Advances in Nano Research, *Vol. 13, No. 1 (2022) 63-75*
https://doi.org/10.12989/anr.2022.13.1.063

Intelligent computer modelling and simulation for the large amplitude of nano systems

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(*Received February 1, 2021, Revised May 8, 2022, Accepted May 10, 2022*)

Abstract. The nonlinear dynamic behavior of a nonuniform small-scale nonlocal beam is investigated in this work. The nanobeam is theoretically modeled using the nonlocal Eringen theory, as well as a few of Von-nonlinear Kármán's theories and the classical beam theory. The Hamilton principle extracts partial differential equations (PDE) of an axially functionally graded (AFG) nano-scale beam consisting of SUS304 and Si_3N_4 throughout its length, and an elastic Winkler-Pasternak substrate supports the tapered AFG nanobeam. The beam thickness is a function of beam length, and it constantly varies throughout the length of the beam. The numerical solution strategy employs an iteration methodology connected with the generalized differential quadratic method (GDQM) to calculate the nonlinear outcomes. The nonlinear numerical results are presented in detail to examine the impact of various parameters such as nonlinear amplitude, nonlocal parameter, the component of the elastic foundation, rate of cross-section change, and volume fraction parameter on the linear and nonlinear free vibration characteristics of AFG nanobeam.

Keywords: dynamic analysis; high-order theory; nanobeams; nonlinear analysis; small-scale structures

1. Introduction

Despite recent advances in small-scale structures, many research groups have focused on theoretical issues due to the time and price required for the experimental examination (Long *et al.* 2021, Chen *et al.* 2022, Gao *et al.* 2022, Gong *et al.* 2022, Zhan *et al.* 2022). The phrase “size-dependent theory” refers to theories dependent on the size of the system (Rasid *et al.* 2019, Li *et al.* 2020a, Wang *et al.* 2021, Zheng *et al.* 2021). The strain gradient theory, the Eringen theory (Ghadiri and Shafiei 2016b, Ghadiri *et al.* 2016a, b, s, d, Shafiei *et al.* 2016b), the modified couple stress theory (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), and the nonlocal strain gradient theory (Liu *et al.* 2020b, 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Zhang *et al.* 2021) are the size-dependent theories. Because of the small-scale consequences, the essential assumptions of the different size-dependent theories differ (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g). These extra deductions result in a wide variety of behavior (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020c, Zare *et al.* 2020, Dai *et al.* 2021b). Some theories, such as the modified connected stress theory (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020b, Zhang *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a), strain gradient theory (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017), and others, anticipate the hardening phenomena because of the action on a small scale (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). These theories employ length-scale factors to modify the stiffness section of the governing equation (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b), but others, such as the nonlocal theory, use mass matrices to predict softening (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b). In recent years, the nonlocal theory has been combined with strain gradient theory, resulting in nonlocal strain gradient theory, which incorporates both softening and hardening processes (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c). According to this theory, the small-scale component acts on both the mass and stiffness sides of the governing equations (Ebrahimi *et al.* 2019a, b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Ebrahimi *et al.* 2020, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020). Among them, the nonlocal theory allows researchers to manage better the stability of small-scale structures, which has led to an inflow of academics from a wide range of professional backgrounds flocking to this field (Habibi *et al.* 2017, 2019, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020). Soleimani-Javid *et al.* (2021) studied the non-homogeneous honeycomb small-scale plate to analyze the dynamic analysis mentioned structures for different boundary conditions via an analytical approach. Kumar *et al.* (2021) investigated the free vibration characteristics of the nonlocal small-scale FG high-order plate, including the porosity, in order to analyze the impact of the shear deformation factor. Zerrouki *et al.* (2021) examined the impact of material distribution according to the nonlinear

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ISSN: 2287-237X (Print), 2287-2388 (Online)

