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On the forced vibration of high-order functionally graded nanotubes under the rotation via intelligent modeling

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Abstract. The present research investigates the dynamic behavior of a rotating functionally graded (FG) nonlocal cylindrical beam. The cylindrical beam is mathematically modeled via third-order beam theory linked with nonlocal strain gradient theory. The tube structure is made of functionally graded materials composed of Aluminum oxide coated on the Nickel, which the mechanical properties vary in the tube radius direction according to the power law. The bending harmonic force is applied in the tube length middle. The nonlocal spinning equations of the tube are derived via the energy method of the Hamilton principle, and they are solved via a robust numerical procedure for different boundary conditions. The main application of the rotating nanostructures is for the production of small-scale motors and devices and the drug-delivery application, the presented results can help the researcher have a better view regarding the different conditions.

Keywords: dynamic analysis; functionally graded material; nanotube; spinning nanostructures

1. Introduction

The advancement of nanotechnology in recent years has increased interest of researchers in this subject and improved equipment performance, drawing attention to small-scale structures (Hu *et al.* 2021, 2022, Huang *et al.* 2022, Li *et al.* 2022a, c). However, this focus comes at a high cost because investigating small-scale sciences is time-consuming and expensive for researchers (Mou and Bai 2018, Li *et al.* 2021, Liu *et al.* 2021a, Wei *et al.* 2021). In the nanomechanical sciences, for example, the actual research of nanostructures necessitates high-tech technological tools (Habibi *et al.* 2016, 2018b, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019). However, the theoretical investigation of the small-scale structures had an excellent development that many applicable theories have been presented that have good agreement with the actual conditions. Among these theories, the couple stress theory (Habibi *et al.* 2019a, Safarpour *et al.* 2019b, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Chen *et al.* 2022), nonlocal elasticity theory (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b), and strain gradient theory (Ebrahimi *et al.* 2019b, c, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Ebrahimi *et al.* 2020b, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020) are the most popular nonclassical theories regarding the size effect (Berghouti *et al.* 2019, Boutaleb *et al.* 2019, Hussain *et al.* 2019, Matouk *et al.* 2020, Kumar *et al.* 2021, Soleimani-Javid *et al.* 2021), which predicted the excellent mathematical simulation of the small-scale structures that are in good agreement with the experiment results (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b). In the modified couple stress theory, the small-scale parameter impacts the stress resultant directly and improves the stiffness of the structure (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020e, Cheshmeh *et al.* 2020, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c). Also, the small-scale parameter in the strain gradient theory impacts the hardening part of the mathematical simulation (whitening section), and the strength of structures enhances (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021b). On the other hand, in the nonlocal theory, the size-dependent parameter works on the mass part of governing equations, and the small-scale structures will be softer by the nonlocal parameter (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b). Nevertheless, recently, Lim *et al.* (2015) defined a new modified theory involving both nonlocal and strain gradient theory called nonlocal strain gradient theory contains both hardening and softening effects regarding the small-scale parameter. According to the mentioned theories, researchers have been focused on the small-scale structures such as nano/- micro-shell (Liu *et al.* 2020b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021c, Zhang *et al.* 2021), nano/- micro-tube (Zhao *et al.* , Huang *et al.* 2021b, Jiao *et al.* 2021, Moradi *et al.* 2021, Xu *et al.* 2021), nano/- micro-beam (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g), nano/- micro-plate, etc., in order to predict the mathematical simulation of them. For example, Park and Gao (2006) applied the modified couple stress theory for bending characteristics of a classical cantilever beam on the basis of the energy principle. Ma *et al.* (2008) investigated the microstructure beam according to the modified couple stress theory and the first-order beam theory utilizing the Hamilton principle. Utilizing the modified couple stress theory, Asghari *et al.* (2010)

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numerical studied the nonlinear impacts on the bending behavior of a first-order beam based on the Hamilton principle. Tsiatas (2009) utilized the modified couple stress theory in order to conduct a static investigation of the size effect of the classic plate for different boundary conditions. Ghayesh *et al*. (2013) presented a numerical response for the dynamic of a microscale beam based on the modified couple stress theory under the external dynamic load. Zhao *et al*. (2012) investigated the nonlinear frequency and static behavior due to the buckling and bending behavior of a microscale beam based on the strain gradient theory. Apuzzo *et al*. (2018) analyzed the dynamic behavior of the fully clamped and cantilever nanobeam based on the modified nonlocal strain gradient theory employing nonlocal boundary condition. Li and Hu (2015) utilized the nonlocal strain gradient theory to investigate the buckling and post-buckling behavior of a nanobeam based on the classical beam theory. Akgöz and Civalek (2016) presented a mathematical simulation for the bending characteristics of a carbon nanotube according to the strain gradient theory along with the high-order shear deformation beam theory utilizing the analytical solution.

The investigation of the nanoscale structures regarding the different types of analysis involving bending (Ghadiri *et al*. 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al*. 2016b), buckling (Liu *et al*. 2020a, Wang *et al*. 2020, Zhou *et al*. 2020, Dai *et al*. 2021a, Guo *et al*. 2021a, Shao *et al*. 2021, Wu and Habibi 2021), free, and forced vibration has been more attention by many researchers (Habibi *et al*. 2018a, 2019b, c, d, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a), among them, the dynamic characteristics of the rotating structures are the most favored analysis (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017). Alghamdi and Youssef (2017) studied the thermoelastic behavior of a small-scale spinning ring under vibrational analysis. Atanasov and Stojanović (2020) investigated the bending vibration behavior of a cantilever nanobeam based on the nonlocal elasticity and classical beam theory under the external dynamic load. According to t the modified couple stress theory, Rostami *et al*. (2018) studied the forced vibration characteristics of a nanocomposite beam under thermal conditions. Preethi *et al*. (2018) scrutinized the nonlinear impact on the bending vibration behavior of a composite nonlocal cantilever beam based on the first-order shear deformation beam theory employing the numerical approach. Li *et al*. (2022b) explained different theories of plates in order to investigate the bending vibration response of the annular laminated plate based on the nonlocal elasticity theory. Malik and Das (2020) considered the Coriolis impact on the vibrational behavior of spinning nonlocal nanobeam based on the classical beam theory. Khaniki (2018) numerically studied the vibration behavior of nanobeam according to the nonlocal elasticity theory for clamped-free boundary conditions compared to other different boundary conditions. In another work, Faroughi *et al*. (2020) investigated the wave analysis of a bi-directional FG porosity-dependent nanobeam based on the general nonlocal theory as well as high-order Reddy beam theory.

As previously discussed, many researchers worked on various architectures based on various theories and situations (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b, Shafiei *et al*. 2017c), nevertheless, examining spinning functionally graded nanotubes still has to be explored more. Therefore, this paper scrutinizes the dynamic behavior of a spinning functionally graded nanotube under the bending harmonic load. The nanotube is mathematically modeled via third-order beam theory and nonlocal strain gradient theory. The centrifugal force, along with the dynamic harmonic load, is applied to the FG tube made of Nickel core coated with Aluminum oxide in the radius direction. Then using the numerical procedure linked with the Newmark beta technique, the time-dependent results are computed.

Table 1 Young's modulus and density of Aluminum oxide and Nickel (Reddy and Chin 1998)

	Nickel	Aluminum oxide
Density (Kg/m^3)	8900	3750
Young's modulus (Pa)	223.95e9	349.55e9

2. Submitting mathematical simulation

2.1 Geometric and material composition

A cylindrical tube is considered in this study that 'R1' is the internal radius, 'R2' is the external radius, and the tube length is 'L', the geometric details are shown in Fig. 1. The tube is rotated around the y-axis, which 'h' is the span of the left side of the tube from the y-axis called the hub radius.

