

On the vibration and energy harvesting of the piezoelectric MEMS/NEMS via nonlocal strain gradient theory

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Abstract. The possibility of energy harvesting as well as vibration of a three-layered beam consisting of two piezoelectric layers and one core layer made of nonpiezoelectric material is investigated using nonlocal strain gradient theory. The three-layered nanobeam is resting on an elastic foundation. Hamilton's principle is used to derive governing equations and associated boundary conditions. The generalized differential quadrature method (GDQM) was used to discretize the equations, and the Newmark beta method was used to solve them. The size-dependency of the elastic foundation is considered using two-phase elasticity. The equations, as well as the solution procedure, are validated utilizing some comparison studies. This work can be a basis for future studies on energy harvesting of small scales.

Keywords: energy harvesting; forced vibration; nano composite; piezoelectric; vibration

1. Introduction

Due to extensive features of smart materials, i.e., piezoelectric, smart structures—nanosensors Wan *et al.* (2004), nanogenerators (Wang and Song 2006), and nano harvesters (Naderi *et al.* 2021) made of these materials has drawn significant attention recently (Liu *et al.* 2021c, Lu *et al.* 2021, Ma *et al.* 2021, Zhou *et al.* 2021, Gao *et al.* 2022a, Shi *et al.* 2022). On nanoscales, the scale of devices is one of the most vital factors to be considered. To study these structures properly, size influences have been considered using quite a few theories such as nonlocal elasticity (Hamidi *et al.* 2015, Allahkarami *et al.* 2017, Ehyaei *et al.* 2017, Akbaş 2018a, b, Arefi and Zenkour 2018, Aydogdu *et al.* 2018, Bensaid *et al.* 2018, Navi *et al.* 2019, Ebrahimi *et al.* 2020b, Gafour *et al.* 2020, Matouk *et al.* 2020).

The classical continuum theory is unable to consider the effect of the size observed in nanostructures. Thus, it is necessary to revise the classical elasticity theory to study the size-dependent behavior. Size-dependent elastic models have been developed using classical theory in some higher-order continuum theories (Habibi *et al.* 2016, 2018a, b, 2019b, d, e, Ebrahimi *et al.* 2019a, Esmailpoor Hajilak *et al.* 2019, Pourjabari *et al.* 2019, Safarpour *et al.* 2019a, Zhu *et al.* 2022). The nonlocal theory, one of the original size-dependent theories, was suggested by Eringen (1972). According to this theory, the stress field at a point is determined by the strains at other locations surrounding the point rather than the strain at the point itself. This elasticity has been utilized to study the static, buckling, and free vibration of small-scale beams since Eringen's proposal

(Reddy 2007, Adali 2008, Murmu and Adhikari 2011, Pradhan and Reddy 2011, Fakher *et al.* 2020, Naderi *et al.* 2020, Behdad *et al.* 2021). Despite the fact that nonlocal elasticity suggested by Eringen (1983) has been broadly utilized in design of small-scaled structures, it is unable to capture the stiffness enhancement. Another approach to capture the size dependency of small structures was proposed by Aifantis (1992), the strain gradient theory. This theory, in contrast to the strain gradient theory by Mindlin (1963), contain only a single micro-scale parameter, which makes it more practical. Wave propagation forced vibrations of a bar modeled based on the Aifantis's strain gradient theory was studied by Tsepoura *et al.* (2002). Papargyri-Beskou *et al.* (2003) investigated the buckling and bending of a Euler-Bernoulli beam using Aifantis's strain gradient elasticity. The governing equations for buckling and bending were derived by combining the related basic equations using a variational framework. It has been shown that, unlike Eringen's nonlocal elasticity, Aifantis's theory possesses the ability of reflecting small-scale structural stiffness enhancement. Thus, combination of these theories leads to a theory which is a better elasticity for the analysis of small-scale structures. the theory of nonlocal proposed by Eringen with the strain gradient theory suggested by Aifantis was combined by Lim *et al.* (2015), the nonlocal strain gradient theory. Based on the nonlocal strain gradient theory, the stress accounts for the both non-gradient nonlocal stress field Eringen (1972) as well as higher order gradient strain field (Aifantis 1992). Şimşek (2016) studied a non-linear free vibration of FG nano-beams using the nonlocal strain gradient theory as well as Euler-Bernoulli beam theory.

