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Intelligent computer modeling of large amplitude behavior of FG inhomogeneous nanotubes

Xiongwei Wu* and Ting Fang

School of Electronics and Information, Nanchang Institute of Technology, Nanchang 330044, Jiangxi, China

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Abstract. In the current study, the nonlinear impact of the Von-Kármán theory on the vibrational response of non-homogeneous structures of functionally graded (FG) nano-scale tubes is investigated according to the nonlocal theory of strain gradient theory as well as high-order Reddy beam theory. The inhomogeneous distributions of temperature-dependent material consist of ceramic and metal phases in the radial direction of the tube structure, in which the thermal stresses are applied due to the temperature change in the thickness of the pipe structure. The general motion equations are derived based on the Hamilton principle, and eventually, the acquired equations are solved and modeled by the Meshless approach as well as a computer simulation via intelligent mathematical methodology. The attained results are helpful to dissect the stability of the MEMS and NEMS.
Keywords: beam theory; nonlinear analysis; nonlocal strain gradient theory; thermal stress; tube theory

1. Introduction

In the non-homogeneous structures, the functionally graded materials (FGM) are one of the best structures which are satisfied the requirements of products with their specific properties (Habibi *et al*. 2016, 2018b, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019). These favorite structures are combined with two or more phases of different materials, and the final structure contains both phases' used properties (Ebrahimi *et al.* 2019a, Habibi *et al.* 2018a, 2019a, b, c, Pourjabari *et al.* 2019). For example, ceramics are high-temperature resistance, and the metals are formable, on the other hand, the thermal resistance of metals and the formable of ceramics are not good. So, the functionally graded material made of ceramic and metal is a suitable structure in both abilities of thermal resistance and formable systems (Pourjabari *et al.* 2019, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022). This relevant material has become increasingly appealing for academics and designers to incorporate into their creations (Habibi *et al.* 2017, Safarpour *et al.* 2018, 2019a, Ebrahimi *et al*. 2020a, Ghazanfari *et al.* 2020). Guellil *et al*. (2021) investigated the bending behavior of the FG and porosity-dependent plate structures, which are laid on a substrate on the basis of high-order plate theory applying the analytical methodology of solution. Bekkaye Tahar Hacen *et al*. (2020) worked on the impact of the shear correction factor on the static analysis due to the mechanical buckling and mechanical bending of imperfect FG plate according to trigonometric plate theory using the Navier methodology. Al-Furjan *et al*. (2021) studied the vibrational characteristics of the high-order disk, including the porosity applying the Halpin–Tsai model using the Hamilton principle and generalized differential quadrature method (GDQM) for different boundary conditions involving the clamped, simply-supported. Zine *et al*. (2020) used the Navier approach to investigate the bending behavior of functionally graded imperfect plates based on the high-order shear deformation plate theory. Kaddari *et al*. (2020) delivered a modified quasi model in order to determine statically and dynamical characteristics of the porosity-dependent functionally graded hyperbolic plate, they established the porosity, thickness ratio, aspect ratio, and FG power index impact the behavior of the porous plate. Addou Farouk *et al*. (2019) modeled the hyperbolic FG plate on the linear substrate in order to study the porosity impact on the vibrational response of the high-order plate theory according to the virtual work principle. Medani *et al*. (2019) studied the stability analysis involving the static and dynamic behavior of the FG reinforced Timoshenko sandwich plate via the Hamilton principle for different mode shapes and different boundary conditions. Berghouti *et al*. (2019) analyzed the dynamic characteristics of the imperfect FG nanosized beam according to a couple of high-order beam theories and nonlocal theory, in which the material distributions according to the power-law were varied along the thickness direction.

The application of small-scale structures has been developed in recent years, but because of the time-consuming and high price of experimental analysis, many groups of researchers focused on theoretical investigations (Ebrahimi *et al.* 2019b, c, 2020b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Ghazanfari *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020). Size-dependent theories, such as the strain gradient theory, nonlocal theory of Eringen, modified couple stress theory, nonlocal strain gradient theory, etc., are some of the small-scale theories which researchers in recent years favored. In

