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Geometry effect in the drug delivery for therapy with nanomedicines based on the conditions of the sport

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Abstract. This study investigates the geometrical impact on the nanomedicine drug delivery via nanodevices. A nanomotor made of the nanotube carrying the drug as the motor blade is considered in the blood flow. Physical activities change the blood flow, and sports training enhances the blood flow and plays a significant role in the stability of drug delivery devices. This paper studies the impact of geometrical parameters on the nanomotors carrying the nanomedicine. The effect of physical exercise on the dynamic response regarding the stability of drug delivery devices is discussed in detail.

Keywords: drug delivery; dynamic analysis; geometric impact; sport effect

1. Introduction

The use of nanodevices in bioengineering has become the center of attention due to the capabilities of these small-scale structures (Ji *et al*. 2020, Yan *et al*. 2020, Lai *et al*. 2021, Obireddy and Lai 2021a, b, Luo *et al*. 2022). One of many uses of these devices, drug delivery, has grown attention since it can be more effective and cause less general toxicity (Al-Furjan *et al*. 2020c, d, f, Bai *et al*. 2020, Li *et al*. 2020a, Zhang *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a). With this in mind, the significant fact that should be considered is that the mechanical behavior of these nanodevices should be explored to design and manufacture more efficient devices (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). To investigate the small-size structures, the vital fact that should be taken into account is that the common elasticity theories cannot help demonstrate the size impact (Behdad *et al*. 2021). Thus, some size-dependent theories such as nonlocal elasticity (Eringen and Wegner 2003), modified couple stress (Ma *et al*. 2008), strain gradient theory (Lim *et al*. 2015), and two-phase elasticity (Naderi *et al*. 2021) were developed with the aid of which it is possible to design nano and microdevices (Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Oyarhossein *et al*. 2020, Shariati *et al*. 2020b).

Among the abovementioned theories, nonlocal elasticity (Ebrahimi *et al*. 2019b, c, 2020b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Shariati *et al*. 2020a, Shokrgozar *et al*. 2020), which explains that the stress in a point of an object is resulted from the strain of the whole domain and not that specific point, has been the leading theory for investigating such structures as beams (Habibi *et al*. 2017, 2019c, Ghazanfari *et al*. 2020, Safarpour *et al*. 2018, 2020), shells (Habibi *et al*. 2019a, Safarpour *et al*. 2019b, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Chen *et al*. 2022), plates (Habibi *et al*. 2018a, 2019b, d, e, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a), rods (Habibi *et al*. 2016, 2018b, 2019a, Esmailpoor Hajilak *et al*. 2019), etc. One of the works in which this theory was employed to model single- along with multi-walled nanotubes to investigate their wave propagation as well as vibration. The displacement field in the abovementioned paper was Euler-Bernoulli (Lu *et al*. 2007). Using different types of beam theories and nonlocal elasticity, Aydogdu (2009) presented research on the buckling, bending, and vibration of nanobeams. Also, the vibrational analysis related to nanobeams made of FG piezo-magnetoelectric material, which are under thermal loading, was carried out in the framework of nonlocal theory (Ebrahimi and Barati 2016). By incorporating the Timoshenko beam theory and nonlocal elasticity, the nonlinear vibration of piezoelectric nanobeams was investigated utilizing DQM as the solution procedure (Ke *et al*. 2012). Şimşek (2011) compared the foced vibration response of a nanotube modeled with classic theory and nonlocal theory using the Newmark method. the nanotube was subjected to moving nanoparticle in the aforementioned paper. Additionally, the axial vibration analysis corresponded to nanotubes based on nonlocal elasticity was presented (Filiz and Aydogdu 2010). By employing Mindlin plate theory in addition to nonlocal elasticity, the vibration of a graphene plate was conducted with the aid of DQM (Ansari *et al*. 2010). Shen *et al*. (2010) managed to present a study on the nonlinear vibration of nonlocal plates based on Von Karmen's theory. The plate in the article mentioned above was subjected to thermal loads, and its end conditions were all simply-supported.

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Additionally, by using the first-order shear deformation theory as well as variational differential quadrature solution procedure, the vibration characteristics of nanotubes was analyzed (Ansari *et al*. 2018). Ansari and Torabi (2016) explored the vibration of carbon nanocores which are placed inside a two-parameter medium using nonlocal elasticity and first-order shear deformation theory.

Nanotubes are one of the most functional nanostructures in various areas of engineering, specially bio-engineering. Diverse characteristics of this structure, such as vibration (Garcia-Sanchez *et al*. 2007), buckling (Zbib *et al*. 2008, Wang *et al*. 2010), wave-propagation (Yoon *et al*. 2003), and static bending (Ru 2000), have been explored. Given this, the paper in which the vibration analysis of a two-layered nanotube was investigated can be cited (Xu *et al*. 2006). In this paper, the nonlinear van der Waals forces between the layers were considered. Also, in another paper, the different geometrical factors that can affect the axial vibration of carbon nanotubes modeled via nonlocal elasticity were examined (Aydogdu and Filiz 2011). By utilizing nonlocal elasticity, Murmu and Pradhan (2009) carried out a study on the vibrational behavior of single-walled nanotubes, which are affected by thermal loading and are embedded in an elastic foundation. Additionally, the dynamic stability along with vibration related to a carbon nanotube, which is affected by a three-dimensional magnetic field, were investigated (Kiani 2014). The equations of motion in the paper, as mentioned above, were obtained utilizing Rayleigh and nonlocal theory. By employing Euler–Bernoulli beam theory as well as nonlocal elasticity, the vibration of a nanotube made of carbon under harmonic load was investigated (Şimşek 2010).