The tube structure is made of functionally graded material composed of ceramic and metal phases. In the functionally graded materials, the mechanical properties smoothly changed among the constructive phases, in which the radial dispersion is used for this study that the inner tube surface is the pure Nickel, the outer surface is made of pure Aluminum oxide, and along the radial direction. The mechanical properties including Young's modulus (E) and density (ρ) are varied between these phases according to the following mathematical equations, which subscript of '$()_{Al}$' directs to Aluminum oxide, and the subscript of '$()_N$' refers to Nickel.

$$E(r) = (E_{Al} - E_N)\left(\frac{r - R1}{R2 - R1}\right)^{\eta} + E_N \tag{1a}$$

$$\rho(r) = (\rho_{Al} - \rho_N)\left(\frac{r - R1}{R2 - R1}\right)^{\eta} + \rho_N \tag{1b}$$

where 'η' is the volume fraction or FG parameter that controls the material dispersion among ceramic and metal phases, and the mechanical properties constant of both Aluminum oxide and Nickel is presented in Table 1.

2.2 Motion equations of spinning cylindrical tube

There are many ways to derive the dynamic motion equations of small-scale structures, the Hamilton principle

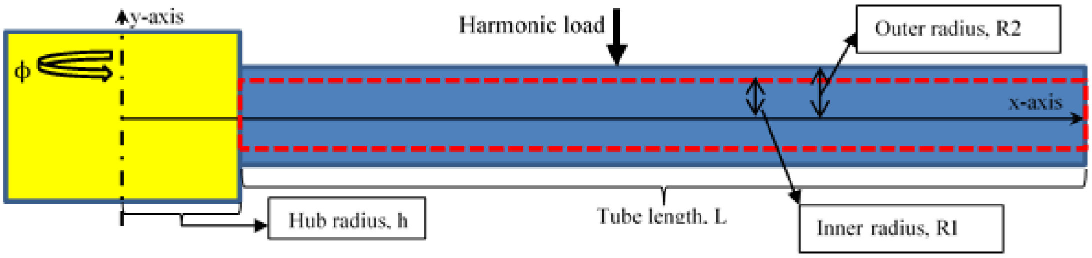

Fig. 1 Schematic and geometric detail of rotating cylindrical tube

based on the energy method is one of them. On the basis of the Hamilton principle, the governing equations are obtained according to substituting the potential energy (P), kinetic energy (K), and energy of external work (W) on the following equation.

$$\int_{t_1}^{t_2} \delta H dt = \int_{t_1}^{t_2} (\delta K - \delta P + \delta W) dt = 0 \tag{2}$$

In this paper, the third-order theory of beam is considered to simulate the mathematical modeling of the tube, and the detail of the displacement components based on the third-order beam theory are as follows:

$$u_1(x,y,z,t) = -\frac{4z^3}{3(R2-R1)^2}\frac{\partial w}{\partial x} + u + \left(z - \frac{4z^3}{3(R2-R1)^2}\right)\psi \tag{3a}$$

$$u_2(x,y,z,t) = 0 \tag{3b}$$

$$u_3(x,y,z,t) = w \tag{3c}$$

'u_1', 'u_2', and 'u_3' are displacement fields along the x-, y-, and z-axis, respectively, and also, 'u' is the axial displacement, 'w' is the lateral displacement, and 'psi' is the rotation. Then according to displacement definitions, the virtual kinetic energy for the rotating tube is assessed as follows:

$$\begin{aligned}
\delta K &= \frac{1}{2}\int_V \rho(r)\delta\left(\dot{u}_1{}^2 + \dot{u}_2{}^2 + \dot{u}_3{}^2\right) dV \\
&= \int_0^L \Bigg\{ m_2\left[-\frac{\partial\psi}{\partial t}\delta\left(\frac{\partial^2 w}{\partial x\partial t}\right) - 2\frac{\partial^2 w}{\partial x\partial t}\delta\left(\frac{\partial^2 w}{\partial x\partial t}\right) - \frac{\partial^2 w}{\partial x\partial t}\delta\left(\frac{\partial\psi}{\partial t}\right)\right] \\
&\quad + m_0\left[\frac{\partial u}{\partial t}\delta\left(\frac{\partial u}{\partial t}\right) + \frac{\partial w}{\partial t}\delta\left(\frac{\partial w}{\partial t}\right)\right] \\
&\quad + m_3\left[\frac{\partial^2 w}{\partial x\partial t}\delta\left(\frac{\partial^2 w}{\partial x\partial t}\right) + \frac{\partial\psi}{\partial t}\delta\left(\frac{\partial^2 w}{\partial x\partial t}\right) + \frac{\partial^2 w}{\partial x\partial t}\delta\left(\frac{\partial\psi}{\partial t}\right) + \left(\frac{\partial\psi}{\partial t}\right)\delta\left(\frac{\partial\psi}{\partial t}\right)\right] \\
&\quad + m_1\frac{\partial^2 w}{\partial x\partial t}\delta\left(\frac{\partial^2 w}{\partial x\partial t}\right)\Bigg\} dx
\end{aligned} \tag{4}$$

where

$$(m_0, m_1, m_2, m_3) = \int_A \rho(r)\left(1, z^2, z^2 - \frac{4z^4}{3(R2-R1)^2}, \left(z - \frac{4z^3}{3(R2-R1)^2}\right)^2\right) dA \tag{5}$$

The potential energy of third-order beam theory is calculated as follows:

$$\begin{aligned}
&\frac{1}{2}\iiint \delta(\sigma:\varepsilon) dv = -\int_0^L \frac{\partial}{\partial x}\left(A\frac{\partial u}{\partial x}\right) dx\, \delta(u) + A\frac{\partial u}{\partial x}\bigg|_0^L \delta(u) \\
&+ \int_0^L \frac{\partial^2}{\partial x^2}\left(E_{11}\frac{\partial^2 w}{\partial x^2}\right) dx\, \delta(w) + E_{11}\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\
&- \frac{\partial}{\partial x}\left(E_{11}\frac{\partial^2 w}{\partial x^2}\right)\bigg|_0^L \delta(w) - \int_0^L \frac{\partial}{\partial x}\left(E_{11}\frac{\partial\psi}{\partial x}\right) dx\, \delta(\psi) \\
&+ \int_0^L \frac{\partial^2}{\partial x^2}\left(D\frac{\partial^2 w}{\partial x^2}\right) dx\, \delta(w) + D\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\
&\qquad - \int_0^L \frac{\partial}{\partial x}\left(E_{11}\frac{\partial^2 w}{\partial x^2}\right) dx\, \delta(\psi) \\
&- \frac{\partial}{\partial x}\left(D\frac{\partial^2 w}{\partial x^2}\right)\bigg|_0^L \delta(w) + E_{11}\frac{\partial\psi}{\partial x}\bigg|_0^L \delta(\psi) + E_{11}\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta(\psi) \\
&+ \int_0^L \frac{\partial^2}{\partial x^2}\left(E_{11}\frac{\partial\psi}{\partial x}\right) dx\, \delta(w) + E_{11}\frac{\partial\psi}{\partial x}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\
&- \frac{\partial}{\partial x}\left(E_{11}\frac{\partial\psi}{\partial x}\right)\bigg|_0^L \delta(w) - 2\int_0^L \frac{\partial^2}{\partial x^2}\left(C_{11}\frac{\partial^2 w}{\partial x^2}\right) dx\, \delta(w) \\
&+ B\frac{\partial w}{\partial x}\bigg|_0^L \delta(w) + \int_0^L B\psi\delta(\psi) + B\frac{\partial w}{\partial x}\delta(\psi)\, dx \\
&- \int_0^L \frac{\partial}{\partial x}(B(\psi)) dx\, \delta(w) + B\psi|_0^L\delta(w) \\
&- 2\, C_{11}\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) + 2\frac{\partial}{\partial x}\left(C_{11}\frac{\partial^2 w}{\partial x^2}\right)\bigg|_0^L \delta(w) \\
&+ \int_0^L \frac{\partial}{\partial x}\left(C_{11}\frac{\partial^2 w}{\partial x^2}\right) dx\, \delta(\psi) - C_{11}\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta(\psi) \\
&- \int_0^L \frac{\partial^2}{\partial x^2}\left(C_{11}\frac{\partial\psi}{\partial x}\right) dx\, \delta(w) - C_{11}\frac{\partial\psi}{\partial x}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\
&+ \frac{\partial}{\partial x}\left(C_{11}\frac{\partial\psi}{\partial x}\right)\bigg|_0^L \delta(w) - \int_0^L \frac{\partial}{\partial x}\left(B_{11}\frac{\partial w}{\partial x}\right) dx\, \delta(w)
\end{aligned} \tag{6}$$