*Corresponding author, Mr.,
E-mail: wuxiongwei@nut.edu.cn

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the different size-dependent theories, the basic assumptions are diverse, and these extra deductions lead to various behavior due to the small-scale impacts (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020a). It means that some theories, such as modified coupled stress theory, strain gradient theory, etc., predict the hardening phenomenon due to small-scale impact, in these theories, the length-scale factors impact the stiffness part of governing equation, while others, such as the nonlocal theory worked on the mass matrices and expect the softening phenomenon (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020c, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020b). However, in recent years, Lim *et al.* (2015) coupled the nonlocal theory along with the strain gradient theory and introduced the nonlocal strain gradient theory, which contains both softening and hardening phenomena, according to this theory, the small-scale factor in this theory works on both mass and stiffness part of governing equations (Al-Furjan *et al.* 2020b, c, d, Bai *et al.* 2020, Moayedi *et al.* 2020a, Zhang *et al.* 2020b, Guo *et al.* 2021b, Liu *et al.* 2021a). Based on the nonlocal strain gradient theory, the stability of the small-scale structures is more controlled by investigators, and this fact caused various statuses of researchers to tend to work in this field (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020, Zare *et al.* 2020, Dai *et al.* 2021b).

As it was reviewed, many studies have been paid to the dynamic and static behavior of small-scale structures such as FG beams (Zhao *et al.* 2021, Huang *et al.* 2021a, Jiao *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021), FG plates (Liu *et al*. 2020, Wang *et al*. 2020, Zhou *et al*. 2020, Dai *et al*. 2021a, Guo *et al*. 2021a, Shao *et al*. 2021, Wu and Habibi 2021), FG shells (Ma *et al.* 2021, Hou *et al.* 2021, Huang *et al.* 2021b, Liu *et al.* 2021b, Yu *et al.* 2022), etc., but the investigation of the nonlinear response of nanotubes still needs to expand. Due to these considerations, the current research concentrated on the large amplitude effect on the thermal vibration response of functionally graded nanotubes utilizing two high-order beam theories: the nonlocal gradient strain theory and the meshless approach.

2. Mathematical description

Tube structures by mathematical simulation of beam theory are considered in the present paper, and it is shown in Fig. 1, in which "L" is the tube length, "Ri" is the inner radius, and "Ro" is the outer radius. The functionally graded material was recognized as the tube construction material according to a power law in the radius direction, meaning the inner tube surface is made of pure metal while the outer surface is made of pure ceramic (Ghadiri and Shafiei 2016b, Ghadiri *et al*. 2016a, b, c, d, Shafiei *et al*. 2016b).

The mathematical formulation of functionally graded pipe structures is deemed as follows:

$$P(r) = P_m + (P_c - P_m)\left(\frac{r-Ri}{Ro-Ri}\right)^n \tag{1}$$

In the presented equation, "P" can be any of the mechanical properties involving mass density (ρ)

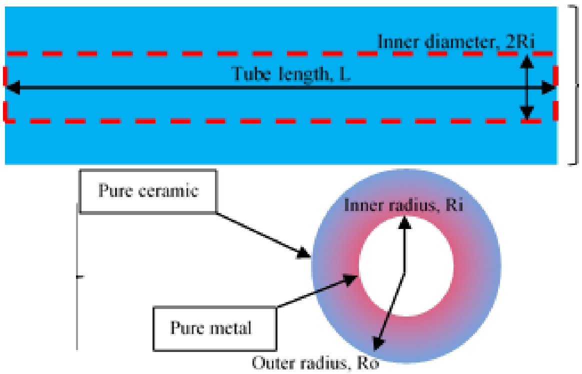

Fig. 1 A schematic and geometric of a functionally graded tube

$$\rho(r) = \rho_m + (\rho_c - \rho_m)\left(\frac{r-Ri}{Ro-Ri}\right)^n \tag{2}$$

Young's modulus (E)

$$(r) = E_m + (E_c - E_m)\left(\frac{r-Ri}{Ro-Ri}\right)^n \tag{3}$$

Thermal expansion coefficient (α)

$$\alpha(r) = \alpha_m + (\alpha_c - \alpha_m)\left(\frac{r-Ri}{Ro-Ri}\right)^n \tag{4}$$

"n" is the FG power index, $()_c$ refers to ceramic, and $()_m$ directs to the metal phase (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, Shafiei *et al.* 2016a, e, g). The mechanical properties of the materials are dependent on the environment temperature, which means they are temperature-dependent, so according to Touloukian and Ho (1970) relation, the following equation can be regarded:

$$Q = Q_0(Q_{-1}T^{-1} + Q_1T + Q_2T^2 + Q_3T^3 + 1) \tag{5}$$

"T" is the environment temperature (Kelvin), and "Q" is the temperature-dependent mechanical properties given in Table 1.