The vibration in addition dynamics of devices can affect their efficiency and behavior. Thus, exploring the mentioned behaviors of structures, specifically in the nanoscale, is essential (Naderi *et al*. 2020). In this area of research, it can refer to a paper by Habibi *et al*. (2021b) in which they investigated the vibration along with buckling of a nanoshell made of reinforced composites through GDQM. Also, the dynamic stability associated with a cylindrical nanoshell with two layers, the base of which was reinforced composite with graphenes, and the outer layer was piezoelectric, was conducted (Habibi *et al*. 2019e). In addition, the vibration and thermal buckling related to nanobeams were studied by GDQM and the analytical solution procedure (Fakher *et al*. 2020). In this article, the effect of size-dependency on the thermal load was shown. By utilizing nonlocal elasticity and Mindlin plate theory, the vibration analysis of a magnetoelectric nanoplate was conducted by Li *et al*. (2014). The impact of nonlocal parameter on the vibration of a nanoplate made of piezoelectric material, which is resting on an elastic foundation and under initial stress, was explored (Asemi *et al*. 2014).

The presented study investigates nanomotors' vibrational and dynamic behavior used as a drug delivery system. The nanomotor is considered a nanotube that is rotating around the normal axis and modeled via nonlocal elasticity. The formulation and boundary conditions of the problem are acquired by the varational energy method. Then, the displacement domain is discretized using GDQM, and the time-dependent part is solved with the help of the Newmark method. The validation study is presented to demonstrate the accuracy and reliability of the results. Additionally, the impact of different factors such as hub radius ratio, the intensity of sports activities, nonlocal parameters, blade radius aspect ratio, as well as rotation speed on the vibrational behavior of the nanomotor is conducted.

2. Mathematical simulation of drug-delivery mechanism

A nanomotor carrying drug is considered through the bloodstream according to Fig. 1. A rotating system made of a nanotube as the drug capsule is considered, that the 'Ri' is the internal value of the radius, 'Re' is the external radius, and 'L' is the capsule length. The tube capsule is spun around the central motor through the bloodstream, and the bloodstream impacts the nanosystem via an external bending load. Since sport and exercise improve and enhances the bloodstream, this factor can play a significant role in the stability of the nanosystems and nanomotors (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020b, Zare *et al*. 2020, Dai *et al*. 2021b).

2.1 Generation of motion equations

According to the classical beam theory, the following displacement fields along the x-axis (u_x), y-axis (u_y), and z-axis (u_z) are assumed for the mathematical simulation of nanomotors (Liu *et al*. 2020b, Habibi *et al*. 2021a, He *et al*. 2021, Huang *et al*. 2021a, Liu *et al*. 2021b, Zhang *et al*. 2021).

$$u_x = -zw'(t,x) + u(t,x) \tag{1a}$$

$$u_y = 0 \tag{1b}$$

$$u_z = w(t,x) \tag{1c}$$

where 'u' and 'w' are the axial and lateral movements. Furthermore, the following assumptions have been used for the circular direction instead of the cartesian system (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).

$$r^2 = y^2 + z^2 \tag{2a}$$

$$z = r\sin(\theta) \tag{2b}$$

$$y = r\cos(\theta) \tag{2c}$$

Based on the classical displacement fields, the strains (ε) and stresses (σ) are defined as follows (Zhao *et al*. 2021, Huang *et al*. 2021b, Jiao *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021).

$$\varepsilon_{xx} = u_{x,x} = u_{,x} - zw_{,xx} \tag{3a}$$

$$\begin{aligned} &\varepsilon_{xy} = \varepsilon_{yx} = \varepsilon_{xz} = \varepsilon_{zx} = \\ &\varepsilon_{zy} = \varepsilon_{yz} = \varepsilon_{zz} = \varepsilon_{yy} = 0 \end{aligned} \tag{3b}$$

where stresses are

$$\sigma_{xx} = E\,\varepsilon_{xx} \tag{3c}$$

'E' is Young's modulus. The virtual strain energy (S) is defined as follows (Ma *et al*. 2021, Hou *et al*. 2021, Huang *et al*. 2021c, Liu *et al*. 2021c, Yu *et al*. 2022):

$$\begin{aligned} \delta S &= \iiint \delta s dv = -\int_0^L \frac{\partial}{\partial x}\left(A_{11}\frac{\partial u}{\partial x}\right)dx\,\delta(u) \\ &+ A_{11}\frac{\partial u}{\partial x}\bigg|_0^L \delta(u) + \int_0^L \frac{\partial^2}{\partial x^2}\left(D_{11}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(w) \\ &+ D_{11}\frac{\partial^2 w}{\partial x^2}\bigg|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - \frac{\partial}{\partial x}\left(D_{11}\frac{\partial^2 w}{\partial x^2}\right)\bigg|_0^L \delta(w) \end{aligned} \tag{4}$$

where

$$\left(A_{11}, D_{11}\right) = \int_A E\left(1, r^2\sin^2(\theta)\right)dA \tag{5}$$

Moreover, the virtual Kinetic energy (K) of the cylindrical tube is obtained as follows (Shafiei and She 2018, Shafiei *et al*. 2019, 2020):

$$\begin{aligned} &\delta K = \int_V \rho\dot{u}_x\,\delta(\dot{u}_x)\,dV = \\ &\int_0^L m_0\left(\dot{u}\,\delta(\dot{u}) + \dot{w}\,\delta(\dot{w})\right) + m_2\dot{w}_{,x}\,\delta\left(\dot{w}_{,x}\right)\,dx \end{aligned} \tag{6}$$

where

$$\left(m_0, m_2\right) = \int_A \rho\left(1, r^2\sin^2(\theta)\right)dA \tag{7}$$

Furthermore, the virtual energy of external forces (EF) due to the rotation of the tube (N^R) and the external load regarding the bloodstream (N^{BS}) are considered as follows:

$$\begin{aligned} &\delta EF = \int_V N^{BS}\,dV\;\;\delta(w) \\ &-\int_0^L \frac{\partial}{\partial x}\left(N^R\frac{\partial w}{\partial x}\right)dx\,\delta(w) + N^R\frac{\partial w}{\partial x}\bigg|_0^L \delta(w) \end{aligned} \tag{8}$$

where

$$N^R = \int_x^L \int_A \rho\phi^2\left(\lambda + x\right)dA\,dx \tag{9a}$$

where 'ϕ' is the rotation speed, and 'λ' is hub radius (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018).

