \mathcal{B}_{11}(x)}{\partial x}\theta_u'' + \frac{\partial^2 \mathcal{B}_{11}(x)}{\partial x^2}\theta_u' \\ \mathrm{I}_D(x)\theta_w'' + \frac{\partial \mathrm{I}_D(x)}{\partial x}\theta_w' - \mathrm{I}_A(x)\theta_w & -\mathcal{D}_{11}(x)\theta_w''' - 2\frac{\partial \mathcal{D}_{11}(x)}{\partial x}\theta_w''' + \left\{-\frac{\partial^2 \mathcal{D}_{11}(x)}{\partial x^2} - N_{th}\right\}\theta_w'' \\ -\mathrm{I}_F(x)\theta_\phi' - \frac{\partial \mathrm{I}_F(x)}{\partial x}\theta_\phi & \mathcal{F}_{11}(x)\theta_\phi''' + 2\frac{\partial \mathcal{F}_{11}(x)}{\partial x}\theta_\phi'' + \frac{\partial^2 \mathcal{F}_{11}(x)}{\partial x^2}\theta_\phi' \end{Bmatrix} \sin(\alpha_m x)dx \quad (60)$$

$$\begin{Bmatrix} c_1 & c_2 \\ c_3 & c_4 \\ c_5 & c_6 \end{Bmatrix} = \int_0^L \begin{Bmatrix} -\mathrm{I}_E(x)\theta_u & \mathcal{E}_{11}(x)\theta_u'' + \frac{\partial \mathcal{E}_{11}(x)}{\partial x}\theta_u' \\ \mathrm{I}_F(x)\theta_w' & -\mathcal{F}_{11}(x)\theta_w''' - \frac{\partial -\mathcal{F}_{11}(x)}{\partial x}\theta_w'' \\ -\mathrm{I}_H(x)\theta_\phi & \mathcal{H}_{11}(x)\theta_\phi'' + \frac{\partial \mathcal{H}_{11}(x)}{\partial x}\theta_\phi' - \mathcal{B}_{xz}(x)\theta_\phi \end{Bmatrix} \cos(\alpha_m x)dx \quad (61)$$

$$\text{and} F_1 = -\int_0^L P(x)\sin(\alpha_n x)\sin(\alpha_m x)$$

with the initial condition:

$$W_n(0) = \dot{W}_n(0) = U_n(0) = \dot{U}_n(0) = \Phi_n(0) = \dot{\Phi}_n(0) \quad (62)$$

To solve the system of equations in the time domain, Laplace transform (LT) is proposed with the following functions: $\mathcal{L}\left\{\ddot{W}_n(t)\right\} = s^2 W_s(s) - sW_n(0) - \dot{W}_n(0)$, where $\mathcal{L}\{W_n(t)\} = W_s(s)$ and $\mathcal{L}\left\{\ddot{U}_n(t)\right\} = s^2 U_s(s) - sU_n(0) - \dot{U}_n(0)$ and $\mathcal{L}\left\{\ddot{\Phi}_n(t)\right\} = s^2\Phi_s(s) - s\Phi_n(0) - \dot{\Phi}_n(0)$.

Finally, by using the initial conditions and applying Laplace transform (LT), the system of equations in Laplace form is obtained as follows:

$$\left(a_1 s^2 + a_2\right)U_s + \left(a_3 s^2 + a_4\right)W_s + \left(a_5 s^2 + a_6\right)\Phi_s = 0 \quad (63)$$

$$\left(b_1 s^2 + b_2\right)U_s + \left(b_3 s^2 + b_4\right)W_s + \left(b_5 s^2 + b_6\right)\Phi_s = \frac{F_1\alpha_n v_0}{(\alpha_n v_0)^2 + s^2} \quad (64)$$

$$\left(c_1 s^2 + c_2\right)U_s + \left(c_3 s^2 + c_4\right)W_s + \left(c_5 s^2 + c_6\right)\Phi_s = 0 \quad (65)$$

Solving Equation (63)–(65), one derives:

$$W_s(s) = \frac{r_1 s^4 + r_2 s^2 + r_3}{\mathcal{K}_1 s^6 + \mathcal{K}_2 s^4 + \mathcal{K}_3 s^2 + \mathcal{K}_4}\left(\frac{1}{(\alpha_n v_0)^2 + s^2}\right) \quad (66)$$

in which

$$\mathcal{K}_1 = a_1(b_3c_5 - b_5c_3) + a_3(b_5c_1 - b_1c_5) + a_5(b_1c_3 - b_3c_1) \quad (67)$$

$$\begin{aligned}\mathcal{K}_2 = {} & a_1(b_3c_6 + b_4c_5 - b_5c_4 - b_6c_3) + a_3(b_5c_2 + b_6c_1 - b_1c_6 - b_2c_5) + a_5(b_1c_4 + b_2c_3 - b_3c_2 - b_4c_1) \\ & + a_2(b_3c_5 - b_5c_3) + a_4(b_5c_1 - b_1c_5) + a_6(b_1c_3 - b_3c_1)\times\end{aligned} \quad (68)$$

