

# Sports impact on the nanomedicine absorption in drug delivery

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(Received March 21, 2022, Revised July 1, 2022, Accepted July 4, 2022)

**Abstract.** Physical activities enhance blood flow in the vessels, which may increase the quality of medicine delivery. The emergence of revolutionary technologies such as nanoscience, made it possible to treat the incurable illnesses such as cancer. This paper investigates the impact of sport and physical exercises on the quality and quantity of the drug-delivery based on the mathematical modeling of a nanomotor made by nanotubes carrying the nano-drug capsules. Accordingly, the mathematical equations of rotating nanomotor are generated by considering the both of higher-order beam model and nonlocal strain gradient model, as a comprehensive continuum theory. Next, through the generalized differential quadrature together with Newmark-beta methods, the differential relations are discretized and solved. Finally, the impact of varied parameters on the dynamical behavior of the nanomotor is examined in detail. The outcomes of this investigation can be useful to achieve an excellent design of nanomotors carrying nano-drugs.

**Keywords:** drug-delivery; dynamic analysis; nanodevice; nonlocal strain gradient theory; nanomotor; nanotube

## 1. Introduction

Drug-delivery technology helps at addressing the deficiencies of traditional methods for administering drugs (Davis *et al.* 2010, Wang *et al.* 2012). Also, the requirement for the progress of new devices and technologies to promote the delivery of therapeutic particles in the body has been extensively recognized (Choi *et al.* 2021, Jin *et al.* 2022, Li *et al.* 2022, Obireddy and Lai 2022, Yang *et al.* 2022). Thanks to the inherent traits of materials and structures in micro and nano scales, and also wide range usage of ones in varied industries such as bio sensors (Reddy *et al.* 2011, Zhang *et al.* 2011), mass sensors (Naderi *et al.* 2020), capacitive sensors (Apigo *et al.* 2017), and micro/nanorotors (Ozin *et al.* 2005, Teo and Pumera 2016), these structures have fascinated a great amount of the attentions (Zhuo *et al.* 2020, Liu *et al.* 2021d, 2022a, Shi *et al.* 2022, Zhang *et al.* 2022b). Among these small-scale devices, micro and nanomotors, thanks to promising application in biomedical fields in conjunction with the transformation of varied energy sources to rotary motions, is chosen as an efficient device in drug-delivery investigations. It is valuable to express that the efficiency of nanocarriers to treat the diseases such as, neurovascular diseases, and neurodegenerative maladies (Faraji and Wipf 2009) have been proved. In the drug-delivery mechanism, the blade of a nanomotor, which is modeled as a nanotube, carries the nanomedicine in its own core and then released into the bloodstream.

Experimental data (Chowdhury *et al.* 2010, Bauer *et al.* 2011) verify that construction of such devices in nano or

micro scales require to capture the long range effects, which are due to the molecules interactions. As a result of incapability of the classic elasticity together with requirement of studying the behavioral traits of micro or nano structures, nonlocal strain-driven theory (Eringen and Edelen 1972) and its local/nonlocal form (Fernández-Sáez and Zaera 2017), nonlocal strain gradient theory (NSGT) (Lim *et al.* 2015), as an exhaustive theory with two small scale factor, along with mixture two-phase strain/stress driven elasticity (Behdad and Arefi 2022) are chosen by numerous researchers to modeling and simulation of micro/nano structures. Accordingly, it is valuable to mention some researches in which the dynamical behavior of different nanostructures has been examined upon the NSGT (Li *et al.* 2017, Sahmani and Aghdam 2017, Bahaadini *et al.* 2018, Sahmani *et al.* 2018). To investigate the influence of various parameters on the instability boundaries and vibration analysis of a fluid-conveying nanotube, which has great usages in biological devices particularly delivering drugs to eliminate the cancer cells, Amiri *et al.* (2019) modeled a fluid-conveying piezoelectric nanotube in conjunction with flexoelectric and surface effects. They displayed that flexoelectricity, applied voltage, alongside surface effect has major role on the instability regions of the nanosystems. Regarding the influence of the size of the nanofluid together with the combination of the viscoelastic features and geometric nonlinearity of structure, the bifurcation characteristics of a fluid-conveying nanotube was probed (Farajpour *et al.* 2019). Upon the thick beam theory and regarding the slip boundary conditions between the nanotube's wall and fluid-flow, the flutter traits of fluid-conveying nanotubes in presence of the magnetic field effect was sought (Ghane *et al.* 2020). Liu and Lyu (2020) designed an innovative three-layer mass nanosensor including two graphene layers at the top and bottom of one with a functionally graded core through the

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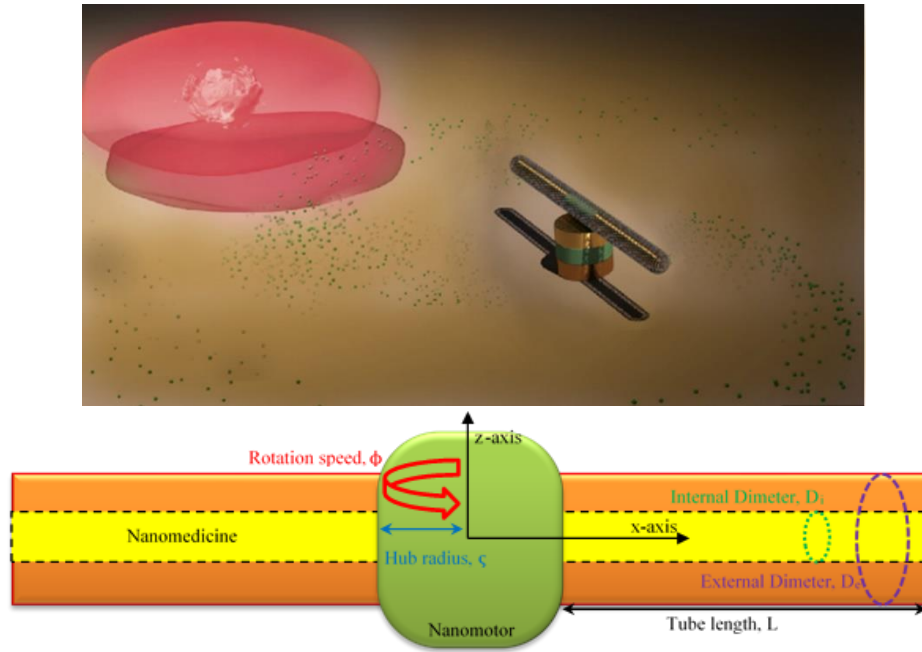


Fig. 1 A schematic and geometric detail of the drug-delivery nanodevice (Ghadiri *et al.* 2017e)

first order shear deformation hypothesis and explored the impact of parameters such as mass location, and mass value on the frequency shift of nanosystem. Their outcomes disclose that considering graphene layers lead to increase the sensitivity of the mass nanosensor. Moreover, Farajpour *et al.* (2021) suggested a nonlinear NSG model of magneto-electro-elastic nanoplates to analyze the nonlinear vibration of one in presence of foreign particles. They extracted vibration frequencies of mass nanosensor through the perturbation technique and analyzed the frequency shifts of the linear and nonlinear models (Wang *et al.* 2020a, Zhang *et al.* 2020a, Li *et al.* 2021, Si *et al.* 2021, Chang *et al.* 2022, Liu *et al.* 2022b).