$$N^{BS} = F_{BS}\sin(\psi t)\sin\left(\pi\frac{n}{L}x\right) \tag{9b}$$

where 'FBS' is the bending dynamic load concerning the bloodstream, and 'ψ' is the external frequency of the bloodstream. Then, utilizing the nonlocal Eringen theory, the following nonlocal governing equations and related boundary conditions will be obtained (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b, Shafiei *et al*. 2017c).

$$A_{11}\frac{\partial^2 u}{\partial x^2} = m_0\frac{\partial^2 u}{\partial t^2} - (ea)^2\,m_0\frac{\partial^4 u}{\partial x^2\partial t^2} \tag{10a}$$

$$\begin{aligned} &D_{11}\frac{\partial^4 w}{\partial x^4} + N^{BS} - (ea)^2\frac{d^2N^{BS}}{dx^2} - \frac{dN^R}{dx}\frac{\partial w}{\partial x} \\ &+(ea)^2\begin{pmatrix} \dfrac{d^3N^R}{dx^3}\dfrac{\partial w}{\partial x} + N^R\dfrac{\partial^4 w}{\partial x^4} \\ +3\dfrac{d^2N^R}{dx^2}\dfrac{\partial^2 w}{\partial x^2} + 3\dfrac{dN^R}{dx}\dfrac{\partial^3 w}{\partial x^3} \end{pmatrix} \\ &-N^R\frac{\partial^2 w}{\partial x^2} = m_2\frac{\partial^4 w}{\partial t^2\partial x^2} - m_0\frac{\partial^2 w}{\partial t^2} \\ &-(ea)^2\left(m_2\frac{\partial^6 w}{\partial x^4\partial t^2} - m_0\frac{\partial^4 w}{\partial x^2\partial t^2}\right) \end{aligned} \tag{10b}$$

Boundary conditions:

$$\delta(u): A_{11}\frac{\partial u}{\partial x} - (ea)^2\,m_0\frac{\partial^3 u}{\partial x\,\partial t^2} = 0 \tag{10c}$$

$$\begin{aligned} &\delta(w): -D_{11}\frac{\partial^3 w}{\partial x^3} + N^R\frac{\partial w}{\partial x} - (ea)^2\frac{dN^R}{dx}\frac{\partial w}{\partial x} \\ &-(ea)^2\left(N^R\frac{\partial^2 w}{\partial x^2} + m_2\frac{\partial^5 w}{\partial x^3\partial t^2} - m_0\frac{\partial^3 w}{\partial x\,\partial t^2}\right) = 0 \end{aligned} \tag{10d}$$

$$\delta\left(\frac{\partial w}{\partial x}\right): D_{11}\frac{\partial^2 w}{\partial x^2} - (ea)^2\left(m_2\frac{\partial^4 w}{\partial x^2\partial t^2} - m_0\frac{\partial^3 w}{\partial x\,\partial t^2}\right) = 0 \tag{10e}$$

where '*ea*' is the nonlocal parameter regarding the Eringen's nonlocal theory.

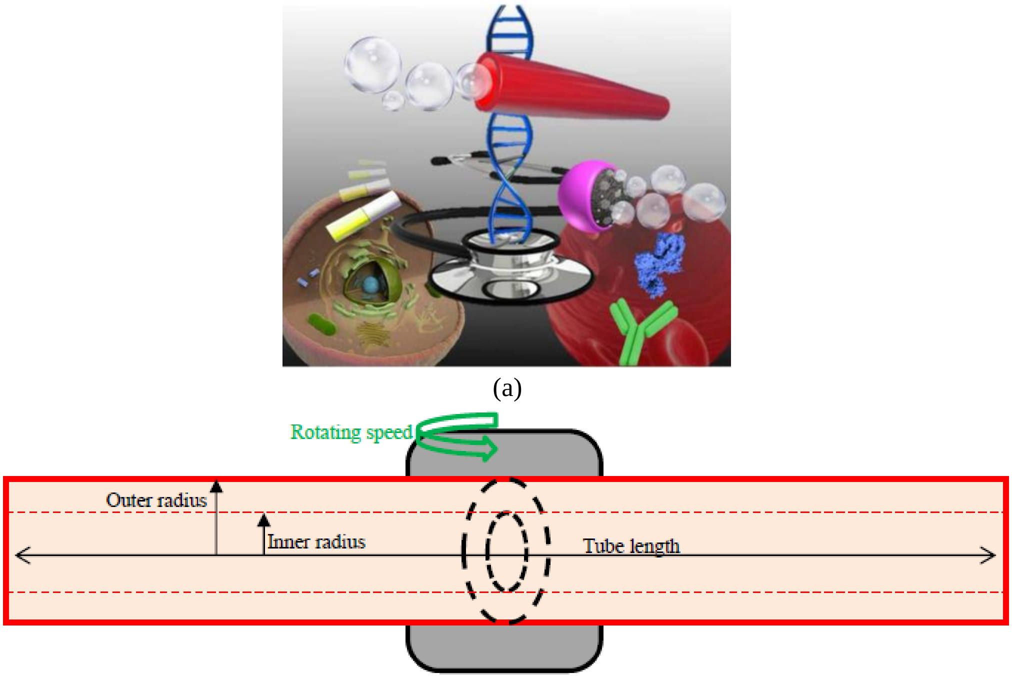
2.2 The strategy of solution method

The generalized differential quadrature method (GDQM) is operated to solve linear ordinary differential equations (ODE) for free vibration of the spinning cantilever nanotubes (Ghadiri *et al*. 2017a, b, Mirjavadi *et al*. 2017b, c, Shafiei *et al*. 2017a, b). Then using the free obtained frequencies of the GDQM, the time-dependent and forced vibration frequencies results are calculated with the Newmark-beta method (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016d, Shafiei *et al*. 2016c, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017). So, first, we explain the GDQM to find the free vibration of rotating cantilever beams and tubes. The following assumptions have been made.

$$u = \bar{u}\exp(i\,\omega t) \tag{11a}$$

$$w = \bar{w}\exp(i\,\omega t) \tag{11b}$$

'ω' is the natural frequency. Then applying the GDQM according to the modal analysis, the following equation will be obtained (Azimi *et al*. 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al*. 2016a, e, g):


