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Buckling and vibrational information of an annular nanosystem covered with piezoelectric layer

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Abstract. Resently, the use of smart structures has been heightened up rapidly. For this issue, vibration analysis related to a graphene nanoplatelet composite (GPLRC) nanodisk which is attached to a piezoelectric layer and is subjected to thermal loads is explored in the current paper. The formulation of this study is obtained through the energy method and nonlocal strain gradient theory, and then it is solved employing generalized differential quadrature method (GDQM). Halpin-Tsai model in addition to the mixture's rule are utilized to capture the material properties related to the reinforced composite layer. The compatibility conditions are presented for exhibiting the perfect bounding between two layers. The results of this study are validated by employing the other published articles. The impact of such parameters as external voltage, the radius ratio, temperature difference, and nonlocality on the vibrational frequency of the system is investigated in detail.
Keywords: compatibility equations; frequency response; GDQM; GPLRC; nanodisk; piezoelectric layer; thermal envirionment

1. Introduction

Composite materials, since they can alter the property of material without causing any drawback to the structure, are an excellent choice for structures and devices which are in high-temperature surroundings (Habibi *et al*. 2016, 2017, 2018a, b, 2019a, b, c, d, e, Safarpour *et al*. 2018, 2019a, b, 2020, Ebrahimi *et al*. 2019, 2020, Esmailpoor Hajilak *et al*. 2019, Pourjabari *et al*. 2019, Alipour *et al*. 2020, Ghazanfari *et al*. 2020, Chen *et al*. 2022). Two types of composites which are used in most of the studies are laminated composites and reinforced composites (Arabnejad Khanouki *et al*. 2010, Shariati *et al*. 2010, 2011a, 2012a, b, c, d, 2013, 2014a, 2015, 2016a, b, c, 2017, 2020b, c, d, Abdolrahim 2012, Ali 2012, Khorramian *et al*. 2015, Tahmasbi *et al*. 2016, Khorami *et al*. 2017a, b, Hosseinpour *et al*. 2018, Ismail *et al*. 2018, Nasrollahi *et al*. 2018, Paknahad *et al*. 2018, Wei *et al*. 2018, Zandi *et al*. 2018, Davoodnabi *et al*. 2019, Naghipour *et al*. 2020a, Nouri *et al*. 2021). Reinforced composites are usually made of a base polymer matrix with small-scale reinforcements. This composite type has been in various shapes, such as plates (Shen 2009), beams (Ke *et al*. 2010), disks (Al-Furjan *et al*. 2020a), and shells (Ansari *et al*. 2016).

Disk as the main part of various devised can be used in many systems such as Refs. (Li *et al*. 2021a, Lu *et al*. 2021a, Zhou *et al*. 2021, Xiao *et al*. 2022). One of the papers in which reinforced composite has been utilized is the work that investigated the nonlinear vibration associated with plates made of carbon nanotube reinforced composites (Wang and Shen 2011). This kind of materials can be used in many complex devices (Jiang *et al*. 2021, Li *et al*. 2021b, Lu *et al*. 2021b, Xu *et al*. 2021b, Yang *et al*. 2021). In this paper, four different dispersion related to the reinforcements were considered. The vibration analysis of a beam whose material is reinforced composites, which are distributed in a uniform and functionally graded manner, was carried out through different beam theories (Lin and Xiang 2014). Additionally, Ke *et al*. (2013), by utilizing Timoshenko beam theory, studied the dynamic stability associated with a beam made of composite materials reinforced via CNTs. The buckling in addition to post-buckling of a three-layered disk whose core was reinforced composites was conducted (Al-Furjan *et al*. 2020b). In the abovementioned paper, the disk was placed in a nonlinear medium and was under thermal loads. by utilizing DQM along with higher-order plate theory, static bending of a annular plates whose materials was reinforced composite was investigated by Al-Furjan *et al*. (2021). Vibrational analysis of a cylendrical shell which is made of reinforced composites was presented by utilizing Rayleigh-Ritz procedure (Qin *et al*. 2019). The nanocomposite shell's buckling and post-buckling response were explored by Shen *et al*. (2012). In this paper, they assumed that the CNTs were distributed uniformly and in a functionally graded fashion through the matrix. In addition, the wave propagation behavior of a shell made of a piezoelectric layer incorporated by a reinforced composite layer was analyzed (Bisheh *et al*. 2019). The outputs of previous reference can be used in Refs. (Sun *et al*. 2022, Yang *et al*. 2022b, Ye *et al*. 2022, Zhang *et al*. 2022a). With the arrival of smart devices in recent years, the investigation of smart structures made of piezoelectric materials has been raised significantly. Various mechanical behavior of such structures, such as vibration (Naderi *et al*. 2021), buckling (Wakabayashi *et al*. 1996), bending (Li and Pan 2015), and dynamic stability (Mojahedin *et al*. 2014) have been explored. In this regard, by using Euler–Bernoulli, the vibration control associated with a piezoelectric beam was studied numerically