Regarding the kinematical respect of beams, quite a few beam theories have been used to study this structure (Jiang *et al.* 2021, Peng *et al.* 2021, Xu *et al.* 2021b, Gao *et al.* 2022b, Li *et al.* 2022b). The basic theory is Euler-Bernoulli

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beam theory (EBBT), the assumption of which explains that the plane of the cross-section of the beam will be nondeformable after the beam's bending. This theory is much helpful for very thin beams. However, EBBT cannot be used for the thicker beams, and the effect of the transverse shear should be considered, Timoshenko beam theory (TBT)—the first-order shear deformable beam theory (FSDBT). According to FSDBT, the plane remains plane, but it is no longer normal to the mid-plane. Shear deformation causes an extra rotation of the cross-section, according to FSDBT. Consideration of the variation of shear stress distribution is a further enhancement to the prior theory. Various higher-order shear distributions depend on the polynomial degree and the assumption of their shear stress. Some of the theories are hyperbolic shear deformation beam theory (HSDBT) (Soldatos 1992), trigonometric shear deformation beam theory (TSDBT) (Touratier 1991), the parabolic shear deformation beam theory (PSDBT) (Reddy 1984), and shear deformation beam theory with a power-law relation (ASDBT) (Aydogdu 2009).

In order to study the size-dependent features of small-scale piezoelectric structures, a model which is based on the nonlocal differential elasticity was developed (Zhou and Wang 2002, Zhou *et al.* 2006, 2007). Therefore, there are many researches in which differential nonlocal elasticity has been used to model the small-scale piezoelectric structure. Thermoelastic-mechanical linear (Ke and Wang 2012) along with nonlinear vibration of nanobeams which are modeled using Timoshenko theory was studied (Ke *et al.* 2012). The nonlocal elasticity as well as higher order shear deformable was used to investigate the Buckling of the FG beams (Ebrahimi and Barati 2017). Furthermore, the mechanical and electrical vibrations of Mindlin plates composed of piezoelectric materials described by nonlocal elasticity were studied by Ke *et al.* (2015).

As stated in the study of the literature on the mechanical and dynamic behavior of small-scale structures, particularly beam structures, nano-scale beams' vibration and energy harvesting still need to improve. The possibility of energy harvesting as well as vibration of a three-layered beam consisting of two piezoelectric layers and one core layer made of nonpiezoelectric material is investigated using nonlocal strain gradient theory. The three-layered nanobeam is resting on an elastic foundation. Hamilton's principle is used to derive governing equations and associated boundary conditions. The generalized differential quadrature method (GDQM) was used to discretize the equations, and the Newmark beta method was used to solve them. The size-dependency of the elastic foundation is considered using two-phase elasticity.

2. Problem statement

2.1 Implementing of governing equations

In this part, the equations of motion and boundary condition of a nanobeam incorporated with two piezoelectric sheets at the bottom and the top, shown in Fig. 1,

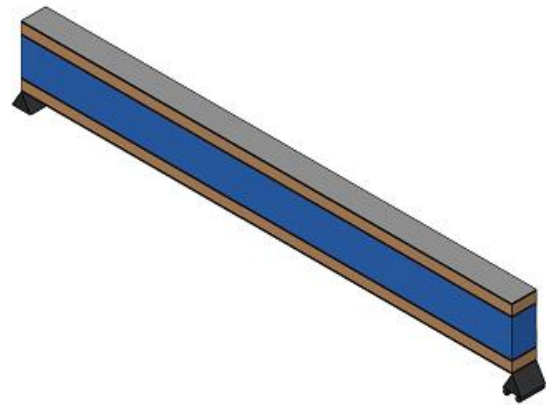


Fig. 1 Schematic of a three-layered beam including a core layer and two piezoelectric layers

are presented to investigate the vibration, and energy of this beam.