(a)

(b)

Fig. 1 (a) A schematic of a nanomotor carrying the drug (Chałupniak *et al*. 2015), (b): The considered nanomotor as the drug-delivery system in this paper

$$\omega^2 = \frac{\begin{bmatrix} [K_{dd}] & [K_{db}] \\ [K_{bd}] & [K_{bb}] \end{bmatrix}}{\begin{bmatrix} [M_{dd}] & [M_{db}] \\ [M_{bd}] & [M_{bb}] \end{bmatrix}} \begin{Bmatrix} \{\gamma_d\} \\ \{\gamma_b\} \end{Bmatrix} \tag{12}$$

'γ' is the mode shape, and $()_b$ and $()_d$ indicate the boundary and domain equations. Also, based on the governing equations of a nanomotor (Eq. (10)), the following matrices will be defined (Ghadiri *et al*. 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al*. 2016b).

$$\begin{aligned}
[K] = {} & N^{BS} - \left(ea^2\right)\frac{d^2N^{BS}}{dx^2} \\
& + \begin{bmatrix} A_{11}\sum_{s=1}^{n} C_{rs}^{(2)} & 0 \\ 0 & D_{11}\sum_{s=1}^{n} C_{rs}^{(2)} \end{bmatrix} + \\
& - \begin{bmatrix} 0 & 0 \\ 0 & \frac{dN^R}{dx}\sum_{s=1}^{n} C_{rs}^{(1)} + N^R\sum_{s=1}^{n} C_{rs}^{(2)} \end{bmatrix} + \\
& \left(ea^2\right)\begin{bmatrix} 0 & 0 \\ 0 & \frac{d^3N^R}{dx^3}\sum_{s=1}^{n} C_{rs}^{(1)} + N^R\sum_{s=1}^{n} C_{rs}^{(4)} \end{bmatrix} + \\
& \left(ea^2\right)3\begin{bmatrix} 0 & 0 \\ 0 & \frac{d^2N^R}{dx^2}\sum_{s=1}^{n} C_{rs}^{(2)} + \frac{dN^R}{dx}\sum_{s=1}^{n} C_{rs}^{(3)} \end{bmatrix}
\end{aligned} \tag{13a}$$

Table 1 The comparison of presented dimensional frequency (φ) of a nonlocal classic cantilever beam with the published results of Lu *et al*. (2006)

	Present study	Lu *et al*. (2006)
ea=0.0	1.8769751	1.8751
ea=0.1L	1.8810792	1.8792
ea=0.2L	1.8937919	1.8919
ea=0.3L	1.9173154	1.9154
ea=0.4L	1.9562543	1.9543
ea=0.5L	2.0239219	2.0219

$$\begin{aligned}
[M] = {} & -(ea)^2\begin{bmatrix} 0 & 0 \\ 0 & \left(m_2\sum_{s=1}^{n} C_{rs}^{(4)} - m_0\sum_{s=1}^{n} C_{rs}^{(2)}\right) \end{bmatrix} \\
& + \begin{bmatrix} m_0 - (ea)^2\, m_0\sum_{s=1}^{n} C_{rs}^{(2)} & 0 \\ 0 & m_2\sum_{s=1}^{n} C_{rs}^{(2)} - m_0 \end{bmatrix}
\end{aligned} \tag{13b}$$

Finally, using the Newmark-beta technique (Singh and Pal 2021), the time-dependent results will be calculated.

3. Results and discussion

Micro/nanomotors, due to their self-propelled feature, are one of the most famous devices for delivering cargo. It was shown that these devices could be beneficial for tumor-targeting delivery, as they can diminish systemic toxicity