function on the bending behavior of high-order carbon nanotube. Heidari *et al*. (2021) suggested reality assumed to investigate the stability behavior of carbon nanotubes regarding the buckling analysis based on the nonlocal elastic theory. Rouabhia *et al*. (2020) applied the first-order shear deformation theory of the plate to investigate the stability concerning the buckling characteristics of graphene sheets resting on a viscoelastic foundation. Matouk *et al*. (2020) studied the hygro-thermal impact on the thermo-mechanical vibrational behavior of FG nanobeam according to first-order shear deformation beam theory and the nonlocal Eringen theory. Bellal *et al*. (2020) supposed a nonclassical graphene sheet on the visco-elastic foundation in order to investigate the buckling treatment of nonlocal plate structure. Asghar *et al*. (2020) presented a chiral nanoscale pipe according to the shell theory coupled with nonlocal elastic theory regarding the vibrational analysis of multi-walled nanotubes employing the numerical method. Balubaid (2019) analytically presented the dynamic response about the pinned functionally graded nanoscale plate via high-order nonlocal theory. Hussain *et al*. (2019) worked on the tube structures versus the various boundary conditions based on the Eringen nonlocal theory to the dynamic properties concerning the stability of the carbon nanotubes and their wave behavior. Boutaleb *et al*. (2019) analyzed the vibration behavior of the FG nonlocal plate on the basis of high-order shear deformation plate theory utilizing the nonlocal Eringen theory. Berghouti *et al*. (2019) used the different high-order theories of the beam to examine the vibration behavior of porosity-dependent functionally graded nanoscale beam based on the nonlocal Eringen theory. Bakoura *et al*. (2021) scrutinized the shear deformation impact on the statical buckling behavior of the high-order plate stress function approach. Bekkaye *et al*. (2020) operated the shear deformation plate theory for the analytical buckling and bending behavior of imperfect FG plates.

Functionally graded materials (FGM) are one of the best non-homogeneous structures because their unique qualities allow them to suit the requirements of goods (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018). These preferred structures are combined with two or more phases of different materials to create a structure that incorporates the best features of each phase (Zhao *et al*. 2022, Huang *et al*. 2021b, Jiao *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021). Ceramics, for example, can withstand high temperatures while metals may be formed, yet, the heat resistance of metals and the formability of ceramics are low (Ma *et al*. 2022, Hou *et al*. 2021, Huang *et al*. 2021c, Liu *et al*. 2021c, Yu *et al*. 2022). As a result, the functionally graded ceramic-metal composite material has a good heat resistance and formability. Academics and designers alike are becoming more interested in applying this critical knowledge to their work. Pompe *et al*. (2003) researched on the biomedical application of functionally graded materials in the biomedical application of artificial implants. Natarajan and Manickam (2012) used the high-order theory of plates to numerically examine the thermo-mechanical vibration and static bending of a functionally graded plate. Shaker *et al*. (2008) employed the novel numerical approach to study the frequency response of the high-order functionally graded plate. Li *et al*. (2009b) investigated the vibration and buckling properties of a functionally graded piezoelectric fully clamped beam under heat settings using a combination of classical beam theory and nonlinear theory. Daikh *et al*. (2020) used nonlocal theory to investigate the vibration behavior of FG simply supported nanobeams in a thermal environment with temperature-dependent material compositions. Pandey and Pradyumna (2017) operated a numerical technique to simulate the FG shell structure based on high-order theory for the theme-mechanical vibration analysis of these structures. Ke *et al*. (2010) utilized a numerical iteration approach to analyze the nonlinear vibration behavior of a functionally graded classical beam. Mollarazi *et al*. (2011) employed the meshless method to investigate the vibrational response on the cylindrical pipe in which the composition of materials varied the radial direction. Wang *et al*. (2019) studied the dynamic behavior of the functionally graded and imperfect microscale beam in the hygro-thermal environment based on the modified couple stress theory and the analytical solution. Bich and Xuan Nguyen (2012) numerically investigated the nonlinear dynamic behavior of functionally graded shells according to the Donnell theory of shell. Moita *et al*. (2020) operated the Kirchhoff-Love theory of functionally graded shell and plate to investigate the vibration response regarding the different conditions. Li *et al*. (2009a) studied the different types of temperature change functions to examine the thermal vibration of the functionally graded plate for both pinned and clamped boundary conditions. The investigation of nonlinear impacts in the thermal environment for the stability regarding the vibrational response of functionally graded paper was done by Sundararajan *et al*. (2005).

It is easily understood that the free linear and nonlinear frequencies of the small-scale nonuniform beams resting in an elastic foundation still need to be investigated, however, many scholars have conducted numerous evaluations of the dynamic features of small-scale beam constructions under diverse settings. Therefore, the linear and nonlinear vibration analysis of a nonuniform and axially functionally graded tapered nanobeam supported by an elastic foundation based on nonlocal elasticity theory, classical theory, and Von-Kármán theory is examined in this study. The axially functionally graded (AFG) material characteristics of SUS304 and Si_3N_4 are modified throughout the beam length, and the beam thickness is adjusted along the beam length. For the beam substrate, both the Winkler and Pasternak foundations are intended. Finally, the numerical approach is used to solve the partial differential equations that have been created.

2. Mathematical simulation of nanobeam behavior

As seen in Fig. 1, a non-uniform beam structure immersed in an elastic foundation is constructed of functionally graded material with a variable distribution of mechanical material qualities over the beam length.