In this research, the dynamic characteristics of a nanomotor made of nanotubes has been investigated. Nanotube (or nanomotor's blade) is modeled through the NSGT, as a comprehensive non-classical theory with two size-dependent variables, in conjunction with higher-order tube theory. All the boundary conditions along with the governing equations are attained upon the Hamilton's principle. The GDQM, as a powerful numerical solution tool, and Newmark-beta method are opted to discretize and obtain the outcomes. After verifying the mathematical modeling and solution method, the role of angular velocity, sports impact parameter, size-dependent parameters, in addition to hub radius, on the mechanical traits of the nanosystem are examined through the several figures.

## 2. Mathematical simulation

Micro/nano-motors are known as innovative platforms to drug-delivery goals and have various merits including quick drug transport, and motion controllability (Ghadiri *et al.* 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al.* 2016b). The nano drugs are put into the core of the nanotube

in order to therapeutic targets. In this regard, a nanotube, as nanomotor's blade, has been depicted in Fig. 1. Coordinates and geometric details including the tube length, ' $L$ ', internal radius, ' $R_i=D_i/2$ ', external radius, ' $R_e=D_e/2$ ', hub radius, ' $\zeta$ ', and the tube spins around the  $z$ -axis, ' $\phi$ ', in addition to the other helpful information are given in this figure. Accordingly, in the following, to mathematical modeling of the rotating nanotube as nanomotor's blade, the Hamilton's principle is utilized as Eq. (1) (Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g, Fernández-Sáez and Zaera).

$$\int_{t_1}^{t_2} \delta \Pi dt = \int_{t_1}^{t_2} \delta (P + E - K) dt = 0 \quad (1)$$

where  $K$ , and  $P$  are the kinetic, and potential energies (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017). Besides,  $E$  denotes the energy that is introduced by the external work (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b). In this study, the high-order tube theory introduced by Zhang and Fu (2013) has been employed to regard the displacement fields of the nanotube structure (Shafiei and She 2018, Shafiei *et al.* 2019, 2020). According to this theory, the following displacement fields,  $(u_x, u_y, u_z)$ , are defined.

$$\begin{aligned} u_x(x, y, z, t) &= u(x, t) - z \frac{\partial w(x, t)}{\partial x} \\ &+ \xi(x, y, z) \left[ \psi(x, t) + \frac{\partial w(x, t)}{\partial x} \right] \\ u_z(x, y, z, t) &= w(x, t) \\ u_y(x, y, z, t) &= 0 \end{aligned} \quad (2)$$

where ' $u(x, t)$ ' is the axial movement, ' $\psi(x, t)$ ' is the bending rotation, ' $w(x, t)$ ' is the lateral displacement, and ' $t$ ' is the time (Ehyaie *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.*

2017c). Also,  $\bar{v}$  is the function defined for the Zhang and Fu (2013) theory based on the Eq. (3).

$$\bar{v}(y, z) = z + z(R_e^2 + R_i^2)^{-1} \left( R_e^2 R_i^2 r^{-2} - \frac{r^2}{3} \right) \quad (3)$$

The following assumption should be regard to modify the circular system from the Cartesian system (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.* 2017d, Azimi *et al.* 2018).

$$\begin{aligned} z &= r \sin(\theta) \\ y &= r \cos(\theta) \\ r^2 &= y^2 + z^2 \end{aligned} \quad (4)$$

Based on the high-order tube theory (Zhang and Fu 2013), the variation of the external works (Hou *et al.* 2021, Huang *et al.* 2021b, Xu *et al.* 2021, Wang *et al.* 2022b), i.e.,  $\delta E$ , due to the rotation and blood flow, is defined as follows:

$$\begin{aligned} \delta E &= \int_V F^B dV \delta(w) + F^R \frac{\partial w}{\partial x} \Big|_0^L \delta(w) \\ &- \int_0^L \frac{\partial w}{\partial x} \left( F^R \frac{\partial w}{\partial x} \right) dx \delta(w) \end{aligned} \quad (5)$$

where ' $F^B$ ' is the blood flow force, and ' $F^R$ ' is the centrifugal force due to the rotation (Ma *et al.* 2021, Huang *et al.* 2021c, Liu *et al.* 2021c, Yu *et al.* 2022), which is defined as follows:

$$F^R = \int_x^L \int_A \rho \phi^2(x + \varsigma) dA dx \quad (6)$$

The external force due to the blood flow is defined according to the following harmonic equation (Zhao *et al.* 2021, Jiao *et al.* 2021, Moradi *et al.* 2021):

$$F^B = \bar{F} \sin(\omega t) \sin\left(\frac{n\pi x}{L}\right) \quad (7)$$

in which  $\bar{F}$  is the dynamic force of blood flow, and the  $\omega$  is the blood flow frequency or excitation frequency (Liu *et al.* 2020a, Wang *et al.* 2020b, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Wu and Habibi 2021). According to the Zhang and Fu (2013), the variation of the kinetic energy, i.e.,  $\delta K$ , due to the rotational effect, is written as:

$$\begin{aligned} \delta K &= \int_V \rho [\dot{u}_x \delta(\dot{u}_x) + \dot{u}_z \delta(\dot{u}_z)] dV = \\ &\int_0^L \{ m_0 [\dot{u} \delta(\dot{u}) + \dot{w} \delta(\dot{w})] \\ &+ m_1 \frac{\partial \dot{w}}{\partial x} \delta \left( \frac{\partial \dot{w}}{\partial x} \right) \\ &- m_2 \left[ \dot{\psi} \delta \left( \frac{\partial \dot{w}}{\partial x} \right) + \frac{\partial \dot{w}}{\partial x} \delta(\dot{\psi}) \right] \\ &+ 2 \frac{\partial \dot{w}}{\partial x} \delta \left( \frac{\partial \dot{w}}{\partial x} \right) \\ &+ m_3 \left[ \frac{\partial \dot{w}}{\partial x} \delta \left( \frac{\partial \dot{w}}{\partial x} \right) + (\dot{\psi}) \delta(\dot{\psi}) \right] \\ &\left. + \left[ \frac{\partial \dot{w}}{\partial x} \delta(\dot{\psi}) + \dot{\psi} \delta \left( \frac{\partial \dot{w}}{\partial x} \right) \right] \right\} dx \end{aligned} \quad (8)$$

in which

$$\begin{pmatrix} m_0 \\ m_1 \\ m_2 \\ m_3 \end{pmatrix} = \int \rho \begin{pmatrix} 1 \\ r^2 \sin^2(\theta) \\ r \bar{v} \sin(\theta) \\ \bar{v}^2 \end{pmatrix} r dr d\theta \quad (9)$$