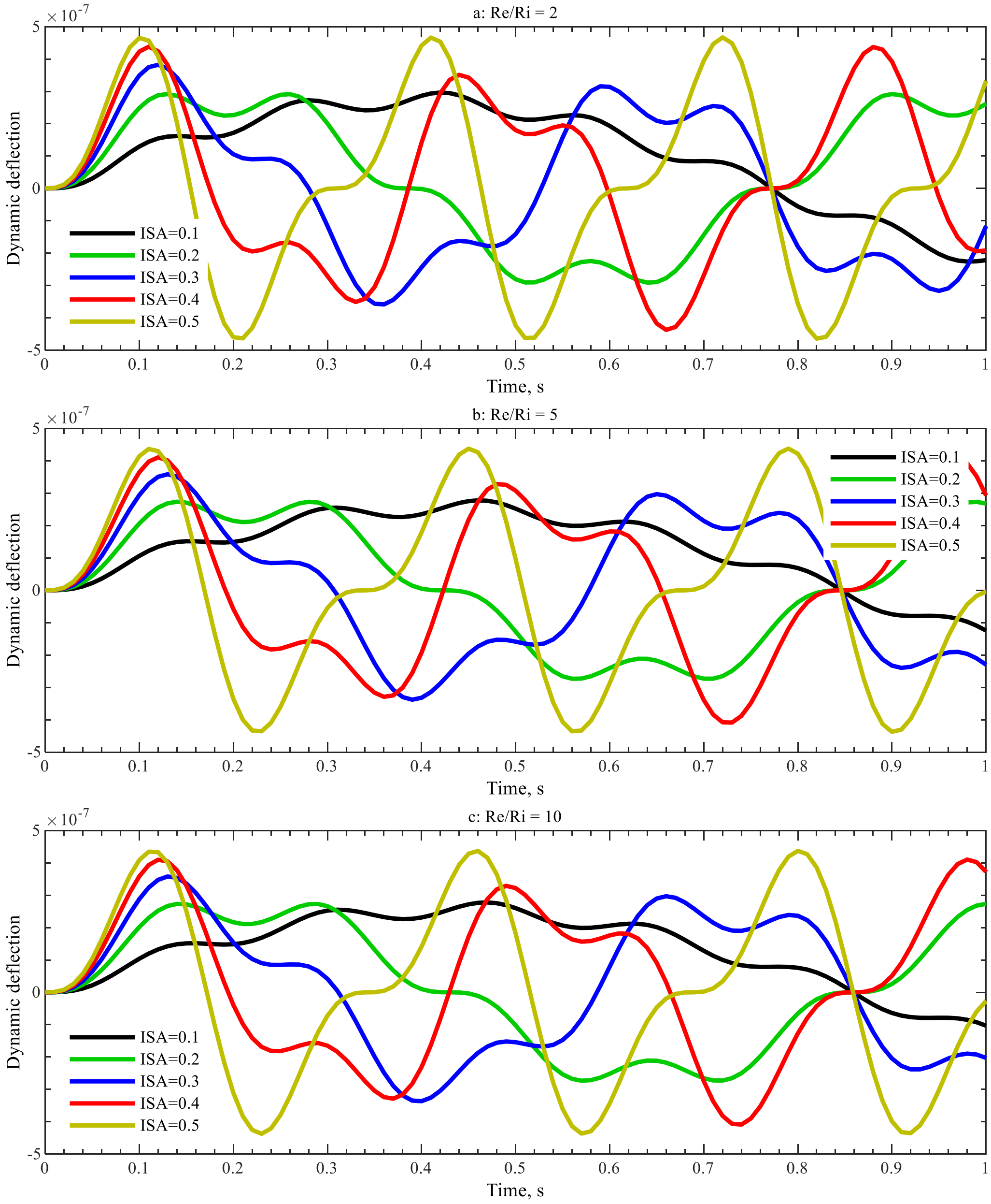


Fig. 3 Dynamic deflection of the nanomotor blade versus the intensities of sports activities (ISA) parameter as well as blade radius aspect ratio (Re/Ri), L/R=50

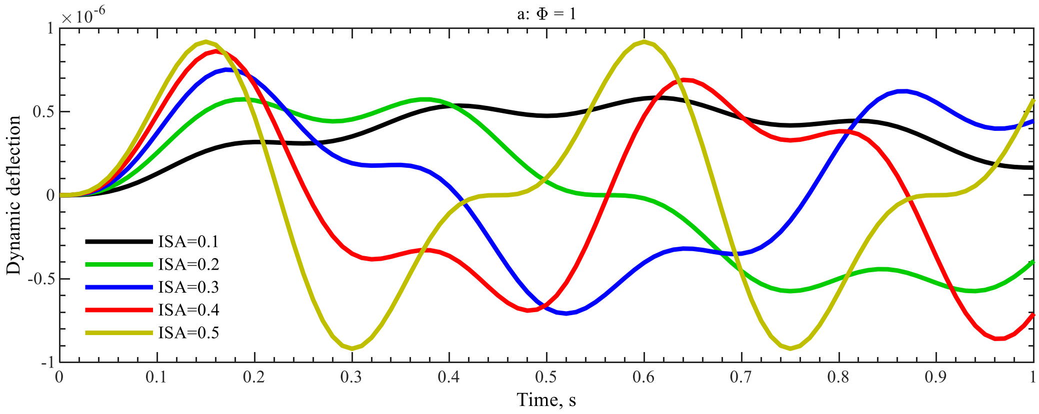


Fig. 4 Impact of rotation speed (Φ) on the dynamic deflection of spinning nanomotor blade for different intensity of exercise activities (ISA), L/R=60, Re/Ri=3