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and experimentally (Gaudenzi *et al.* 2000). Additionally, the vibration of magneto-piezoelectric nanobeam placed on the viscoelastic foundation was explored (Naderi *et al.* 2022). The nanobeam in this investigation was subjected to magnetic and electric loading. Ke *et al.* (2012) presnted the nonlinear frequency analysis of a piezoelectric nanobeam with the aid of Timoshenko theory as well as the DQ method. additionally, the vibration of piezoelectric nanobeams which are modeled via nonlocal theory and are under thermal loading was examined (Ke and Wang 2012). By incorporating DQM, the frequency response of a nanobeam which is placed on a two-parameter substrate, was explored by Ragb *et al.* (2019). By considering the surface effect togather with the van der Waals forces, dynamic stability and vibrational behavior of a nanobeam made of piezoelectric materials were conducted (Mehrdad Pourkiaee *et al.* 2017). The formulation related to a sandwich plate whose face sheets was piezoelectric was obtained based on Mindlin plate theory, and solved through GDQM coupled with the Newmark procedure (Wen *et al.* 2022). The possibility of harvesting energy from a multilayered piezoelectric beam modeled by considering the nonlinearity was studied (dos Santos *et al.* 2021). The outputs of previous reference can be used as the input in Refs. (Guo *et al.* 2022, He *et al.* 2022, Liu *et al.* 2022, Zhong *et al.* 2022).

Nonlocal strain gradient theory is one of the most prominent theories for exploring the mechanical behavior of small-size structures. Based on this theory, She *et al.* (2018) investigated the wave dispersion in nanobeams which are modeled based on ready beam theory. Also, by utilizing NSGT as the base theory, the formulation corresponded to vibrational response of a beam made of FG composite under thermal loading was obtained (Ebrahimi and Barati 2017). Rajasekaran and Bakhshi Khaniki (2019) managed to present a paper in the area of dynamic responses of nanobeam with nonuniform shape through NSGT. In this paper, the material of the nanobeam was axial FG. With the help finite element method, the reinforced composite beam's vibration characteristics were explored (Merzouki *et al.* 2022). The wave propogation associated with a shell made of porous composites which is subjected to thermal load was investigated through NSGT by Ebrahimi *et al.* (2019). By incorporating NSGT Safarpour *et al.* (Safarpour *et al.* 2018) presented a wave propogation nanlysis on the reinforced composite shells.

Also, Refs. (Hadji and Adda Bedia 2015, Abdelbari *et al.* 2016, Abdelhak *et al.* 2016, Bakhadda *et al.* 2018, Ebrahimi and Safarpour 2018, Bourada *et al.* 2019, Djedid *et al.* 2019) studies dynamic stability related to structures using various solution methods. This paper deals with the vibrational analysis related to a two-layered nanodisk made of a piezoelectric layer incorporated via a GPLRC layer which is subjected to external electrical in addition to thermal loads. NSGT along with the energy method is employed to present the formulations as well as end conditions. Halpin-Tsai model and the mixture's rule are utilized to capture the properties related to the reinforced composite layer. The compatibility conditions are presented for exhibiting the perfect bounding between two layers. The results of this study are validated by employing the other published articles. The influences of parameters such as external voltage, the radius ratio, temperature difference, and nonlocality on the vibrational frequency of the system is investigated in detail.

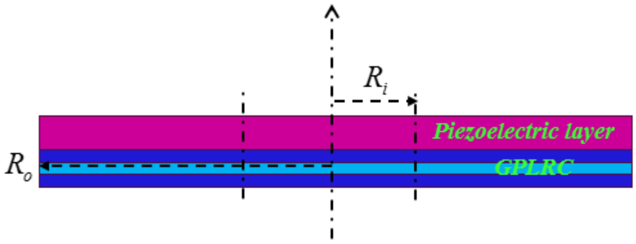

Fig. 1 Two-layered nanodisk with different GPL patterns

2. Multilayer composites reinforced GPL nanodisk

A two-layered disk made of a GPLRC and a piezoelectric layer whose schematic is shown in Fig.1is considered. The four different dispersion patter related to the reinforcements can be seen in this figure. Also, the volume fractions associated with different patterns are introduced in Ref. (Song *et al.* 2017).

Here, V^*_{GPL} is defined by using weight fraction g_{GPL} of GPL as follows:

$$V^*_{GPL} = \frac{g_{GPL}}{g_{GPL} + (\rho_{GPL}/\rho_m)(1 - g_{GPL})} \tag{1}$$

where ρ_{GPL} and ρ_m represnts the densities related to GPL and matrix. With the help of modified Halpin-Tsai, the effective elasticity modulus associated with the GPLRC layer can be defined as below (De Villoria and Miravete 2007).

$$\bar{E} = \left(\frac{3}{8}\left(\frac{1+\xi_L\eta_L V_{GPL}}{1-\eta_L V_{GPL}}\right) + \frac{5}{8}\left(\frac{1+\xi_W\eta_W V_{GPL}}{1-\eta_W V_{GPL}}\right)\right) \times E_M$$
$$\xi_L = 2\frac{L_{GPL}}{t_{GPL}}, \qquad \xi_W = 2\frac{w_{GPL}}{t_{GPL}} \tag{2}$$
$$\eta_L = \frac{\left(\frac{E_{GPL}}{E_M}\right) - 1}{\left(\frac{E_{GPL}}{E_M}\right) + \xi_L}, \qquad \eta_W = \frac{\left(\frac{E_{GPL}}{E_M}\right) - 1}{\left(\frac{E_{GPL}}{E_M}\right) + \xi_W}$$

Also, themass density ρ_c in addition Poisson's ratio ν_c of the GPLRC are:

$$\bar{\nu} = \nu_{GPL}V_{GPL} + \nu_M V_M, \tag{3}$$

$$\bar{\rho} = \rho_{GPL}V_{GPL} + \rho_M V_M. \tag{4}$$

2.1 Displacement fields in the disk:

By using First-order shear deformation theory (FOSDT), displacement fields related to the base layer of the structure (GPLRC) can be written as:

$$\begin{aligned} w^c(R,\theta,z,t) &= w^c{}_0(R,t) \\ v^c(R,\theta,z,t) &= 0 \\ u^c(R,\theta,z,t) &= u^c{}_0(R,t) + z^c u^c{}_1(R,t) \end{aligned} \tag{5}$$