According to the following equation, the Hamilton principle is used to generate the governing equations and associated boundary conditions (Habibi *et al.* 2017, 2019a, c, Safarpour *et al.* 2018, 2019b, 2020, Alipour *et al.* 2020, Ebrahimi *et al.* 2020a, Ghazanfari *et al.* 2020, Chen *et al.* 2022).

$$\int_0^t (\delta U - \delta K - \delta W_b - \delta W_k) dt = 0 \quad (1)$$

where 'U', 'K', and 'W' are the strain energy, kinetic and external energy of external work, respectively. The elasticity theory to capture the size effect of this beam is nonlocal strain gradient theory. Also, the HSDBT theory is utilized to obtain the governing equations and associated boundary conditions. According to this theory, the displacement field can be defined as below (Ebrahimi *et al.* 2019b, c, 2020c, Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Habibi *et al.* 2020, Oyarhossein *et al.* 2020, Shariati *et al.* 2020a, b, Shokrgozar *et al.* 2020).

$$\begin{aligned} u_1(x, z, t) &= u(x, t) - z \frac{\partial w(x, t)}{\partial x} + \Phi(z) \left(\frac{\partial w(x, t)}{\partial x} - \psi(x, t) \right) \\ u_2(x, z, t) &= 0 \\ u_3(x, z, t) &= w(x, t) \end{aligned} \quad (2)$$

where 'u' is the axial displacement and 'w' is the transverse displacement of the nanobeam. Furthermore, 'ψ' denotes the rotation of the cross-section, and 'Φ(z)' denotes the beam shape function, which is considered as follows

$$\Phi(z) = h \sinh\left(\frac{z}{h}\right) - z \cosh\left(\frac{1}{2}\right) \quad (3)$$

the nonzero strains of the nanobeam are

$$\varepsilon_{xx} = \frac{\partial u(x, t)}{\partial x} - z \frac{\partial^2 w(x, t)}{\partial x^2} + \Phi(z) \left(\frac{\partial^2 w(x, t)}{\partial x^2} - \frac{\partial \psi(x, t)}{\partial x} \right) \quad (4)$$

$$\gamma_{xz} = \frac{\partial \Phi(z)}{\partial z} \left(\frac{\partial w(x, t)}{\partial x} - \psi(x, t) \right)$$

The relation between stress and strain in the core layer are as follows (Hashemi *et al.* 2019, Al-Furjan *et al.* 2020c, d, e, f, Bai *et al.* 2020, Cheshmeh *et al.* 2020, Li *et al.* 2020a, Lori *et al.* 2020, Najaafi *et al.* 2020, Shariati *et al.* 2020c, Xiong *et al.* 2020, Guo *et al.* 2021b, Liu *et al.* 2021a).

$$\begin{aligned} \sigma_{xx}^c &= C_{11} \varepsilon_{xx} \\ \tau_{xz}^c &= C_{44} \gamma_{xz} \end{aligned} \quad (5)$$

In which elastic constants are defined as C_{11} and C_{44} . Additionally, for piezoelectric sheets, the relations can be written as follows (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Liu *et al.* 2020b, 2021b, Zare *et al.* 2020, Dai *et al.* 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Zhang *et al.* 2021).