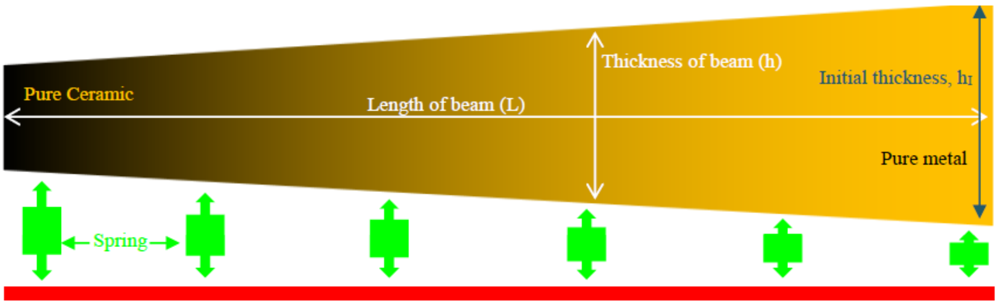

Fig. 1. Illustration of a tapered AFG beam placed in an elastic foundation

Table 1 The coefficient values of SUS304 and Si_3N_4 regarding the Poison ratio, density, and Young's modulus

	Poison ratio	Density (Kg/m^3)	Young's modulus (MPa)
SUS304	0.3177	8166	322.269e3
Si_3N_4	0.24	2370	207.79e3

As demonstrated in Fig. 1, the tapered beam is composed of ceramic and metal. The following equation takes into account how the mechanical characteristics of the material, such as Young's modulus, density, and Poison ratio, fluctuate with the beam length.

$$E(x) = (E_{SN} - E_{St})\left(1 - \frac{x}{L}\right)^{\eta} + E_{St} \tag{1a}$$

$$\rho(x) = (\rho_{SN} - \rho_{St})\left(1 - \frac{x}{L}\right)^{\eta} + \rho_{St} \tag{1b}$$

$$v(x) = (v_{SN} - v_{St})\left(1 - \frac{x}{L}\right)^{\eta} + v_{St} \tag{1c}$$

The subscript '$()_{SN}$' denotes Si_3N_4 regarding the ceramic phase, and '$()_{St}$' directs to SUS304 concerning the metal phase, furthermore, 'η' is the volume fraction parameter regarding the FG index, moreover, Table 1 provides the mechanical parameter values for SUS304 and Si_3N_4.

In the non-uniform section, the thickness is altered along the beam length concerning the following mathematical equation.

$$h(x) = h0\left(1 - \alpha\frac{L - x}{L}\right) \tag{2}$$

where 'α' is the rate of section change. The definition of geometric and material dispersion was done, then the motion equation relation will be defined. In order to represent and simulate the nanobeam mathematically, the classical beam theory is combined with Eringen's nonlocal theory and Von-Kármán's nonlinear theory. The displacement components along the x/-, y/-, and z-axis in the classical beam theory are as follows.

$$u_x = u(t,x) - z\frac{\partial w(t,x)}{\partial x} \tag{3a}$$

$$u_y = 0 \tag{3b}$$

$$u_z = w(t,x) \tag{3c}$$

Thus, the following nonlinear strains are assumed to be Euler-Bernoulli beam-based linked with Von-Kármán's nonlinear theory.

$$\varepsilon_{xx} = \frac{\partial u}{\partial x} - z\frac{\partial^2 w^2}{\partial x} + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2 \tag{4a}$$

$$\varepsilon_{xy} = \varepsilon_{yx} = \varepsilon_{yy} = \varepsilon_{yz} = \varepsilon_{zy} = \varepsilon_{xz} = \varepsilon_{zx} = \varepsilon_{zz} = 0 \tag{4b}$$

The virtual potential energy (δP) will be estimated in the following manner using the derived strains equation.

$$\begin{aligned} \delta P &= \iiint \delta(E\varepsilon{:}\,\varepsilon)dv \\ &= C\frac{\partial^2 w}{\partial x^2}\delta\left(\frac{\partial^2 w}{\partial x^2}\right)dx + \int_0^L A\frac{\partial u}{\partial x}\delta\left(\frac{\partial u}{\partial x}\right) \\ &+ \int_0^L A\left(\begin{matrix}\frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^3\delta\left(\frac{\partial w}{\partial x}\right) + \frac{\partial u}{\partial x}\frac{\partial w}{\partial x}\delta\left(\frac{\partial w}{\partial x}\right) \\ + \frac{1}{2}\left(\frac{\partial w}{\partial x}\right)^2\delta\left(\frac{\partial u}{\partial x}\right)\end{matrix}\right)dx \end{aligned} \tag{5a}$$

where

$$(A, C) = \iint_A E(x)(1, z^2)dA \tag{5b}$$

The virtual Kinetic energy (δK) associated with the nonlinear classical beam displacement is determined in the following manner.