$$\begin{aligned}\mathcal{K}_3 = {} & a_1(b_3c_6 + b_4c_5 - b_5c_4 - b_6c_3) + a_3(b_5c_2 + b_6c_1 - b_1c_6 - b_2c_5) + a_5(b_1c_4 + b_2c_3 - b_3c_2 - b_4c_1) \\ & + a_2(b_3c_5 - b_5c_3) + a_4(b_5c_1 - b_1c_5) + a_6(b_1c_3 - b_3c_1)\end{aligned} \quad (69)$$

$$\mathcal{K}_4 = \mathrm{a}_2(\mathrm{b}_4\mathrm{c}_6 - \mathrm{b}_6\mathrm{c}_4) + \mathrm{a}_4(\mathrm{b}_6\mathrm{c}_2 - \mathrm{b}_2\mathrm{c}_6) + \mathrm{a}_6(\mathrm{b}_2\mathrm{c}_4 - \mathrm{b}_4\mathrm{c}_2) \quad (70)$$

and

$$\begin{Bmatrix} r_1 \\ r_2 \\ r_3 \end{Bmatrix} = F_1\alpha_n v_0 \begin{Bmatrix} a_1c_5 - a_5c_1 \\ a_1c_6 + a_2c_5 - a_5c_2 - a_6c_1 \\ a_2c_6 - a_6c_2 \end{Bmatrix} \quad (71)$$

The roots of the sixth-order polynomial of the dominator of $W_s(s)$ can be found as

$$\left\{\begin{array}{c}\psi_{1,2}\\ \psi_{3,4}\\ \psi_{5,6}\end{array}\right\}=\left\{\begin{array}{c}\pm\sqrt{\frac{\Delta_1-\left(12\mathcal{K}_1\mathcal{K}_3-4\mathcal{K}_2^2\right)-2\mathcal{K}_2\Delta_1}{6\mathcal{K}_1\Delta_1}}\\ \pm\sqrt{\frac{1}{12\mathcal{K}_1\Delta_1}\left[-\Delta_1^2+\left(12\mathcal{K}_1\mathcal{K}_3-4\mathcal{K}_2^2\right)-4\mathcal{K}_2\Delta_1+\sqrt{3}i\left(\Delta_1^2+12\mathcal{K}_1\mathcal{K}_3-4\mathcal{K}_2^2\right)\right]}\\ \pm\sqrt{\frac{1}{12\mathcal{K}_1\Delta_1}\left[-\Delta_1^2+\left(12\mathcal{K}_1\mathcal{K}_3-4\mathcal{K}_2^2\right)-4\mathcal{K}_2\Delta_1-\sqrt{3}i\left(\Delta_1^2+12\mathcal{K}_1\mathcal{K}_3-4\mathcal{K}_2^2\right)\right]}\end{array}\right] \quad (72)$$

where

$$\Delta_1=\sqrt[3]{-108\,\mathcal{K}_4\,\mathcal{K}_1^2+36\,\mathcal{K}_3\,\mathcal{K}_2\,\mathcal{K}_1+12\,\sqrt{3}\,\mathcal{K}_1\sqrt{27\,\mathcal{K}_4^2\mathcal{K}_1^2-18\,\mathcal{K}_4\,\mathcal{K}_1\,\mathcal{K}_2\,\mathcal{K}_3+4\,\mathcal{K}_4\mathcal{K}_2^3+4\,\mathcal{K}_1\mathcal{K}_3^3-\mathcal{K}_2^2\mathcal{K}_3^2}-8\,\mathcal{K}_2^3} \quad (73)$$

By using the inverse Laplace transform (ILT) to $W_s(s)$, the dynamic response can be obtained by

$$w(x,t)=\frac{1}{\mathcal{K}_1 d_0}\left(d_1\sinh(\psi_5 t)+d_2\sinh(\psi_1 t)-d_3\sinh(\psi_3 t)+d_4\sin(\alpha_n v_0 t)\right)\sin(\alpha_n x) \quad (74)$$