In this paper, on the basis of the Hamiltonian methodology, the governing equations and related boundary conditions have been generated (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017), this principle is represented as follows:

$$\int_{t_1}^{t_2} \delta H dt = \int_{t_1}^{t_2} \delta(U + V - K)dt = 0 \tag{3}$$

"U", "K", and "V" are the strain energy, Kinetic energy, and the energy of the external work, respectively. According to the third-order beam theory, the following displacement equation is considered.

$$u_1(x,y,z,t) = u(x,t) - z\frac{\partial w(x,t)}{\partial x} + \left(z - \frac{4z^3}{3(R_o-R_i)^2}\right)\left[\psi(x,t) + \frac{\partial w(x,t)}{\partial x}\right] \tag{4a}$$

$$u_2(x,y,z,t) = 0 \tag{4b}$$

$$u_3(x,y,z,t) = w(x,t) \tag{4c}$$

Table 1 Temperature-dependent coefficients for Si_3N_4 and SUS304

Materials	Proprieties	Q_0	Q_{-1}	Q_1	Q_2	Q_3
Si_3N_4	E_c(Pa)	348.43e+9	0.0	-3.070e-4	2.160e-7	-8.964e-11
	α_c (1/K)	5.8723e-6	0.0	9.095e-4	0.0	0.0
	ρ_c(Kg/m^3)	2370	0.0	0.0	0.0	0.0
SUS304	E_m(Pa)	201.04e+9	0.0	3.079e-4	-6.543e-7	0.0
	α_m (1/K)	12.33e-6	0.0	8.086e-4	0.0	0.0
	ρ_m(Kg/m^3)	8166	0.0	0.0	0.0	0.0

where, "ψ", "w", and "u" are rotation, transverse, and axial component, also, "t" is time. The strain energy will be calculated using the following equation based on the third-order beam theory. (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b).

$$U = \frac{1}{2}\iiint \sigma : \varepsilon dv \tag{5}$$

where "ε" and "σ" are the strain and stress (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c). Also, the following equation will calculate kinetic energy (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018).

$$K = \int_V \frac{1}{2}\rho(r,T)\frac{\partial}{\partial t}({u_1}^2 + {u_2}^2 + {u_3}^2)dV \tag{6}$$

Furthermore, the following equation calculates the energy of external work due to thermal stresses in the thermal environment.

$$V = \int_V \frac{1}{2}\int_0^L N^T\left(\frac{\partial w}{\partial x}\right)^2 dx\, dV \tag{7}$$

where "N^T" is the thermal force and calculated as follows:

$$N^T = \iint E(r,T)\alpha(r,T)\Delta T dA \tag{8}$$

To derive the local governing equation and related boundary conditions (Shafiei and She 2018, Shafiei *et al.* 2019, 2020), Eqs. (5), (6), and (7) are substituted in Eq. (3).

$$A_{11}\left(\frac{\partial^2 u}{\partial x^2} + \frac{1}{2}\frac{\partial}{\partial x}\left(\frac{\partial w}{\partial x}\right)^2\right) = m_0\frac{\partial^2 u}{\partial t^2} \tag{9a}$$

$$\begin{aligned}&-E_{11}\left(\frac{\partial^2\psi}{\partial x^2} + \frac{\partial^3 w}{\partial x^3}\right) + C_{11}\frac{\partial^3 w}{\partial x^3} + B_{11}\left(\psi + \frac{\partial w}{\partial x}\right)\\ &= -m_2\frac{\partial^3 w}{\partial x\partial t^2} + m_3\left(\frac{\partial^3 w}{\partial x\partial t^2} + \frac{\partial^2\psi}{\partial t^2}\right)\end{aligned} \tag{9b}$$

$$\begin{aligned}&(E_{11} - C_{11})\left(\frac{\partial^3\psi}{\partial x^3} + \frac{\partial^4 w}{\partial x^4}\right) + (D_{11} - C_{11})\frac{\partial^4 w}{\partial x^4}\\ &-B_{11}\left(\frac{\partial\psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + A_{11}\left(\frac{\partial u}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\right)\frac{\partial w}{\partial x}\\ &-N^T\frac{\partial^2 w}{\partial x^2} = -m_0\frac{\partial^2 w}{\partial t^2} + m_1\frac{\partial^4 w}{\partial x^2\partial t^2}\\ &-m_2\left(2\frac{\partial^4 w}{\partial x^2\partial t^2} + \frac{\partial^3\psi}{\partial x\partial t^2}\right) + m_3\left(\frac{\partial^4 w}{\partial x^2\partial t^2} + \frac{\partial^3\psi}{\partial x\partial t^2}\right)\end{aligned} \tag{9c}$$