2.2 Strain- stress equations of core

According to FOSDT the strain- stress equations are:

$$\begin{Bmatrix} \sigma^c{}_{RR} \\ \sigma^c{}_{\theta\theta} \\ \sigma^c{}_{rz} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon^c{}_{RR} - \alpha \Delta T \\ \varepsilon^c{}_{\theta\theta} \\ \gamma^c{}_{rz} \end{Bmatrix} \tag{6}$$

$$Q_{55} = \frac{E^c}{2(1+\nu^c)}, Q_{12} = \frac{E_c \nu_c}{1-\nu^{c2}}, Q_{11} = Q_{22} = \frac{E^c}{1-\nu^{c2}},$$

Additionally, the nonzero starins are:

$$\begin{Bmatrix} \varepsilon^c{}_{RR} \\ \varepsilon^c{}_{\theta\theta} \\ \gamma^c{}_{Rz} \end{Bmatrix} = \begin{bmatrix} \frac{\partial u^c{}_0}{\partial R} + z\frac{\partial u^c{}_1}{\partial R} \\ \frac{u^c{}_0}{R} + z\frac{u^c{}_1}{R} \\ \left(u^c{}_1 + \frac{\partial w^c{}_0}{\partial R}\right) \end{bmatrix} \tag{7}$$

2.3 Displacement fields in the Piezoelectric layer

Additionally, the displacement fields related to the piezo layer, by employing FOSDT, can be written as below:

$$\begin{aligned} w^p(R,\theta,z,t) &= w^p{}_0(R,t) \\ v^p(R,\theta,z,t) &= 0 \\ u^p(R,\theta,z,t) &= u^p{}_0(R,t) + z^p u^p{}_1(R,t) \end{aligned} \tag{8}$$

2.4 Strain- stress equations of piezoelectric layer

The stress components can be written based on strain as follows (Mahinzare *et al*. 2018):

$$\begin{Bmatrix} \sigma^p{}_{RR} \\ \sigma^p{}_{\theta\theta} \\ \sigma^p{}_{Rz} \end{Bmatrix} = \begin{bmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & Q_{22} & 0 \\ 0 & 0 & Q_{55} \end{bmatrix} \begin{Bmatrix} \varepsilon^p{}_{RR} \\ \varepsilon^p{}_{\theta\theta} \\ \gamma^p{}_{Rz} \end{Bmatrix} - \begin{bmatrix} 0 & 0 & e_{31} \\ 0 & e_{32} & 0 \\ e_{15} & 0 & 0 \end{bmatrix} \begin{Bmatrix} E^p{}_R \\ E^p{}_\theta \\ E^p{}_z \end{Bmatrix} \tag{9}$$

$$\begin{Bmatrix} D^p{}_R \\ D^p{}_\theta \\ D^p{}_z \end{Bmatrix} = \begin{bmatrix} 0 & 0 & e_{15} \\ 0 & e_{22} & 0 \\ e_{31} & 0 & 0 \end{bmatrix} \begin{bmatrix} \varepsilon^p{}_{RR} \\ \varepsilon^p{}_{\theta\theta} \\ \varepsilon^p{}_{Rz} \end{bmatrix} + \begin{bmatrix} s_{11} & 0 & 0 \\ 0 & s_{22} & 0 \\ 0 & 0 & s_{33} \end{bmatrix} \begin{Bmatrix} E^p{}_R \\ E^p{}_\theta \\ E^p{}_z \end{Bmatrix} \tag{10}$$

In which s_{im}, $e_{mij,}$ and Q_{ij} denotes dielectric constants, piezoelectric constants, as well as elasticity. In addition, E_m and D_i represent electric fields as well as displacements. The electric fields, i.e. E_x, E_z which can be defined as below:

$$E_R = -\frac{\partial \tilde{\Phi}}{\partial R} \quad E_z = -\frac{\partial \tilde{\Phi}}{\partial z}. \tag{11}$$

where the electrical potential are obtained in the following equation based on the theory of Wang (Wang 2002)

$$\Phi(R,\theta,z,t) = \frac{2z\phi_0}{h} - cos(\beta z)\phi(R,\theta,t). \tag{12}$$

where ϕ_0 exhibits the external voltage and $\beta=\pi/h$.

2.5 Compatibility equations

It is considered that the bounding between the piezo and nanocomposite layers is perfect, based on which the following can be written at $z_p = -h_p/2$:

$$\begin{aligned} w^c(z_c = h_c/2) &= w(z_p = -h_p/2), \\ u^c(z_c = h_c/2) &= u^p(z_p = -h_p/2) \end{aligned} \tag{13}$$

Based on Eq. (18), the displacement fields in the piezoelectric layer can be rewritten as:

$$\begin{aligned} u^c{}_0 &= u^p{}_0 + u^c{}_1\left[-\frac{h^c}{2}\right] - u^p{}_1\left[\frac{h^p}{2}\right], \\ w^c{}_0 &= w^p{}_0. \end{aligned} \tag{14}$$