in which

$$\left\{\begin{array}{c}d_0\\ d_1\\ d_2\\ d_3\\ d_4\end{array}\right\}=\left\{\begin{array}{c}\psi_1\psi_3\psi_5\alpha_n v_0\left(\psi_1^2-\psi_3^2\right)\left(\psi_1^2-\psi_5^2\right)\left(\psi_3^2-\psi_5^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_5^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_3^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_1^2\right)\\ \alpha_n v_0\psi_3\psi_1\left(\psi_1^2-\psi_3^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_1^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_3^2\right)\left(\psi_5^4 r_1+\psi_5^2 r_2+r_3\right)\\ \alpha_n v_0\psi_3\psi_5\left(\psi_3^2-\psi_5^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_3^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_5^2\right)\left(\psi_1^4 r_1+\psi_1^2 r_2+r_3\right)\\ \alpha_n v_0\psi_1\psi_5\left(\psi_1^2-\psi_5^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_5^2\right)\left(\left(\alpha_n v_0\right)^2+\psi_1^2\right)\left(\psi_3^4 r_1+\psi_3^2 r_2+r_3\right)\\ \psi_1\psi_3\psi_5\left(\psi_1^2-\psi_5^2\right)\left(\psi_3^2-\psi_5^2\right)\left(\psi_1^2-\psi_3^2\right)\left(-\left(\alpha_n v_0\right)^4 r_1+\left(\alpha_n v_0\right)^2 r_2-r_3\right)\end{array}\right\} \quad (75)$$

The following nondimensional quantities are proposed in the analysis to generalize the problem:

$$\overline{w}(x,t)=\frac{w(x,t)}{D_0},\ \ \overline{\omega}_1=\omega_1 L^2\sqrt{\rho_c bh/E_c I}\,,\ \ \overline{v}=\frac{v}{V_c},\ \ V_c=\frac{L\omega_1}{\pi},\ \ \tau=\frac{t}{L/v} \quad (76)$$

where $\overline{w}(x,t)$ represents the normalized dynamic deflections. D_0 is the peak transverse deflection of the beam with full metal constituent under a point load $\left(D_0=P_0\,L^3/48E_m\,I\right)$, $I=bh^3/12$. ω_1 is the dimensionless first natural frequency. $\overline{v}$ is the dimensionless velocity of the moving load. V_c is the critical velocity (the maximum magnitudes of the maximum deflections to occur). τ $(0<\tau<1)$ signifies the dimensionless time. When $\tau>1$, the load is away from the beam.

5. Model Validation

This section presents the convergence and accuracy of the present model and solution procedure by comparing our results with previous works. Since there is no previous work considering bidirectional sigmoidal graded beams, the SBDFG is validated with power law results for the $k_z=1$ case and also for the homogeneous case $k_z=k_x=0$. Table 1 compares the peak deflections $\left(\overline{w}_p\right)$ and the corresponding absolute velocities $\left(v_p\right)$ of an SS transverse power functionally graded (TPFG) SUS304/Al2O3 beam with the results reported by [29,35,69,70] at $\Omega_f=0$ (ignoring temperature effect). In Table 1, the beam is composed of a mixture of metal SUS304 stainless steel (E_m = 210 GPa and mass density of ρ_m^B = 7800 kg/m^3) and ceramic (Al_2O_3) (E_c = 390 GPa, and ρ_c^B = 3960 kg/m^3). The beam has 0.4 m width, 0.9 m thickness, and 20 m length. As concluded, the current results for dynamic deflection and absolute velocity are close to all previous works, within 1% maximum deviation.

Table 1. Peak normalized dynamic deflection $(\overline{w}_p)$ and corresponding absolute velocity v_p of simply supported beams, at $T(z) = 0$.

	Source	Pure SUS304	k_z = 1.0	Pure Al_2O_3
$(\overline{w}_p)$	Present, SBDFG	1.7475	1.2641	0.9433
	Ref. [29] (RBT)	1.7384	1.2575	0.9384
	Ref. [70] (TBT)	1.7379	1.2287	0.9382
	Ref. [69] (TBT)	1.7420	1.2566	0.9380
	Ref. [35] (EBT)	1.7324	1.2503	0.9328
v_p	Present, SBDFG	130	177	249
	Ref. [29] (RBT)	131	178	252
	Ref. [70] (TBT)	132	179	252
	Ref. [69] (TBT)	131	178	251
	Ref. [35] (EBT)	132	179	252

To validate the temperature effect, a beam with constituents of metal (SUS304 stainless steel) and silicon nitride (Si_3N_4) is considered. The material properties are temperature-dependent according to Equation (3) for SUS304 and Si_3N_4. The constants $\mathcal{P}_0$, $\mathcal{P}_{-1}$, $\mathcal{P}_2$, $\mathcal{P}_2$ and $\mathcal{P}_3$ are given in Table 2 for metal and ceramic phases. Considering the validation of the temperature effect, the fundamental dimensionless frequency $\overline{\omega}$ of the simply supported TSFG SUS304/Si_3N_4 beam is validated by Ebrahimi and Salari [71] for EBT at different temperature differences ΔT (LTR), as in Table 3. As seen, the natural frequencies of isotropic and FG material are decreased with increasing temperature differences or by increasing the gradation index through thickness. The same observation was predicted by Ebrahimi and Salari [71].

Table 2. Temperature-dependent coefficients for metal (SUS304) and ceramic (Si_3N_4) constituents [71].

