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Stability analysis of drug delivery equipment in sports and exercise actions

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Abstract. Nanomotors are gaining popularity as novel drug delivery methods since they can move rapidly, penetrate deeply into tissues, and be regulated. The ability of manufactured nanomotors to swiftly transport therapeutic payloads to their intended location constitutes a revolutionary nanomedicine strategy. The nanomotors for the drug delivery purpose are released in the blood flow under the different physical conditions, so the stability investigation of these devices is essential before the production, especially in the sport and physical exercise conditions that the blood flow enhances. As a result, using dynamic analysis, this article investigates the stability of the nanomotor released in the blood flow when sport and physical activity circumstances increase blood flow. The considered nanodevice is made of a central motor, and nanotubes are used for the nanomotor blade, which is the drug capsule. Finally, the stability examination of nanomotor as the drug delivery equipment is discussed in detail, and the proposed results can present beneficial results in designing and producing small-scale intelligent devices.

Keywords: drug-delivery; dynamic analysis; nanomotors; nanotubes; sport conditions; stability analysis

1. Introduction

Drug delivery is one of the most crucial measures toward treatment. One can take medications in several different ways, including eating (Deshpande *et al.* 1996), inhaling (Keller 1999), absorbing via the skin (Vogt *et al.* 2016), or injecting them intravenously. Every technique has benefits and drawbacks, and not every medication can be treated using every technique. Medications are improving because of advancements in biotechnology and can now tackle diseases more effectively and precisely (Sokolov *et al.* 2017). One of the ways that can help the efficiency of medicines is delivering the drug to a specific place in the body via drug delivery systems (Wang *et al.* 2019). This system eliminates the chances of affecting the healthy cells and reducing the drug's effectiveness through acidic reactions in the stomach (Choi *et al.* 2020). One of the devices through which drug delivery can be performed are micro-and nano-scale structures that can transform the chemical (Munaweera *et al.* 2016) or external loads into mechanical motions. Micro-and nano-motors are one of the best designs to carry chemicals through the body by transforming the surrounding energy into mechanical form. These devices are commonly made of rods (Gao and Wang 2014, Azimi *et al.* 2016, Ghadiri and Shafiei 2016a, c, Shafiei *et al.* 2016a, e, g), tubes (Zha *et al.* 2018, Hou *et al.* 2021, Huang *et al.* 2021b, Xu *et al.* 2021, Wang *et al.* 2022b), wires (Ma *et al.* 2021, Gao *et al.* 2012, Huang *et al.* 2021c, Liu *et al.* 2021c, Yu *et al.* 2022), and helices (Zhao *et al.* 2021, Hu *et al.* 2020, Jiao *et al.* 2021, Moradi *et al.* 2021).

One of the essential steps toward designing and fabricating devices, specifically small-scale ones, is the investigation of their mechanical characteristics through theoretical examples (Fakher *et al.* 2020). This step reduces the waste of money in addition to the time. Also, the better the understanding of a structure is, the better and more effective design can be achieved (Esmailpoor Hajilak *et al.* 2019). In this regard, various studies on the micro-and nano-scale structures have been carried out to explore such structures' bending (He *et al.* 2021), buckling (Adamian *et al.* 2020, Al-Furjan *et al.* 2020a, b, Li *et al.* 2020b, Moayedi *et al.* 2020b, Zare *et al.* 2020, Dai *et al.* 2021b), vibration (Liu *et al.* 2020b, Habibi *et al.* 2021, He *et al.* 2021, Huang *et al.* 2021a, Liu *et al.* 2021b, Naderi *et al.* 2021, Zhang *et al.* 2021), and stability (Liu *et al.* 2020a, Wang *et al.* 2020b, Zhou *et al.* 2020, Dai *et al.* 2021a, Guo *et al.* 2021a, Shao *et al.* 2021, Shariati *et al.* 2021, Wu and Habibi 2021). With this in mind, it can refer to a paper which deals with the vibrational behavior of a spinning nanotube (Narendar 2012). The formulation in this paper was acquired by using nonlocal elasticity and considering rotary inertia and shear deformation. In addition, by utilizing NSGT and HSDT, the formulation associated with the vibration of a rotating disk made of piezoelectric material was obtained and solved via GDQM (Al-Furjan *et al.* 2021). In this investigation, the impact of Coriolis in addition to centrifugal forces was considered. Also, the vibration associated with a nanoshell made of reinforced composites along with a layer of piezoelectric was examined with the help of GDQM (Habibi *et al.* 2019a). The shell in the abovementioned paper was rotating about its axial axes. By considering the centrifugal forces, the vibrational characteristics related to a nanoshell which is placed on an elastic foundation and subjected to electro-magnetic forces were explored (Shojaeefard *et al.* 2018).