$$\begin{aligned} \sigma_{xx}^p &= Q_{11} \varepsilon_{xx} - e_{31} E_z \\ \tau_{xz}^p &= Q_{44} \gamma_{xz} - e_{15} E_x \\ D_x &= e_{15} \gamma_{xz} + \epsilon_{11} E_x \\ D_z &= e_{31} \varepsilon_{xx} + \epsilon_{33} E_z \end{aligned} \quad (6)$$

where Q_{11} and Q_{44} are elastic constants, e_{31} , e_{15} are the piezoelectric constants, ϵ_{11} , ϵ_{33} are dielectric constants, and E_x and E_z denote electric displacement in 'x' and 'z' directions. Electric fields are defined as follows:

$$E_i = -\Delta \Gamma_i = x, z \quad (7)$$

In which the electric potential, for the bottom and the top layers are

$$\begin{aligned} \Gamma^t(x, z, t) &= -\cos\left(\frac{\pi(z - \frac{h_c}{2})}{h_t}\right) \phi^a(x, t) + \frac{2V_0(z - \frac{h_c}{2})}{h_t} \\ \Gamma^b(x, z, t) &= -\cos\left(\frac{-\pi(z + \frac{h_c}{2})}{h_b}\right) \phi^s(x, t) \end{aligned} \quad (8)$$

where external voltage applied to the top layer—actuator—is denoted by 'V₀'. The corresponding potential energy of the given structure can be obtained through the following equation (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).

$$U = \frac{1}{2} b \left(\int_{-h_c/2}^{h_c/2} \int_0^L \left(\sigma_{xx}^c \varepsilon_{xx} + \tau_{xz}^c \gamma_{xz} + \sigma_{xx}^{c(1)} \varepsilon_{xx} + \tau_{xz}^{c(1)} \gamma_{xz} \right) dx dz \right. \\ \left. + \int_{-h_c/2}^{-h_c/2-h_b} \int_0^L \left(\sigma_{xx}^p \varepsilon_{xx} + \tau_{xz}^p \gamma_{xz} + \sigma_{xx}^{p(1)} \varepsilon_{xx} + \tau_{xz}^{p(1)} \gamma_{xz} - D_x E_x - D_z E_z \right) dx dz \right. \\ \left. + \int_{h_c/2}^{h_c/2+h_t} \int_0^L \left(\sigma_{xx}^p \varepsilon_{xx} + \tau_{xz}^p \gamma_{xz} + \sigma_{xx}^{p(1)} \varepsilon_{xx} + \tau_{xz}^{p(1)} \gamma_{xz} - D_x E_x - D_z E_z \right) dx dz \right) \quad (9)$$

Using Eq. (4) and Eq. (8), the potential energy can be rewritten (Ma *et al.* year, Zhao *et al.* year, Hou *et al.* 2021, Huang *et al.* 2021b, c, Jiao *et al.* 2021, Liu *et al.* 2021d, Moradi *et al.* 2021, Xu *et al.* 2021a, Dong *et al.* 2022, Luo *et al.* 2022, Michael *et al.* 2022, Wang *et al.* 2022b, Yang *et al.* 2022, Yu *et al.* 2022).

$$U = \frac{1}{2} b \left(\int_0^L \left(N(x, t) \left(\frac{\partial u(x, t)}{\partial x} \right)^2 - M(x, t) \frac{\partial^2 w(x, t)}{\partial x^2} + F(x, t) \left(\frac{\partial^2 w(x, t)}{\partial x^2} - \frac{\partial \psi(x, t)}{\partial x} \right) + Q(x, t) \left(\frac{\partial w(x, t)}{\partial x} - \psi(x, t) \right) \right) dx \right. \\ \left. + \int_{h_c/2}^{h_c/2+h_t} \left(-D_x \left(\cos\left(\frac{\pi(z - \frac{h_c}{2})}{h_t}\right) \frac{\partial \phi^a(x, t)}{\partial x} \right) - D_z \left(\frac{-\pi}{h_t} \sin\left(\frac{\pi(z - \frac{h_c}{2})}{h_t}\right) \phi^a(x, t) - \frac{2V_0}{h_t} \right) \right) dz \right. \\ \left. + \int_{-h_c/2}^{-h_c/2-h_b} \left(-D_x \left(\cos\left(\frac{-\pi(z + \frac{h_c}{2})}{h_b}\right) \frac{\partial \phi^s(x, t)}{\partial x} \right) - D_z \left(\frac{-\pi}{h_b} \sin\left(\frac{-\pi(z + \frac{h_c}{2})}{h_b}\right) \phi^s(x, t) \right) \right) dz \right) \quad (10)$$