Material	Properties	$\mathcal{P}_{-1}$	$\mathcal{P}_0$	$\mathcal{P}_1$	$\mathcal{P}_2$	$\mathcal{P}_3$
SUS304 (Metal)	E(Pa)	0	201.04×10^9	3.079×10^{-4}	-6.534×10^{-7}	0
	ρ(Kg/m^3)	0	8166	0	0	0
	ν	0	0.3262	0	0	0
	α(1/K)	0	12.330×10^{-6}	8.086×10^{-4}	0	0
Si_3N_4 (Ceramic)	E(Pa)	0	348.43×10^9	-3.070×10^{-4}	2.160×10^{-7}	-8.946×10^{-11}
	ρ(Kg/m^3)	0	2170	0	0	0
	ν	0	0.24	0	0	0
	α(1/K)	0	5.8723×10^{-6}	9.095×10^{-4}	0	0

Table 3. Comparison of the fundamental dimensionless frequency of simply supported TFG SUS304/Si_3N_4 beams at different temperature differences $\Delta T(LTR)$.

Source	ΔT	k_z = 0.0	k_z = 1.0
Present, SBDFG	10	9.7643	5.7294
Ref. [71] (TBT)		9.6461	5.7717
Present, SBDFG	30	9.6074	5.5964
Ref. [71] (TBT)		9.4538	5.6105
Present, SBDFG	60	9.3682	5.3889
Ref. [71] (TBT)		9.1475	5.3537

In Figures 2 and 3, the fundamental frequency and the maximum dynamic response at the center are calculated to give comparisons with two available results in the literature. First, a comparison is performed with Liu et al. [41], showing the dependency of the dimensionless fundamental frequency of the SBDFG on temperature under LTR. Secondly, to show the accuracy of the present analytical solution, the relation between dimensionless dynamic deflection and moving load speed is validated by Abdelrahman et al. [44] and

Şimşek [36]. Through these validations and as can be observed, there is good agreement with the literature results, which demonstrates the validity of the present model and its analytical solution.

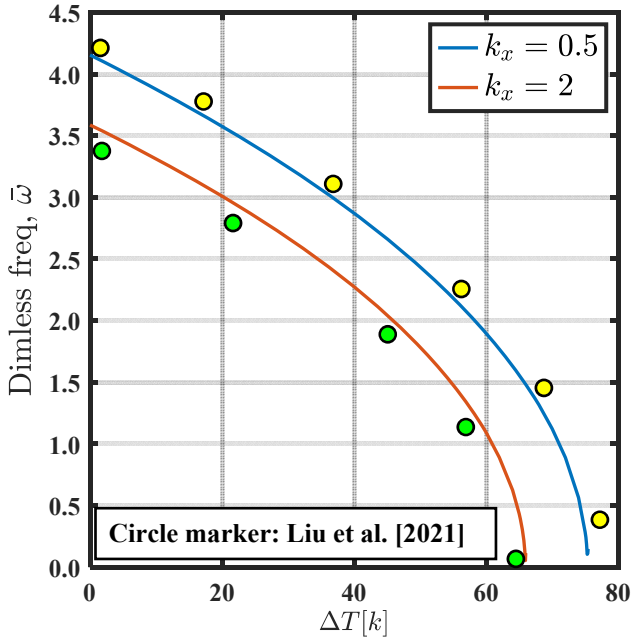


Figure 2. Comparison of the dependency of the dimensionless fundamental frequency of the beam at different temperature differences ΔT under LTR for $k_x = (0.5,\ 2)$, $k_z = 0.5$, $lcs = 0.25\ h$.

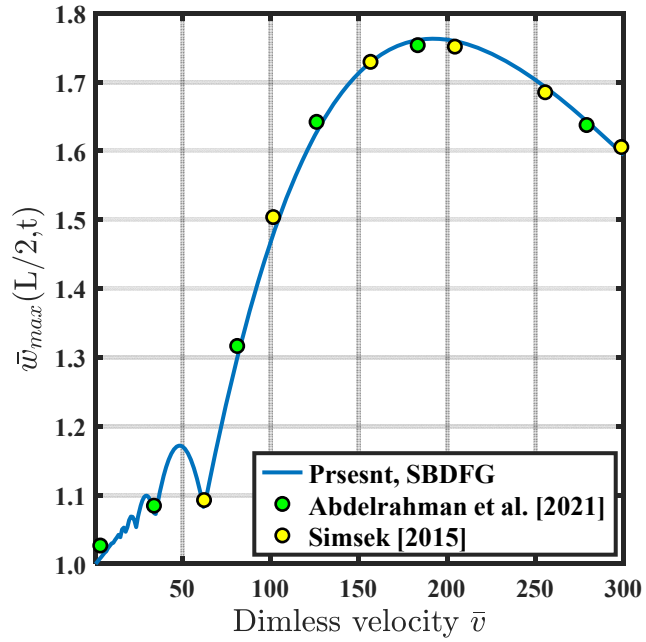


Figure 3. The variation in the dynamic deflection at the center of the beam vs. moving load velocity.