Furthermore, the variation of the potential energy, i.e.,  $\delta P$ , with regarding the Ref. (Zhang and Fu 2013) is characterized as:

$$\begin{aligned} \delta P &= +T_{10} u_x \Big|_0^L \delta(u) + \int_0^L T_{22} w_{,xxxx} dx \delta(w) \\ &\quad + T_{22} w_{,xx} \Big|_0^L \delta(w_x) \\ &- T_{22} w_{,xxx} \Big|_0^L \delta(w) - \int_0^L T_{10} u_{,xx} dx \delta(u) \\ &\quad + \int_0^L T_{23} w_{,xxx} dx \delta(w) \\ &+ T_{23} w_{,xx} \Big|_0^L \delta(w_x) - T_{23} w_{,xxx} \Big|_0^L \delta(w) \\ &\quad - \int_0^L T_{23} \psi_{,xx} dx \delta(\psi) \\ &- \int_0^L T_{23} w_{,xxx} dx \delta(\psi) + T_{23} \psi_x \Big|_0^L \delta(\psi) \\ &\quad + T_{23} w_{,xx} \Big|_0^L \delta(\psi) \\ &+ \int_0^L T_{23} \psi_{,xxx} dx \delta(w) + T_{23} \psi_x \Big|_0^L \delta(w_x) \\ &\quad - T_{23} \psi_{,xx} \Big|_0^L \delta(w) \\ &- 2 \int_0^L T_{21} w_{,xxxx} dx \delta(w) - T_{22} w_{,xx} \Big|_0^L \delta(\psi) \\ &\quad - \int_0^L T_{21} \psi_{,xxx} dx \delta(w) \\ &- 2T_{21} w_{,xx} \Big|_0^L \delta \left( \frac{\partial w}{\partial x} \right) + 2T_{21} w_{,xxx} \Big|_0^L \delta(w) \\ &\quad + \int_0^L T_{21} w_{,xxx} dx \delta(\psi) \\ &- T_{21} \psi_x \Big|_0^L \delta(w_x) + T_{21} \psi_{,xx} \Big|_0^L \delta(w) \\ &\quad - \int_0^L T_{11} w_{,xx} dx \delta(w) \\ &+ T_{11} w_x \Big|_0^L \delta(w) + \int_0^L T_{11} \psi \delta(\psi) + T_{11} w_x \delta(\psi) dx \\ &- \int_0^L T_{11} \psi_{,x} dx \delta(w) + T_{11} \psi \Big|_0^L \delta(w) \end{aligned} \quad (10)$$

where

$$\begin{pmatrix} T_{10} \\ T_{11} \\ T_{21} \\ T_{22} \\ T_{23} \end{pmatrix} = \int E \left( \int_A K_s G \left( \left( \frac{\partial \bar{v}}{\partial y} \right)^2 + \left( \frac{\partial \bar{v}}{\partial z} \right)^2 \right) \right) \begin{pmatrix} \bar{v} r \sin(\theta) \\ r^2 \sin^2(\theta) \\ \bar{v}^2 \end{pmatrix} dA \quad (11)$$

in which  $G = 0.5E(1 + \nu)^{-1}$ , and also  $K_s$  is the shear correction factor (Ma *et al.* 2020). Upon the NSGT (Liu *et al.* 2020b, 2021b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Zhang *et al.* 2021), the constitutive relation between the stress field,  $\sigma_{ij}$  and strain field,  $\epsilon_{ij}$ , is (Lim *et al.* 2015):

$$\sigma_{ij} - (ea)^2 \frac{\partial^2 \sigma_{ij}}{\partial x^2} = \bar{C} \left( \varepsilon_{ij} - l^2 \frac{\partial^2 \varepsilon_{ij}}{\partial x^2} \right) \quad (12)$$

where ‘ $ea$ ’ is the nonlocality factor, ‘ $l$ ’ denotes the strain gradient parameter. Additionally,  $\bar{C}$  mentions the elastic modulus tensor (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b). By applying the NSGT, the governing equations together with essential boundary conditions are expressed as (Al-Furjan *et al.* 2020c, d, f, Bai *et al.* 2020, Li *et al.* 2020a, Zhang *et al.* 2020b, Guo *et al.* 2021b, Liu *et al.* 2021a):

$$\delta(u): T_{10}u_{,xx} - l^2 T_{10}u_{,xxxx} = m_0 \ddot{u} - (ea)^2 m_0 \ddot{u}_{,xx} \quad (13a)$$

$$\begin{aligned} \delta(\psi): & (T_{23} - T_{21})w_{,xxx} - l^2(T_{23} - T_{21})w_{,xxxxx} \\ & - T_{11}(w_{,x} + \psi) + l^2 T_{11}(\psi_{,xx} + w_{,xxx}) + T_{23}\psi_{,xx} \\ & - l^2 T_{23}\psi_{,xxxx} = (m_3 - m_2)_2 \ddot{w}_{,x} + m_3 \ddot{\psi} \\ & - (ea)^2(m_3 - m_2)\ddot{w}_{,xxx} - (ea)^2 m_3 \ddot{\psi}_{,xx} \end{aligned} \quad (13b)$$

$$\begin{aligned} \delta(w): & -l^2(T_{23} + T_{22} - 2T_{21})w_{,xxxxxx} + (ea)^2(F^R w_{,xxxxx}) \\ & (T_{23} + T_{22} - 2T_{21})w_{,xxxx} - T_{11}(w_{,xx} + \psi_{,x}) + F^B \\ & - F^{R'}w_{,x} - F^R w_{,xx} - l^2(T_{23} - T_{21})\psi_{,xxxxx} \\ & + (ea)^2(F^{R''}w_{,x} + 3F^{R''}w_{,xx} + 3F^{R'}w_{,xxx}) \\ & + (T_{23} - T_{21})\psi_{,xxx} - (ea)^2 F_B'' + l^2(T_{11}\psi_{,xxx}) \\ & + l^2(T_{11}w_{,xxxx}) = (m_3 - m_2)\ddot{\psi}_{,x} - m_0 \ddot{w} \\ & + (ea)^2(2m_2 - m_3 - m_1)\ddot{w}_{,xxx} + (ea)^2 m_0 \ddot{w}_{,xx} \\ & + (ea)^2(m_2 - m_3)\ddot{\psi}_{,xxx} + (m_3 + m_1 - 2m_2)\ddot{w}_{,xx} \end{aligned} \quad (13c)$$

