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Vibration analysis of nonlocal porous nanobeams made of functionally graded material

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Abstract. In this work, dynamic behavior of functionally graded (FG) porous nano-beams is studied based on nonlocal *n*th-order shear deformation theory which takes into the effect of shear deformation without considering shear correction factors. It has been observed that during the manufacture of "*functionally graded materials*" (FGMs), micro-voids and porosities can occur inside the material. Thus, in this work, the investigation of the dynamic analysis of FG beams taking into account the influence of these imperfections is established. Material characteristics of the FG beam are supposed to be vary continuously within thickness direction according to a "*power-law scheme*" which is modified to approximate material characteristics for considering the influence of porosities. A comparative study with the known results in the literature confirms the accuracy and efficiency of the current nonlocal nth-order shear deformation theory.

Keywords: porosity; nonlocal elasticity theory; FG nanobeam; free vibration; nth-order shear deformation theory

1. Introduction

Functional Grade Materials (FGMs) are the novel type of composite materials that offer a wide range of applications for various equipment subject to extreme thermo-mechanical stresses, such as the thermal shields of the "*spacecraft body*", "*nuclear reactor components*", "*jet fighter structures*" and "*thermal engine components*" (Kar and Panda 2015, Avcar 2015, Barati and Shahverdi 2016, Houari *et al*. 2016, Sekkal *et al*. 2017a, Avcar and Mohammed 2018, Tlidji *et al*. 2019, Karami *et al*. 2019a, Meksi *et al*. 2019). Due to the continuous variation in material properties compared to conventional composites, FGM has several advantages: avoiding cracking and delamination phenomena, minimizing or eliminating stress concentrations and residual stresses, ensuring a smooth transition of distributions constraints, etc.

In the manufacture of FGMs, porosities may appear in the materials during the sintering process. The porosity contrasts with the harmful composite material with high performance. The impact of this failure has been the topic of much attention, as evidenced by the large number of investigations conducted on this subject. The linear and nonlinear dynamic stability of a circular porous plate has been studied to obtain the critical loads in two separate works by Mugnucka-Blandzi (2010). Wattanasakulpong and Ungbhakor (2014) studied the linear and nonlinear dynamic problems of FG beams with porosities. Wattanasakulpong *et al*. (2012) provided a work on porosities happening inside FGM samples manufactured by a multi-step sequential infiltration method. Ebrahimi and Zia (2015) investigated nonlinear vibration of FG Timoshenko beams with porosities. Yahia *et al*. (2015) employed higher-order shear deformation theories to examine the wave propagation of an infinite FG plate with porosities. Benferhat *et al*. (2016) presented a static analysis of the FG plate with porosities. Akbas (2017) studied post-buckling of porous FG beams subjected to compression load. Chen *et al*. (2017) examined the nonlinear vibration and post-buckling of FG graphene reinforced porous nanocomposite beams. Mirjavadi *et al*. (2017) analyzed thermo-mechanical dynamic response of two dimensional FG porous nanobeam. Ehyaei *et al*. (2017) investigated the influence of porosity and axial preload on vibration behavior of rotating FG nanobeam. Benadouda *et al*. (2017) presented an efficient shear deformation theory for wave propagation in FG beams with porosities. Thang *et al*. (2018) studied stability and dynamic behavior of porous-cellular plates having uniform and non-uniform porosity variations using first-order shear deformation theory. Avcar (2019) presented an original study on free vibration of imperfect sigmoid and power law functionally graded beams.

Nowadays, nanotechnology is primarily about the fabrication of nano-sized functionally graded materials and engineering structures, enabling a new generation of breakthrough materials and improved functionality (Akgöz and Civalek 2014, Arani and Kolahchi 2016, Madani *et al*. 2016, Bilouei *et al*. 2016, Kolahchi *et al* 2016a, Boukhari *et al*

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al. 2016, Zamanian *et al*. 2017, Kolahchi and Cheraghbak 2017, Kolahchi *et al*. 2017a, b, Besseghier *et al*. 2017, Hajmohammad *et al*. 2017, Amnieh *et al*. 2018, Golabchi *et al*. 2018, Fakhar and Kolahchi 2018, Hosseini and Kolahchi 2018, Hajmohammad *et al*. 2018a, b, c, Chaabane *et al*. 2019). In some cases, the porosity of materials at the micro/nano scale has been largely managed in different applications, such as biomedical systems lightweight structures, catalysts in electrochemical actuators and fuel cells (Detsi *et al*. 2013), a piezoelectric ceramic gradient actuator (Li *et al*. 2003), nano-layers of porous titanium dioxide to improve the hydrophilicity of materials (Kim *et al*. 2009). Various studies were carried out on perfect and imperfect FG nanostructures. Ebrahimi and Jafari (2016) examined thermo-mechanical dynamic characteristics of porous FG Reddy beams under different thermal loadings. Ahouel *et al*. (2016) studied size-dependent mechanical behavior of FG trigonometric shear deformable nanobeams including neutral surface position concept. Kolahchi and Moniri Bidgoli (2016) presented a size-dependent sinusoidal beam model for dynamic instability of single-walled carbon nanotubes. Ebrahimi and Daman (2017) presented an analytical solution for dynamic response of curved FG nanobeam subjected to thermal loading by taking into account porosity variation using nonlocal elasticity theory. Al Rjoub and Hamad (2017) provided an analytical procedure to investigate the vibration response of FG porous beams by transfer matrix method. Fu *et al*. (2018) presented a comparison of mechanical properties of C-S-H and portlandite between nano-indentation experiments and a modeling approach using various simulation techniques. Eltaher *et al*. (2018) investigated the bending and dynamic behavior of FG nonlocal porous nanobeams by employing finite elements method and a modified porosity model. Other on nanostructures can be found in literature such as (Kolahchi *et al*. 2016b, 2017c, Bensaid 2017, Karami *et al*. 2017, 2018a, b, c, d, 2019b, c, Mouffoki *et al*. 2017, Gupta *et al*. 2018, Cherif *et al*. 2018, Aydogdu *et al*. 2018, Akbas 2018, Bensaid *et al*. 2018, Mokhtar *et al*. 2018, Selmi and Bisharat 2018, Yazid *et al*. 2018, Hussain and Naeem 2019, Karami and Karami 2019, Boutaleb *et al*. 2019, Adda Bedia *et al*. 2019, Semmah *et al*. 2019).