The kinetic energy (Wang *et al.* 2018, Li *et al.* 2021, 2022a, He *et al.* 2022, Ju *et al.* 2022) corresponding with the structure can be defined as

$$K = \frac{\rho_c + \rho_p}{2} \int \left(\left(\frac{\partial u}{\partial t} - z \frac{\partial^2 w}{\partial x \partial t} + z \left(\frac{\partial^2 w}{\partial x \partial t} - \frac{\partial \psi}{\partial t} \right) \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right) dV \quad (11)$$

In which ' ρ_p ' and ' ρ_c ' indicate the density of the piezoelectric and the core layer. Eq. (14) can be re-written as follows:

$$K = \frac{1}{2} \int_0^L \left(I_0 \left(\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right) - 2I_1 \left(\frac{\partial u}{\partial t} \frac{\partial^2 w}{\partial x \partial t} \right) + I_2 \left(\frac{\partial^2 w}{\partial x \partial t} \right)^2 + I_3 \left(\frac{\partial^2 w}{\partial x \partial t} - \frac{\partial \psi}{\partial t} \right) - I_4 \frac{\partial^2 w}{\partial x \partial t} \left(\frac{\partial^2 w}{\partial x \partial t} - \frac{\partial \psi}{\partial t} \right) + I_5 \left(\frac{\partial^2 w}{\partial x \partial t} - \frac{\partial \psi}{\partial t} \right)^2 \right) dx \quad (12)$$

To capture the size dependency, nonlocal strain gradient theory-based of which the following constitutive relations for the given structure are expressed is used (Fan *et al.* 2022, Wang *et al.* 2022a, Xia *et al.* 2022).

$$\begin{aligned} (1 - (e_0 a)^2 \nabla^2) \sigma_{xx}^c &= (1 - (l_m)^2 \nabla^2) (C_{11} \varepsilon_{xx}) \\ (1 - (e_0 a)^2 \nabla^2) \tau_{xz}^c &= (1 - (l_m)^2 \nabla^2) (C_{44} \gamma_{xz}) \\ (1 - (e_0 a)^2 \nabla^2) \sigma_{xx}^p &= (1 - (l_m)^2 \nabla^2) (Q_{11} \varepsilon_{xx}) - e_{31} E_z \\ (1 - (e_0 a)^2 \nabla^2) \tau_{xz}^p &= (1 - (l_m)^2 \nabla^2) (Q_{44} \gamma_{xz}) - e_{15} E_x \\ (1 - (e_0 a)^2 \nabla^2) D_x &= (1 - (l_m)^2 \nabla^2) (e_{15} \gamma_{xz}) + \epsilon_{11} E_x \\ (1 - (e_0 a)^2 \nabla^2) D_z &= (1 - (l_m)^2 \nabla^2) (e_{31} \varepsilon_{xx}) + \epsilon_{33} E_z \end{aligned} \quad (13)$$

In which ' $\nabla^2 = \partial^2 / \partial x^2$ ', indicate Laplacian operator, ' $e_0 a$ ' is nonlocal parameter, and ' l_m ' is the strain gradient length scale parameter.

2.2 Energy harvesting

In order to obtain the energy harvesting voltage, the voltage produced by the bottom and top piezoelectric layers should be accumulated, as the electric circuit is shown in Fig. 2.