2.6 Hamilton's principle

Now, by employing variational energy method, the formulations and end conditions are extracted (Ma *et al*. 2022, Zhao *et al*. 2022, Hou *et al*. 2021, Huang *et al*. 2021a, b, Jiao *et al*. 2021, Liu *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021a, Dong *et al*. 2022, Luo *et al*. 2022, Michael *et al*. 2022, Wang *et al*. 2022a, b, Yang *et al*. 2022a, Yu *et al*. 2022):

$$\int_{t_1}^{t_2} (\delta T^i - \delta U^i + \delta W^i)\ dt = 0, i = c,p \tag{15}$$

In which the kinetic energy is

$$T^i = \int_A \frac{1}{2}\rho_i\left[\left(\frac{\partial u^i}{\partial t}\right)^2 + \left(\frac{\partial w^i}{\partial t}\right)^2\right] dRdz: i = c,p$$

$$\delta T^i = \int_{R_1}^{R_2} \begin{bmatrix} \left(-I^i{}_0\frac{\partial^2 u^i{}_0}{\partial t^2} - I^i{}_1\frac{\partial^2 u_1}{\partial t^2}\right)\delta u^i{}_0 \\ + \left(-I^i{}_1\frac{\partial^2 u^i{}_0}{\partial t^2} - I^i{}_2\frac{\partial^2 u^i{}_1}{\partial t^2}\right)\delta u^i{}_1 \\ + \left(c_1 I^i{}_3\frac{\partial^2 u^i{}_0}{\partial t^2} + c_1 I^i{}_4\frac{\partial^2 u^i{}_1}{\partial t^2}\right)\delta u^i{}_1 \\ + \left(-I^i{}_0\frac{\partial^2 w^i{}_0}{\partial t^2}\right)\delta w^i{}_0 \end{bmatrix} dR^i \tag{16}$$

where:

$$\{I^i{}_0, I^i{}_1, I^i{}_2, I^i{}_3, I^i{}_4, I^i{}_5, I^i{}_6\} = \int_{-h/2}^{h/2} \rho\left\{1, z^i, z^{i2}, z^3, z^{i4}, z^{i5}, z^{i6}\right\} dz, i = c,p \tag{17}$$

Additionally, the strain energy of the system can be defined as follows

$$\delta U^c = \frac{1}{2}\iiint_V \sigma^c{}_{ij}\delta\varepsilon^c{}_{ij} dV = \int \begin{bmatrix} \left[N^c{}_{RR}\frac{\partial \delta u^c{}_0}{\partial R^c} + M^c{}_{RR}\frac{\partial \delta u^c{}_1}{\partial R^c}\right] \\ + \left[N^c{}_{\theta\theta}\frac{\delta u^c{}_0}{R^c} + M^c{}_{\theta\theta}\frac{\delta u^c{}_1}{R^c}\right] \\ + \left[(Q^c{}_{Rz})\left(\delta u^c{}_1 + \frac{\partial \delta w^c{}_0}{\partial R^c}\right)\right] \end{bmatrix} dR \tag{18}$$

$$\delta U^p = \frac{1}{2}\iiint_V \sigma^p{}_{ij}\delta\varepsilon^p{}_{ij} dV \tag{19}$$

$$-\iiint_{V_{piezolayer}}(D^p{}_R\delta E^p{}_R + D^p{}_z\delta E^p{}_z)dV_{piezolayer}$$

$$=\int\begin{bmatrix}\left[N^p{}_{RR}\frac{\partial\delta u^p{}_0}{\partial R^p} + M^p{}_{RR}\frac{\partial\delta u^p{}_1}{\partial R^p}\right]\\ +\left[N^p{}_{\theta\theta}\frac{\delta u^p{}_0}{R^p} + M^p{}_{\theta\theta}\frac{\delta u^p{}_1}{R^p}\right]\\ +\left[(Q^p{}_{Rz})\left(\delta u^p{}_1 + \frac{\partial\delta w^p{}_0}{\partial R^p}\right)\right]\end{bmatrix}dR^p$$

$$-\int_0^{2\pi}\int_{R_i}^{R_o}\int_{-h_p/2}^{h_p/2}\begin{bmatrix}D^p{}_R\left\{cos(\beta z)\frac{\partial}{\partial R^p}\delta\phi\right\}\\ -D^p{}_z(\beta\, sin(\beta z)\delta\phi)\end{bmatrix}RdRd\theta$$

where:

$$\begin{aligned}\{N^i{}_{\theta\theta}, M^i{}_{\theta\theta}\} &= \int_z\{\sigma^i{}_{\theta\theta}, z\sigma^i{}_{\theta\theta}\}dz, i = c,p\\ \{N^i{}_{RR}, M^i{}_{RR}\} &= \int_z\{\sigma^i{}_{RR}, z\sigma^i{}_{RR}\}dz, i = c,p\\ \{Q^i{}_{Rz}, S^i{}_{Rz}\} &= \int_z\{\sigma^i{}_{Rz}, z^2\sigma^i{}_{Rz}\}dz, i = c,p\end{aligned}\tag{20}$$

The following represents the energy related to external work done by the external voltage.

$$W_1 = \frac{1}{2}\int_z\left[(N^P)w^2{}_{,x}\right]dR \tag{21}$$

In which N_i^P is external loads resulting from the external voltage, which can be written as(Ke *et al.* 2014):

$$N^P = -2(e_{31} - \frac{c_{13}e_{33}}{c_{33}})\phi_0 \tag{22}$$

Additionally, the work done by external heat, assuming that it is distributed in thickness, can be defined as follows.