In this paper, a nonlocal nth-order shear deformation theory is utilized to study the free vibrational analysis of the FG nano-beams. The theory takes into account the parabolic transverse shear effect. The small scale effect is introduced by using the differential constitutive relation of Eringen. Also, the effective properties of FG nano-beam are computed by introducing the imperfection of material in the form of porosities. The equation of motion are determined by the Hamilton's principle and solved by Navier's method. To show the efficiency and accuracy of the present model, several comparisons with existing models in the literature are performed. Finally, parametric studies are presented and discussed to illustrate the effects of material imperfection, small scales effect, slenderness ratio and the volume fraction on fundamental frequencies of FG nano-beams.

2. Problem formulations

In this research, in consider a short functionally graded (FG) porous nano-beam of thickness "h" width "b" and length "L" (as shown in Fig. 1). The studied FG porous nano-beam occupies the following limited intervals:

$$-\frac{h}{2} \leq z \leq \frac{h}{2}; \quad -\frac{b}{2} \leq y \leq \frac{b}{2} \quad \text{and} \quad 0 \leq x \leq L \tag{1}$$

where$x$, y, z are Cartesian coordinates.

2.1 Power law FG porous nano-beam

Taking into account the imperfections in the form of porosity produced during the manufacturing time of the FG nano-beams (Zhu *et al*. 2001, Wattanasakulpong and Ungbhakorn 2014, Yahia *et al*. 2015), the Effective materials properties of FG porous nano-beams (the mass density "ρ (z)", Young's modulus "$E(z)$" and shear modulus "$G(z)$") can be expressed as (Gupta and Talha 2017, Bourada *et al*. 2019)

$$P(z) = (P_t - P_b)\left(\frac{2z+h}{2h}\right)^k - log\left(1+\frac{\xi}{2}\right)(P_t + P_b)\left(1-\frac{2|z|}{h}\right) + P_b \tag{2}$$

where the index "t and b" present the top (alumina) and bottom (steel) surfaces of the FG- nano beam, exponent "k" is the power low index with "$k \geq 0$" and "ξ" is the term that takes into account the porosity. Based to the Eq. 1, the young modulus "$E(z)$", shear modulus "$G(z)$" andthe mass density"$\rho(z)$" can be given as (Shahsavari *et al*. 2018)

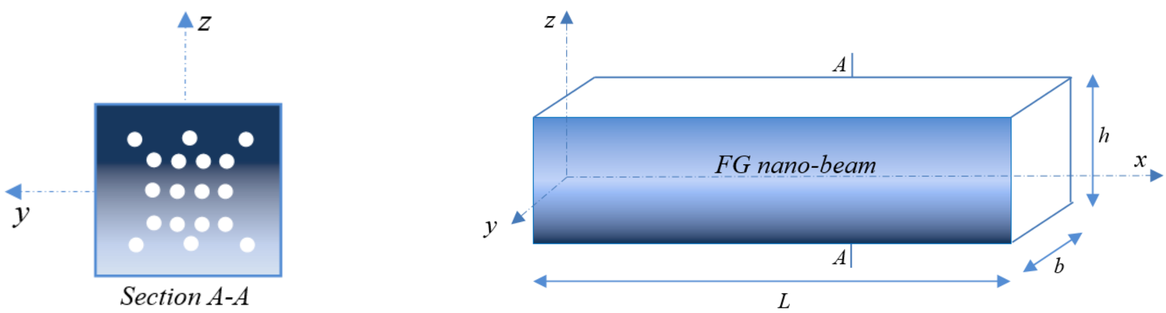

Fig. 1 Geometry of the FG porous nano-beam

Table 1 Material properties of Alumina (Al_2O_3) and steel

Material	Young's modulus E (GPa)	Mass density ρ (kg/m^3)	Poisson's ratio v
Alumina (Al_2O_3)	390	3960	0,3
Steel	210	7800	

$$E(z) = (E_c - E_m)\left(\frac{2z+h}{2h}\right)^k - log\left(1+\frac{\xi}{2}\right)(E_c + E_m)\left(1-\frac{2|z|}{h}\right) + E_m \quad (3a)$$

$$G(z) = \frac{E(z)}{2(1+v)} \quad (3b)$$

$$\rho(z) = (\rho_c - \rho_m)\left(\frac{2z+h}{2h}\right)^k - log\left(1+\frac{\xi}{2}\right)(\rho_c + \rho_m)\left(1-\frac{2|z|}{h}\right) + \rho_m \quad (3c)$$

where "E_c, ρ_c" are the corresponding property of ceramic and "E_m, ρ_m"are the corresponding property of metal.