$$\begin{aligned} \delta K &= \frac{1}{2}\int_V \rho(x)\,\delta\left(\dot{u}_x{}^2 + \dot{u}_z{}^2\right)dV \\ &= \int_0^L m_0[\dot{u}\delta(\dot{u}) + \dot{w}\delta(\dot{w})] + m_2\frac{\partial \dot{w}}{\partial x}\delta\left(\frac{\partial \dot{w}}{\partial x}\right)dx \end{aligned} \tag{6a}$$

where

$$(m_0, m_2) = \int_A \rho(x)\,(1, z^2)dA \tag{6b}$$

The non-uniform beam is embedded in an elastic foundation, and the impact of the external foundation is considered as the external work, so the virtual energy due to the external work (W) is assumed as follows.

$$\delta W = \int_0^L \left(K_w w - K_P\frac{\partial^2 w}{\partial x^2}\right)w\delta(w)\,dx \tag{7}$$

The Winkler and Pasternak elastic foundation constants are denoted by 'K_W' and 'K_P'. The Hamilton principle extracts the governing nonlinear and partial differential equations in the following manner.

$$\int (\delta K - \delta P + \delta W)dt = 0 \tag{8}$$

Then, we get the following Euler-Lagrange equation by plugging Eqs. (5), (6) and (7) into Eq.(8).

$$\delta u\text{:} -\frac{\partial}{\partial x}\left(Au' + \frac{1}{2}A(w')^2\right) = m_0\ddot{u} \tag{9a}$$

$$\begin{aligned}\delta w\text{:}&\frac{\partial^2}{\partial x^2}(Cw'') - K_w w + K_P\frac{\partial^2 w}{\partial x^2}\\ &+\frac{\partial}{\partial x}\left[\left(Au' + \frac{1}{2}A(w')^2\right)w'\right] = m_0\ddot{w} - m_2\ddot{w}''\end{aligned} \tag{9b}$$

Boundary conditions:

$$u = 0 \quad \text{Or} \quad Au' + \frac{1}{2}A(w')^2 = 0 \tag{9c}$$

$$\psi = 0 \quad \text{Or} \quad Cw'' = 0 \tag{9d}$$

$$w = 0 \quad \text{Or} \quad \frac{\partial}{\partial x}(Cw'') = 0 \tag{9e}$$

where indicates the '$\ddot{u} = \partial^2 u/\partial t^2$', '$\ddot{w} = \partial^2 w/\partial t^2$' and '$()' = \partial()/\partial \mathrm{x}$'. The nonlocal theory of Eringen will convert the nonlinear partial differential governing equations and related boundary conditions to the following format.

$$\begin{aligned}\delta u\text{:} &-\frac{\partial}{\partial x}\left(Au' + \frac{1}{2}A(w')^2\right)\\ &= m_0\ddot{u} - (ea)^2\frac{\partial^2}{\partial x^2}(m_0\ddot{u})\end{aligned} \tag{10a}$$

$$\begin{aligned}\delta w\text{:}&\frac{\partial^2}{\partial x^2}(Cw'') - K_w w + K_P\frac{\partial^2 w}{\partial x^2}\\ &+\frac{1}{2}\frac{\partial}{\partial x}[(Au' + A(w')^2)w'] + (ea)^2 K_w w'' + m_2\ddot{w}''\\ &-(ea)^2 K_P w'''' - \frac{1}{2}(ea)^2\frac{\partial^2}{\partial x^2}\left(\frac{\partial}{\partial x}(A(w')^2 w')\right)\\ &= m_0\ddot{w} - (ea)^2\frac{\partial^2}{\partial x^2}(m_0\ddot{w} - m_2\ddot{w}'')\end{aligned} \tag{10b}$$

Nonlocal boundary conditions:

$$u = 0 \quad \text{Or} \quad Au' + \frac{1}{2}A(w')^2 - (ea)^2 m_0\ddot{u} = 0 \tag{10c}$$

$$\psi = 0 \quad \text{Or} \quad \begin{aligned}Cw'' - (ea)^2(K_W w - K_P w'' + m_0\ddot{w}\\ - m_2\ddot{w}'') = 0\end{aligned} \tag{10d}$$

$$w = 0 \quad \text{Or} \quad \begin{aligned}\frac{\partial}{\partial x}\left(Cw'' - (ea)^2(m_0\ddot{w} - m_2\ddot{w}'')\right)\\ -(ea)^2(K_W w' - K_P w''') = 0\end{aligned} \tag{10e}$$