$$W = \frac{1}{2}\int_z N^T(\frac{\partial w_0}{\partial x})^2 dR \tag{23}$$

where N_1^T is:

$$\begin{aligned}N_1^T &= \int_{-h/2}^{h/2}(\bar{Q}_{11} + \bar{Q}_{12})\alpha(T - T_0)dz,\\ T &= T_c - (T_c - T_m)(0.5 + \frac{z}{h})\end{aligned}\tag{24}$$

2.7 Nonlocal strain gradient theory

In this paper, the size dependency of nanodisk is considered via NSGT. According to this theory, the following equation between strains as well as stress can be defined:

$$(1-\mu^2\nabla^2)t^i{}_{ij} = C^i{}_{ijck}(1 - l^2\nabla^2)\varepsilon^i{}_{ck},{}^i = c,p \tag{25}$$

In which $\nabla^2 = \partial^2/\partial\theta^2 + \partial/R\partial\theta$. Additionally, C_{ijck}, ε_{ck} as well as t_{ij} Represents elasticity tensors, strain tensors, and stress tensors. The following equation presents the stress tensor of the NSGT:

$$t^i{}_{ij} = \sigma^i{}_{ij} - \nabla\sigma^{i}{}^{(1)}_{ij},{}^i = c,p \tag{26}$$

By using Eq. (26), the stress-strain relations for this problem can be written (Reddy 2004):

$$(1-\mu^2\nabla^2)\begin{Bmatrix}t^i{}_{RR}\\ t^i{}_{\theta\theta}\\ t^i{}_{Rz}\end{Bmatrix} = (1-l^2\nabla^2)\begin{bmatrix}Q_{11} & Q_{12} & 0\\ Q_{12} & Q_{22} & 0\\ 0 & 0 & Q_{55}\end{bmatrix}\begin{Bmatrix}\varepsilon^i{}_{rr} - \alpha\Delta T\\ \varepsilon^i{}_{\theta\theta}\\ \gamma^i{}_{rz}\end{Bmatrix},{}^i = c,p \tag{27}$$

The relation between stress and strain in the framework of NSGT can be written as::

$$\begin{aligned}(1-\mu^2\nabla^2)t^i{}_{RR} &= (1-l^2\nabla^2)\varepsilon^i{}_{RR},\\ (1-\mu^2\nabla^2)t^i{}_{\theta\theta} &= (1-l^2\nabla^2)\varepsilon^i{}_{\theta\theta},{}^i = c,p\\ (1-\mu^2\nabla^2)t^i{}_{Rz} &= (1-l^2\nabla^2)\varepsilon^i{}_{Rz}\end{aligned}\tag{28}$$

Finally, the current system's motion equations can be obtained using Eq. (28).

3. Solution procedure

Here, in order to extract the vibrational response of a two-layered disk, a numerical solution (Shariati 2008, 2011b, 2018, 2019, 2020a, Hamidian *et al*. 2011, Shah *et al*. 2015, 2016a, b, Khanouki *et al*. 2016, Toghroli *et al*. 2017, 2018, 2020, Chen *et al*. 2019, Habibi *et al*. 2019c, Naghipour *et al*. 2020b, Razavian *et al*. 2020, Hosseini and Toghroli 2021, Mehrabi *et al*. 2021) procedure—GDQM—is employed. This kind of solution procedure can be used in various systems such as Refs. (Shang *et al*. 2021a, b, Wang *et al*. 2021, Li *et al*. 2022, Zhang *et al*. 2022b). Based on this theory, the n-th order derivative corresponded to a function can be written as follows (Shu 2012):

$$\frac{\partial^n f}{\partial R^n} = \sum_{m=1}^{M} C^{(n)}{}_{j,m}f_{m,k} \tag{29}$$

In which $C^{(n)}$ are weighting coefficients which can be obtained through the following equation.

$$\begin{aligned}C_{ij}^{(1)} &= \frac{M(x_i)}{(x_i - x_j)M(x_j)}i,j = 1,2,\ldots,n \quad \text{and}\, i \neq j\\ C_{ij}^{(1)} &= -\sum_{j=1,i\neq j}^{n} C_{ij}^{(1)}\; i = j\end{aligned}\tag{30}$$

In which,

$$M(x_i) = \prod_{j=1,j\neq i}^{n}(x_i - x_j) \tag{31}$$

Other derivatives of weighting coefficients are

$$\begin{aligned}C_{ij}^{(r)} &= r\left[C_{ij}^{(r-1)}C_{ij}^{(1)} - \frac{C_{ij}^{(r-1)}}{(x_i - x_j)}\right]i,j\\ &= 1,2,\ldots,n, i\neq j \quad \text{and} 2\leq r\leq n-1\\ C_{ii}^{(r)} &= -\sum_{j=1,i\neq j}^{n} C_{ij}^{(r)}\; i,j = 1,2,\ldots,n \quad \text{and} 1\leq r\leq n-1\end{aligned}\tag{32}$$

Also, the dispersion of the greed points are as follows

$$r_i = \frac{L\left(1 - cos\left(\frac{(i-1)}{(N_i-1)}\pi\right)\right)}{2}\; i = 1,2,3,\ldots,N_i \tag{33}$$

Now, by using this method, the formulations and end conditions can be rewritten in the following format

Table 1 the vibrational frequency of the disk for different *h/Ro* and boundary conditions

R_o/R_i	h/R_o	presented (n=1)	Ref. (Han and Liew 1999) (n=1)	presented (n=2)	Ref. (Han and Liew 1999) (n=2)
0.4	0.001	61.5412	61.871	170.541	170.89
	0.05	57.9958	58.754	152.325	153.11
	0.1	50.9985	51.704	120.896	121.88
0.5	0.001	89.1456	89.248	264.365	246.33
	0.05	82.8745	83.051	210.990	211.95
	0.1	69.9985	70.277	159.563	159.78