where " and " are the stresses and strains tensors, and the following constants are also employed:

$$(A, C_{11}, D, E_{11}) = \int_A E(r)\left(1, z^2 - \frac{4z^4}{3(R2-R1)^2}, z^2, \left(z - \frac{4z^3}{3(R2-R1)^2}\right)^2\right) dA \tag{7a}$$

$$B = \int_A K_S \frac{E(r)}{2(1+\nu)}\left(\left(1 - \frac{4z^2}{(R2-R1)^2}\right)^2\right) dA \tag{7b}$$

'K_S' indicates the shear correction impact that is introduced for the cylindrical beams and tubes according to the following equation (Ma *et al*. 2020).

$$K_S = \frac{6(1+(R1/R2)^2)^2(1+\nu)^2}{(7+14\nu+8\nu^2)\left(1+\left(\frac{R1}{R2}\right)^2\right)^2 + 4(R1/R2)^2(5+10\nu+4\nu^2)} \tag{8}$$

The virtual energy of the external work of rotation is calculated as follows.

$$\delta W = F^R\frac{\partial w}{\partial x}\Big|_0^L \delta(w) - \int_0^L \frac{\partial}{\partial x}\left(F^R\frac{\partial w}{\partial x}\right)dx\,\delta(w) + F^B\,sin(\frac{n\pi}{L}x)\,sin(\Omega t)\delta(w) \tag{9}$$

'F^B' is the bending load, and 'F^R' is the centrifugal force of rotation which is defined as follows:

$$F^R = \int_x^L \int_A \rho(r)\phi^2(h+x)dAdx \tag{10}$$

'ϕ' is the rotation speed. Then by substituting Eqs. (4), (6) and (9) into the Hamilton principle (Eq. (2)), and according to the Euler-Lagrange procedure, the following governing equations along with the boundary conditions will be obtained.

$$\delta u: \frac{\partial}{\partial x}\left(A\frac{\partial u}{\partial x}\right) = m_0\frac{\partial^2 u}{\partial t^2} \tag{11a}$$

$$\begin{aligned}&\delta(w): (D-C_{11})\left(\frac{\partial^4 w}{\partial x^4}\right) + (E_{11}-C_{11})\left(\frac{\partial^3\psi}{\partial x^3}+\frac{\partial^4 w}{\partial x^4}\right)\\&-\frac{\partial}{\partial x}\left(F^R\frac{\partial w}{\partial x}\right) + F^B\,sin(\frac{n\pi}{L}x)\,sin(\Omega t)\\&-\frac{\partial}{\partial x}\left(B\left(\psi+\frac{\partial w}{\partial x}\right)\right)\\&= m_1\frac{\partial^2\ddot{w}}{\partial x^2} + m_3\left(\frac{\partial^2\ddot{w}}{\partial x^2}+\frac{\partial\ddot{\psi}}{\partial x}\right) - m_0\ddot{w}\\&-m_2\left(2\frac{\partial^2\ddot{w}}{\partial x^2}+\frac{\partial\ddot{\psi}}{\partial x}\right)\end{aligned} \tag{11b}$$

$$\begin{aligned}&\delta\psi: \frac{\partial}{\partial x}\left(C_{11}\frac{\partial^2 w}{\partial x^2}\right) - \frac{\partial}{\partial x}\left[E_{11}\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial\psi}{\partial x}\right)\right]\\&+B\left(\psi+\frac{\partial w}{\partial x}\right) = m_3\left(\frac{\partial^3 w}{\partial x\partial t^2}+\frac{\partial^2\psi}{\partial t^2}\right) - m_2\frac{\partial^3 w}{\partial x\partial t^2}\end{aligned} \tag{11c}$$

And related general boundary conditions are as follows:

$$u = 0 \quad \text{Or} \quad A\frac{\partial u}{\partial x} = 0 \tag{11d}$$

$$\psi = 0 \quad \text{Or} \quad (E_{11}-C_{11})\frac{\partial^2 w}{\partial x^2} + E_{11}\frac{\partial\psi}{\partial x} = 0 \tag{11e}$$

$$w = 0 \quad \text{Or} \quad \begin{aligned}&B\left(\psi+\frac{\partial w}{\partial x}\right) + F^R\frac{\partial w}{\partial x} - (E_{11}-C_{11})\frac{\partial^2\psi}{\partial x^2}\\&+(2C_{11}-E_{11}-D)\frac{\partial^3 w}{\partial x^3} = 0\end{aligned} \tag{11f}$$

$$\frac{\partial w}{\partial x} = 0 \quad \text{Or} \quad (E_{11}-C_{11})\left(\frac{\partial\psi}{\partial x}+\frac{\partial^2 w}{\partial x^2}\right) + (D-C_{11})\frac{\partial^2 w}{\partial x^2} = 0 \tag{11g}$$

2.3 Applying the nonlocal strain gradient theory

The nonlocal strain gradient theory is a combination of the nonlocal elasticity theory and the gradient strain theory introduced by Lim *et al*. (2015). In this modified high-order and nonclassical theory, the small-scale has a significant impact on both hardening and softening parts of the governing equation in the form of the following equation.

$$E[1-(ea)^2\nabla^2]\sigma_{ij} = (1-l^2\nabla^2)C:\varepsilon_{ij} \tag{12}$$

'C' is the elastic modulus, '*l*' and '*ea*' are the strain gradient and nonlocal parameters, respectively. By applying the nonlocal strain gradient theory to the stresses and strains components of the tube, the following nonlocal governing equations can be obtained.