The material properties used in this work is abstracted in the Table 1.

2.2 Nonlocal nth-order shear deformation theory

The assumptions made in the refined high order shear deformation theory (Benachour *et al.* 2011, Zidi *et al.* 2014, Meziane *et al.* 2014, Al-Basyouni *et al.* 2015, Bellifa *et al.* 2016, Abdelaziz *et al.* 2017, Kolahchi 2017, Bourada *et al.* 2019) are considered, the displacement field of the nth order shear deformation theory can be expressed as

$$u(x,z,t) = u_0(x,t) - z\frac{\partial w_b}{\partial x} + \frac{z^n}{n}\left(\frac{2}{h}\right)^{n-1}\frac{\partial w_s}{\partial x} \quad (4a)$$

$$w(x,z,t) = w_b(x,t) + w_s(x,t) \quad (4b)$$

where the components "u_0, u_b and u_s" are corresponding to extension, bending and shear displacements. w_b and w_s are the transverse displacements components corresponding to bending and shear.

The formulations of the nonzero axial strain and the shear strain associated with the kinematics of Eq. (4) can be obtained as

$$\varepsilon = \varepsilon_x^0 + zk_x^b + f(z)k_x^s \quad \text{and} \quad \gamma_{xz} = g(z)\gamma_{xz}^s \quad (5)$$

Where

$$\begin{Bmatrix} \varepsilon_x^0 \\ k_x^b \\ k_x^s \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u_0}{\partial x} \\ -\dfrac{\partial^2 w_b}{\partial x^2} \\ -\dfrac{\partial^2 w_s}{\partial x^2} \end{Bmatrix}, \quad \gamma_{xz}^s = \frac{\partial w_s}{\partial x} \quad (6)$$

$$\text{and} \quad f(z) = \frac{1}{n}\left(\frac{2}{h}\right)^{n-1} z^n, \quad g(z) = 1 - f'(z)$$

2.3 The nonlocal elasticity for the "P-FGM" nano-beam

By assuming that the normal and tangential stresses "σ, τ" at a reference point depends on the all deformation field of each point of the body. The non-local constitutive relation can be expressed in the differential form as (Eringen 1972 and 1983, Belkorissat *et al.* 2015, Bellifa *et al* 2017a, Bouazza *et al.* 2018, Bouadi *et al.* 2018, Kadari *et al.* 2018)

$$\sigma_x - \mu\frac{d^2\sigma_x}{dx^2} = E\varepsilon_x \quad (7a)$$

$$\tau_{xz} - \mu\frac{d^2\tau_{xz}}{dx^2} = G\gamma_{xz} \quad (7b)$$

where

$$\mu = (e_0 a)^2 \quad (8)$$

where "e_0" and "a" are constant (depend to material) and internal characteristic length.

For SWCNT (single walled carbon nanotube), the nonlocal parameter "e_0a" is estimated to be smaller than 2 nm (Boumia *et al.* 2014, Tounsi *et al.* 2013a, Semmah *et al.* 2014, Zidour *et al.* 2014, Bensattalah *et al.* 2018).

2.4 Equations of motion

Hamilton's principle is used herein to derive the equations of motion for the free vibration analysis of nonlocal porous beams. The mathematical formulation of the Hamilton's principle can be expressed as (Zidi *et al.* 2017, Bellifa *et al.* 2017b, Klouche *et al.* 2017, Ait Sidhoum *et al.* 2017, 2018, Zine *et al.* 2018, Belabed *et al.* 2018, Bakhadda *et al.* 2018, Kaci *et al.* 2018, Bourada *et al.* 2019)

$$\int_0^t (\delta U - \delta K)dt = 0 \quad (9)$$

where "δU" and "δK" are the variation of the strain and the kinetic energy, respectively.

In the present investigation, The Hamilton's principle can be written as function of the stresses and strains as follows (Mahi *et al.* 2015, Bourada *et al.* 2019)

$$\int_0^L \int_A (\sigma_x \delta\varepsilon_x + \tau_{xz}\delta\gamma_{xz})dAdx - \int_0^L \int_A \rho[\ddot{u}_0 \delta u_0 + (\ddot{w}_b + \ddot{w}_s)\delta(w_b + w_s)]dAdx = 0 \quad (10)$$

By replacing Eqs. (4) and (6) into Eq. (10) and performing the integration by part and collecting the coefficients "δu", "δw_b", and "δw_s" yields the three following equations of motion

$$\delta u_0: \frac{dN}{dx} = I_0\ddot{u}_0 - I_1\frac{d\ddot{w}_b}{dx} - J_1\frac{d\ddot{w}_s}{dx} \quad (11a)$$

$$\delta w_b: \frac{d^2 M_b}{dx^2} = I_0(\ddot{w}_b + \ddot{w}s) + I_1 \frac{d\ddot{u}_0}{dx} - I_2 \frac{d^2\ddot{w}_b}{dx^2} - J_2 \frac{d^2\ddot{w}_s}{dx^2} \tag{11b}$$

$$\delta w_s: \frac{d^2 M_s}{dx^2} + \frac{dQ}{dx} = I_0(\ddot{w}_b + \ddot{w}_s) + J_1 \frac{d\ddot{u}_0}{dx} - J_2 \frac{d^2\ddot{w}_b}{dx^2} - K_2 \frac{d^2\ddot{w}_s}{dx^2} \tag{11c}$$

where the resultants stress and moments N, M_b, M_s and Q are defined as follow

$$\begin{Bmatrix} N \\ M^b \\ M^s \end{Bmatrix} = \int_A \begin{Bmatrix} 1 \\ z \\ f \end{Bmatrix} \sigma_x dA \quad \text{and} \quad Q = \int_A g(z)\tau_{xz} dA \tag{12a}$$

and

$$(I_0, I_1, I_2, J_1, J_2, K_2) = \int_A (1, z, z^2, f(z), zf(z), f^2(z))\rho(z) dA \tag{12b}$$