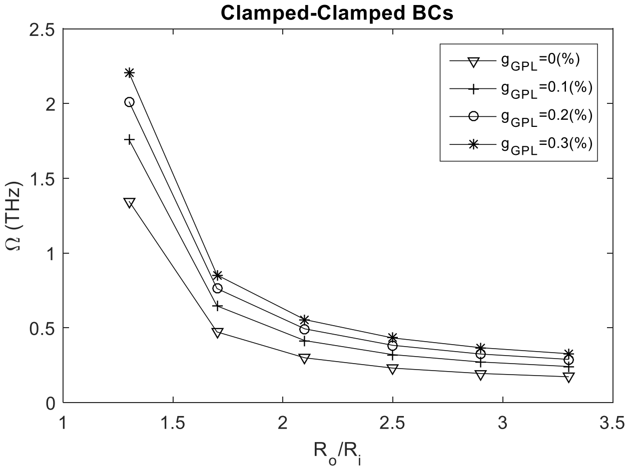

Fig. 2 Variation of vibrational frequency against R_o/R_i for CC end condition and various g_{GPL}

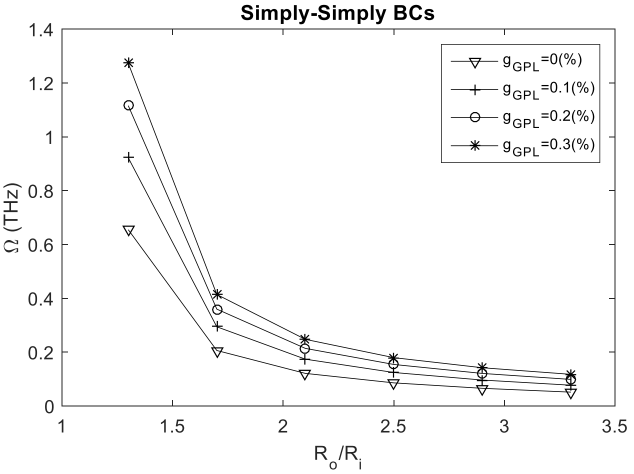

Fig. 4 Variation of vibrational frequency against R_o/R_i for SS end condition and various g_{GPL}

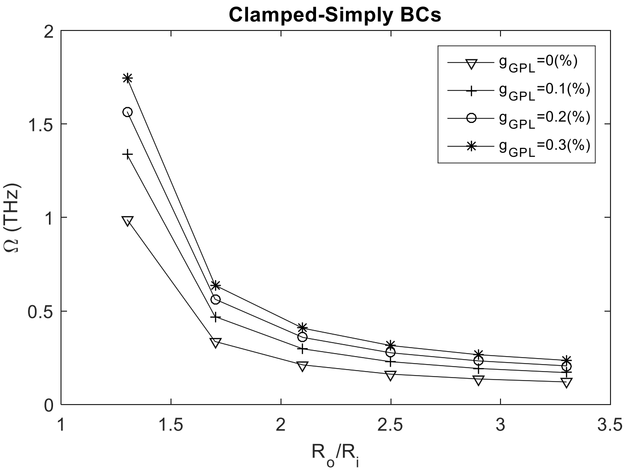

Fig. 3 Variation of vibrational frequency against R_o/R_i for CS end condition and various g_{GPL}

$$\left\{\begin{bmatrix}[M_{dd}] & [M_{db}]\\ [M_{bd}] & [M_{bb}]\end{bmatrix}\Omega^2+\begin{bmatrix}[K_{dd}] & [K_{db}]\\ [K_{bd}] & [K_{bb}]\end{bmatrix}\right\}\begin{Bmatrix}\delta_d\\ \delta_b\end{Bmatrix}=0 \quad (34)$$

where b and d are boundary and domain points. Additionally, Ω denotes the vibrational frequency of the disk. Now, Eq. (34) can be rewritten as:

$$\begin{aligned}&[K^*]\{\delta_i\}=(\Omega^2)[M^*]\{\delta_i\}\\ &[K^*]=[K_{dd}-K_{db}K_{bb}{}^{-1}K_{bd}]\\ &[M^*]=[M_{dd}-M_{db}K_{bb}{}^{-1}K_{bd}]\end{aligned} \quad (35)$$

4. Validation

To begin with, Table 1, in which the vibrational frequency of the system for different h/R_o and R_o/R_i are extracted and compared with the results of Ref. (Han and Liew 1999), is presented to investigate the validity of the current results. As it can be observed, the little difference between the current results and those extracted from the reference exhibits that this formulations and solution procedure are valid in investigating the vibrational behavior of two-layered nanodisk. Also, it can be seen that increasing *h/Ro*, the vibrational frequency of the disk diminishes.