6. Numerical Results

In this section, the influences of different key parameters on the dynamical response of SBDFG microbeams under a moving harmonic load are extensively explored, i.e., the transverse and axial gradient indices, velocity, frequency, temperature, and the small-scale effects due to the microstructure energy. Consider a simply supported SBDFG microbeam made of metal (SUS304) and ceramic (Si_3N_4) with the material properties in Table 2. In the following results, the material length scale constants $\mathcal{P}_0$ for metal and ceramic phases

are $l_m = l_c = l = 22.5\ \mu$m, and the other material length constants are set to zero [65,72]. The beam dimensions are $h = b = 2l$ and $L = 25h$. The other geometrical and material parameters are fixed through analysis.

6.1. Influence of the Gradation Indices

Variations in the dimensionless fundamental frequency of SBDFG microbeams with SS boundaries vs. temperature variations are portrayed in Figures 4 and 5, respectively. From Figures 4 and 5, we can conclude that frequencies of SBDFG microbeams reduce with the rise in temperature until reaching the critical frequency temperature. This is because the geometrical stiffness decreases when the temperature rises without any variation in equivalent mass. The frequency reaches zero at the critical temperature point. After that, the stiffness induced by thermal load is higher than the structural stiffness; hence, the increase in temperature yields higher frequency after the branching point [71]. The branching point of the SBDFG microbeam is delayed by consideration of the lower axial gradient index, as seen in Figure 5. However, by increasing the transverse gradation index of the SBDFG microbeam, the critical temperature will be increased insignificantly, as concluded from Figure 4.

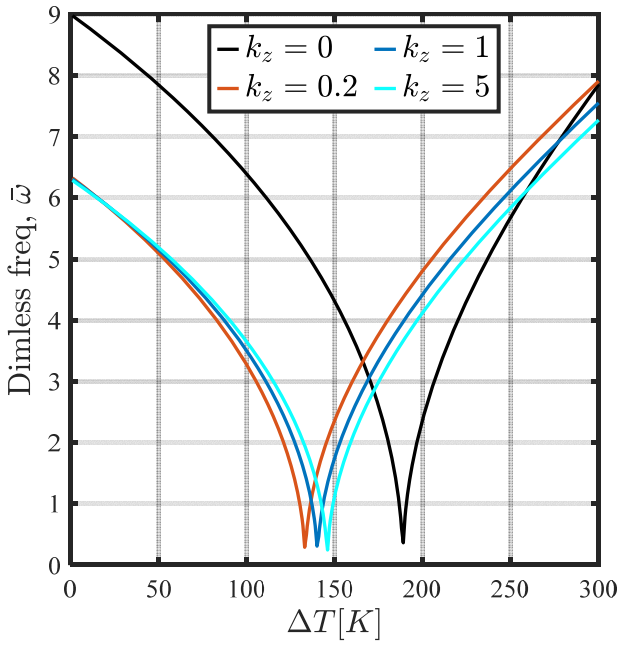


Figure 4. Influence of the transverse gradient index on the dimensionless fundamental frequency at different temperature differences ΔT under LTR and based on classical analysis ($l = 0$, $k_x = 0.2$).

Figures 6 and 7 illustrate the variation in the maximum normalized central dynamic deflection (dynamic magnification factor, $\overline{w}_{max}(L/2, t)$) vs. the dimensionless moving velocity at different values of k_z and k_x, respectively. Both temperature-dependent and -independent LTR are considered at ΔT = 80. It is depicted from Figures 6 and 7 that $\overline{w}_{max}(L/2, t)$, over the entire time history, both increases and decreases, then increases to reach the peak value when the velocity reaches critical values. After that, $\overline{w}_{max}$ gradually decreases as the moving load velocity increases, which is consistent with Olsson's observation [73]. The velocity at which $\overline{w}_{max}$ attains its peak value is denoted as the beam critical velocity [74]. At lower velocities of the moving load, the repeated increase and decrease in the $\overline{w}_{max}$ is due to the beam oscillations. It is noted that by increasing the gradation index through the thickness, the dynamic deflection increases for temperature-independent material. However, in the case of temperature-dependent material, increasing in k_z from 0 to 0.2, the dynamic deflection increases significantly, and after that, dynamic deflection reduces by increasing the gradation index k_z. The effect of gradation index in the axial

direction on the dynamic deflection is increased significantly in the case of LTR relative to temperature-independent material, as seen from Figure 7. The maximum deflection increased from 2.1 to 6.1 as k_x changed from 0 to 5 in the case of LTR. However, it increased from 0.9 to 1.2 as k_x changed from 0 to 5 in the case of temperature-independent material.