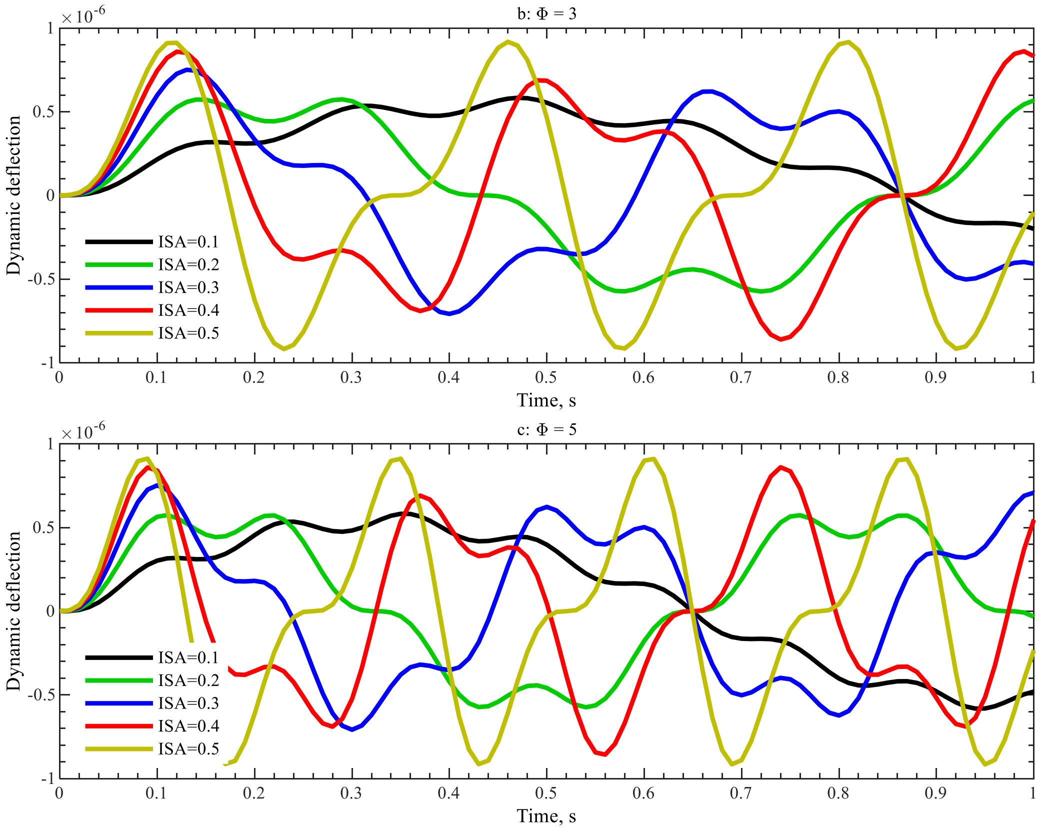


Fig. 4 Continued

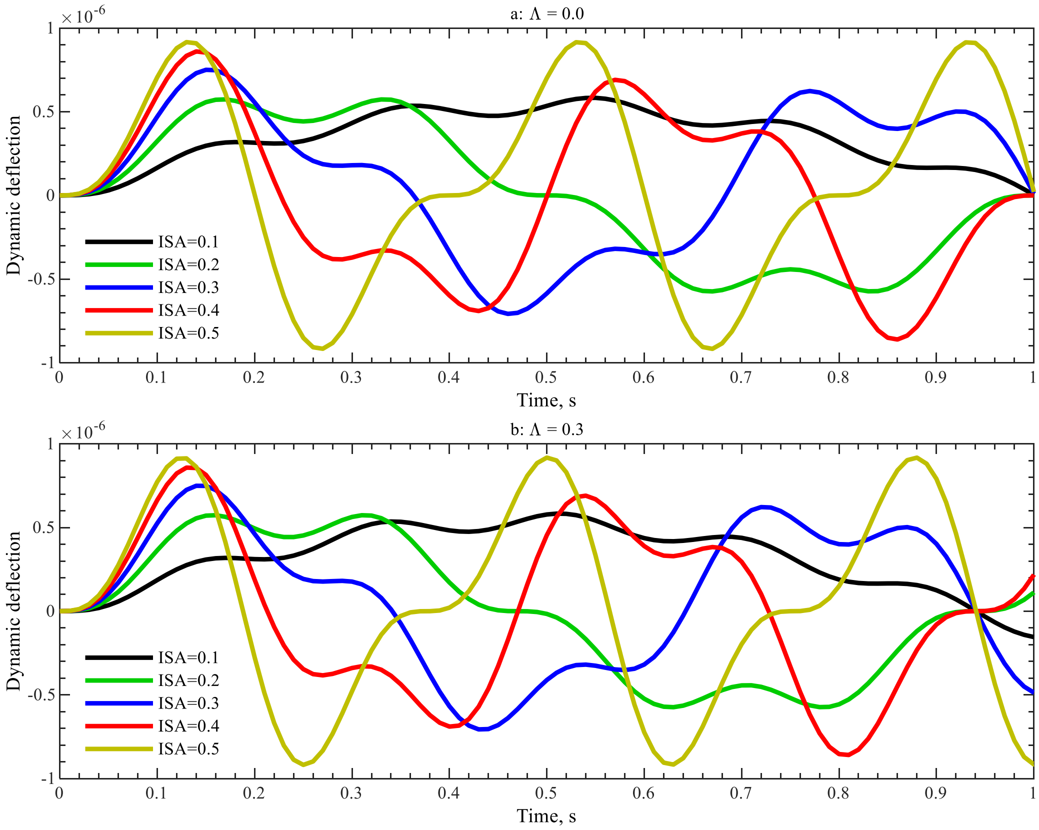


Fig. 5 Influence of hub radius (Λ) on the dynamic deflection of rotating nanomotor blade versus intensity of exercise activities parameters (ISA), L/R=60, Re/Ri=3, Φ=2