5. Results and discussion

The mechanical properties of the GPL are based on Ref. (Wu *et al*. 2017) and also h_{GNP} =1.5nm. Additionally, the properties associated with the piezoelectric layer are presented in Ref (Habibi *et al*. 2019d). Now, the influence of parameters on the vibrational response of a two-layered nanodisk made of a piezoelectric layer coupled with a GPLRC layer is investigated. Firstly, the ipcat of R_o/R_i on vibrational frequency of a disk with CC, CS, and SS end conditions is studied in Figs. 2-4, respectively. In these figures, the variation of vibrational frequency of the nanodisk is plotted against the value of R_o/R_i for various

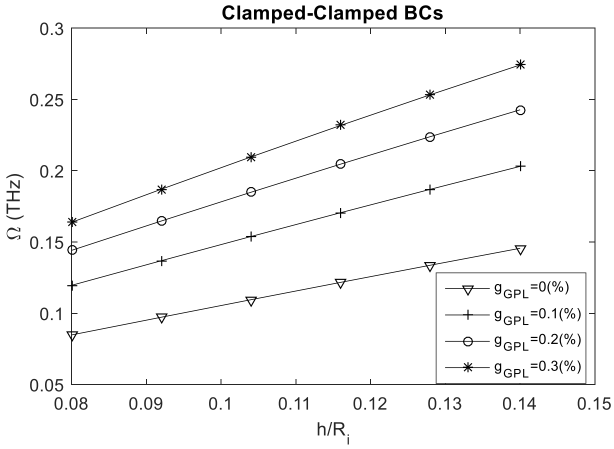

Fig. 5 Variation of vibrational frequency against $\hbar/R_i$ for CC end condition and various g_{GPL}

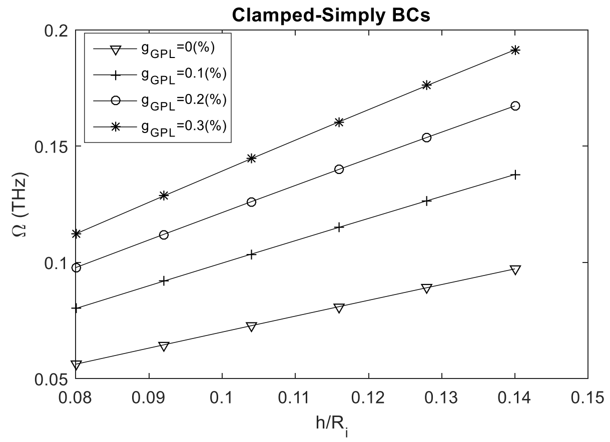

Fig. 6 Variation of vibrational frequency against $\hbar/R_i$ for CS end condition and various g_{GPL}

weight fraction g_{GPL} of the reinfocments. The results in these figures show that, no matter what the boundary conditions or g_{GPL} are, increasing R_o/R_i leads in an decrease in the vibrational frequency of the system. Additionally, in all types of end conditions, it can be seen that the vibration frequency of the disk intensifies by increasing the value of g_{GPL}, so much so that the lowest frequabcy is associated with the case in which g_{GPL} is equal to zero. Also, the stiffer the boundry condition is, the higher the frequency of the disk is.

Here, in Figs. 5-7, respectively, the influence of h/R_i on the vibrational frequency associated with a two-layered nanodisk with CC, CS, and SS end conditions is explored. In the following Figs., the variation of vibration frequency of the system against the value of h/R_i for different values related to weight fractions of GPLs is plotted. Similar to the previous figures, the vibrational frequency of the nanodisk is higher, provided that the g_{GPL} posses a higher value, regardless of the boundry conditions or h/R_i . In addition, it can be observed that heightening up the value corresponded to h/R_i can increase the value of frequency in all types of boundary conditions. Also, the increasing impact of stiffer

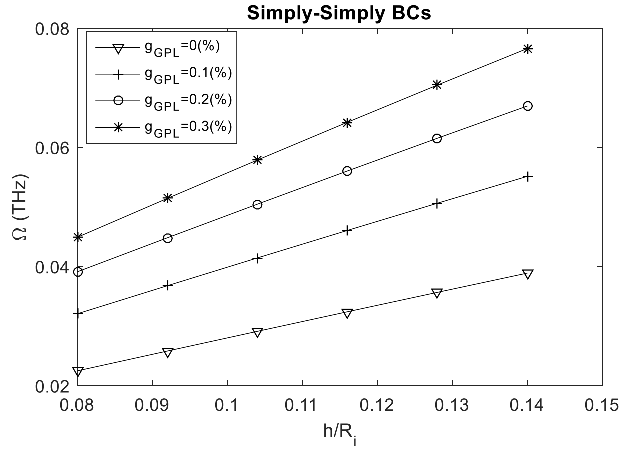

Fig. 7 Variation of vibrational frequency against $\hbar/R_i$ for CC end condition and various g_{GPL}

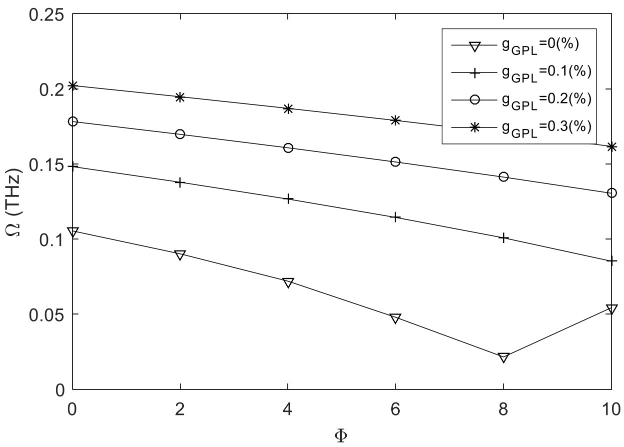

Fig. 8 Variation of vibrational frequency Φ or various g_{GPL}

boundary conditions on the vibrational frequency is evident in these figures as well. The other notable result of these figures is that the difference between the cases with different g_{GPL} intensifies by inceasing $\hbar/R_i$.