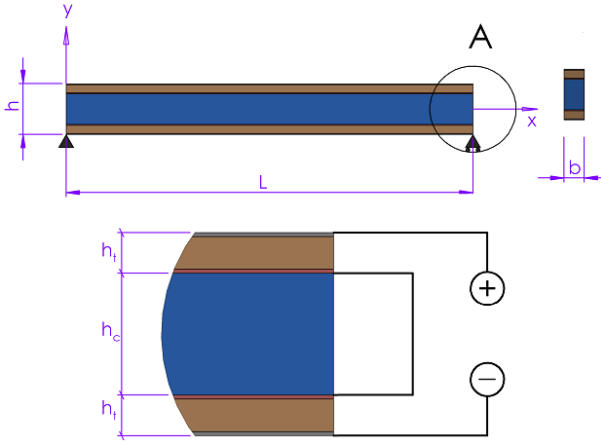


Fig. 2 Schematic of a three-layer beam including a core layer as well as two piezoelectric layers used as energy harvester

The force which is used in this study is a shockwave produced from a blast load which can be defined as follows:

$$F = P_{s0} \left[1 - \frac{t}{t_0} \right] \exp\left(\frac{-at}{t_0}\right) \quad (13)$$

where and denote maximum static pressure (P_{s0}) as well as positive phase time (t_0) which can be expressed as:

$$P_{s0} = P_0 \frac{808 \left(1 + \left(\frac{Z}{4.5} \right)^2 \right)}{1 + \left(\frac{Z}{0.048} \right)^2 \sqrt{1 + \left(\frac{Z}{1.35} \right)^2}} \quad (14a)$$

$$t_0 = \tilde{W}^{1/3} \frac{980 \left(1 + \left(\frac{Z}{0.54} \right)^{10} \right)}{\left(1 + \left(\frac{Z}{0.02} \right)^3 \right) \left(1 + \left(\frac{Z}{0.74} \right)^6 \right) \sqrt{1 + \left(\frac{Z}{6.9} \right)^2}} \text{ms} \quad (14b)$$

In which ' P_0 ' is atmosphere pressure and

$$Z = \frac{\tilde{R}}{\tilde{W}^{0.33}} \quad (15)$$

$$a = 1.5Z^{-0.38}$$

where and are distance to of blast to the center of the beam and explosive material mass.

3. Solution methodology

Because of the higher-order coupled equation in this research, a numerical solution technique, namely the generalized differential quadrature method (GDQM), was used to achieve the forced vibration and energy harvesting findings (Wu and Liu 2001).

$$\begin{aligned} \Psi^{(r)}(x_i) &= \sum_{j=1}^{ns} h_{j0}^{(r)}(x_i) \Psi_j + h_{11}^{(r)}(x_i) \Psi_1^{(1)} + h_{ns1}^{(r)}(x_i) \Psi_{ns}^{(1)} \\ &= \sum_{j=1}^{ns+2} \beta_{ij}^{(r)} V_j \quad (i = 1, 2, \dots, ns) \end{aligned} \quad (16)$$

Table 1 The first non-dimensional frequency of nanobeams for different boundary conditions versus γ

B.Cs	γ	$\kappa = 0.5$	
		Present	Al-shujairi and Mollamahmutoğlu (2018)
C-C	0.50	2.1858	2.1208
	0.75	3.2320	3.2320
	1	4.2873	4.2883

where ' ns ' and ' x_i ' show the sampling point number and the location of the points. In addition, $h_{j0}^{(r)}(x_i)$, $h_{11}^{(r)}(x_i)$, and $h_{ns1}^{(r)}(x_i)$ denote to Hermite shape functions for all of the sample points, and the first derivative of the first point as well as the first derivative of the last point. Where ' $\Gamma_{ijl}^{(r)}$ ' is the r -th order derivative at each point (x_i). The discrete form of the function for fourth-order GDQM, V_j , is defined as follows (Shariati 2008, 2011, 2018, 2019, Hamidian *et al.* 2011, Shah *et al.* 2015, 2016a, b, Khanouki *et al.* 2016, Toghroli *et al.* 2017, 2018, 2020, Chen *et al.* 2019, Li *et al.* 2019, Naghipour *et al.* 2020, Razavian *et al.* 2020, Shariati *et al.* 2020d, Hosseini and Toghroli 2021, Mehrabi *et al.* 2021).