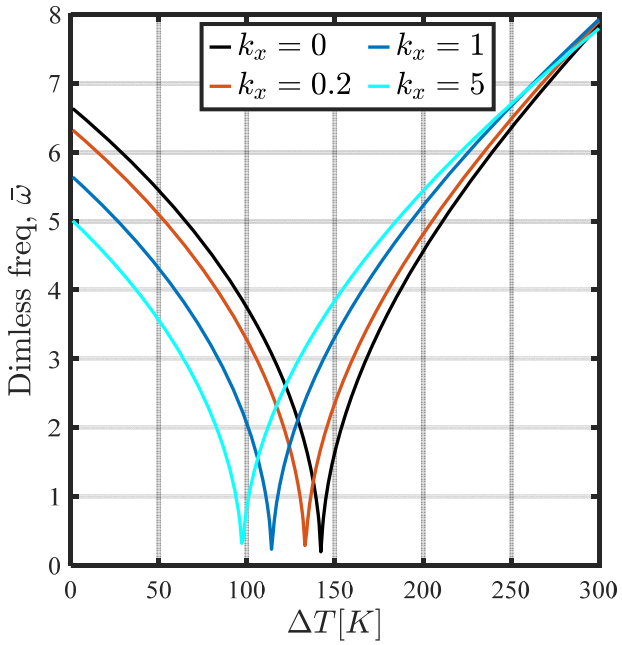


Figure 5. Influence of the axial gradient index on the dimensionless fundamental frequency at different temperature differences ΔT under LTR and based on classical analysis ($l = 0$, $k_z = 0.2$).

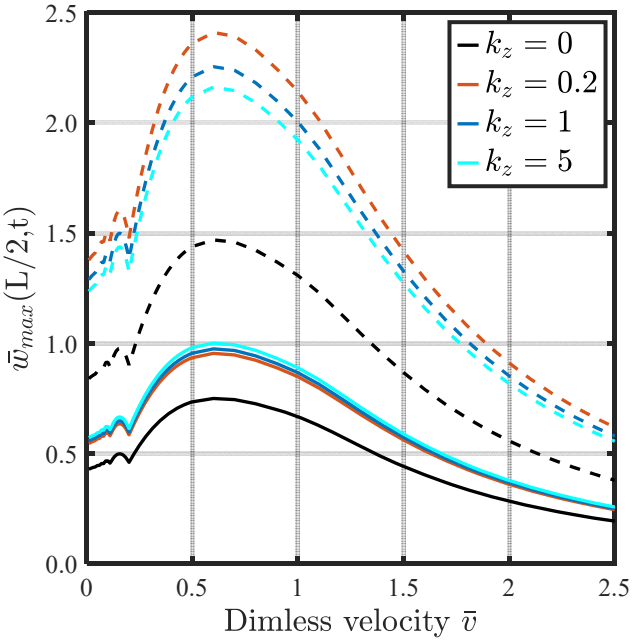


Figure 6. Influence of the transverse gradient index on the variation in the maximum normalized central dynamic deflection with the velocity ($k_x = 0.2$); (__) temperature-independent, (- -) temperature-dependent ($\Delta T = 80$, LTR).

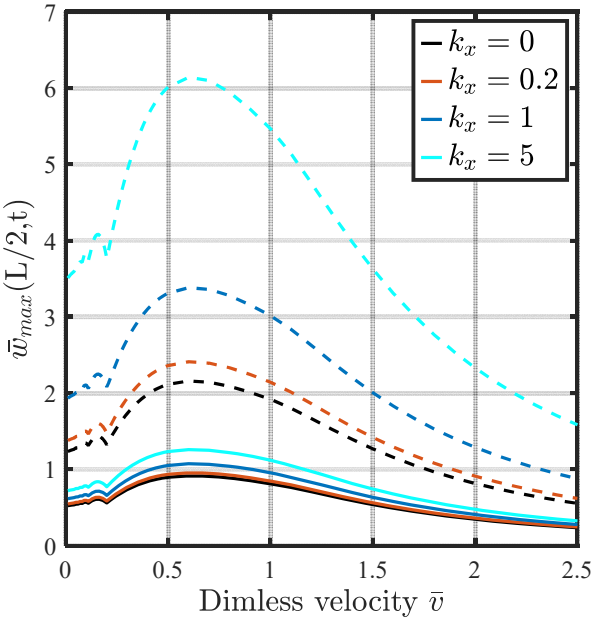


Figure 7. Influence of the axial gradient index on the variation in the maximum normalized central dynamic deflection with the velocity ($k_z = 0.2$); (__) temperature-independent, (- -) temperature-dependent ($\Delta T = 80$, LTR).