$$\delta u: A\frac{\partial^2 u}{\partial x^2} - l^2 A\frac{\partial^4 u}{\partial x^4} = m_0\ddot{u} - (ea)^2 m_0\frac{\partial^2\ddot{u}}{\partial x^2} \tag{13a}$$

$$\begin{aligned}&\delta w: (E_{11}-C_{11})\left(\frac{\partial^3\psi}{\partial x^3}+\frac{\partial^4 w}{\partial x^4}\right) + (D-C_{11})\frac{\partial^4 w}{\partial x^4}\\&-B\left(\frac{\partial\psi}{\partial x}+\frac{\partial^2 w}{\partial x^2}\right) + (ea)^2\frac{\partial^2}{\partial x^2}\left(\frac{dF^R}{dx}\frac{\partial w}{\partial x}\right)\\&\qquad + F^B\,sin(\frac{n\pi x}{L})\,sin(\Omega t)\\&-l^2\left(\begin{aligned}&(E_{11}-C_{11})\left(\frac{\partial^5\psi}{\partial x^5}+\frac{\partial^6 w}{\partial x^6}\right)\\&+(D_{11}-C_{11})\frac{\partial^6 w}{\partial x^6} - B\left(\frac{\partial^3\psi}{\partial x^3}+\frac{\partial^4 w}{\partial x^4}\right)\end{aligned}\right)\\&+(ea)^2\frac{\partial^2}{\partial x^2}\left(F^R\frac{\partial^2 w}{\partial x^2}\right) - \frac{dF^R}{dx}\frac{\partial w}{\partial x} - F^R\frac{\partial^2 w}{\partial x^2}\\&+(ea)^2F^B\left(\frac{n\pi}{L}\right)^2 sin(\frac{n\pi x}{L})\,sin(\Omega t)\\&= m_1\frac{\partial^4 w}{\partial x^2\partial t^2} - m_0\frac{\partial^2 w}{\partial t^2} + m_3\left(\frac{\partial^4 w}{\partial x^2\partial t^2}+\frac{\partial^3\psi}{\partial x\partial t^2}\right)\\&-m_2\left(2\frac{\partial^4 w}{\partial x^2\partial t^2}+\frac{\partial^3\psi}{\partial x\partial t^2}\right)\\&-(ea)^2\left(\begin{aligned}&m_1\frac{\partial^6 w}{\partial x^4\partial t^2} - m_0\frac{\partial^4 w}{\partial x^2\partial t^2}\\&+m_3\left(\frac{\partial^6 w}{\partial x^4\partial t^2}+\frac{\partial^5\psi}{\partial x^3\partial t^2}\right)\\&-m_2\left(2\frac{\partial^6 w}{\partial x^4\partial t^2}+\frac{\partial^5\psi}{\partial x^3\partial t^2}\right)\end{aligned}\right)\end{aligned} \tag{13b}$$

$$\begin{aligned}&\delta\psi: (C_{11}-E_{11})\frac{\partial^3 w}{\partial x^3} + B\left(\psi+\frac{\partial w}{\partial x}\right) - E_{11}\left(\frac{\partial^2\psi}{\partial x^2}\right)\\&-l^2\left((C_{11}-E_{11})\frac{\partial^5 w}{\partial x^5} + B\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^3 w}{\partial x^3}\right) - E_{11}\left(\frac{\partial^4\psi}{\partial x^4}\right)\right)\\&= m_3\left(\frac{\partial^3 w}{\partial x\partial t^2}+\frac{\partial^2\psi}{\partial t^2}\right) - m_2\frac{\partial^3 w}{\partial x\partial t^2}\\&-(ea)^2\left(\left(\frac{\partial^5 w}{\partial x^3\partial t^2}+\frac{\partial^4\psi}{\partial x^2\partial t^2}\right) - m_2\frac{\partial^5 w}{\partial x^3\partial t^2}\right)\end{aligned} \tag{13c}$$

Also, the modified nonlocal boundary conditions equations as presented as follows:

$$u=0 \quad \text{Or} \quad A_{11}\frac{\partial u}{\partial x}-l^2A_{11}\frac{\partial^3 u}{\partial x^3}-(ea)^2m_0\frac{\partial \ddot{u}}{\partial x}=0 \tag{13d}$$

$$\psi=0 \quad \text{Or} \quad \begin{array}{l} E_{11}\left(\frac{\partial\psi}{\partial x}+\frac{\partial^2 w}{\partial x^2}\right)-C_{11}\frac{\partial^2 w}{\partial x^2} \\ -l^2\left(E_{11}\left(\frac{\partial^3\psi}{\partial x^3}+\frac{\partial^4 w}{\partial x^4}\right)-C_{11}\frac{\partial^4 w}{\partial x^4}\right) \\ -(e_0a^2)\left((m_3-m_2)\frac{\partial^2\ddot{w}}{\partial x^2}+m_3\frac{\partial\ddot{\psi}}{\partial x}\right)=0 \end{array} \tag{13e}$$

$$w=0 \quad \text{Or} \quad \begin{array}{l} B\left(\psi+\frac{\partial w}{\partial x}\right)+F^R\frac{\partial w}{\partial x}-(E_{11}-C_{11})\frac{\partial^2\psi}{\partial x^2} \\ +(2C_{11}-E_{11}-D)\frac{\partial^3 w}{\partial x^3} \\ -l^2\begin{pmatrix} B\left(\frac{\partial^2\psi}{\partial x^2}+\frac{\partial^3 w}{\partial x^3}\right)+F^R\frac{\partial^3 w}{\partial x^3} \\ -(E_{11}-C_{11})\frac{\partial^4\psi}{\partial x^4} \\ +(2C_{11}-E_{11}-D)\frac{\partial^5 w}{\partial x^5} \end{pmatrix} \\ -(ea^2)\begin{pmatrix} (m_3+m_1-2m_2)\frac{\partial^3\ddot{w}}{\partial x^3} \\ +(m_3-m_2)\frac{\partial^2\ddot{\psi}}{\partial x^2}-m_0\frac{\partial\ddot{w}}{\partial x} \end{pmatrix} \end{array} \tag{13f}$$

3. Numerical solution methodology

This section provided a numerical method to calculate the results based on the generalized differential quadratic method (GDQM). In the first step, the time-independent equations are solved via GDQM to find the free vibration frequency, and then, according to the Newmark beta technique, the time-dependent results of forced vibration will be obtained. In the GDQ procedure, the derivative functions replace via the modified matrices, which are defined in the following. The eigenvalue of the final assembled matrix, which is obtained by assembling all matrices along with the boundary conditions, the final frequencies of the problem will be generated (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018). The r-order derivative function of 'f', on the basis of the GDQ approach, is defined as follows.

$$C_{ij}^{(r)}=r\left[C_{ij}^{(r-1)}C_{ij}^{(1)}-\frac{C_{ij}^{(r-1)}}{(x_i-x_j)}\right];i\neq j \tag{14a}$$

$$C_{ii}^{(r)}=-\sum_{j=1,i\neq j}^{n}C_{ij}^{(r)};i=j \tag{14b}$$

where 'x' is the mesh point (grid point) along the tube length, defined as follows.

$$x_i=\frac{L}{2}\left(1-cos\left(\frac{(i-1)}{(N-1)}\pi\right)\right)i=1,2,3,\ldots,n \tag{15}$$

'C' is the weighing coefficient and the first-order of it is defined as follows:

$$C_{ij}^{(1)}=\frac{\widetilde{M}(x_i)}{(x_i-x_j)\widetilde{M}(x_j)};i\neq j \tag{16a}$$

$$C_{ij}^{(1)}=-\sum_{j=1,i\neq j}^{n}C_{ij}^{(1)};i=j \tag{16b}$$

where

$$\widetilde{M}(x_i)=\prod_{j=1,j\neq i}^{n}(x_i-x_j) \tag{16c}$$

Utilizing the GDQ method, the governing equations (Eqs. (13)) are modified to the following format (Shafiei and She 2018, Shafiei *et al*. 2019, 2020).