By replacing the strain field of Eqs. (5) and (6) into non-local constitutive relation of Eq. (7) and the obtained results into Eq. (12a), the stress resultants of the non-local FG beam can be obtained in the following form

$$N - \mu \frac{d^2 N}{dx^2} = A \frac{du_0}{dx} - B \frac{d^2 w_b}{dx^2} - B_s \frac{d^2 w_s}{dx^2} \tag{13a}$$

$$M_b - \mu \frac{d^2 M_b}{dx^2} = B \frac{du_0}{dx} - D \frac{d^2 w_b}{dx^2} - D_s \frac{d^2 w_s}{dx^2} \tag{13b}$$

$$M_s - \mu \frac{d^2 M_s}{dx^2} = B_s \frac{du_0}{dx} - D_s \frac{d^2 w_b}{dx^2} - H_s \frac{d^2 w_s}{dx^2} \tag{13c}$$

$$Q - \mu \frac{d^2 Q}{dx^2} = A_s \frac{dws}{dx} \tag{13d}$$

where "A, B, D, B_s, D_s, H_s" and "A_s" are the stiffness components.
with

$$\begin{Bmatrix} A \\ B \\ D \\ B_s \\ D_s \\ H_s \end{Bmatrix} = \int_A \begin{Bmatrix} 1 \\ z \\ z^2 \\ f(z) \\ zf(z) \\ f^2(z) \end{Bmatrix} E(z) dA, \quad A_s = \int_A g^2(z)\, G(z) dA \tag{14}$$

By replacing the stress resultants of Eq. (13) into equations of motion of Eq. (11), the present nonlocal equations of motion can be obtained in terms of displacements "u, w_b, w_s" as

$$A \frac{d^2 u_0}{dx} - B \frac{d^3 w_b}{dx^2} - B_s \frac{d^3 w_s}{dx^2} = I_0 \left(\ddot{u}_0 - \mu \frac{d^2 \ddot{u}_0}{dx^2} \right) - I_1 \left(\frac{d\ddot{w}_b}{dx} - \mu \frac{d^3 \ddot{w}_b}{dx^2} \right) - J_1 \left(\frac{d\ddot{w}_s}{dx} - \mu \frac{d^3 \ddot{w}_s}{dx^2} \right) \tag{15a}$$

$$B \frac{d^3 u_0}{dx^3} - D \frac{d^4 w_b}{dx^2} - D_s \frac{d^4 w_s}{dx^2} = I_0 \left((\ddot{w}_b + \ddot{w}s) - \mu \frac{d^2(\ddot{w}_b + \ddot{w}s)}{dx^2} \right) + I_1 \left(\frac{d\ddot{u}_0}{dx} - \mu \frac{d^3 \ddot{u}_0}{dx^3} \right) - I_2 \left(\frac{d^2 \ddot{w}_b}{dx^2} - \mu \frac{d^4 \ddot{w}_b}{dx^4} \right) - J_2 \left(\frac{d^2 \ddot{w}_s}{dx^2} - \mu \frac{d^4 \ddot{w}_s}{dx^4} \right) \tag{15b}$$

$$B_s \frac{d^3 u_0}{dx^3} - D_s \frac{d^4 w_b}{dx^4} - H_s \frac{d^4 w_s}{dx^4} + A_s \frac{d^2 ws}{dx^2} = -I_0 \left((\ddot{w}_b + \ddot{w}s) - \mu \frac{d^2(\ddot{w}_b + \ddot{w}s)}{dx^2} \right) - J_1 \left(\frac{d\ddot{u}_0}{dx} - \mu \frac{d^3 \ddot{u}_0}{dx^3} \right) + J_2 \left(\frac{d^2 \ddot{w}_b}{dx^2} - \mu \frac{d^4 \ddot{w}_b}{dx^4} \right) + K_2 \left(\frac{d^2 \ddot{w}_s}{dx^2} - \mu \frac{d^4 \ddot{w}_s}{dx^4} \right) \tag{15c}$$

To obtain the equations of motion of local beam theory, just put "$\mu = 0$" into Eqs. (15).

3. Solution procedure of FG-nanobeam

The Navier's procedure is used in this study to solve the previous nonlocal equations of motion for vibrational analysis of non-local FG beam. The Navier's procedure can be presented in the following form (Tagrara *et al*. 2015, Bounouara *et al*. 2016, Hachemi *et al*. 2017, Fourn *et al*. 2018, Bourada *et al*. 2018, 2019, Draoui *et al*. 2019)

$$\begin{Bmatrix} u_0 \\ w_b \\ w_s \end{Bmatrix} = \sum_{m=1}^{\infty} \begin{Bmatrix} U_m\, cos(\alpha x)\, e^{i\omega t} \\ W_{bm}\, sin(\alpha x)\, e^{i\omega t} \\ W_{sm}\, sin(\alpha x)\, e^{i\omega t} \end{Bmatrix} \tag{16}$$

with

$$\alpha = n\pi/L \tag{17}$$

where "U_m, W_{bm} and W_{sm}" are unknowns functions to be determined, ω is the frequency of the free vibration of FG nano-beam and "$\sqrt{i}=-1$" is the imaginary unite.