Besides, the NSGT form of the boundary conditions are generated as follows (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):

$$\begin{aligned} \delta\left(\frac{\partial w}{\partial x}\right): & (T_{23} + T_{22} - 2T_{21})w_{,xx} \\ & + (T_{23} - T_{21})\psi_{,x} - (ea)^2(m_2 - m_3)\ddot{\psi}_{,x} \\ & - l^2\left((T_{23} + T_{22} - 2T_{21})w_{,xxxx} + (T_{23} - T_{21})\psi_{,xxx}\right) \\ & - (ea)^2\left((m_3 + m_1 - 2m_2)\ddot{w}_{,xx} - m_0 \ddot{w}_{,x}\right) = 0 \end{aligned} \quad (13d)$$

$$\begin{aligned} \delta(w): & -(T_{23} + T_{22} - 2T_{21})w_{,xxx} - (T_{23} - T_{21})\psi_{,xx} \\ & + B_{11}(\psi + w_{,x}) + N^R w_{,x} + (ea)^2(m_2 - m_3)\ddot{\psi}_{,x} \\ & l^2(T_{23} + T_{22} - 2T_{21})w_{,xxxxx} + l^2(T_{23} - T_{21})\psi_{,xxxxx} \\ & - l^2 B_{11}(\psi_{,xx} + w_{,xxx}) - (ea)^2(F^R w_{,x} + F^R w_{,xx}) \\ & - (ea)^2(m_3 + m_1 - 2m_2)\ddot{w}_{,xxx} + (ea)^2 m_0 \ddot{w}_{,x} = 0 \end{aligned} \quad (13e)$$

$$\begin{aligned} \delta(\psi): & l^2 T_{21}w_{,xxxx} - l^2 T_{23}(\psi_{,xxx} + w_{,xxxx}) + \\ & T_{23}(\psi_{,x} + w_{,xx}) - T_{21}w_{,xx} + (ea)^2 m_2 \ddot{w}_{,xx} \\ & - (ea)^2 m_3 \ddot{w}_{,xx} - (ea)^2 m_3 \ddot{\psi}_{,x} = 0 \end{aligned} \quad (13f)$$

$$\delta(u): T_{10}u_{,x} - l^2 T_{10}u_{,xxx} - (ea)^2 m_0 \ddot{u}_{,x} = 0 \quad (13g)$$

### 3. Solution

The generalized differential quadrature method (GDQM) is considered to discretize and solve the linear partial differential equations corresponded to the free

vibration of cantilever nanobeams and tubes under both rotation and blood flow effects (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, b, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b). After attaining the vibration frequencies and related mode shapes through the GDQM, through the Newmark-beta approach, the time-dependent response and traits of the system are calculated (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). Accordingly, at first, separation of variable method is considered to reintroduce the displacement field of the rotating cantilever nanobeams and nanotubes. Also, in this work, the external forces are neglected. (Wang and Gu 1997, Liu and Liew 1999):

$$\begin{pmatrix} w \\ \psi \\ u \end{pmatrix} = \begin{pmatrix} \bar{w} \\ \bar{\psi} \\ \bar{u} \end{pmatrix} \exp(i\omega t) \quad (14)$$

where ‘ $\omega$ ’ expresses the natural frequency.

Upon the GDQM definition (Wang and Gu 1997, Liu and Liew 1999): the  $r$ -th order derivative of a function as  $\psi(x)$  at a desire point as  $C_i$  can be approximated as:

$$\psi^{(r)}(\Omega_i) = \sum_{j=0}^n C_{ij}^{(r)} U_j \quad (15)$$

Now, by means of the Eqs. (14) and (15) together with governing equations, the discrete form of Eqs. (13) can be introduced as:

$$\begin{aligned} \delta(u): & T_{10} \sum_{s=1}^n C_{rs}^{(2)} u_s - l^2 T_{10} \sum_{s=1}^n C_{rs}^{(4)} u_s \\ & = \omega^2 m_0 u_s - (ea)^2 \omega^2 m_0 \sum_{s=1}^n C_{rs}^{(2)} u_s \end{aligned} \quad (16a)$$

$$\begin{aligned} \delta(w): & -l^2(T_{23} + T_{22} - 2T_{21}) \sum_{s=1}^n C_{rs}^{(6)} w_s \\ & (T_{23} + T_{22} - 2T_{21}) \sum_{s=1}^n C_{rs}^{(4)} w_s \\ & + (T_{23} - T_{21}) \sum_{s=1}^n C_{rs}^{(2)} \psi_s \\ & - T_{11} \left( \sum_{s=1}^n C_{rs}^{(2)} w_s + \sum_{s=1}^n C_{rs}^{(1)} \psi_s \right) + F^B \\ & + (ea)^2 \left( F^R \sum_{s=1}^n C_{rs}^{(4)} w_s \right) - F^{R'} \sum_{s=1}^n C_{rs}^{(1)} w_s \\ & - F^R \sum_{s=1}^n C_{rs}^{(2)} w_s - l^2(T_{23} - T_{21}) \sum_{s=1}^n C_{rs}^{(5)} \psi_s \\ & + l^2 T_{11} \sum_{s=1}^n C_{rs}^{(4)} w_s + l^2 T_{11} \sum_{s=1}^n C_{rs}^{(3)} \psi_s - (ea)^2 F_B' \\ & + (ea)^2 \left( F^{R''} \sum_{s=1}^n C_{rs}^{(1)} w_s + 3F^{R''} \sum_{s=1}^n C_{rs}^{(2)} w_s \right. \\ & \quad \left. + 3F^{R'} \sum_{s=1}^n C_{rs}^{(3)} w_s \right) \\ & = m_0 \omega^2 w_s + (m_2 - m_3) \omega^2 \sum_{s=1}^n C_{rs}^{(1)} \psi_s \end{aligned} \quad (16b)$$

$$\begin{aligned}
& +(ea)^2 m_0 \omega^2 \sum_{s=1}^n C_{rs}^{(2)} w_s \\
& +(ea)^2 (2m_2 - m_3 - m_1) \omega^2 \sum_{s=1}^n C_{rs}^{(4)} w_s \\
& -(ea)^2 (m_2 - m_3) \omega^2 \sum_{s=1}^n C_{rs}^{(3)} \psi_s \\
& -(m_3 + m_1 - 2m_2) \omega^2 \sum_{s=1}^n C_{rs}^{(2)} w_s \\
& \delta(\psi): (T_{23} - T_{21}) \sum_{s=1}^n C_{rs}^{(3)} w_s \\
& -l^2 (T_{23} - T_{21}) \sum_{s=1}^n C_{rs}^{(5)} w_s \\
& -T_{11} \left( \sum_{s=1}^n C_{rs}^{(1)} w_s + \psi_s \right) \\
& +l^2 T_{11} \left( \sum_{s=1}^n C_{rs}^{(2)} \psi_s + \sum_{s=1}^n C_{rs}^{(3)} w_s \right) \\
& +T_{23} \sum_{s=1}^n C_{rs}^{(2)} \psi_s - l^2 T_{23} \sum_{s=1}^n C_{rs}^{(4)} \psi_s \\
& = (m_3 - m_2) \omega^2 \sum_{s=1}^n C_{rs}^{(1)} w_s \\
& +m_3 \omega^2 \psi_s - (ea)^2 (m_3 - m_2) \omega^2 \sum_{s=1}^n C_{rs}^{(3)} w_s \\
& -(ea)^2 m_3 \omega^2 \sum_{s=1}^n C_{rs}^{(2)} \psi_s
\end{aligned} \tag{16c}$$

where  $n$  describes the number of sample points, and  $C$  is the weighting coefficient that is obtained for the  $r$ -th order derivative of a function as follows (Habibi *et al.* 2017, 2019b, Safarpour *et al.* 2018, 2020, Ghazanfari *et al.* 2020):

$$C_{ij}^{(r)} = r C_{ij}^{(1)} C_{ij}^{(r-1)} + r(x_j - x_i)^{-1} C_{ij}^{(r-1)} \tag{17a}$$