6.2. Influence of Temperature Distribution

The impact of temperature distribution type on the dynamic deflection of the SBDFG microbeam is described in this subsection. The temperature rise for linear temperature rise (LTR) and nonlinear temperature rise (NTR) distribution is assumed as $\Delta T = 100$ $[K]$ by adjusting the initial temperature T_0 to room temperature at 300 K. Figure 8 shows that different temperature formulations and the moving velocity considerably affect the amplitude of dynamic deflection. Obviously, the temperature for the LTR type is larger than that for both the NTR type and temperature-independent material. As seen, by increasing the velocity, the profile of dynamic deflection vs. time τ is changed completely from oscillatory to parabolic to exponential functions. Thus, it can be concluded that the dynamic deflection profile response is dependent on the velocity of the moving mass.

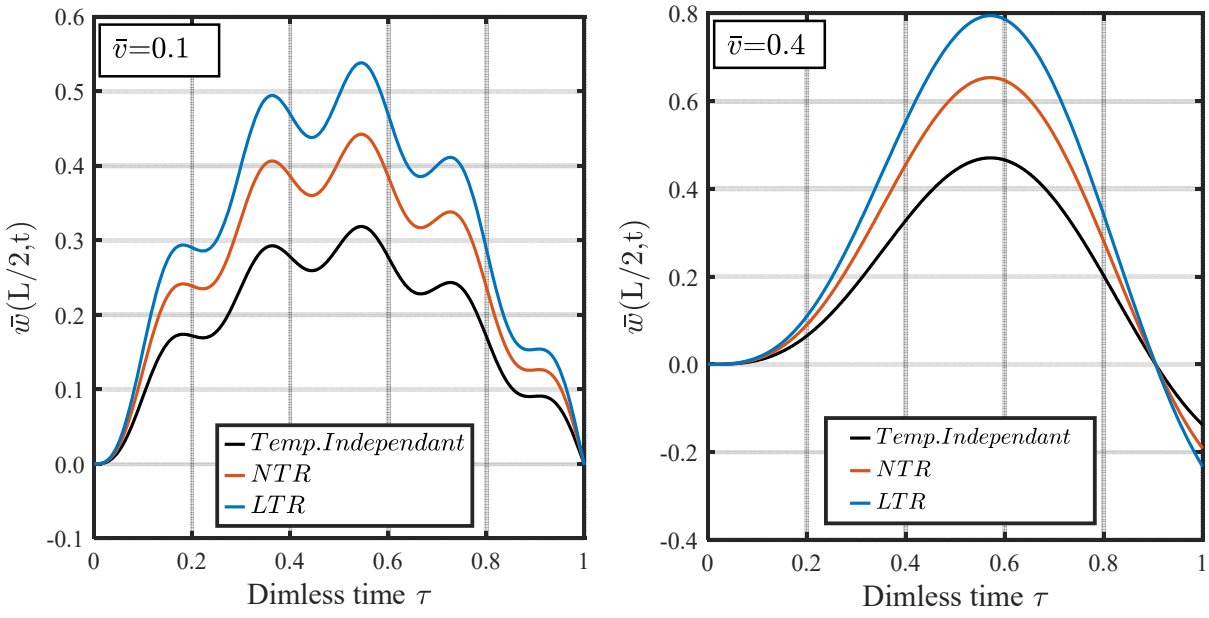


Figure 8. *Cont.*

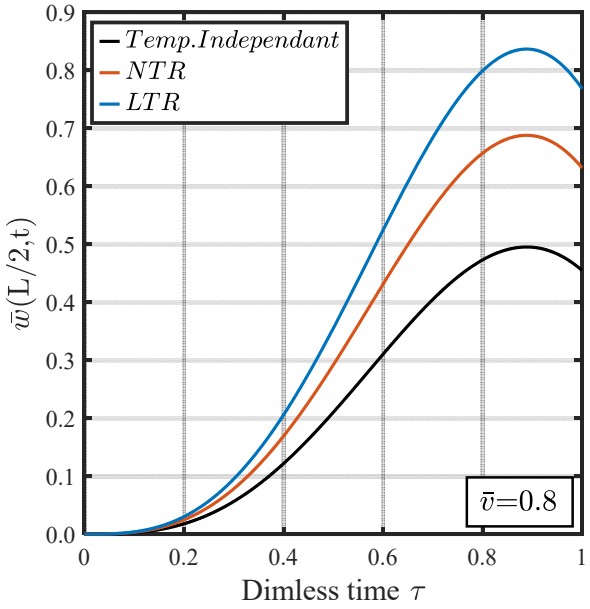


Figure 8. Influence of temperature distribution (temperature-independent, LTR and NTR with $\alpha_T = 2$) on the dimensionless central deflection vs. time under a uniform moving load ($k_x = k_z$ = 0.2) at $\bar{v}$ = 0.1, 0.4, and 0.8 and $\Delta T = 100$.

6.3. Influence of the Moving Load Velocity

Figure 9 shows that for both classical (CL) and couple stress (CS) formulations, the moving velocity considerably affects the amplitude of dynamic deflection. The shapes of the time history curves are strongly affected by the moving velocity. The number of vibration cycles of the microbeam is enlarged at low velocities of the moving load because the ratio of moving load velocity to critical velocity becomes low.