Replacing the functions "u_0, w_b, w_s" of Eq. (16) into equation of motion of Eqs. (17), the analytical solutions can be obtained in the following matrix form

$$([S] - \lambda\omega^2[M])\{\Delta\} = \{0\} \tag{18}$$

where "[S] and [M]" are the matrix of stiffness and mass, respectively. "{Δ}" is the displacement vector.
with

$$[S] = \begin{bmatrix} A\alpha^2 & -B\alpha^3 & -B_s\alpha^3 \\ Sym. & D\alpha^4 & D_s\alpha^4 \\ Sym. & Sym. & H_s\alpha^4 + A_s\alpha^2 \end{bmatrix}, \tag{19}$$

$$[M]=\begin{bmatrix} I_0 & -I_1\alpha & -J_1\alpha \\ Sym. & I_0+I_2\alpha^2 & I_0+J_2\alpha^2 \\ Sym. & Sym. & I_0+K_2\alpha^2 \end{bmatrix},\quad \{\Delta\}=\begin{Bmatrix} U_n \\ W_{bn} \\ W_{sn} \end{Bmatrix} \tag{19}$$

and

$$\lambda = 1+\mu\alpha^2 \tag{20}$$

4. Numerical results and discussion

In this part, several numerical examples are presented and discussed to verify the efficiency and accuracy of current model in predicting the fundamental frequencies of simply supported FG nano-beam. For all presented results, the following non-dimensional fundamental frequency is utilized

$$\overline{\omega}=\omega L^2\sqrt{\frac{\rho_t A}{E_t I}} \tag{21}$$

Table 2 Comparison of Dimensionless frequency "ϖ" of the FG nano-beam

L/h	e_0a	Theories	*k* = 0	*k* = 0.3	*k* = 1	*k* = 3	*k* = 10
10	0	EBT (Zemri *et a*l. 2015)	9.8293	8.2694	6.965	6.1575	5.6544
		TBT (Zemri *et al*. 2015)	9.7075	8.1700	6.8814	6.0784	5.5794
		RBT (Zemri *et al*. 2015)	9.7075	8.1709	6.8814	6.0755	5.5768
		Present (*n* = 3)	9.7075	8.1709	6.8814	6.0755	5.5768
		Present (*n* = 5)	9.7099	8.1727	6.8831	6.0778	5.5785
		Present (*n* = 7)	9.7128	8.1750	6.8851	6.0801	5.5805
	0.5	EBT (Zemri *et a*l. 2015)	9.7102	8.1692	6.8807	6.0829	5.5859
		TBT (Zemri *et al*. 2015)	9.5899	8.0711	6.7981	6.0019	5.5118
		RBT (Zemri *et al*. 2015)	9.5899	8.0719	6.7981	6.0019	5.5092
		Present (*n* = 3)	9.5899	8.0719	6.7981	6.0019	5.5092
		Present (*n* = 5)	9.5923	8.0738	6.7997	6.0042	5.5109
		Present (*n* = 7)	9.5952	8.0760	6.8017	6.0065	5.5129
	1.5	EBT (Zemri *et a*l. 2015)	8.8915	7.4804	6.3005	5.5700	5.1150
		TBT (Zemri *et al*. 2015)	8.7813	7.3905	6.2249	5.4985	5.0470
		RBT (Zemri *et al*. 2015)	8.7813	7.3913	6.2249	5.4959	5.0447
		Present (*n* = 3)	8.7813	7.3913	6.2249	5.4959	5.0447
		Present (*n* = 5)	8.7835	7.3930	6.2264	5.4979	5.0463
		Present (*n* = 7)	8.7861	7.3951	6.2282	5.5000	5.0481
30	0	EBT (Zemri *et a*l. 2015)	9.8651	8.3015	6.9929	6.1806	5.6744
		TBT (Zemri *et al*. 2015)	9.8511	8.2901	6.9832	6.1715	5.6658
		RBT (Zemri *et al*. 2015)	9.8511	8.2902	6.9832	6.1712	5.6655
		Present (*n* = 3)	9.8511	8.2902	6.9832	6.1712	5.6655
		Present (*n* = 5)	9.8514	8.2904	6.9834	6.1714	5.6657
		Present (*n* = 7)	9.8517	8.2907	6.9837	6.1717	5.6660
	0.5	EBT (Zemri *et a*l. 2015)	9.8516	8.2902	6.9833	6.1722	5.6667
		TBT (Zemri *et al*. 2015)	9.8376	8.2787	6.9737	6.1631	5.6581
		RBT (Zemri *et al*. 2015)	9.8376	8.2788	6.9737	6.1627	5.6578
		Present (*n* = 3)	9.8376	8.2788	6.9737	6.1627	5.6578
		Present (*n* = 5)	9.8379	8.2791	6.9739	6.1630	5.6580
		Present (*n* = 7)	9.8382	8.2793	6.9741	6.1633	5.6582
	1.5	EBT (Zemri *et a*l. 2015)	9.7456	8.2010	6.9082	6.1058	5.6057
		TBT (Zemri *et al*. 2015)	9.7318	8.1897	6.8987	6.0968	5.5972
		RBT (Zemri *et al*. 2015)	9.7318	8.1898	6.8987	6.0964	5.5969
		Present (*n* = 3)	9.7318	8.1898	6.8987	6.0964	5.5969
		Present (*n* = 5)	9.7320	8.1900	6.8988	6.0967	5.5971
		Present (*n* = 7)	9.7324	8.1902	6.8991	6.0970	5.5973