3. The strategy and solving procedure

The numerical technique for solving nonlinear partial differential equations is presented in this section. The extended differential quadrature method is used to solve the extracted equations in combination with the iteration strategy. The following specification will translate the derivative terms to matrix format based on the GDQM.

$$\left.\frac{\partial^q g(x)}{\partial x^q}\right|_{x=x_P} = \sum_{j=1}^{n} B_{ij}^{(q)} g(x_i) \tag{11a}$$

where 'q' is the order of the derivative function of 'g', and

$$B_{iji}^{(q)} = q\left[B_{ji}^{(q-1)}B_{ji}^{(1)} - \frac{B_{ji}^{(q-1)}}{(x_j - x_i)}\right], j \neq i \tag{11b}$$

$$B_{jj}^{(q)} = -\sum_{i=1,j\neq i}^{n} B_{ji}^{(q)}, i = j \tag{11c}$$

Also

$$B_{ij}^{(1)} = \frac{T(x_i)}{(x_i - x_j)T(x_j)}, i \neq j \tag{11d}$$

$$B_{ji}^{(1)} = -\sum_{i=1,j\neq i}^{n} B_{ji}^{(1)}, i = j \tag{11e}$$

where '*x*' is the mesh grid point, and

$$T(x_i) = \prod_{i=1,i\neq j}^{n} (x_j - x_i) \tag{11f}$$

The following format will be used to determine the results for the nonlinear eigenvalue issue.

$$\omega^2 = \frac{[K]_{Nonlinear} + [K]_{Linear}}{[M]}\{\gamma\} \tag{12}$$

where 'γ' denotes the eigenvector and '[K]' and '[M]' denote the following:

The frequencies will be derived using the boundary conditions and applying the GDQM (Eq. (11)) to the eigenvalue issue (Eq. (13)). The nonlinear components will be ignored in the first stage, and the natural frequency will be determined, the nonlinear frequency will then be calculated using the linear eigenvalue and eigenvector. The new nonlinear frequency and mode shapes will be automatically assigned to the new eigenvalue, and the new frequency will be determined, this iteration procedure will continue until the findings concur (Shafiei and She 2018, Shafiei *et al.* 2019, 2020).

4. Presentation of calculated findings

This section provided the nonlinear numerical results of the free vibration of the nonuniform small-scale beam based on the Euler-Bernoulli beam theory in conjunction with the nonlocal elasticity theory. The validation of numerical solution procedure as well as nonlinear generated partial differential governing equations are also required before the presentation of the new results. To confirm the numerical findings, Tables 2 and compare linear and nonlinear frequency distributions, respectively. The numerical linear

$$[K]_{Nonlinear} = \begin{bmatrix} 0 & -\left(\frac{1}{2}\right)\frac{\partial}{\partial x}\left(Aw'\frac{\partial}{\partial x}\right) \\ \left(\frac{1}{4}\right)\frac{\partial}{\partial x}\left(A\left(\frac{\partial w}{\partial x}\right)\frac{\partial}{\partial x}\right) - (ea)^2\left(\frac{1}{4}\right)\frac{\partial^2}{\partial x^2}\left(\frac{\partial}{\partial x}\left(A\left(\frac{\partial w}{\partial x}\right)\frac{\partial}{\partial x}\right)\right) & \left(\frac{1}{2}\right)\frac{\partial}{\partial x}\left[A\left(\frac{\partial w}{\partial x}\right)\left(\frac{\partial w}{\partial x}\right)\frac{\partial}{\partial x}\right] \end{bmatrix} \tag{13a}$$

$$[K]_{Linear} = \begin{bmatrix} -\frac{\partial}{\partial x}\left(A\frac{\partial}{\partial x}\right) & 0 \\ 0 & \frac{\partial^2}{\partial x^2}\left(C\frac{\partial^2}{\partial x^2}\right) - K_W + K_P\frac{\partial^2}{\partial x^2 + (ea)^2K_w\frac{\partial^2}{\partial x^2}} - (ea)^2K_P\frac{\partial^4}{\partial x^4} \end{bmatrix} \tag{13b}$$

$$[M] = \begin{bmatrix} m_0 - (ea)^2 m_0'' - (ea)^2 m_0\frac{\partial^2}{\partial x^2} & 0 \\ 0 & m_0 - m_2\frac{\partial^2}{\partial x^2} + (ea)^2\frac{\partial^2}{\partial x^2}\left(m_2\frac{\partial^2}{\partial x^2}\right) - (ea)^2\left(m_0'' + m_0\frac{\partial^2}{\partial x^2}\right) \end{bmatrix} \tag{13c}$$