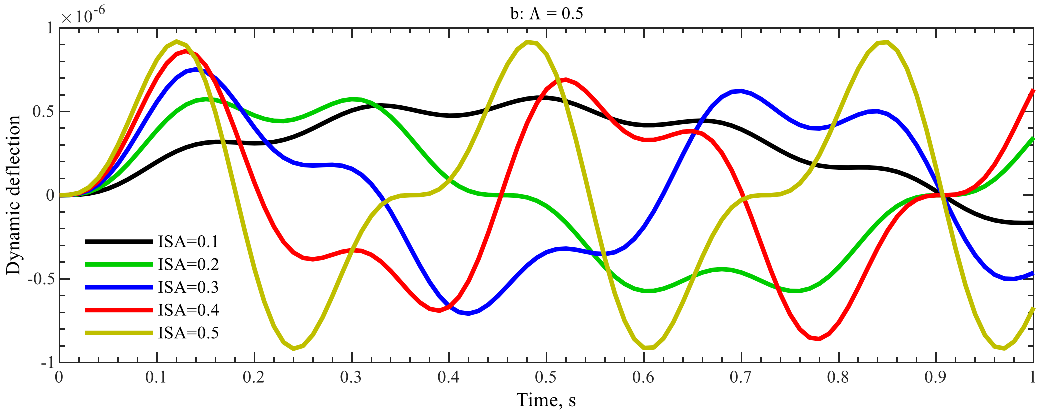


Fig. 5 Continued

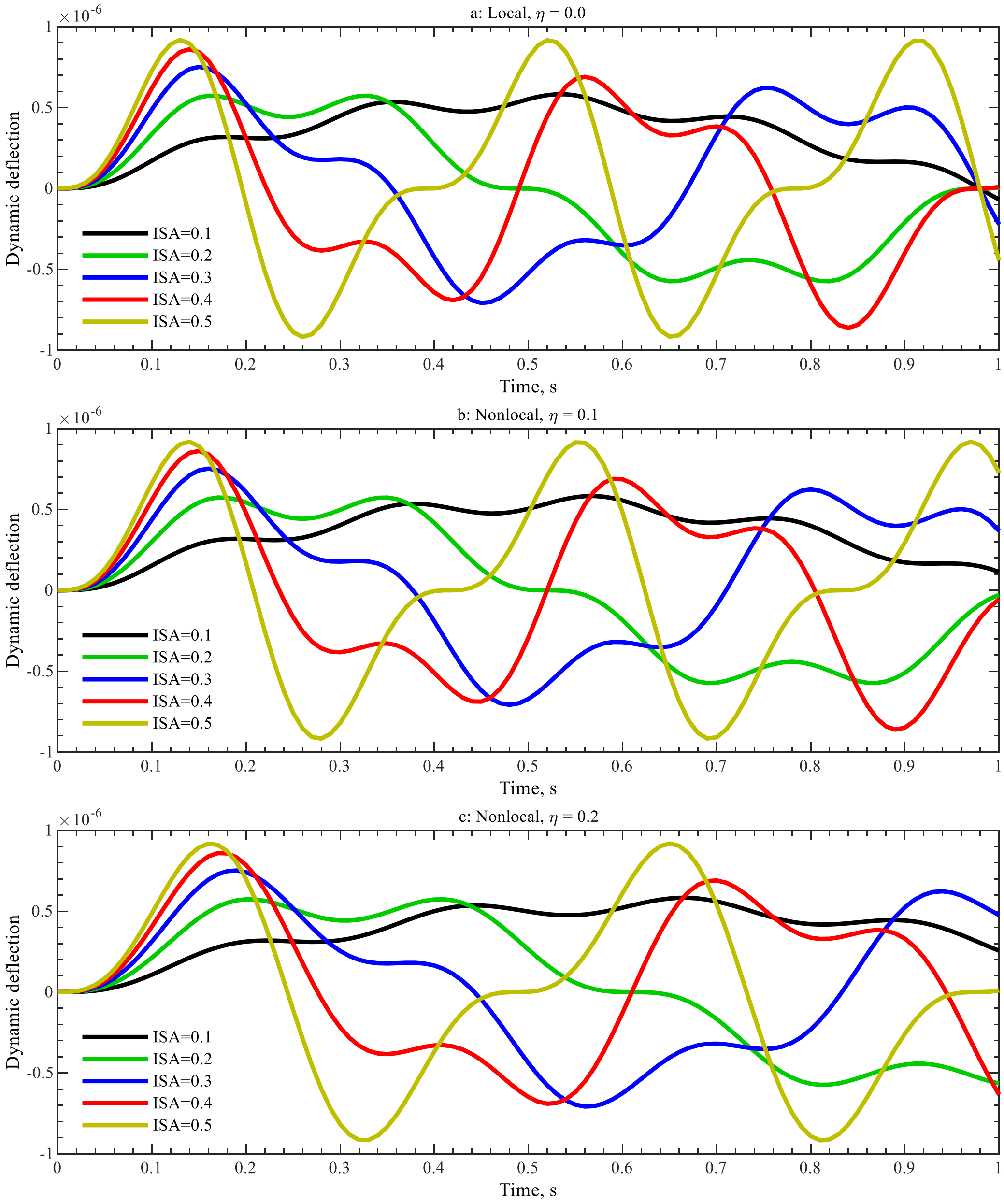


Fig. 6 Dynamic deflection of nanomotor blade versus nonlocal parameter (η) along with the intensity of exercise activities parameters (ISA), L/R=60, Re/Ri=3, Φ=2

and intensify the efficiency of the drugs. micro/ nanomotors can either be self-propelled or controlled through the liquids by external powers such as acoustic, magnetic, or catalytic. These devices are usable in diagnostics and therapeutics, as they can be manufactured in various shapes, mechanical movements, materials, and sizes. Now, the propulsion, vitro in addition vivo applications, fabrication way, as well as strategies associated with oligonucleotides, tissues, drug-delivery, and proteins are discussed. In this paper, the application of nanomotor through the bloodstream is investigated, and the main application of the mentioned structures is for the drug-delivery. The nanomotor is made of a carbon nanotube carrying the drug into the tube, spun in the blood vessel. to have the better description of results discussion, some non-dimensional forms of parameters are required to introduce, which are:

Nonlocal parameter (η):

$$\eta^2 L = (ea)^2 \tag{14a}$$

Rotation speed (Φ):

$$\Phi^2 = m_0 L^4 \phi^2 / D_{11} \tag{14b}$$

Hub radius (Λ):

$$\Lambda L = \lambda \tag{14c}$$

Natural frequency (φ):

$$\varphi^2 = \omega L^2 \sqrt{2m_0 / \pi D_{11}} \tag{14d}$$

Firstly, to validate the presented problem formulation and solution procedure which is used in this study, Table 1 is given. In this table, the fist vibrational frequency of a cantilevered nanobeam are extracted and compared with those of Lu *et al.* (2006) for different values of nonlocal parameter. As shown, the current results have very low difference with the results of the reference, demonstrating the accuracy and validity of the results in studying the vibration response of nanomotors and nanotubes. Thus, having been validated, the current formulation and solution method is utilized to investigate different parameters which can affect vibrational behavior of nanomotors.

It is clear that sports training and exercise improve the blood flow and bloodstream in the body, and also, physical activities lower blood pressure in individuals with hypertension (Börjesson *et al*. 2016). According to this explanation, the investigation of the impact of the sport on the stability of nanomotors and other nanodevices concerning the drug-delivery is an essential issue that this study focused on the physical and training activities on the stability of drug-delivery nanodevices. As it was explained, the sport enhances the blood flow, and in order to the examination of this matter, the following parameter which is called intensity of sports activities (ISA) is defined:

$$ISA = \psi / \omega \tag{14e}$$

ISA can be a symbol of sports activities in the bloodstream, which means increasing the intensity of sports activities enhances the ISA. So, in the following, the exercise impacts are shown by ISA, and an increase in the ISA means enhances the intensity of sports activities.

Now, in the current segment of the research, the influence of different parameters which can affect the dynamic deflection of a nanomotor which is modeled with the aid of nonlocal elasticity, is investigated in detail. To begin with, in the following figure, the variation of dynamic deflection of the nanomotor is plotted for different values of ISA and three values of ISA. Also, the other constant in this figure is Ro=3Ri.

The results shown in Fig. 2 indicate that, regardless of the nanomotor's blade aspect ratio, the nanomotor's deflection and period increase by intensifying ISA. Additionally, the other notable result is that the higher the blade aspect ratio is, the higher the deflection and the period of the nanomotor are.

Next, in Fig. 3, the variation of the nanomotor deflection versus the time is plotted for various ISA and blade radius aspect ratios for L/R=50.