In which

$$C_{ij}^{(1)} = Y(x_j)^{-1} Y(x_i) (x_i - x_j)^{-1} \tag{17b}$$

$$Y(x_i) = \prod_{j=1, j \neq i}^n (x_i - x_j) \tag{17c}$$

Finally, to gain the system's characteristics, it is vital to rewrite the governing equations along with boundary conditions in matrix form as (Cao *et al.* 2022, Cheng *et al.* 2022, Wang *et al.* 2022a, Zhang *et al.* 2022a, Zhao *et al.* 2023):

$$\omega^2 \begin{Bmatrix} \lambda_d \\ \lambda_b \end{Bmatrix} = \begin{bmatrix} [K_{dd}] & [K_{db}] \\ [K_{bd}] & [K_{bb}] \end{bmatrix} \begin{bmatrix} [M_{dd}] & [M_{db}] \\ [M_{bd}] & [M_{bb}] \end{bmatrix}^{-1} \tag{18}$$

where  $\lambda_d$  and  $\lambda_b$  show the grid points at the domain and boundaries of the structure, respectively. By solving the simple eigenvalue problem as Eq. (18), the vibration frequencies and related mode shapes can be attained

(Habibi *et al.* 2018, 2019a, c, d, Pourjabari *et al.* 2019, Safarpour *et al.* 2019). Finally, using the Newmark-beta technique (Singh and Pal 2021), the time-dependent results will be calculated.

#### 4. Numerical results

Since the resonant frequency of an infected cell is higher than the resonant frequency of a health cell, nanocapsules are designed based on the frequency of these cells. Accordingly, it is vital to investigate the vibrational behavior of nanomotors. Therefore, to seek the impact of different factors on the drug-delivery traits of a nanomotor, the free and force vibration of a cantilevered nanotube is accomplished and several outcomes have been reported in detail. Firstly, to prove the integrity of the present formulation and results, Table 1 has been provided. Also, the following non-dimensional parameters are assumed as:

$$\begin{aligned} \text{Dimensionless deflection (Y):} \\ Y = -w \times 100\pi Q_{11} / TL^4 \end{aligned} \tag{19a}$$

$$\begin{aligned} \text{Nondimensional nonlocal parameter (\Delta):} \\ \Delta L = ea \end{aligned} \tag{19b}$$

$$\begin{aligned} \text{Nondimensional rotation speed (\Phi):} \\ \Phi^2 T_{10} = I_0 L^4 \phi^2 \end{aligned} \tag{19c}$$

$$\begin{aligned} \text{Nondimensional hub radius (\Gamma):} \\ \Gamma L = \varsigma \end{aligned} \tag{19d}$$

$$\begin{aligned} \text{Nondimensional frequency (\Omega):} \\ \Omega T_{10} = \omega^2 L^4 m_0 \end{aligned} \tag{19e}$$

$$\begin{aligned} \text{Nondimensional strain gradient parameter (\Xi):} \\ \Xi R_0 = l \end{aligned} \tag{19f}$$

Also, the sports impact parameter  $\theta$  is presented as:

$$\theta = \varpi / \omega \tag{19g}$$

$\Theta$  is the rate of excitation frequency of external work i.e. blood flow ( $\varpi$ ), to the natural frequency ( $\omega$ ) of the spinning nanoblade carrying nanomedicine. It should be noted that the increment of physical activities escalates the values of  $\varpi$  and  $\theta$ . Also, in state that  $\varpi = \omega$ , the nanomedicines are released to the target cells at the resonant frequency, i.e.,  $\theta = 1.0$ .

In Table 1, the first natural frequency ( $0.5\omega\pi L^2 \sqrt{m_0/T_{10}}$ ) of a cantilevered rotating nanotube have been derived and compared with the similar outcomes existing in Zhou (2022) for varied values of the rotational speed, nonlocality, and strain gradient parameter. Also, to produce this table, it is supposed that  $L = 20R_0$  and  $R_0 = 2R_i$ . Upon the Table 1, the outcomes of the current study have a good degree of accuracy with those available in Zhou (2022).

Fig. 2 is plotted to examine the variation of the dynamic deflection,  $Y$ , with respect to the time, to clear the influence of different values of the angular velocity,  $\Phi$ , and sports impact parameter,  $\theta$ . Also, it is supposed that  $L = 25R_0$