$$\begin{array}{l}\delta u: A\sum_{s=1}^{n}C_{rs}^{(2)}u-l^2A\sum_{s=1}^{n}C_{rs}^{(4)}u \\ =\omega^2\left[m_0u-(ea)^2m_0\sum_{s=1}^{n}C_{rs}^{(2)}u\right]\end{array} \tag{17a}$$

$$\begin{array}{l}\delta w: (E_{11}-C_{11})\left(\sum_{s=1}^{n}C_{rs}^{(3)}\psi+\sum_{s=1}^{n}C_{rs}^{(4)}w\right) \\ +(D-C_{11})\frac{\partial^4 w}{\partial x^4}-B\left(\sum_{s=1}^{n}C_{rs}^{(1)}\psi+\sum_{s=1}^{n}C_{rs}^{(2)}w\right) \\ +(ea)^2\frac{\partial^2}{\partial x^2}\left(\frac{dF^R}{dx}\sum_{s=1}^{n}C_{rs}^{(1)}w\right)+F^B sin(\frac{n\pi x}{L})sin(\Omega t) \\ -l^2\begin{pmatrix}(E_{11}-C_{11})\left(\sum_{s=1}^{n}C_{rs}^{(5)}\psi+\sum_{s=1}^{n}C_{rs}^{(6)}w\right) \\ +(D_{11}-C_{11})\sum_{s=1}^{n}C_{rs}^{(6)}w \\ -B\left(\sum_{s=1}^{n}C_{rs}^{(5)}\psi+\sum_{s=1}^{n}C_{rs}^{(6)}w\right)\end{pmatrix} \\ +(ea)^2\frac{\partial^2}{\partial x^2}\left(F^R\sum_{s=1}^{n}C_{rs}^{(2)}w\right)-\frac{dF^R}{dx}\sum_{s=1}^{n}C_{rs}^{(1)}w \\ -F^R\sum_{s=1}^{n}C_{rs}^{(2)}w+(ea)^2F^B\left(\frac{n\pi}{L}\right)^2sin(\frac{n\pi x}{L})sin(\Omega t) \\ =\omega^2\left[\begin{array}{c}m_1\sum_{s=1}^{n}C_{rs}^{(2)}w-m_0w \\ +m_3\left(\sum_{s=1}^{n}C_{rs}^{(1)}\psi+\sum_{s=1}^{n}C_{rs}^{(2)}w\right) \\ -m_2\left(\sum_{s=1}^{n}C_{rs}^{(1)}\psi+\sum_{s=1}^{n}C_{rs}^{(2)}w\right) \\ -(ea)^2\begin{pmatrix}m_1\sum_{s=1}^{n}C_{rs}^{(4)}w-m_0\sum_{s=1}^{n}C_{rs}^{(2)}w \\ +m_3\left(\sum_{s=1}^{n}C_{rs}^{(3)}\psi+\sum_{s=1}^{n}C_{rs}^{(4)}w\right) \\ -m_2\left(2\sum_{s=1}^{n}C_{rs}^{(2)}w+\sum_{s=1}^{n}C_{rs}^{(3)}\psi\right)\end{pmatrix}\end{array}\right]\end{array} \tag{17b}$$

$$\delta\psi: (C_{11}-E_{11})\sum_{s=1}^{n}C_{rs}^{(3)}w \tag{17c}$$

$$-l^2\begin{pmatrix}(C_{11}-E_{11})\sum_{s=1}^{n}C_{rs}{}^{(5)}w\\+B\left(\sum_{s=1}^{n}C_{rs}{}^{(2)}\psi+\sum_{s=1}^{n}C_{rs}{}^{(3)}w\right)\\-E_{11}\left(\sum_{s=1}^{n}C_{rs}{}^{(4)}\psi\right)\end{pmatrix}$$
$$-E_{11}\left(\sum_{s=1}^{n}C_{rs}{}^{(2)}\psi\right)+B\left(\psi+\sum_{s=1}^{n}C_{rs}{}^{(1)}w\right)$$
$$=\omega^2\begin{bmatrix}m_3\left(\sum_{s=1}^{n}C_{rs}{}^{(1)}w+\psi\right)-m_2\sum_{s=1}^{n}C_{rs}{}^{(1)}w\\-(ea)^2\begin{pmatrix}\left(\sum_{s=1}^{n}C_{rs}{}^{(3)}w+\sum_{s=1}^{n}C_{rs}{}^{(2)}\psi\right)\\-m_2\sum_{s=1}^{n}C_{rs}{}^{(3)}w\end{pmatrix}\end{bmatrix}$$

The obtained free frequencies, along with the Newmark beta technique, are used to find the time-dependent results of forced vibration of considered FG tubes.

4. Discussion of acquired results

In this section, the presented numerical results for the dynamic response of an FGM tube under the bending harmonic load are discussed in detail, but before the discussion of the new results, the validation of the derived motion equations as well as associated boundary conditions should be done. To validate methodology and the mathematical modeling, the spinning functionally graded nanotube, the presented frequency in this study, has been compared to the results of Fan *et al*. (2022) for the rotating a functionally graded cantilever tube versus the different FG parameters. The comparison proved the excellent agreement between the results.

The dimensionless parameters involving non-dimensional nonlocal parameter (μ), strain gradient parameter (λ), hub radius (γ), rotation speed (Ξ), bending deflection (β), and frequency (ϖ) listed below are specified to better characterize the presentation of the findings.

$$\mu=\frac{(ea)^2}{L} \tag{18a}$$

$$\lambda=\frac{l^2}{L} \tag{18b}$$

$$\gamma^2=\frac{h}{L} \tag{18c}$$

$$\Xi=\sqrt{\frac{L^4\rho_{Al}A}{2E_{Al}I}}\phi \tag{18d}$$

$$\beta=-w\times 10\pi\frac{E_{Al}\times I}{F\times L^4} \tag{18e}$$

$$\varpi=\omega\sqrt{\frac{L^4\rho_{Al}A}{\pi E_{Al}I}} \tag{18f}$$

Table 2 Comparison of the presented fundamental frequency of the presented study with Fan *et al*. (2022) for the homogenous and FG cantilever beam under the rotation, $\phi=2\sqrt{EI/EAL^4}$, L=100R2

Present high-order theory	First-order beam theory (Fan *et al*. 2022)	Third order beam theory (Fan *et al*. 2022)
4.137560399	4.1361	4.1417
3.404015635	3.4504	3.4559
2.901526846	2.8998	2.9044

Table 3 lists the fundamental free frequency (ϖ) of the spinning cantilever nanotube for different rotation velocities (Ξ) versus the various nonlocal parameters (μ). According to the presented results, the fundamental frequency increases with both rotation speed and nonlocal parameters, in fact, the increment of velocity increases the centrifugal force and increases the stability of the tube. Also, the increment of nonlocal parameters increases the tube strength and improves tube stability.

The time-dependent deflection (β) response due to the rotation speed and nonlocal parameters are presented in Fig. 2 and Fig. 3. Based on the presentation of these results, which are the complement results of Table 3, the angular velocity impacts the cycle period, decreasing the time cycle. The nonlocal parameters also have the same impact, reducing the cycle time and not affecting the amplitude deflection. Fig. 2 and Fig. 3 also present the effect of excitation frequency (Ω/ω) on the time-dependent nonlocal tube deflection, the submitted results prove that the deflection in the neighboring resonance frequency (Ω/ω=1) increases with time, and for each excitation frequency, both nonlocal parameter and velocity speed just worked on the cycle time.