From comparing the results in a, b, and c, shown in Fig. 3, it can be understood that the blade radius aspect ratio can affect both the amplitude of the deflection of the nanomotor in addition to its vibrational period. Blade radius aspect ratio can decrease the amplitude and increase the period time for the nanomotor provided that it has higher values.

Fig. 4 exhibits the effect of rotation speed (Φ) on the nanomotor vibrational response. In this figure, L/R=60, Re/Ri=3. It can be observed from this figure that intensifying the value related to rotation speed (Φ) does not affect the amplitude of the nanomotor's deflection. However, increasing this value can significantly decrese the oscillation period time. Additionally, the increasing impact of ISA can be seen in this figure.

Here, in order to investigate the influence of hub radius (Λ) associated with nanomotor, Fig. 5 is presented in which the time response of the nanomotor is plotted for different values of ISA and Λ. Also, other parameters are L/R=60, Re/Ri=3, Φ=2. The results in this figure demonstrate that increasing hub radius can decrease the period time of the vibration, while it does not change the deflection amplitude. In other words, the frequency of the nanomotor is the lowest amount when the hub radius is equal to zero.

Fig. 6 presents the nonlocality impact on the vibrational time response of the nanomotor. In this figure, the time response is plotted for different nonlocality values. In addition, the other parameter which can affect the vibrational response are L/R=60, Re/Ri=3, Φ=2. The exciting results which are presented in this figure show that increasing nonlocality can soften the nanomotor, the higher the η is, the higher the period of the nanomotor is, meaning the lower the frequency is. Also, it is observable that nonlocality can barely change the deflection amplitude.

Now, the effect of rotation velocity (Φ) and hub radius (Λ), respectively, on the non-dimensional vibrational frequency of the nanomotor is studied in Tables 2 and 3. In these figures, the variation of non-dimensional frequency is tabulated for different values of the nonlocal parameter. Table 2 shows that increasing the values related to rotation velocity (Φ) as well as nonlocal parameters (η) escalate the vibration frequency of the system, so much so that the lowest vibration frequency can be seen in the case in which both Φ and are equal to zero. Similar to the previous table, Table 3 indicates that the vibrational frequency of the nanomotor can be higher in the cases in which hub radius and nonlocal parameters are higher.

Table 2 Effect of rotation velocity (Φ) as well as nonlocal parameters (η) on the dimensionless frequency (φ) of nanomotor blade

	$\Phi=0$	$\Phi=1$	$\Phi=2$	$\Phi=3$	$\Phi=4$	$\Phi=5$
$\eta=0.0$	1.674926	1.789272	2.039747	2.318073	2.586553	2.837609
$\eta=0.5$	1.675105	1.789869	2.041032	2.319921	2.588869	2.840367
$\eta=1.0$	1.675646	1.791662	2.044896	2.325491	2.595856	2.848683
$\eta=1.5$	1.676551	1.794661	2.051367	2.334857	2.60764	2.862699
$\eta=2.0$	1.677826	1.79888	2.060495	2.348145	2.624438	2.882688
$\eta=2.5$	1.679479	1.804344	2.072352	2.365538	2.64657	2.909096
$\eta=3.0$	1.681523	1.811083	2.087034	2.38728	2.674474	2.94257
$\eta=3.5$	1.68397	1.819136	2.104669	2.413688	2.708734	2.983997
$\eta=4.0$	1.68684	1.828556	2.125426	2.445177	2.750117	3.034577
$\eta=4.5$	1.690153	1.839408	2.149525	2.482299	2.79967	3.095986
$\eta=5.0$	1.693936	1.851776	2.177262	2.525815	2.858912	3.170774

Table 3 Influence of hub radius (Λ) along with the nonlocal parameters(η) on the dimensionless frequency (φ) of nanomotor blade, $\Phi=1$

	$\Lambda=0$	$\Lambda=0.1$	$\Lambda=0.2$	$\Lambda=0.3$	$\Lambda=0.4$	$\Lambda=0.5$
$\eta=0.0$	1.906263	1.9311	1.955001	1.978045	2.000299	2.021824
$\eta=0.5$	1.907211	1.932074	1.956	1.979068	2.001346	2.022894
$\eta=1.0$	1.910063	1.935004	1.959004	1.982144	2.004491	2.026105
$\eta=1.5$	1.914834	1.939901	1.964024	1.987281	2.009741	2.031465
$\eta=2.0$	1.921549	1.946791	1.971081	1.994499	2.017114	2.038987
$\eta=2.5$	1.93025	1.95571	1.980209	2.003826	2.026632	2.04869
$\eta=3.0$	1.940992	1.966708	1.99145	2.015301	2.038331	2.060604
$\eta=3.5$	1.953845	1.979849	2.004866	2.028979	2.05226	2.074773
$\eta=4.0$	1.968906	1.995223	2.020537	2.044933	2.068484	2.091257
$\eta=4.5$	1.986298	2.012943	2.038569	2.063261	2.087096	2.11014
$\eta=5.0$	2.006182	2.03316	2.059103	2.084097	2.10822	2.131539

4. Conclusions

The presented study investigates nanomotors' vibrational used as a drug delivery system. The nanomotor is rotating around the normal axis and modeled by using nonlocal elasticity. The formulation in addition to end conditions are acquired by the variational energy method. Then, the displacement domain is discretized using GDQM, and the time-dependent part is solved with the help of the Newmark method. The validation study is presented to demonstrate the accuracy and reliability of the results. Additionally, the impact of different factors such as hub radius ratio, the intensity of sports activities, nonlocal parameters, blade radius aspect ratio, as well as rotation speed on the vibrational behavior of the nanomotor is conducted. The following are the important results extracted from this paper:

- The vibrational frequency of the nanomotor can be higher in the cases in which hub radius and nonlocal parameters are higher.
- Increasing the values related to rotation velocity (Φ) as well as nonlocal parameters (η) escalate the vibration frequency.
- The higher the η is, the higher the period of the nanomotor is.
- Increasing hub radius can decrease the period time of the vibration, while it does not change the deflection amplitude.
- Blade radius aspect ratio can decrease the amplitude and increase the period time for the nanomotor provided that it has higher values.

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