Table 2 Continued

L/h	e_0a	Theories	$k = 0$	$k = 0.3$	$k = 1$	$k = 3$	$k = 10$
100	0	EBT (Zemri *et al*. 2015)	9.8692	8.3052	6.9961	6.1833	5.6767
		TBT (Zemri *et al*. 2015)	9.8679	8.3042	6.9952	6.1825	5.6760
		RBT (Zemri *et al*. 2015)	9.8679	8.3042	6.9952	6.1824	5.6759
		Present (n = 3)	9.8679	8.3042	6.9952	6.1824	5.6759
		Present (n = 5)	9.8680	8.3042	6.9952	6.1824	5.6760
		Present (n = 7)	9.8680	8.3042	6.9952	6.1825	5.6760
	0.5	EBT (Zemri *et al*. 2015)	9.8680	8.3042	6.9952	6.1825	5.6761
		TBT (Zemri *et al*. 2015)	9.8667	8.3031	6.9943	6.1817	5.6753
		RBT (Zemri *et al*. 2015)	9.8667	8.3032	6.9943	6.1817	5.6752
		Present (n = 3)	9.8667	8.3032	6.9943	6.1817	5.6752
		Present (n = 5)	9.8667	8.3032	6.9943	6.1817	5.6753
		Present (n = 7)	9.8668	8.3032	6.9944	6.1817	5.6753
	1.5	EBT (Zemri *et al*. 2015)	9.8583	8.2960	6.9883	6.1764	5.6705
		TBT (Zemri *et al*. 2015)	9.8570	8.2950	6.9874	6.1756	5.6697
		RBT (Zemri *et al*. 2015)	9.8570	8.2950	6.9874	6.1756	5.6697
		Present (n = 3)	9.8570	8.2950	6.9874	6.1756	5.6697
		Present (n = 5)	9.8570	8.2950	6.9874	6.1756	5.6697
		Present (n = 7)	9.8571	8.2950	6.9875	6.1756	5.6697

Table 3 The non-dimensional fundamental frequency “ϖ” versus power index “k” and slenderness ratio “L/h” of the FG porous nano-beam with (e_0a = 1 nm)

L/h	ξ	Theory	Material index “k”				
			0	0.5	1	5	10
5	0.05	Present (n = 3)	7,9556	6,2119	5,5929	4,7102	4,4987
	0.1	Present (n = 3)	8,0618	6,2563	5,6191	4,7146	4,4999
	0.2	Present (n = 3)	8,2863	6,3479	5,6723	4,7220	4,5007
	0.3	Present (n = 3)	8,5290	6,4433	5,7265	4,7270	4,4988
10	0.05	Present (n = 3)	9,3884	7,3268	6,6007	5,5809	5,3285
	0.1	Present (n = 3)	9,5203	7,3845	6,6368	5,5928	5,3365
	0.2	Present (n = 3)	9,7997	7,5037	6,7106	5,6161	5,3521
	0.3	Present (n = 3)	10,1024	7,6288	6,7868	5,6387	5,3669
20	0.05	Present (n = 3)	9,8444	7,6815	6,9214	5,8588	5,5932
	0.1	Present (n = 3)	9,9847	7,7435	6,9608	5,8733	5,6037
	0.2	Present (n = 3)	10,2820	7,8720	7,0417	5,9023	5,6246
	0.3	Present (n = 3)	10,6045	8,0070	7,1253	5,9313	5,6455
50	0.05	Present (n = 3)	9,9812	7,7879	7,0177	5,9423	5,6728
	0.1	Present (n = 3)	10,1241	7,8513	7,0581	5,9576	5,6839
	0.2	Present (n = 3)	10,4269	7,9827	7,1411	5,9884	5,7065
	0.3	Present (n = 3)	10,7554	8,1207	7,2271	6,0194	5,7293
100	0.05	Present (n = 3)	10,0011	7,8034	7,0317	5,9544	5,6843
	0.1	Present (n = 3)	10,1444	7,8670	7,0723	5,9699	5,6956
	0.2	Present (n = 3)	10,4480	7,9988	7,1556	6,0009	5,7184
	0.3	Present (n = 3)	10,7774	8,1372	7,2419	6,0322	5,7415

Table 4 Effect of the nonlocal parameter “e_0a” and porosity effect on dimensionless fundamental frequency “ϖ” of the thick FG porous nano-beam with (L/h)