Table 2 The fundamental frequency ($\sqrt{\omega^2 L^4\,\rho A/EI}$) simply supported ceramic beam (η=0) compared with the results of Zhao and Yu (2021) versus the nonlocal parameter (ea)

	Local	$(ea)^2$=0.5	$(ea)^2$=1	$(ea)^2$=2	$(ea)^2$=3	$(ea)^2$=4
Present study	9.859719693	9.625123602	9.406573269	9.010550158	8.660681288	8.348564996
Zhao and Yu (2021)	9.86959	9.63476	9.41599	9.01957	8.66935	8.35692

Table 3 The normalized nonlinear frequency (Nonlinear frequency/Linear frequency) the clamped beam is compared to findings of Zhao and Yu (2021) various nonlinear amplitudes ($Amplitude\sqrt{I/A}$)

	Amplitude=1	Amplitude=2	Amplitude=3
Present study	1.022098687	1.08560263	1.183068764
Zhao and Yu (2021)	1.0222	1.08571	1.18319

findings are compared to published results of Zhao and Yu (2021) for different nonlocal parameters in Table 2 that demonstrates a great agreement between the provided data. Additionally, the nonlinear frequencies of the clamped beam are shown against the nonlinear amplitude, which provides strong support for the results of Zhao and Yu (2021) in Table 3.

To better characterize the display of the findings, the following non-dimensional parameter is defined.

Dimensionless frequency (Φ):

$$\omega^2 = \Phi^2\frac{\pi E_{SN} I_{x=L}}{\rho_{SN} L^4 A_{x=L}} \tag{14a}$$

Dimensionless nonlocal parameter (γ):

$$(ea)^2 = \gamma L \tag{14b}$$

Dimensionless nonlinear amplitude:

$$Amplitude \times \frac{\pi}{2}\sqrt{\frac{I_{x=L}}{A_{x=L}}} \tag{14c}$$

Dimensionless Winkler component (Kw):

$$k_w = Kw\frac{E_{SN} I_{x=L}}{L^4} \tag{14d}$$

Dimensionless Pasternak component (Kp):

$$k_p = Kp\frac{E_{SN} I_{x=L}}{L^2} \tag{14e}$$

Table 4 lists both linear and nonlinear fundamental frequencies (Φ) of the uniform (α=0) and nonuniform (α≠0) clamped beam for various nonlinear amplitude values versus the section change rate (α). It is demonstrated that the free frequencies are improved via nonlinear amplitude because the additional strains improve the beam strength, and the beam stability develops. Furthermore, the section change rate impacts are also investigated in Table 4, in which both linear and nonlinear frequencies develop via section change rate (α), increment of 'α' improves the effective beam thickness, which means the development of the beam stiffness. So, both nonlinearity and section change impacts to enhance the beam frequency and beam stability.

The nonlocal impact (γ) on the linear and nonlinear frequencies (Φ) of nonuniform fully clamped nanobeam versus the nonlinear amplitude is presented in Table 5. The reported findings reveal that the nonlocal parameter (γ) reduces fundamental linear and nonlinear frequencies by affecting the mass matrices and reducing the beam stiffness, hence, the softening phenomena is anticipated in terms of

Table 4 The linear and nonlinear free frequencies (Φ) of the fully clamped nonuniform beam versus the nonlinear amplitude and the section change rate (α)

	Linear	Amplitude=1	Amplitude=2	Amplitude=3	Amplitude=4	Amplitude=5
α=-0.5	10.44078059	11.27810867	13.45217617	16.41633817	19.81683289	23.46700901
α=-0.4	10.76066012	11.58017574	13.72039418	16.65564263	20.03660879	23.6752478
α=-0.3	11.12529432	11.90934259	13.97415294	16.83074745	20.14128156	23.71832719
α=-0.2	11.54518482	12.29212369	14.27651136	17.04777634	20.28127447	23.79084722
α=-0.1	12.03454011	12.74613468	14.65312875	17.34211986	20.50217919	23.94873761
α=0 (Uniform)	12.61308052	13.29152821	15.12536663	17.73679995	20.82895582	24.21912751
α=0.1	13.3090236	13.95698391	15.7232648	18.26383756	21.29603119	24.63919891
α=0.2	14.16428829	14.78487771	16.49063309	18.96928566	21.95232868	25.26127611
α=0.3	15.24418993	15.8341398	17.47027528	19.8750976	22.79746821	26.06265892
α=0.4	16.65709893	17.19544518	18.70585335	20.96047754	23.73822034	26.87501264
α=0.5	18.5990898	19.0895418	20.48110856	22.59144351	25.23035553	28.24650444