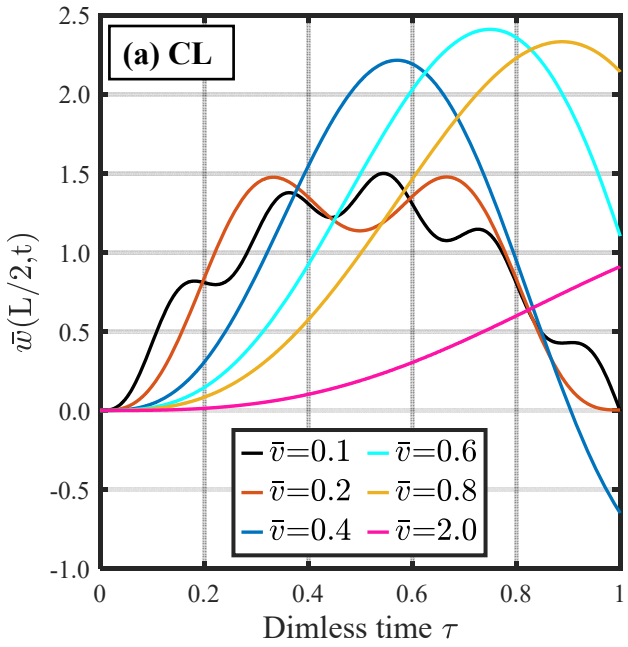


Figure 9. *Cont.*

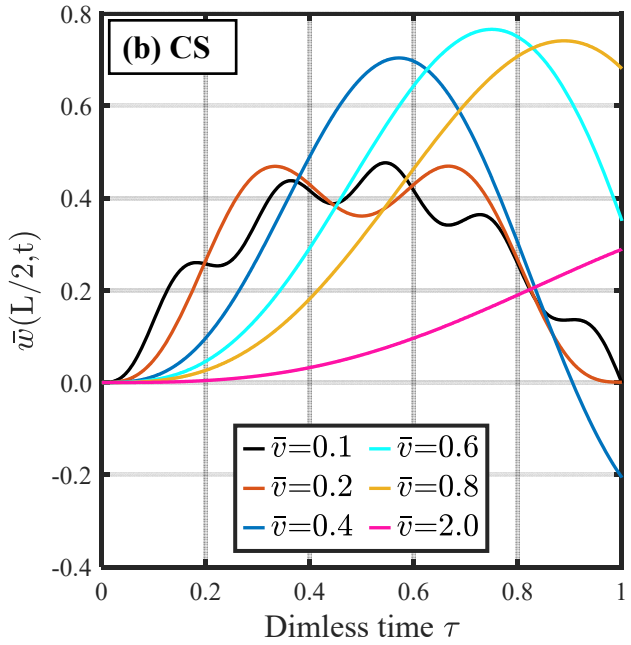


Figure 9. Influence of the dimensionless velocity on the variation in the dimensionless central deflection vs. the dimensionless time under a uniform moving load based on CL and CS formulations ($\Delta T = 80$, *LTR*, $k_x = k_z = 0.2$.

7. Conclusions

A dynamic response in closed-form solutions for sigmoid bidirectional functionally graded microbeams excited by a moving harmonic mechanical load under a thermal environment was developed by considering the microstructure effect. Temperature-dependent thermomechanical materials with linear and nonlinear temperature profiles were considered. The nonclassical equations of motion and boundary conditions were developed and solved by Galerkin's decomposition technique in conjunction with Laplace transform and the implicit Newmark time integration method. The main points can be drawn from this analysis as follows:

- ✓ Fundamental frequencies of SBDFG microbeams reduce with a rise in temperature until it reaches the critical frequency temperature. This is because the geometrical stiffness decreases when the temperature rises without any variation in equivalent mass.
- ✓ By increasing the gradation index through the thickness, the dynamic deflection increases for temperature-independent material. However, in the case of temperature-dependent material, increasing in k_z from 0 to 0.2, the dynamic deflection increased significantly, and after that, dynamic deflection reduced with the increasing gradation index k_z.
- ✓ The effect of gradation index in the axial direction on the dynamic deflection is increased significantly in the case of LTR relative to temperature-independent material.
- ✓ The temperature for the LTR type is larger than that for both the NTR type and temperature-independent material. As seen, by increasing the velocity, the profile of dynamic deflection vs. time τ is changed completely from oscillatory to parabolic to exponential functions. Therefore, the dynamic deflection profile response is dependent on the velocity of the moving mass.
- ✓ The shapes of the time history curves are strongly affected by the moving velocity. The number of vibration cycles of the microbeam is enlarged at low velocities of the moving load because the ratio of moving load velocity to critical velocity becomes low.

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