e_0a	k	Theory	ξ			
			0.05	0.1	0.2	0.3
0	0	Present (n = 3)	9,3956	9,5211	9,7862	10,0729
	0.5	Present (n = 3)	7,3363	7,3888	7,4969	7,6096
	1	Present (n = 3)	6,6053	6,6362	6,6990	6,7630
	5	Present (n = 3)	5,5628	5,5680	5,5768	5,5826
	10	Present (n = 3)	5,3130	5,3144	5,3153	5,3131
0.5	0	Present (n = 3)	8,9637	9,0834	9,3363	9,6098
	0.5	Present (n = 3)	6,9991	7,0491	7,1523	7,2598
	1	Present (n = 3)	6,3016	6,3312	6,3911	6,4521
	5	Present (n = 3)	5,3070	5,3121	5,3204	5,3260
	10	Present (n = 3)	5,0688	5,0701	5,0710	5,0689
1	0	Present (n = 3)	7,9556	8,0618	8,2863	8,5290
	0.5	Present (n = 3)	6,2119	6,2563	6,3479	6,4433
	1	Present (n = 3)	5,5929	5,6191	5,6723	5,7265
	5	Present (n = 3)	4,7102	4,7146	4,7220	4,7270
	10	Present (n = 3)	4,4987	4,4999	4,5007	4,4988
1.5	0	Present (n = 3)	6,8375	6,9287	7,1217	7,3303
	0.5	Present (n = 3)	5,3389	5,3770	5,4557	5,5377
	1	Present (n = 3)	4,8068	4,8294	4,8751	4,9216
	5	Present (n = 3)	4,0482	4,0520	4,0584	4,0626
	10	Present (n = 3)	3,8664	3,8674	3,8681	3,8665
2	0	Present (n = 3)	5,8504	5,9285	6,0936	6,2721
	0.5	Present (n = 3)	4,5682	4,6008	4,6681	4,7383
	1	Present (n = 3)	4,1129	4,1322	4,1713	4,2112
	5	Present (n = 3)	3,4638	3,4671	3,4725	3,4762
	10	Present (n = 3)	3,3083	3,3092	3,3097	3,3084

with “A” and “I” are the section area and moment inertia, respectively.

Table 2 show the non-dimensional fundamental frequencies values “ϖ” of simply supported FG nano-beam as function of nonlocal parameter “e_0a”, material index “k” and slenderness ratio “L/h”. The results obtained using the present nth order shear deformation theory are compared with those given by Euler Bernoulli beam theory, Timoshenko beam theory and refined shear deformation theory published by Zemri *et al*. (2015). From the Table 2, it can be seen that the current results obtained with “n = 3” are in good agreement with those obtained by Zemri *et al*. (2015) using both Timoshenko beam theory (TBT, with shear correction factor “k_s = 5/6”) and refined shear deformation theory (RBT). It can be noted that the non-dimensional fundamental frequencies “ϖ” is in inverse relation with both power index “k” and nonlocal parameter “e_0a”.

Table 3 present the dimensionless fundamental frequencies values “ϖ” versus power index”k”and aspect ratio “L/h” of the FG porous nano-beam with “e_0a = 1 nm”.From the table, it can be seen that the fundamental frequency “ϖ” is in direct correlation relation with “L/h” because the beam becomes slender. It can also be noted that the increase of the power index “k” lead to a decrease of the fundamental frequency “ϖ”.

The effect of the volume fraction of the porosity “ξ” and nonlocal parameter “e_0a” on the non-dimensional fundamental frequencies “ϖ” of simply supported FG porous nano-beam with slenderness ratio “L/h = 5” is presented in Table 4. From the results, it can be noticed that thecomputed results show that the values of “ϖ” increase as the volume fraction of porosity “ξ” increases. It can also be remarkable that the smallest values of the fundamental frequency are obtained for nonlocal parameter e_0a = 2 nm.

Fig. 2 illustrates the dimensionless fundamental frequencies “ϖ” as function of slenderness ratio “L/h” using local “e_0a = 0” and nonlocal “e_0a = 2 nm” theories with power index “k = 0.3”. From the plotted graphs, it can be noted that the fundamental frequencies”ϖ” increase with increasing of the aspect ratio and this is due that the FG nano-beam becomes flexible. It is clear in Fig. 2 that the greatest values of the fundamental frequencies “ϖ” are obtained with local theory “e_0a = 0” and this for the

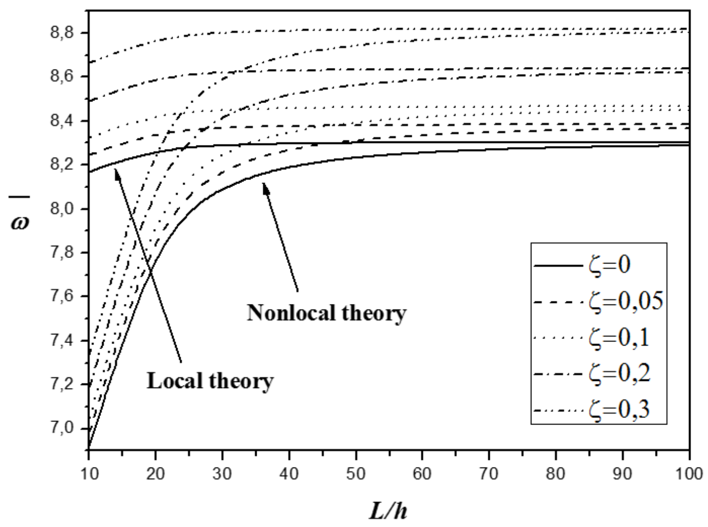

Fig. 2 Effect of the porosity and slenderness ratio "L/h" on dimensionless fundamental frequency "$\overline{\omega}$" with (n = 3, k = 0.3 and e_0a = 2 nm)