The impact of the strain gradient parameter (γ) on both fundamental frequency (ϖ) and time-dependent deflection (β) investigate in Table 4 and Fig. 4, Table 4 present the frequency response for rotating speed along with the strain gradient parameter, while Fig. 4 displays the time-dependent dynamic deflection of nanotube versus the strain gradient as well as the excitation frequency. The calculated results show that an increment of the strain gradient parameter enhances the fundamental frequency because this parameter improves the tube stiffness, and also, this parameter has a significant effect on the dynamic deflection of the tube. The strain gradient parameter affects both amplitude deflection and time cycle (period), which means the strain gradient parameter reduces both domain deflection and cycle time.

Table 5 indicates the volume fraction impact on the fundamental frequency (ϖ) of spinning functionally graded cantilever nanotube for different FG parameter (η) values under the different rotation speed values (Ξ). Since ceramics are usually stiffer than metals, the frequency of Aluminum oxide (η=0) tubes is more remarkable than Nickel tubes (η=∞), and the frequency of FG tubes made of Al_2O_3/Nickel is between them. The dynamic time-dependent deflection (β) of nanotube versus FG parameter indexes (η) along with the excitation

Table 3 The fundamental frequency (ϖ) of a nonlocal cantilever tube versus the different rotating speeds (Ξ) and nonlocal parameter (μ), L=50R2

	μ=0	μ=1	μ=2	μ=3	μ=4	μ=5
Ξ=0	1.9837	1.98541	1.99058	1.99936	2.01202	2.02899
Ξ=1	2.1664	2.171	2.18494	2.20862	2.24276	2.28853
Ξ=2	2.63655	2.64767	2.68144	2.73912	2.82311	2.93743
Ξ=3	3.26618	3.28477	3.34158	3.43991	3.58588	3.79015
Ξ=4	3.9741	4.0003	4.08093	4.22256	4.43747	4.74768
Ξ=5	4.72067	4.75465	4.85983	5.0467	5.33583	5.76566
Ξ=6	5.48721	5.52944	5.66021	5.89407	6.26151	6.82249
Ξ=7	6.2647	6.31583	6.47353	6.75589	7.20467	7.90624
Ξ=8	7.04856	7.1094	7.29542	7.62748	8.1598	9.00956
Ξ=9	7.83633	7.90776	8.12346	8.50614	9.12354	10.1275
Ξ=10	8.62663	8.70955	8.95618	9.39014	10.0937	11.2567

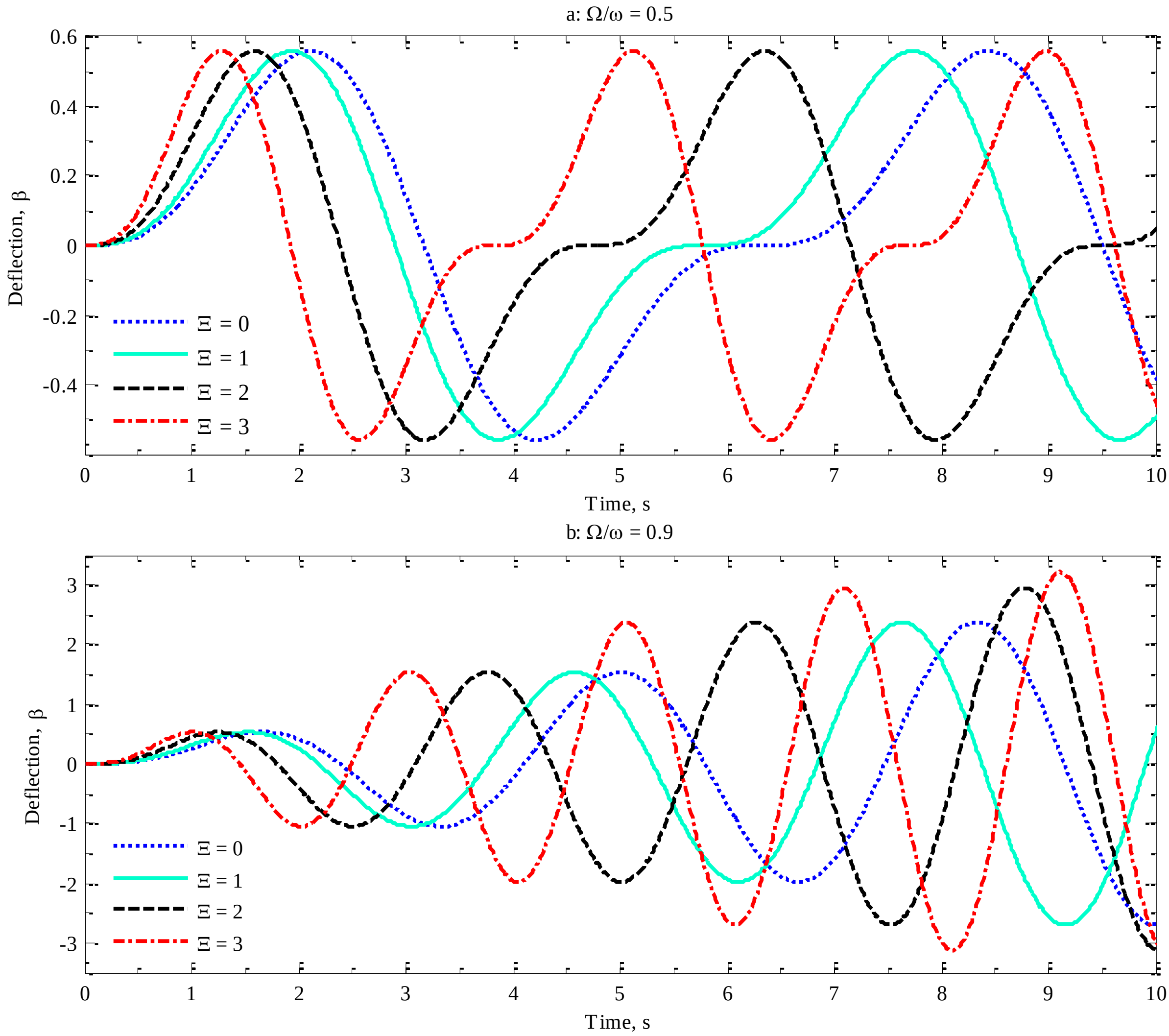

Fig. 2 The time-dependent dimensionless deflection (β) of the nonlocal clamped-free tube versus the velocity (Ξ) and excitation frequency (Ω/ω), L=50R2

frequency is also shown in Fig. 5. The volume fraction parameters impact both dynamic domain deflection and cycle time (period) in both excitation frequencies (Ω/ω = 0.5 and 0.9), which means the deflection domain and period growth by volume fraction parameters.