where

$$\begin{aligned}(A_{11}, C_{11}, D_{11}, E_{11}) = \int_A E(r,T)\Bigg(1, z\left(z - \frac{4z^3}{3(Ro-Ri)^2}\right),\\ z^2, \left(z - \frac{4z^3}{3(Ro-Ri)^2}\right)^2\Bigg)dA\end{aligned} \tag{10a}$$

$$B_{11} = \int_A K_S G(r,T)\left(1 - \frac{4z^2}{(Ro-Ri)^2}\right)^2 dA \tag{10b}$$

$$\begin{aligned}(m_0, m_1, m_2, m_3) = \int_A \rho(r,T)\Bigg(1, z^2, z^2 - \frac{4z^4}{3(Ro-Ri)^2},\\ \left(z - \frac{4z^3}{3(Ro-Ri)^2}\right)^2\Bigg)dA\end{aligned} \tag{10c}$$

"K_S" is the shear deformation factor, which the following equation for the tube structures is considered (Ma *et al.* 2020).

$$K_S = \frac{6(1+\xi^2)^2(1+\nu)^2}{(7+14\nu+8\nu^2)(1+\xi^2)^2 + 4\xi^2(5+10\nu+4\nu^2)},\quad \xi = \frac{Ri}{Ro} \tag{11}$$

Also, the general boundary conditions are derived by the following equation.

$$u = 0 \qquad A_{11}\frac{\partial u}{\partial x} = 0 \tag{12a}$$

$$\psi = 0 \qquad E_{11}\left(\frac{\partial\psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) - C_{11}\frac{\partial^2 w}{\partial x^2} = 0 \tag{12b}$$

$$w = 0 \qquad \begin{aligned}&-(D_{11} + E_{11} - 2C_{11})\frac{\partial^3 w}{\partial x^3} - (E_{11} - C_{11})\left(\frac{\partial^2\psi}{\partial x^2}\right)\\ &+B_{11}\left(\psi + \frac{\partial w}{\partial x}\right) + N^T\frac{\partial w}{\partial x} = 0\end{aligned} \tag{12c}$$

$$\frac{\partial w}{\partial x} = 0 \quad (D_{11} + E_{11} - 2C_{11})\frac{\partial^2 w}{\partial x^2} + (E_{11} - C_{11})\frac{\partial\psi}{\partial x} = 0 \tag{12d}$$

The following nonlocal governing equations will be obtained in agreement with the nonlocal strain gradient theory (Lim *et al.* 2015).

$$\begin{aligned}&A_{11}\left(\frac{\partial^2 u}{\partial x^2} + \frac{1}{2}\frac{\partial}{\partial x}\left(\frac{\partial w}{\partial x}\right)^2\right) - l^2 A_{11}\left(\frac{\partial^4 u}{\partial x^4} + \frac{1}{2}\frac{\partial^3}{\partial x^3}\left(\frac{\partial w}{\partial x}\right)^2\right)\\ &= m_0\frac{\partial^2 u}{\partial t^2} - (e_0 a^2)m_0\frac{\partial^4 u}{\partial x^2\partial t^2}\end{aligned} \tag{13a}$$

$$\begin{aligned}&(H_{11}-E_{11})\frac{\partial^3 w}{\partial x^3}+H_{11}\frac{\partial^2\psi}{\partial x^2}-B_{11}\left(\frac{\partial w}{\partial x}+\psi\right)\\&-l^2\left((H_{11}-E_{11})\frac{\partial^5 w}{\partial x^5}+H_{11}\frac{\partial^4\psi}{\partial x^4}-B_{11}\frac{\partial^3 w}{\partial x^3}\right)\\&+l^2B_{11}\frac{\partial^2\psi}{\partial x^2}=(m_3-m_2)\frac{\partial^3 w}{\partial t^2\partial x}+m_3\frac{\partial^2\psi}{\partial t^2}\\&-(e_0a^2)\left((m_3-m_2)\frac{\partial^5 w}{\partial x^3\partial t^2}+m_3\frac{\partial^4\psi}{\partial x^2\partial t^2}\right)\end{aligned}\tag{13b}$$