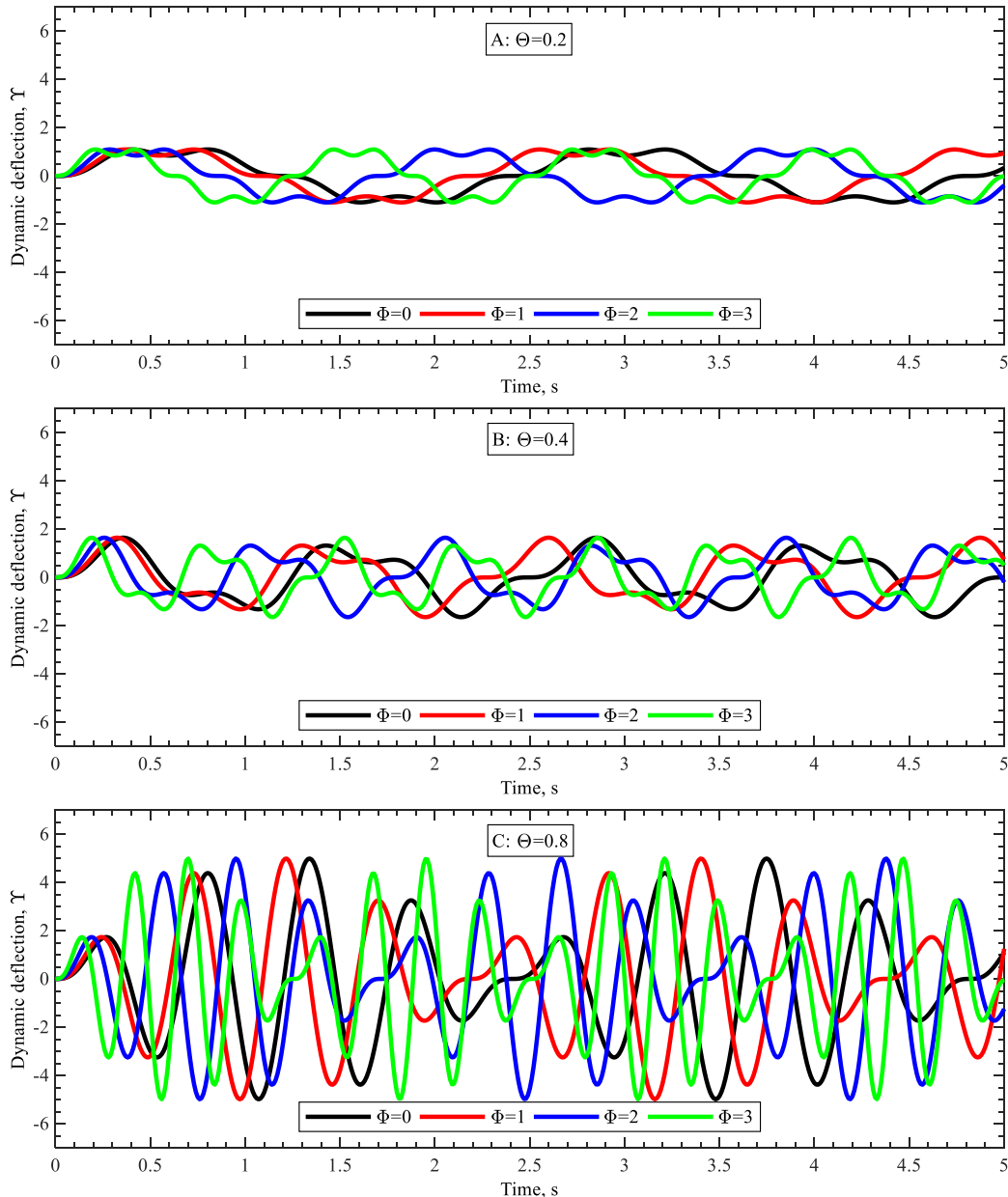


Fig. 2 Impact of angular velocity ( $\Phi$ ) on the dynamic response of the rotating nanoblade versus the physical activity parameter ( $\Theta$ ),  $L/25R_o$ ,  $R_o=2R_i$

and  $R_o = 2R_i$ . Comparing between the results in Fig. 2-a to Fig. 2-c disclose that increasing the values of  $\theta$  leads to enlarge the maximum values of  $Y$  while  $\Phi$  has no role on the change of the one. Also, from each part of this figure it can be found that increasing the values of  $\Phi$  leads to increase the system's period, that is, intensifying the  $\Phi$  has softening effect on the vibration characteristics of the system. Additionally,  $\theta$  has no impact on the variation of the system's period.

Fig. 3 compares the effects of the sports impact parameter,  $\theta$ , together with nonlocality factor,  $\Delta$ , on the dynamic deflection,  $Y$ , with respect to the time. To this end, it is considered that  $\Phi = 1.0, L = 20R_o$  and  $R_o = 3R_i$ . Regarding the Fig. 3(a) to Fig. 3(c), it can be realized that intensifying the nonlocality, i.e. increasing the  $\Delta$ , causes

increase the system's period, similar to the impact of  $\Phi$ , and without any change in the maximum values of  $Y$ . In other words,  $\Delta$  has softening effect on the vibration frequencies and leads to decrease the bending rigidity to mass ratio of the system. Also,  $\theta$  has a major role in growing or declining the the maximum values of  $Y$ , however, it has no role on the changes of system's period. Also, as a result of increasing the  $\theta$ , the resonant phenomena happens sooner.

Fig. 4 illustrates the role of the hub radius,  $\Gamma$ , on the dynamic deflection,  $Y$ , with respect to the time and for three different values of the sports impact parameter,  $\theta$ . Accordingly, it is assumed that  $\Delta = 0.1$ ,  $\Phi = 1.0, L = 20R_o$  and  $R_o = 3R_i$ . This figure revealed that rising the  $\Gamma$  has increasing effect on the period of the system, and without any change in the maximum values of  $Y$ .