Table 5 The linear and nonlinear free frequencies (Φ) of the clamped tapered beam versus the nonlinear amplitude as well as the nonlocal parameter (γ), α=0.25

	Linear	Amplitude=0.5	Amplitude=1	Amplitude=1.5	Amplitude=2	
Local	14.67073649	14.82549337	15.27893029	16.00230626	16.95747832	Local
γ=0.5	14.23942713	14.42070854	14.94939732	15.786191	16.880916	γ=0.5
γ=1.0	13.13892026	13.39121517	14.11723646	15.24183716	16.67851288	γ=1.0
γ=1.5	11.75616156	12.10638159	13.09362206	14.57697615	16.41558149	γ=1.5
γ=2.0	10.38899524	10.84927684	12.113339	13.9482217	16.15455558	γ=2.0
γ=2.5	9.173443866	9.747263872	11.27679511	13.42063503	15.92877313	γ=2.5
γ=3.0	8.140691405	8.827175546	10.59923306	13.00135213	15.74633737	γ=3.0
γ=3.5	7.277112839	8.073291449	10.06153313	12.67495919	15.60316793	γ=3.5
γ=4.0	6.556258285	7.458156281	9.636682288	12.42174452	15.49173172	γ=4.0
γ=4.5	5.951622195	6.954797291	9.29977471	12.22428033	15.40476552	γ=4.5
γ=5.0	5.440562667	6.540389404	9.030603509	12.0688626	15.33635348	γ=5.0

Table 6 The linear and nonlinear free frequencies (Φ) of the fully clamped nonuniform nonlocal beam versus the nonlinear amplitude along with the volume fraction parameter (η), α=0.25, γ=1

	Linear	Amplitude=1	Amplitude=2	Amplitude=3	Amplitude=4	Amplitude=5
Pure Si_3N_4	13.13892026	14.11723646	16.67851288	20.20019821	24.26384812	28.64221928
η=1	7.949963614	8.513404345	9.99635595	12.04668053	14.421761	16.98729325
η=2	6.876878725	7.362338273	8.640581395	10.40865635	12.4574226	14.67092956
η=3	6.447748567	6.904455545	8.106562683	9.768700549	11.69419728	13.77415778
η=4	6.23332067	6.675979707	7.840793275	9.450903207	11.3157483	13.32992226
η=5	6.11260331	6.547222847	7.69073265	9.271178417	11.10148868	13.07823666
η=6	6.039294498	6.468835703	7.598946748	9.160819738	10.96957631	12.92301455
η=7	5.992112711	6.418225988	7.539338353	9.088803929	10.88321586	12.82117903
η=8	5.959995395	6.383684616	7.498458273	9.039220026	10.82359879	12.75075918
η=9	5.936795109	6.358712633	7.468858853	9.003274484	10.78034444	12.69964002
η=10	5.919005331	6.339597742	7.446274276	8.97591884	10.74748346	12.66084743

the nonlocal influence. Additionally, the nonlinear amplitude is applied to the beam structures, and as previously stated, nonlinearity increases beam stability, which is evident in all nonlocal parameters employed. Additionally, in all cases of nonlinearity, the nonlocal parameter sets the frequency limit.

Table 6 shows the influence of the volume proportion of FG parameters (η) on the free linear and nonlinear

Table 7 The linear and nonlinear free frequencies (Φ) of the axially functionally graded non-uniform nonlocal clamped beam versus the nonlinear amplitude along with the elastic Winkler foundation parameter (Kw), α=0.25, γ=1, η=2

	Linear	Amplitude=1	Amplitude=2	Amplitude=3	Amplitude=4	Amplitude=5
Kw=0	6.876878725	7.362338273	8.640581395	10.40865635	12.4574226	14.67092956
Kw=100	7.462512172	7.910451365	9.109179741	10.79677726	12.77763958	14.93632228
Kw=200	8.003696312	8.421839967	9.554943341	11.1733107	13.09404703	15.2033398
Kw=300	8.508937985	8.902861035	9.981005644	11.53943179	13.40685723	15.47173551
Kw=400	8.984323566	9.358216198	10.38983024	11.89611669	13.71625451	15.74128851
Kw=500	9.434387134	9.791500444	10.78339822	12.24418866	14.02240151	16.01180146
Kw=600	9.862614971	10.20553676	11.16333263	12.58435115	14.3254439	16.28309863
Kw=700	10.27175689	10.6025908	11.53098429	12.91721218	14.62551393	16.55502407
Kw=800	10.6640278	10.98451431	11.88749259	13.24330257	14.92273303	16.82743983
Kw=900	11.04124337	11.3528443	12.23382982	13.56308987	15.21721387	17.10022438
Kw=1000	11.40491443	11.70887354	12.57083418	13.87698918	15.50906192	17.3732711