$$\begin{aligned} \{V\}^T &= \{\Psi_1^{(0)}, \Psi_1^{(1)}, \Psi_2, \Psi_3, \dots, \Psi_{ns-1}, \Psi_{ns}^{(0)}, \Psi_{ns}^{(1)}\} \\ &= \{V_1, V_2, \dots, V_{ns+2}\} \end{aligned} \quad (17)$$

Also, Hermite shape functions are defined as follows

$$\beta_{ijl}^{(r)} = h_{jl}^{(r)}(x_i) = \frac{d^r h_{jl}(x_i)}{dx^r} \quad (18)$$

4. Results and discussions

Before the discussion of results, the validation of this study and associated boundary conditions along with the numerical approach should be done. As a consequence, for a three-layered beam, the fundamental nondimensional vibration frequencies ($\Gamma = \omega L^2 \sqrt{\frac{m_1}{D_{11}}}$) for different ' γ ' and ' κ ' values are tabulated and compared in Table 1 with the results obtained by Al-shujairi and Mollamahmutoğlu (2018), for fully clamped (C-C) boundary conditions. It can be seen that the presented validation has an excellent agreement with the previously reported results.

The factors that influence the collected voltage and regulated vibration of a three-layered nanobeam with two piezoelectric layers and a nanocomposite nonpiezoelectric layer exposed to an external shock wave are then investigated. It should also be noted that, with the exception of the instances shown in the images, the constant parameters are $R = 10$, $K_w = 0$, $K_p = 0$, $\kappa = 0.5$, $\gamma = 0.5$, $V_{CNT} \rightarrow FG - X$, $N_t = 12$ and $V_F = 0.3$, $W_{CNT} = 0.02$.

To begin, to evaluate the impact of the beam's thickness ratio, R , the vibration and harvested voltage of a three-layered beam exposed to a blast load for various values are shown in Figs. 3 and 4, respectively. As it can be seen from

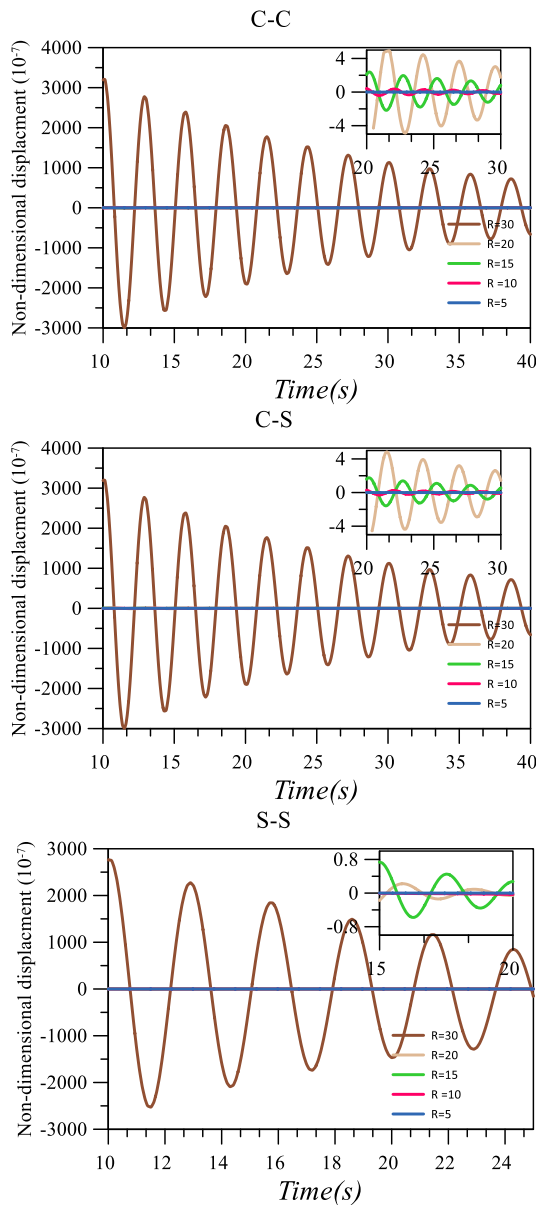


Fig. 3 vibration of a three-layered beam subjected to a blast load for diffret values of R