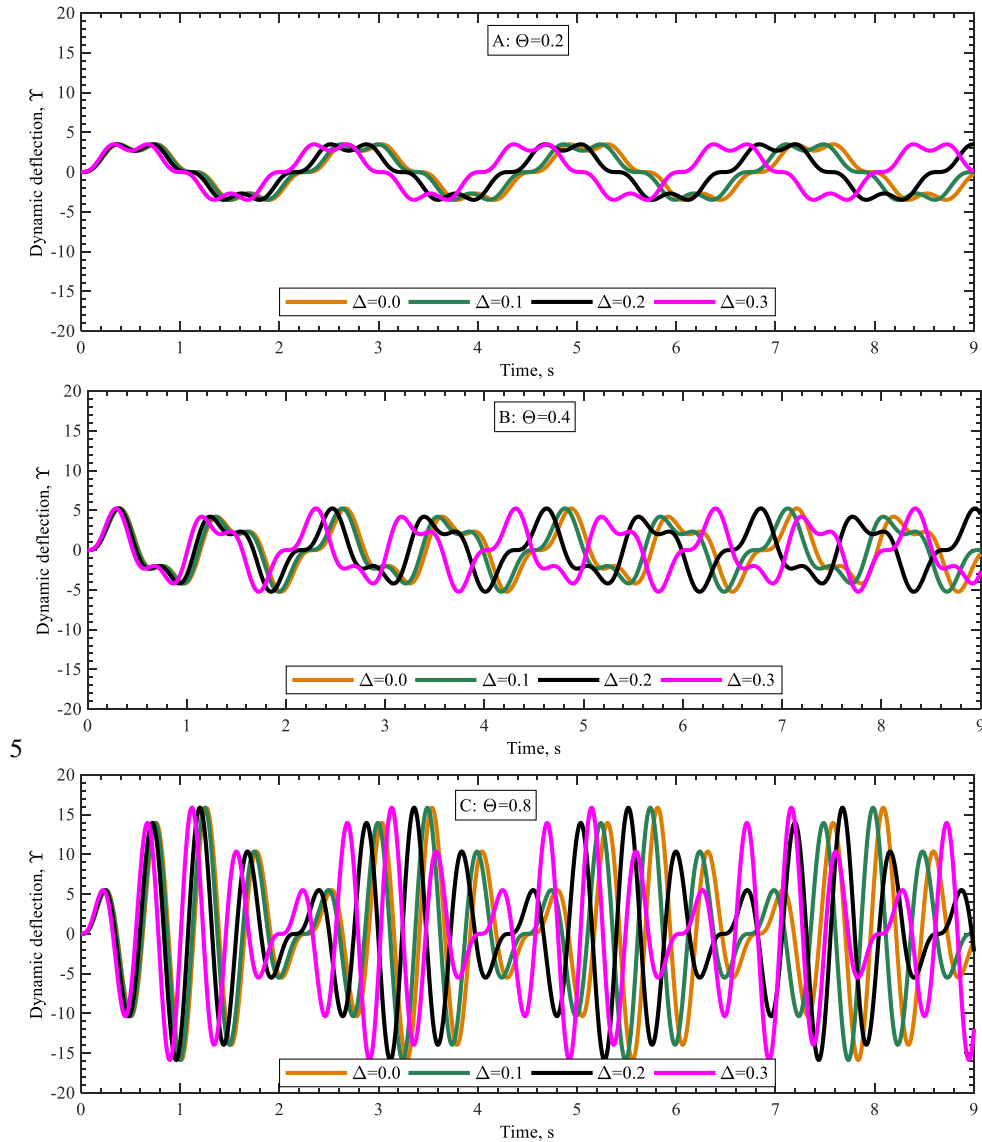


Fig. 3 Influence of nonlocal parameters ( $\Delta$ ) on the dynamic deflection of the spinning nanoblade for different physical activity parameters ( $\Theta$ ),  $\Phi=1$ ,  $L/20R_0$ ,  $R_0=3R_i$

Table 1 Comparison between the fundamental natural frequency of a rotating nanotube with the outcomes of Zhou (2022)

	Zhou (2022)				Present study			
	$\Phi=0$	$\Phi=1$	$\Phi=2$	$\Phi=3$	$\Phi=0$	$\Phi=1$	$\Phi=2$	$\Phi=3$
$'(ea)^2/L'=0$	5.45706	5.71711	6.43123	7.46259	5.457604	5.717686	6.431871	7.463336
$'(ea)^2/L'=0.2$	5.46137	5.72445	6.44621	7.48738	5.461918	5.725024	6.446855	7.488132
$'(ea)^2/L'=0.4$	5.47444	5.74664	6.49144	7.5622	5.474984	5.747213	6.492084	7.562959
$'(ea)^2/L'=0.6$	5.49663	5.78421	6.56777	7.68842	5.497182	5.784784	6.568425	7.689189
$'(ea)^2/L'=0.8$	5.52863	5.83811	6.67677	7.86848	5.529186	5.838693	6.677435	7.869263
$'(ea)^2/L'=1.0$	5.57148	5.90983	6.82089	8.10618	5.57204	5.910419	6.821572	8.106993
$'l^2/L'=0.0$	5.46381	5.72859	6.45466	7.50136	5.464354	5.729165	6.455303	7.502111
$'l^2/L'=0.1$	5.45551	5.71993	6.44498	7.49024	5.456057	5.720497	6.445628	7.490992
$'l^2/L'=0.2$	5.43061	5.69412	6.41663	7.45807	5.431156	5.694686	6.417275	7.458815
$'l^2/L'=0.3$	5.39031	5.65158	6.3719	7.40856	5.390845	5.652143	6.372541	7.409297
$'l^2/L'=0.4$	5.31134	5.60528	6.28221	7.33277	5.311871	5.605845	6.282836	7.333507
$'l^2/L'=0.5$	4.3033	4.51511	4.84725	5.54251	4.303726	4.515566	4.847734	5.543064

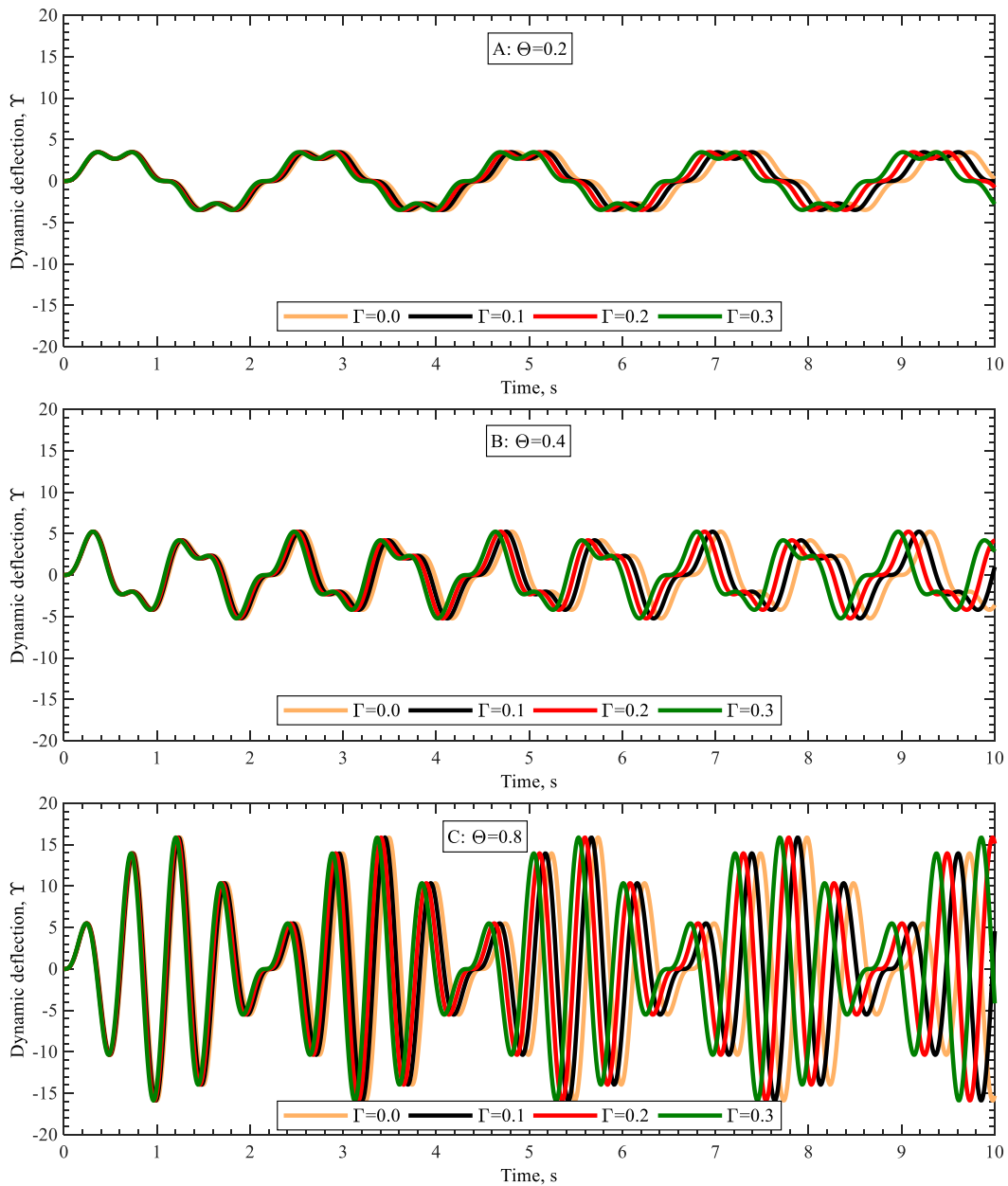


Fig. 4 Effect of hub radius ( $\Gamma$ ) on the dynamic deflection of the rotating nanoblade carrying the nanomedicine when the different exercise intensities ( $\Theta$ ) are applied,  $\Delta=0.1$ ,  $\Phi=1$ ,  $L/20R_o$ ,  $R_o=3R_i$