Table 8 The linear and nonlinear free frequencies (Φ) of the axially functionally graded non-uniform nonlocal clamped beam based on the elastic Winkler substrate versus the nonlinear amplitude along with the elastic Pasternak foundation parameter (Kp), α=0.25, γ=1, η=2, Kw=150

	Linear	Amplitude=1	Amplitude=2	Amplitude=3	Amplitude=4	Amplitude=5
Kp=0	7.738058131	8.170291586	9.334701564	10.98641365	12.93630549	15.06964398
Kp=2	7.540038085	7.98387393	9.17380526	10.85248686	12.8259543	14.97887053
Kp=4	7.336078058	7.792594559	9.010063324	10.71745714	12.71580899	14.88930482
Kp=6	7.125593814	7.596049801	8.843367638	10.58144283	12.6061534	14.80136393
Kp=8	6.907898965	7.393778609	8.673617662	10.44461581	12.49735918	14.715582
Kp=10	6.682178396	7.185251054	8.500728308	10.30722228	12.38991638	14.63264968
Kp=12	6.44745223	6.969853897	8.32464235	10.16961278	12.28447711	14.55347013
Kp=14	6.202525864	6.746872412	8.145350105	10.03228629	12.18191876	14.47923969
Kp=16	5.945919027	6.51546741	7.96292101	9.895956524	12.0834377	14.41156685
Kp=18	5.675762065	6.274646258	7.777555142	9.761653731	11.99069139	14.35265207
Kp=20	5.389639176	6.023226726	7.589669104	9.630885559	11.90602021	14.30556716

frequencies (Φ) of the tapered nano-scale AFG clamped beam for various nonlinear amplitude values. The axially functionally graded nanobeam is comprised of Si_3N_4 and SUS304, and increasing the FG parameter increases the volume of SUS304 in the complex structure. The Si_3N_4 is clearly stiffer than the SUS304, the softer beam may be created by raising the volume fraction (η), in other words, the beam stiffness reduces through the AFG parameter, and the linear and nonlinear frequencies drop. The provided result holds true for all nonlinear amplitudes.

Table 7 examines the effect of the Winkler substrate on the free linear and nonlinear frequencies (Φ) of an AFG nonuniform nanobeam resting on an elastic foundation. The findings show that increasing the Winkler parameter (Kw) enhances the beam frequencies. According to the mathematical modelling of the AFG nanobeam (Eq. (10)), the Winkler parameter improves the weighting section of the beam modelling in the eigenvalue problem, therefore the beam stiffness is predicted to rise, allowing for better beam frequencies and beam stability. The different nonlinear amplitude values are also included in this study, the impact of the Winkler parameter (Kw) is the same in all nonlinear amplitudes, indicating that this sort of elastic foundation raises the linear and nonlinear beam frequencies.

Table 8 investigates a different sort of elastic foundation examined in this research. The linear and nonlinear free frequency response on the AFG nonlocal and nonuniform beam resting in a Winkler foundation is investigated in Table 8 for various values of the Pasternak foundation parameter (Kp). According to the findings, the Pasternak parameter reduces the linear and nonlinear frequencies for all nonlinear amplitude values. This sort of elastic foundation has the opposite effect of the Winkler foundation in that it lowers beam stability by lowering beam strength.

5. Conclusions

The nonlinear dynamic behavior of a nanobeam placed in an elastic foundation was the primary goal of this investigation. In combination with the nonlinear Von-Kármán theory, many nonlocal elastic and classical beam theories have been used to represent the small-scale beam. An axially functionally graded material constituted of Si_3N_4 coated on SUS304 was used in the nanobeam's construction. The tapered AFG beam was encased in an elastic Winkler-Pasternak base. The key findings are summarized here.

- In all applicable settings, the nonlinear amplitudes enhance the beam frequencies and beam stability.
- The stability and frequency of the beam are greatly affected by the nonuniformity of the section, and the cross-section change rate (α) increases linear and nonlinear frequencies alike.
- Nonlocal (γ) characteristics reduce the stiffness of the nonuniform beam, and the softening phenomena are anticipated in terms of nonlocal consequences.
- In all nonlinear amplitudes, the volume fraction (η) increases the metal part of the AFG structures and affects beam stability and frequency.
- The elastic foundations have a considerable and diversified effect on the stability and frequency response of the nonuniform AFG nanobeam, with the Winkler substrate increasing the linear and nonlinear beam frequencies and the Pasternak substrate diminishing them.

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