$$\begin{aligned}&-l^2\begin{pmatrix}(H_{11}+D_{11}-2E_{11})\dfrac{\partial^6 w}{\partial x^6}-B_{11}\dfrac{\partial^3\psi}{\partial x^3}\\-B_{11}\dfrac{\partial^4 w}{\partial x^4}+(H_{11}-E_{11})\dfrac{\partial^5\psi}{\partial x^5}\end{pmatrix}\\&(H_{11}+D_{11}-2E_{11})\frac{\partial^4 w}{\partial x^4}+(H_{11}-E_{11})\frac{\partial^3\psi}{\partial x^3}\\&-B_{11}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial\psi}{\partial x}\right)-A_{11}\left(\frac{\partial u}{\partial x}+\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\right)\frac{\partial^2 w}{\partial x^2}\\&-A_{11}\left(\frac{\partial^2 u}{\partial x^2}+\frac{1}{2}\frac{\partial}{\partial x}\left(\frac{\partial w}{\partial x}\right)^2\right)\frac{\partial w}{\partial x}\\&+l^2\left(\frac{3}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial^2 w}{\partial x^2}dx+\frac{1}{L}A_{11}\int_0^L\frac{\partial^4 w}{\partial x^4}\frac{\partial w}{\partial x}dx\right)\frac{\partial w}{\partial x}\\&+l^2\left(\frac{1}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial w}{\partial x}dx+\frac{1}{L}A_{11}\int_0^L\left(\frac{\partial^2 w}{\partial x^2}\right)^2dx\right)\frac{\partial^2 w}{\partial x^2}\\&-l^2(ea)^2\left[\begin{aligned}&\begin{pmatrix}\dfrac{10}{L}A_{11}\displaystyle\int_0^L\frac{\partial^4 w}{\partial x^4}\frac{\partial^3 w}{\partial x^3}dx+\frac{5}{L}A_{11}\int_0^L\frac{\partial^5 w}{\partial x^5}\frac{\partial^2 w}{\partial x^2}dx\\+\dfrac{1}{L}A_{11}\displaystyle\int_0^L\frac{\partial^6 w}{\partial x^6}\frac{\partial w}{\partial x}dx\end{pmatrix}\frac{\partial w}{\partial x}\\&+\begin{pmatrix}\dfrac{9}{L}A_{11}\displaystyle\int_0^L\left(\frac{\partial^3 w}{\partial x^3}\right)^2dx+\frac{12}{L}A_{11}\int_0^L\frac{\partial^4 w}{\partial x^4}\frac{\partial^2 w}{\partial x^2}dx\\+\dfrac{3}{L}A_{11}\displaystyle\int_0^L\frac{\partial^5 w}{\partial x^5}\frac{\partial w}{\partial x}dx\end{pmatrix}\frac{\partial^2 w}{\partial x^2}\\&\left(\frac{9}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial^2 w}{\partial x^2}dx+\frac{3}{L}A_{11}\int_0^L\frac{\partial^4 w}{\partial x^4}\frac{\partial w}{\partial x}dx\right)\frac{\partial^3 w}{\partial x^3}\\&+\left(\frac{1}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial w}{\partial x}dx+\frac{1}{L}A_{11}\int_0^L\left(\frac{\partial^2 w}{\partial x^2}\right)^2dx\right)\frac{\partial^4 w}{\partial x^4}\end{aligned}\right]\\&+(ea)^2\left[\begin{aligned}&\left(\frac{3}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial^2 w}{\partial x^2}dx+\frac{1}{L}A_{11}\int_0^L\frac{\partial^4 w}{\partial x^4}\frac{\partial w}{\partial x}dx\right)\frac{\partial w}{\partial x}\\&+3\left(\frac{1}{L}A_{11}\int_0^L\frac{\partial^2 w}{\partial x^2}\frac{\partial w}{\partial x}dx\right)\frac{\partial^3 w}{\partial x^3}\\&\left(\frac{3}{L}A_{11}\int_0^L\frac{\partial^3 w}{\partial x^3}\frac{\partial w}{\partial x}dx+\frac{3}{L}A_{11}\int_0^L\left(\frac{\partial^2 w}{\partial x^2}\right)^2dx\right)\frac{\partial^2 w}{\partial x^2}\\&+\left(\frac{1}{2L}A_{11}\int_0^L\left(\frac{\partial w}{\partial x}\right)^2dx\right)\frac{\partial^4 w}{\partial x^4}\end{aligned}\right]\\&=(m_3+m_1-2m_2)\frac{\partial^4 w}{\partial t^2\partial x^2}-m_0\frac{\partial^2 w}{\partial t^2}+(m_3-m_2)\frac{\partial^3\psi}{\partial x\partial t^2}\\&-(ea)^2\begin{pmatrix}(m_3+m_1-2m_2)\dfrac{\partial^6 w}{\partial x^4\partial t^2}\\+(m_3-m_2)\dfrac{\partial^5\psi}{\partial x^3\partial t^2}-m_0\dfrac{\partial^4 w}{\partial x^2\partial t^2}\end{pmatrix}\end{aligned}\tag{13c}$$