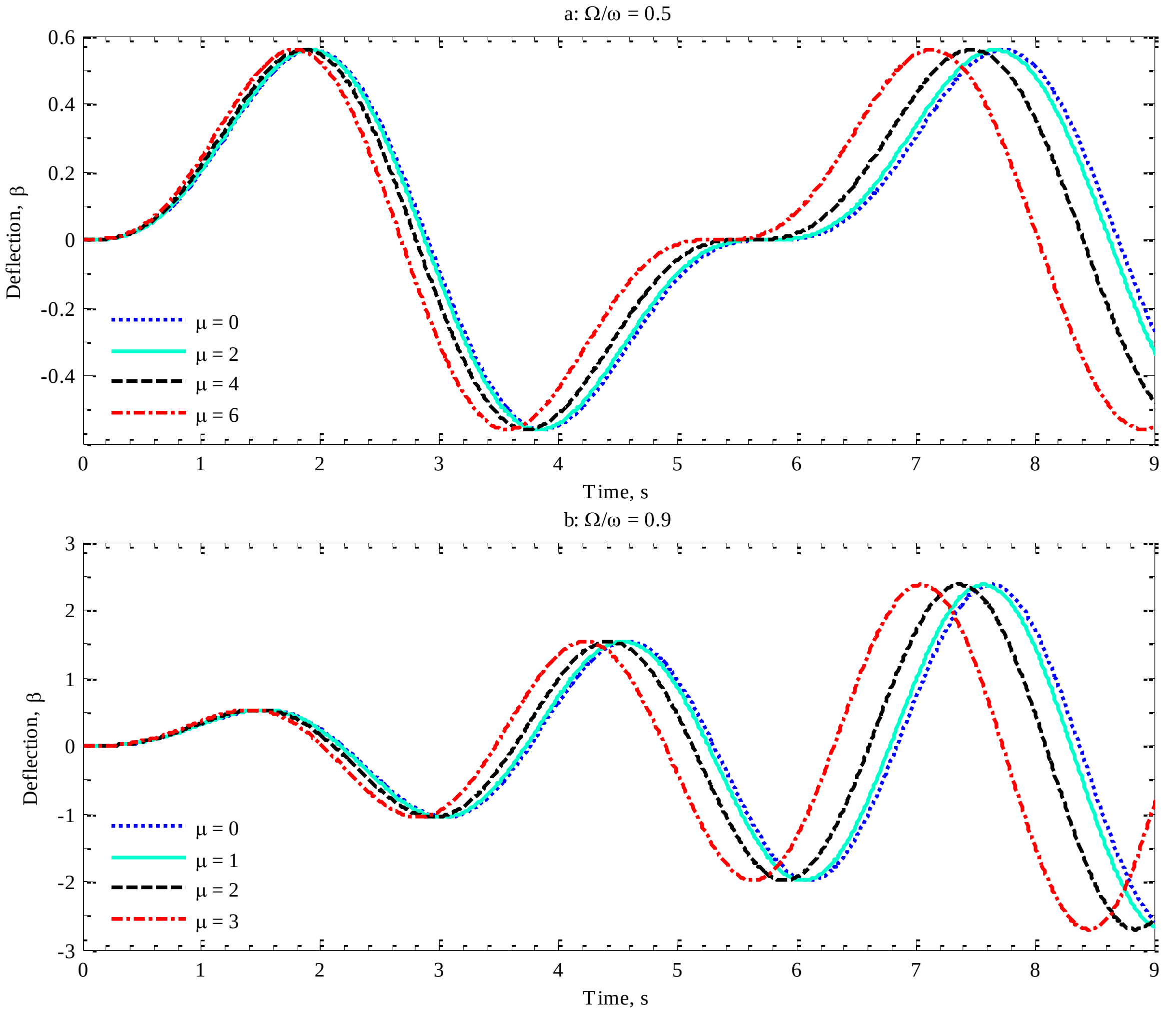

Fig. 3. The time-dependent dimensionless deflection (β) of the nonlocal clamped-free tube versus the nonlocal parameters (μ) and excitation frequency (Ω/ω), L=50R2

Table 4 The fundamental frequency (ϖ) of a nonlocal cantilever tube versus the different rotating speeds (Ξ) and nonlocal parameter (γ), L=50R2

	γ=0	γ=0.1	γ=0.2	γ=0.3	γ=0.4	γ=0.5
Ξ=0	1.9837	1.98541	1.99058	1.99936	2.01202	2.02899
Ξ=1	2.1664	2.171	2.18494	2.20862	2.24276	2.28853
Ξ=2	2.63655	2.64767	2.68144	2.73912	2.82311	2.93743
Ξ=3	3.26618	3.28477	3.34158	3.43991	3.58588	3.79015
Ξ=4	3.9741	4.0003	4.08093	4.22256	4.43747	4.74768
Ξ=5	4.72067	4.75465	4.85983	5.0467	5.33583	5.76566
Ξ=6	5.48721	5.52944	5.66021	5.89407	6.26151	6.82249
Ξ=7	6.2647	6.31583	6.47353	6.75589	7.20467	7.90624
Ξ=8	7.04856	7.1094	7.29542	7.62748	8.1598	9.00956
Ξ=9	7.83633	7.90776	8.12346	8.50614	9.12354	10.1275
Ξ=10	8.62663	8.70955	8.95618	9.39014	10.0937	11.2567

5. Conclusions

The present paper studied the dynamic response of a spinning functionally graded nonlocal nanotube according to the high-order beam theory along with the nonlocal strain gradient theory. The nanotube was made of functionally graded materials composed of a Nickel core coated by Aluminum oxide along the radius direction. The nonlocal governing equations were derived via the Hamilton principle; then, the generated equations were solved with