Next, in Fig. 8, the vibration frequency of the two-layered disk containing a piezoelectric layer is plotted versus different values of external voltage Φ for various values of reinforcements' weight fraction.

As a general conclusion, Fig. 8 exhibits that increasing Φ causes the vibrational frequency of the system to diminish, regardless of g_{GPL} value. Additionally, it can be seen that the case with $g_{GPL}=0$ reach to its critical amount of external voltage, the point that the vibration frequency changes its trend from reducing to increasing. Finally, the influence of increasing temperature on the vibrational frequency of the two-layered nanodisk made of a piezoelectric layer coupled with a GPLRC layer subjected to thermal loading is investigated. To do so, the variation of frequency against the value of ΔT for various values of g_{GPL}, μ/h, and $\hbar/R_i$ are plotted in Figs. 9-11, respectively.

The interesting results in Fig. 9 show that increasing

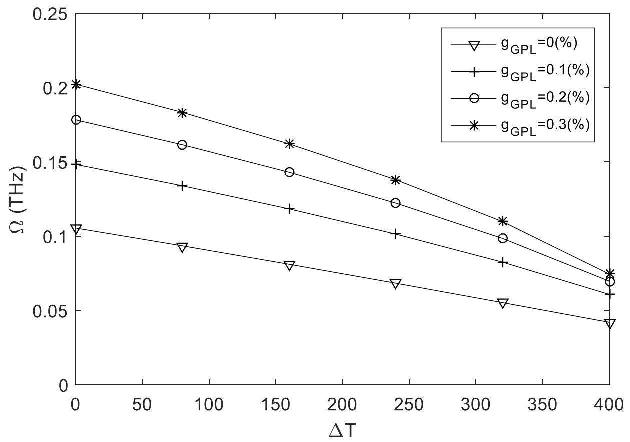

Fig. 9 Variation of vibrational frequency ΔT or various g_{GPL}

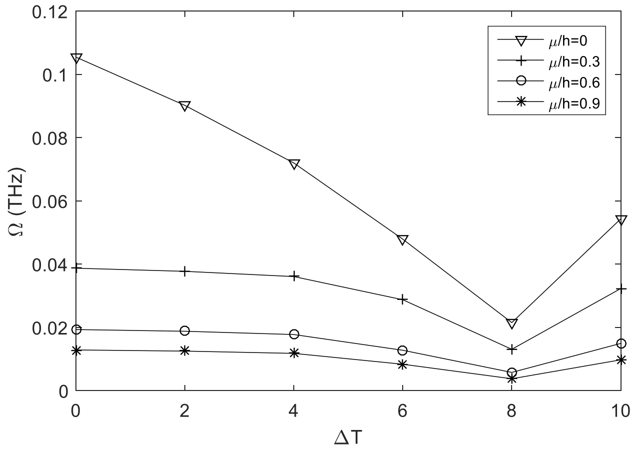

Fig. 10 Variation of vibrational frequency ΔT or various $\mu/\hbar$

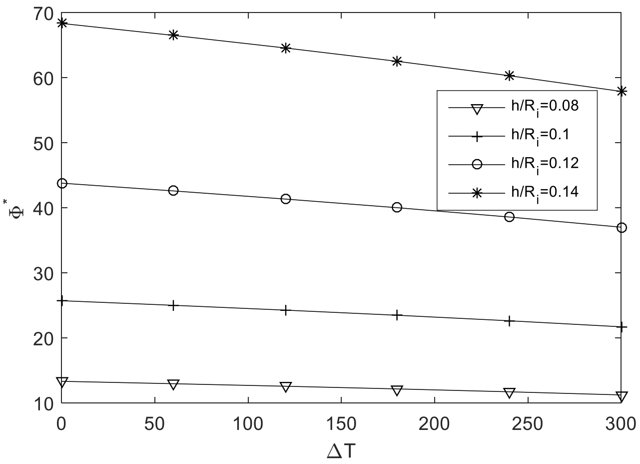

Fig. 11 Variation of vibrational frequency ΔT or various $\hbar/R_i$

temperature diminishes the vibrational frequency due to the compressive force induced by the thermal load. Also, it can be seen that the difference between the cases with different g_{GPL} is reduced by increasing the temperature.

Fig. 10 indicates that different values of μ/h cannot change the value of critical temperature. However, it is notable that increasing $\mu/\hbar$ leads to diminishing the vibrational frequency.

Lastly, as expected, it is evident that the higher $\hbar/R_i$ is, the higher the vibrational frequency can be. Additionally, the reducing effect related to thermal load on frequency can be seen in this figure as well.

6. Conclusions

This paper deals with the vibrational analysis related to a two-layered nanodisk made of a piezoelectric layer incorporated via a GPLRC layer which is subjected to external electrical in addition to thermal loads. NSGT along with the energy method is utilized to present the formulations as well as end conditions. Halpin-Tsai model and the mixture's rule are utilized to capture the material properties related to the reinforced composite layer. The compatibility conditions are presented for echibiting the prefect bounding between two layers. The results of this study are validated by employing the other published articles. The impact of such parameters as external voltage, the radius ratio, temperature difference, and nonlocality on the vibrational frequency of the system is investigated in detail, and the highlight of these investigations are as follows:

• The higher h/R_i is, the higher the vibrational frequency can be.

• Increasing temperature diminishes the vibrational frequency.

• Increasing Φ causes the vibrational frequency of the system to diminish, regardless of g_{GPL} value.

• Increasing R_o/R_i leads to a decrease in the vibrational frequency of the system.

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