Here "*ea*" is the nonlocal parameter, and "*l*" is the strain gradient parameter (Liu *et al*. 2022, Sun *et al*. 2022, Xiao *et al*. 2022, Yang *et al*. 2022, Ye *et al*. 2022, Zhang *et al*. 2022, Zhong *et al*. 2022).

3. Solving strategy

Astronomical difficulties began to be solved in the late 1970s using meshless techniques (MMs). Instead of using discretized components as in other mesh-based approaches, MMs relies on a collection of nodes (a cloud of points) to describe the spatial domain (finite difference method, finite element method, finite volume method). Machine learning models (MMs) in computational biomechanics will be explored in this chapter, including their benefits, disadvantages, and potential future applications. Interpolation strategies such as the meshless total Lagrangian explicit dynamics method modified moving least squares, and the discretization corrective particle strength exchange approach will be examined. Several examples will demonstrate the approaches' applicability to problems at several scales, their inherent parallelism, and their benefits over more traditional mesh-based numerical methods. Mathematical procedures for resolving complicated engineering problems, such as modeling and simulation, have widespread acceptance among engineers. MMs must be thoroughly tested in the field before they can be used in the workplace (Shivanian et al. 2017). In proportion to modal analysis, the following assumptions are considered (Wu *et al.* 2020, 2021, Zhang *et al.* 2020a, Bai *et al.* 2021, Long *et al.* 2021, Zhou *et al.* 2021, Cao *et al.* 2022).

$$u=Ue^{i\omega t}\tag{14a}$$

$$\psi=\Psi e^{i\omega t}\tag{14b}$$

$$w=We^{i\omega t}\tag{14c}$$

4. Discussion and outcomes

Before delving into the findings, several dimensionless parameters including the nonlocal parameter (μ), strain gradient parameter (β), frequency (ϖ), and large deflection amplitude (χ) are defined as follows.

$$\mu=\frac{(ea)^2}{L}\tag{15a}$$

$$\beta=\frac{l^2}{L}\tag{15b}$$

$$\varpi=\omega\frac{L^2}{\pi}\sqrt{\frac{\int\rho_c dA}{\int E_c z^2 dA}}\tag{15c}$$

$$\chi=a\sqrt{\frac{\int E_c z^2 dA}{\int\rho_c dA}}\tag{15d}$$

The nonlinear deflection owing to the large deflection amplitude is denoted by "*a*". To assess the obtained motion equations and solution approach, Table 2 compares the present research to previously published work by Zuo *et al*. (2021), confirming that the output findings of this study are in great agreement with the published literature.

The results were presented in Table 3 show the impact of temperature change (ΔT) on the linear and nonlinear frequencies of a fully clamped cylindrical tube versus the nonlinear amplitude (χ) of nonlinear impacts. It is shown that both linear and nonlinear frequency decreases with temperature change, which means the stability of tubes is limited in higher temperature change because the stiffness of tubes decreases with higher thermal stresses. Results also

Table 2 Comparison of the current dimensionless frequency ($\sqrt[4]{\omega^2 L^4\, \rho_c A/E_c I}$) results with the result of Zuo *et al.* (2021) for high-order functionally graded clamped tube versus the various nonlocal parameter. (n=1, l/Ro=1, 40Ro=80Ri=L, ΔT=10)