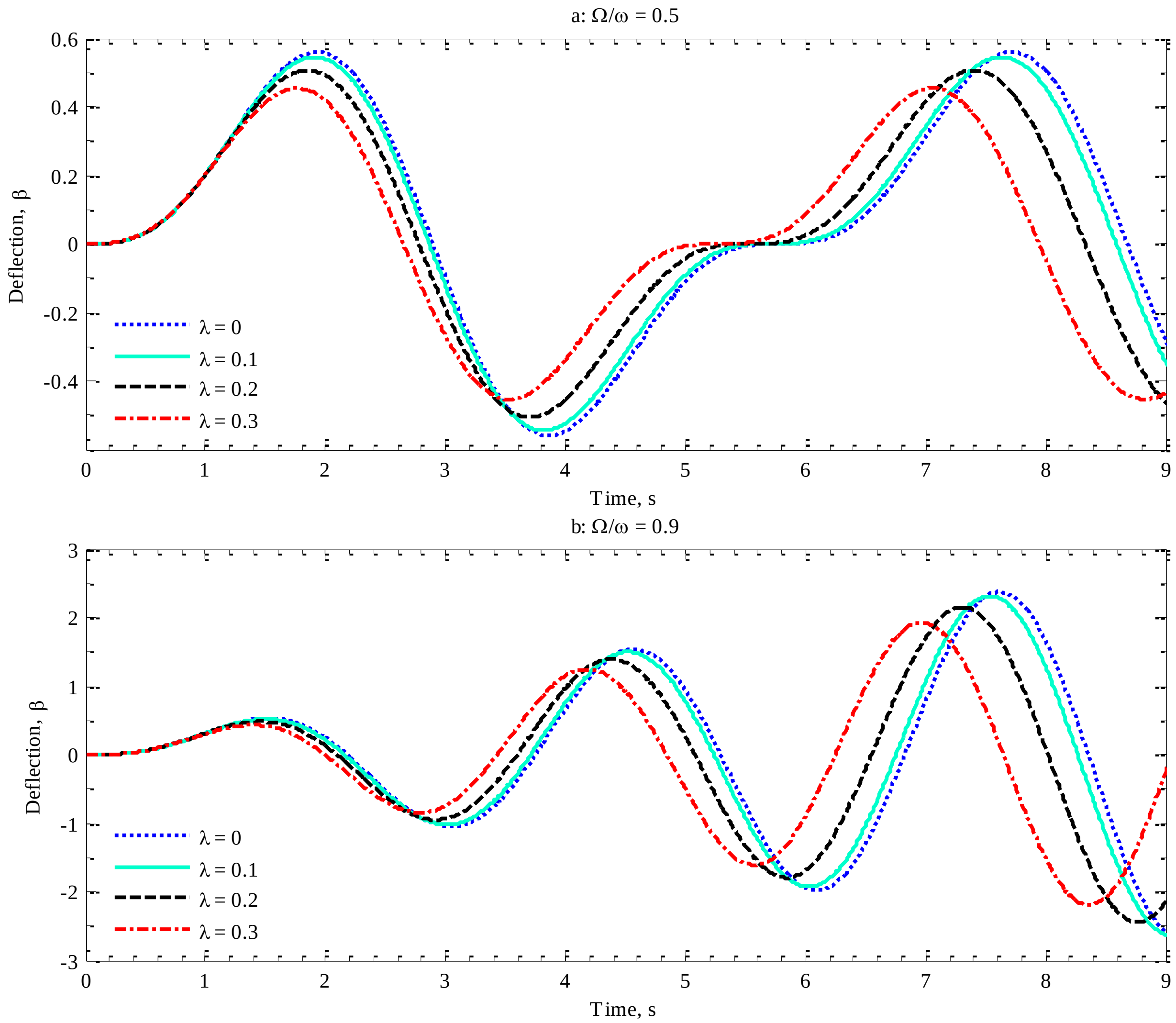

Fig. 4 The time-dependent dimensionless deflection (β) of the cantilever nanotube versus the strain gradient parameters (γ) and excitation frequency (Ω/ω), μ=1, L=50R2

Table 5 The fundamental frequency (ϖ) of a cantilever nanotube versus the volume fraction parameter (η) and rotating speeds (Ξ), μ=1, γ=0.1, L=50R2

	Aluminum oxide, η=0	FGM, η=1	FGM, η=2	Nickel, η=∞
Ξ=0.0	2.01086	1.49592	1.36002	1.04569
Ξ=0.2	2.01853	1.50536	1.3694	1.06036
Ξ=0.4	2.04137	1.53332	1.39713	1.10317
Ξ=0.6	2.07885	1.57879	1.44214	1.1709
Ξ=0.8	2.13017	1.64026	1.50283	1.25933
Ξ=1.0	2.19431	1.71595	1.57733	1.36422
Ξ=1.2	2.27014	1.80401	1.66372	1.48182
Ξ=1.4	2.35645	1.90264	1.76018	1.60911
Ξ=1.6	2.45208	2.0102	1.86507	1.74374
Ξ=1.8	2.55591	2.12525	1.97699	1.88395
Ξ=2.0	2.66692	2.24657	2.09473	2.02841

the generalized differential quadratic method and the Newmark beta technique. The numerical findings are discussed in detail, and the following remarks were the main conclusion.

• An increment of rotating speed develops the fundamental frequency and decreases the period of

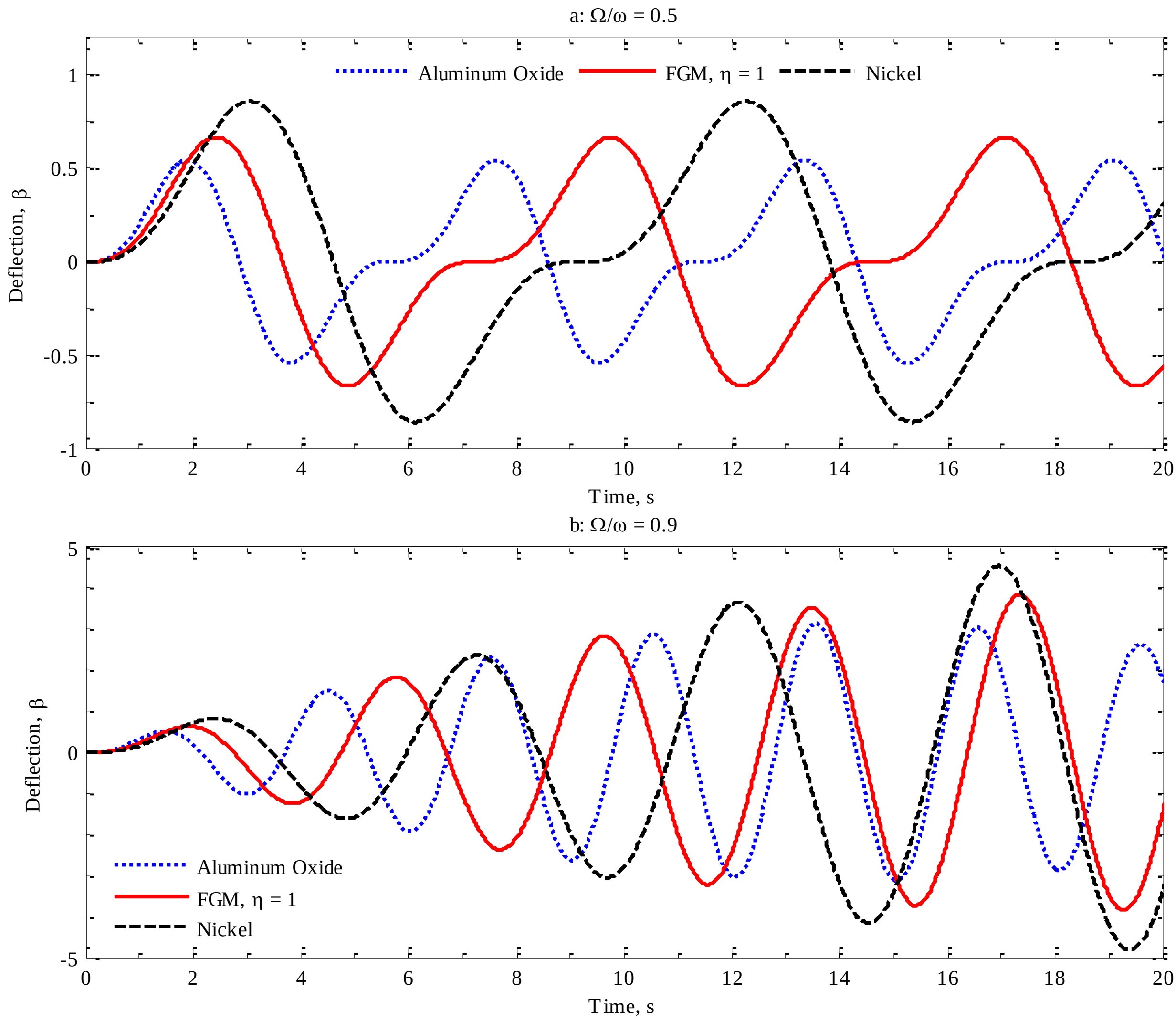

Fig. 5 The time-dependent dimensionless deflection (β) of the cantilever nanotube versus the FGM parameter (η) and excitation frequency (Ω/ω), μ=1, γ=0.1, L=50R2

dynamic deflection of the tube.

- The parameter of nonlocal impact improves the tube stability and the tube frequency and limits the time cycle of dynamic deflection of the tube.
- The parameter of strain gradient enhances the tube frequency and has a significant effect on the dynamic deflection of the tube, leading to limiting both domain deflection and the period of the spinning tube.
- The frequency of the spinning tube decreases by the FG parameter, while the domain of dynamic deflection and period of time-dependent deflection raises by the volume fraction parameter.

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