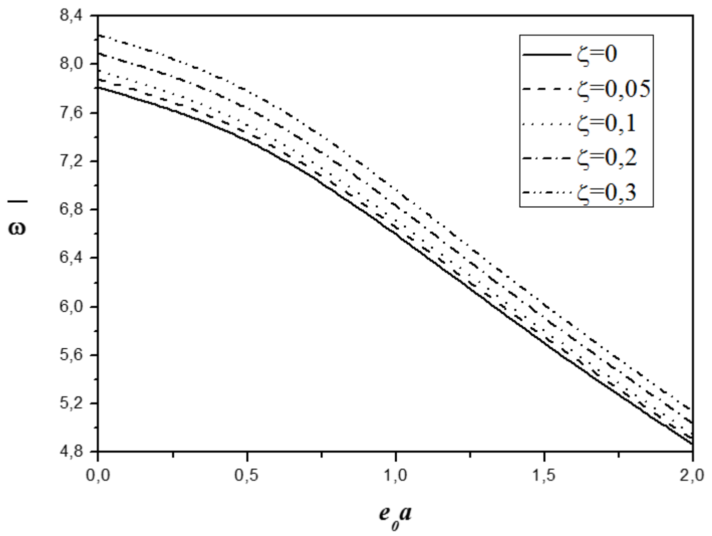

Fig. 3 Effect of nonlocal parameter "e_0a" on dimensionless fundamental frequency "$\overline{\omega}$" of simply supported FG porous nano-beam with (n = 3, k = 0.3 and L/h = 5)

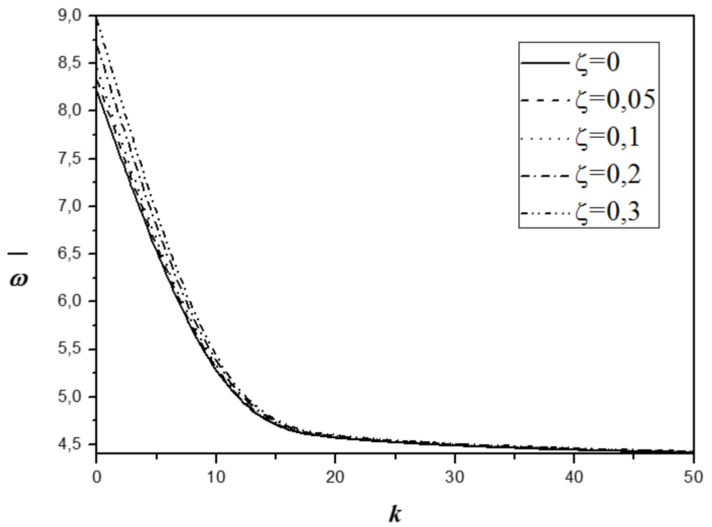

Fig. 4 Dimensionless fundamental frequency "$\overline{\omega}$" versus material index "k" of the FG nano-beam with (n = 3, L/h = 10 and e_0a = 2 nm)

different values of porosity index "ξ".

The Effect of the nonlocal parameter "e_0a" on dimensionless fundamental frequency "ϖ" of simply supported FG nano-beam is presented in Fig. 3 for the different values of the porosity index "ξ" with (k = 0.3 and L/h = 5). From the obtained graphs, it is clearly remarkable that the fundamental frequency parameter"ϖ" is in inverse relation with the scale effect "e_0a". The largest values of the fundamental frequency "ϖ" are obtained for porosity index "ξ = 0.3" and this can be justified by the reduction of the Young modulus "$E(z)$" when volume faction of porosity "ξ" increase.

In Fig. 4 the non-dimensional fundamental frequencies versus material index "k" of the FG nano-beam "$e_0a=2nm$" with "L/h = 10". The obtained results are for the various values of porosity index (ξ = 0, 0.05, 0.1, 0.2 and 0.3). From the plotted curves, it can be noted that the fundamental frequencies diminish with the increase of the power index "k". It can be also concluded that the fundamental frequencies is in direct correlation relation with the volume fraction of the porosity.

5. Conclusions

In the current investigation, the free vibrational behavior of FG porous nano-beams was analyzed by using a nonlocal *n*th order shear deformation theory. The present model does not require the introduction of the shear correction factors. The nonlocal equations of motion are derived by utilizing the constitutive relations of Eringen and Hamilton's principle. The obtained equations have been solved by Navier's solution. The effects of several parameters influencing the vibrational response of the FG nano-beams such as porosity index, the slenderness of the beam and small scale effect are studied and discussed in detail. An improvement of present formulation will be considered in the future work to consider the thickness stretching effect by using quasi-3D shear deformation models (Belabed *et al*. 2014, Bousahla *et al*. 2014, Hebali *et al*. 2014, Larbi Chaht *et al*. 2015, Bennoun *et al*. 2016, Bourada *et al*. 2015, Draiche *et al*. 2016, Ait Atmane *et al*. 2017, Sekkal *et al*. 2017b, Bouafia *et al*. 2017, Benahmed *et al*. 2017, Benchohra *et al*. 2018, Abualnour *et al*. 2018, Younsi *et al*. 2018, Bouhadra *et al*. 2018, Boukhlif *et al*. 2019, Khiloun *et al*. 2019, Zaoui *et al*. 2019) and the thermal effect (Tounsi *et al*. 2013, Bouderba *et al*. 2013 and 2016, Attia *et al*. 2015 and 2018, Hamidi *et al*. 2015, Bousahla *et al*. 2016, Beldjelili *et al*. 2016, Menasria *et al*. 2017, Chikh *et al*. 2017, El-Haina *et al*. 2017, Khetir *et al*. 2017, Fahsi *et al*. 2017).

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