	First frequency			Second frequency		
Materials	Present study	Zuo *et al*. (2021)	error	Present study	Zuo *et al*. (2021)	Error
ea/Ro=0	4.24599733	4.267334	>0.001	6.99715269	7.067831	>0.01
ea/Ro=1	4.237698035	4.258993	>0.001	6.9490575	7.01925	>0.01
ea/Ro=2	4.213221035	4.234393	>0.001	6.81354036	6.882364	>0.01
ea/Ro=3	4.17376431	4.194738	>0.001	6.61265649	6.679451	>0.01
ea/Ro=4	4.12113677	4.141846	>0.001	6.37260525	6.436975	>0.01
ea/Ro=5	4.05753239	4.077922	>0.001	6.11608536	6.177864	>0.01
ea/Ro=6	3.98528743	4.005314	>0.001	5.85911502	5.918298	>0.01

Table 3 Linear and nonlinear dimensionless fundamental (ϖ_1) and second (ϖ_2) frequencies of temperature-dependent clamped cylindrical beam versus the temperature change (ΔT) as well as various values of nonlinear amplitude (χ), Ri=2Ro, L=40Ro

	First frequency (ϖ_1)			Second frequency (ϖ_2)		
	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1
ΔT=0	7.116169	7.274099	7.725864	19.57214	20.52089	23.10801
ΔT=10	7.063284	7.222496	7.677612	19.5006	20.45278	23.04772
ΔT=20	7.0092	7.169742	7.628331	19.42776	20.38346	22.98638
ΔT=30	6.953888	7.115811	7.577998	19.3536	20.3129	22.92401
ΔT=40	6.897316	7.060673	7.52659	19.2781	20.2411	22.86059
ΔT=50	6.839449	7.004298	7.474084	19.20126	20.16804	22.79611
ΔT=60	6.780253	6.946653	7.420454	19.12304	20.09372	22.73056
ΔT=70	6.71969	6.887704	7.365674	19.04343	20.0181	22.66393
ΔT=80	6.65772	6.827416	7.309715	18.96242	19.94118	22.5962
ΔT=90	6.594301	6.765749	7.252548	18.87998	19.86294	22.52738
ΔT=100	6.529387	6.702663	7.194142	18.7961	19.78336	22.45745

Table 4 Free first and second frequencies of fully clamped nonlocal nanotube versus the different values of large deflection (χ) along with the nonlocal parameter (μ) in the thermal environment, **Δ**T=50, Ri=2Ro, L=40Ro

	First frequency (ϖ_1)			Second frequency (ϖ_2)		
	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1
μ=0	6.839449	7.004298	7.474084	19.20126	20.16804	22.79611
μ=0.1	6.828696	6.994733	7.467711	19.10673	20.08496	22.74039
μ=0.2	6.796648	6.966238	7.448736	18.83046	19.84244	22.57801
μ=0.3	6.743924	6.919392	7.417586	18.39286	19.45926	22.32232
μ=0.4	6.671516	6.855128	7.374944	17.82349	18.96262	21.99261
μ=0.5	6.580738	6.77468	7.321714	17.15602	18.38344	21.61074
μ=0.6	6.473153	6.679517	7.258971	16.42363	17.75213	21.1981
μ=0.7	6.350504	6.571277	7.187912	15.65576	17.09554	20.77338
μ=0.8	6.214633	6.451695	7.1098	14.87636	16.43542	20.35146
μ=0.9	6.067413	6.322535	7.025915	14.10356	15.78804	19.94321
μ=1.0	5.910681	6.185529	6.93751	13.35016	15.16471	19.55584

confirmed that both first and second frequencies have the same behavior regarding temperature change. Moreover, the nonlinearity enhances the tube strength by adding extra strain.

Table 5 First and second linear and nonlinear frequency response of nonlocal nanoscale cylindrical tube for different nonlinear amplitude (χ) and strain gradient parameter (β) in the thermal conditions, $\boldsymbol{\mu}$=0.5, $\boldsymbol{\Delta}$T=50, Ri=2Ro, L=40Ro