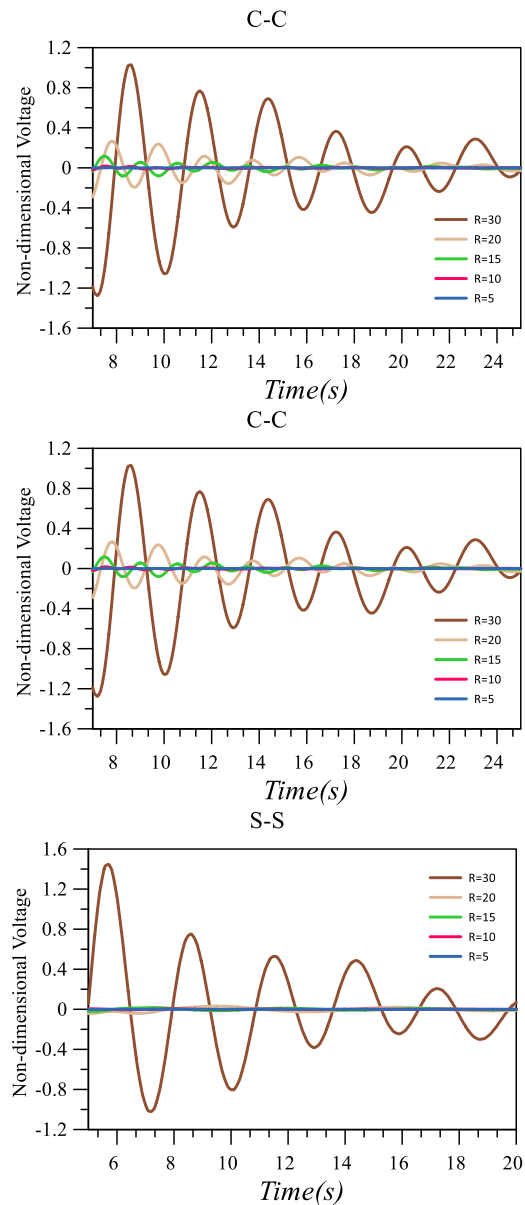


Fig. 4 nondimensional harvested voltage of a three-layered beam subjected to a blast load for diffret values of R

Fig. 2, the more R is, the more deflection the beam can have, so much so that the thinnest beam has the highest deflection among all cases. The dimensionless deflection rises by ‘ R ’ in all applicable boundary conditions including the fully simply supported (S-S), fully clamped (C-C), and clamped-simply supported (C-S), and this parameter has a minor effect on the frequency period. It may be carried out as an increase of the ‘ R ’ restricts the frequency. The same dimensionless deflection, an increment of ‘ R ’ improve the voltage generated in all mentioned boundary conditions. In fact, similar to the deflection from Fig. 3, the possibility of harvesting voltage (Fig. 4) for beams with less R —thinner beams—intensifies. Therefore, the beams with less thickness can be used to harvest more voltage from a three-layered beam. Also, it should be mentioned that if the system is used for vibration, against the case for harvesting voltage, the thicker beam should be used.

5. Conclusions

Using paradox-free local/nonlocal theory, the feasibility of energy harvesting as well as vibration of a three-layered beam consisting of two piezoelectric layers and one core layer comprised of nonpiezoelectric material has been examined. A blast load was applied to the three-layered nanobeam, sitting on an elastic basis. The core layer has also been constructed of Nanocomposites with carbon nanotubes (CNTs) and carbon fibers as reinforcement (MHCD). The governing equations and accompanying boundary conditions were derived using Hamilton’s principle. The equations were discretized using the generalized differential quadrature technique (GDQM) and solved using the Newmark beta method. Two-phase elasticity was used to model the elastic foundation’s size dependence. The impact of elastic foundations, nonlocal

variables, and core material properties on forced vibration and energy harvesting has been thoroughly explored. Some compassion studies were used to verify the equations as well as the solution process.

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