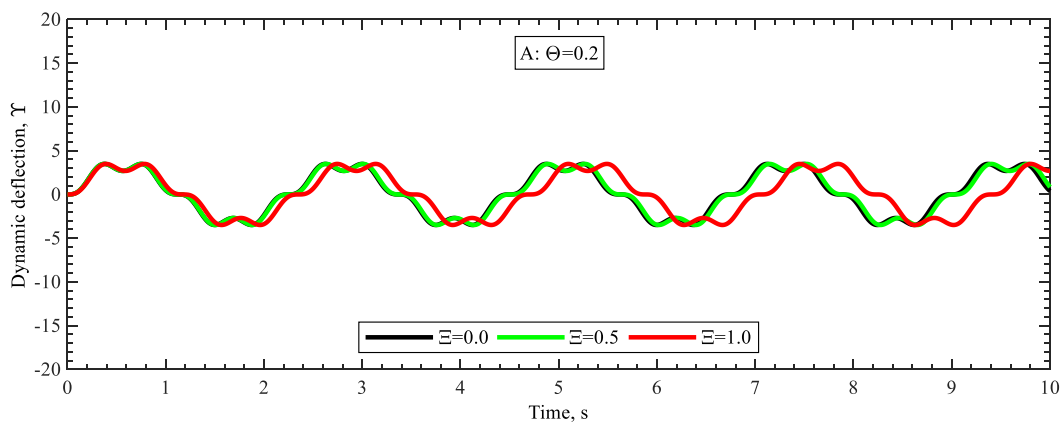


Fig. 5 Impact of strain gradient parameter ( $\Xi$ ) on the dynamic response of the stability of drug-delivery mechanism regarding the different sport intensifies parameter ( $\Theta$ ),  $\Gamma=0.1$ ,  $\Delta=0.1$ ,  $\Phi=1$ ,  $L/20R_o$ ,  $R_o=3R_i$

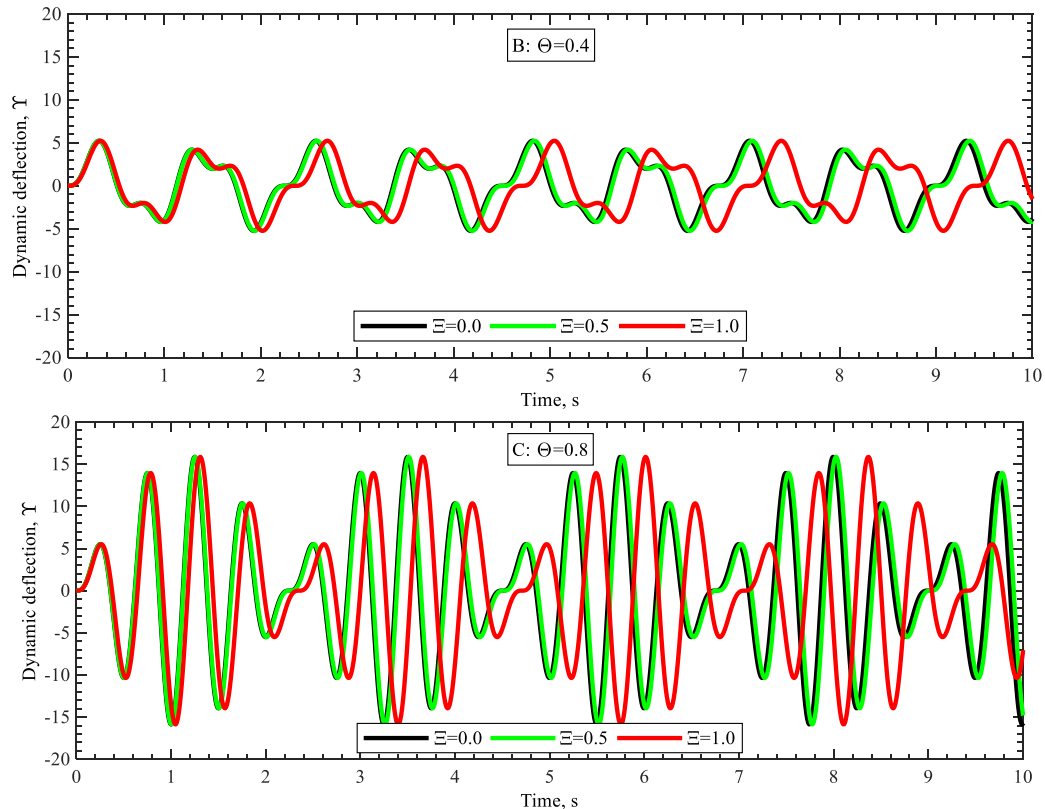


Fig. 5 Continued

In Fig. 5, the influence of the strain gradient parameter,  $\mathcal{E}$ , on the dynamic deflection,  $Y$ , of the rotating nanoblade carrying the nanomedicine has been explored. Additionally, the constant parameters regarded to introduce this figure are:  $\Delta = \Gamma = 0.1$ ,  $\Phi = 1.0$ ,  $L = 20R_0$  and  $R_0 = 3R_i$ . Despite the results corresponded to the role of the parameters such as  $\Delta$ ,  $\Gamma$ , and  $\Phi$ , intensifying the  $\mathcal{E}$  leads to the decrease of the system's period, that is, this parameter leads to happen the hardening effect on the nanosystem with enlarging the bending rigidity to mass ratio. Consequently, reduction in the system's period causes growth in the system's frequency.

## 5. Conclusions

In the current research, the dynamic response of a rotating nanotube, which can be assumed as nanomotor's blade, was explored. Nanotube was modeled by means of the higher-order tube theory together with NSGT, with both of softening and hardening effects. The boundary conditions along with the governing equations were derived upon the Hamilton's principle. Through the GDQM, the discrete form of all relations were obtained. After analogical study, the impact of several parameters on the mechanical behavior of the nanosystem were investigated. Finally, the following key points were concluded:

1- Variation of the sports impact parameter, i.e., has a great impact on the the values of  $Y$ , however, it has no impact on the variation of the system's period.

2- Escalation of the  $\Theta$  leads to happen the resonant phenomena sooner.

3- Increasing the angular velocity, i.e., intensifies the softening effect through the reduction of bending rigidity to mass ratio and leads to increase the system's period.

4- Reducing the nonlocality, i.e., or hub radius, i.e., has reduction impact on the period of the system, and without any change in the values of  $Y$ . In other words, these parameters have softening effect on the characteristics of the system.

5- Escalation of the strain gradient parameter, i.e., has a reduction impact on the system's period, that is, it increases the bending rigidity to mass ratio of the system.

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