	First frequency (ϖ_1)			Second frequency (ϖ_2)		
	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1
β=0.	6.580738	6.77468	7.321714	17.15602	18.38344	21.61074
β=0.05	6.583654	6.777508	7.324321	17.18096	18.40672	21.63061
β=0.1	6.592362	6.785953	7.332107	17.25526	18.4761	21.68988
β=0.15	6.606741	6.7999	7.344967	17.37739	18.59021	21.78748
β=0.2	6.626589	6.819154	7.362726	17.5448	18.74681	21.92166
β=0.25	6.651627	6.843446	7.38514	17.75401	18.94275	22.08997
β=0.3	6.681499	6.872434	7.411898	18.00053	19.17399	22.28916
β=0.35	6.715769	6.905697	7.442618	18.27873	19.43539	22.51503
β=0.4	6.753927	6.942743	7.476848	18.58121	19.72012	22.76188
β=0.45	6.795378	6.982995	7.514062	18.89732	20.01821	23.02118
β=0.5	6.839437	7.02579	7.553644	19.20937	20.31298	23.27843

Table 6 The first two frequencies of the functionally graded nanoscale nonlocal cylindrical doubly clamped tube in the heat state versus the nonlinear amplitude (χ) along with the volume fraction parameter (n), $\boldsymbol{\beta}$=0.1, $\boldsymbol{\mu}$=0.5, $\boldsymbol{\Delta}$T=50, Ri=2Ro, L=40Ro

	First frequency (ϖ_1)			Second frequency (ϖ_2)		
	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1	Linear, χ=0	Nonlinear, χ=1
Pure Si_3N_4	6.592362	6.785953	7.332107	17.25526	18.4761	21.68988
FGM, n=1	4.195307	4.31846	4.665905	11.07995	11.84964	13.8797
FGM, n=2	3.68287	3.792113	4.100136	9.761852	10.44179	12.23463
FGM, n=3	3.442607	3.545836	3.83672	9.145261	9.786056	11.47463
FGM, n=4	3.300116	3.400008	3.681343	8.780259	9.399174	11.02906
FGM, n=5	3.204925	3.302708	3.57798	8.536777	9.141762	10.73407
FGM, n=6	3.136512	3.232848	3.503942	8.361995	8.957357	10.52357
FGM, n=7	3.084833	3.180117	3.448165	8.230092	8.818423	10.36547
FGM, n=8	3.044351	3.138839	3.404571	8.126852	8.709826	10.24222
FGM, n=9	3.011749	3.105613	3.369528	8.043763	8.622526	10.14337
Pure SUS304	2.704337	2.79326	3.042489	7.263254	7.807571	9.231614

The effect of nonlocal parameters (μ) on the linear and nonlinear first and second frequency of temperature-dependent nanoscale clamped tubes are listed in Table 4. The presented results demonstrated that both linear and nonlinear frequencies reduce by nonlocal parameters, the decrement of frequency because of nonlocal impact leads to decreases in the stability of the tube because the nonlocal effect limited the tube stiffness. The discussed results about the nonlocal impacts are valid for both first and second frequencies.

In the following, the influence of the strain gradient parameter (β) on the free vibrational behavior of nonlocal nanotube in the thermal environment is investigated in Table 5. The results for both fundamental and second frequencies of the clamped tube are listed, and it is confirmed that the strain gradient parameter increases the first two linear and nonlinear frequencies, which leads to an improvement in the tube stability because the strain gradient parameter impacts the stress component and this fact conduct to enhance the stiffness.

This section investigates the influence of the volume fraction parameter (n) of functionally graded temperature-dependent material on the first and second linear and nonlinear frequencies on the FG nanotube with fully clamped boundary conditions. The results listed in Table 6 show that the volume fraction parameter tends to decrease both linear and nonlinear frequencies since SUS304 is softer than Si3N4, and the FG parameter decreases the tube stiffness by adding the volume of the metal instead of the ceramic phase. Also, the nonlinear amplitude develops the tube stability by modification of frequency.

5. Conclusions

The main framework of the current study was to analyze the impact of the nonlinearity of the Von-Kármán strains on the thermal vibrational characteristics of the functionally graded nanotube according to the nonlocal strain gradient theory and high-order shear deformation beam theory in thermal conditions. The following is a list of the most important results.

• The nonlinear amplitude on the nonlinear strains enhances the frequency and stability of the FG nanotubes.

• The temperature change decreases the tube stiffness, and this parameter limits the stability and frequencies of the temperature-dependent tubes.

• The nonlocal parameter destroyed the tube stability and frequency.

• Unlike the nonlocal parameter, the strain gradient factor improves the nanotube structures' frequency and stability.

• The volume fraction has a significant impact on the stability of the nanotubes, and it can be limited the frequency by softening phenomenon.

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