It should be noted that the behavior of small-scale

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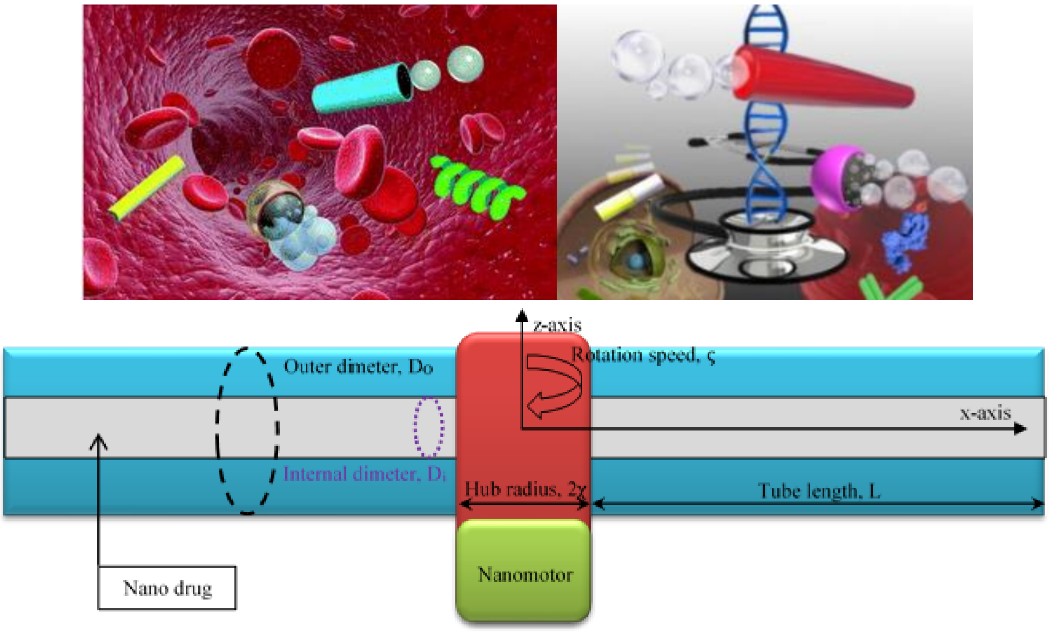

Fig. 1 Geometrical detail and schematic of supposed nanodevice, and schematic of drug-delivery mechanism in the blood flow (Gao and Wang 2014, Chałupniak *et al.* 2015)

structures is at the mercy of the interaction of forces in these sizes. The typical classical elasticity theories cannot consider these interactions (Ghadiri *et al.* 2016a, b, c, d, Ghadiri and Shafiei 2016b, Shafiei *et al.* 2016b, Fakher *et al.* 2020), and such theories as strain gradient (Lam *et al.* 2003), two-phase (Naderi *et al.* 2022), and nonlocal (Eringen and Wegner 2003) must be implemented (Ebrahimi and Shafiei 2016, Shafiei *et al.* 2016c, d, f, Ebrahimi *et al.* 2017, Shivanian *et al.* 2017). One of the papers in which nonlocal elasticity is utilized is the article by De Rosa *et al.* (2021) in which the vibrational response associated with tapered nanotubes made of single-walled carbon was investigated by means of DQM. By utilizing nonlocal theory as well as the Galerkin and Newmark as the numerical solution methods, the forced vibration of a two-layered carbon nanotube, the layers of which were connected with an elastic medium, was explored (Şimşek 2011). It was assumed that the tube was subjected to a moving load. by means of GDQM, the vibrational analysis associated with a carbon nanotube which is under thermal loading and placed in an elastic foundation was presented based on nonlocal theory (Murmu and Pradhan 2009). In addition Şimşek (2010) managed to present an investigation on the forced vibration of carbon nanotubes which are modeled via Euler Bernoulli and nonlocal theories. In the article as mentioned earlier, the force source was a harmonic moving load.

In addition, one of the challenges in making such devices is the fabrication of structures in these sizes (Ghadiri *et al.* 2017a, b, Mirjavadi *et al.* 2017b, c, Shafiei *et al.* 2017a, b). One of the significant methods is using template-directed electroplating to create metallic nanorods (Nicewarner-Peña Sheila *et al.* 2001). Also, another way to make nanomotors is Physical vapor deposition which basically is the process of applying a thin layer to a substrate. In this instance, the foundation is positioned at a vapor angle θ of 0° exactly above the source material (Love *et al.* 2002). In order to to make more complex geometry for the nanomotor, self-assembly is the technic used by the researcher (Ismagilov *et al.* 2002, Sundararajan *et al.* 2008).

This paper presents the mathematical modeling nanomotor made of a rotating nanotube as a drug delivery model. The mechanical behavior—stability and vibration—of the nanotube is investigated. The formulations are obtained through nonlocal elasticity, Sinusoidal shear deformation beam theory, and the energy method. Also, two types of end conditions, local and nonlocal, are presented. Then, using GDQM, the results are extracted. The nanomotors for the drug delivery purpose are released in the blood flow under the different physical conditions, so the stability investigation of these devices is essential before the production, especially in the sport and physical exercise conditions that the blood flow enhances. Thus, physical activity as one of the critical factors is formulated, and its effect on the stability of the nanotube is investigated. The validation study is presented to prove the credibility of the results. The impact of parameters such as rotation speed, nonlocality, boundary condition type, and physical activity factor on the system's dynamic response is explored.

2. Mathematical formulation

The drug-delivery system considered in the current study is made of the nanomotor, in which the nanotubes carrying the nanomedicine are assumed for the blade. This investigation aims to conduct a stability analysis of the nanotube carrying the nano-drug as the nanoblade of the drug-delivery system under rotation regarding the dynamic analysis (Ehyaei *et al.* 2017, Ghadiri *et al.* 2017c, d, Mirjavadi *et al.* 2017d, Shafiei and Kazemi 2017b, Shafiei *et al.* 2017c). As it was shown in Fig. 1, the detail of the geometry of the assumed system is given, and then according to the Sinusoidal shear deformation beam theory coupled with the nonlocal theory, the mathematical formulation of rotating nanoblade in order to obtain the stability analysis (Ebrahimi and Shafiei 2017, Ghadiri *et al.* 2017e, Mirjavadi *et al.* 2017a, Shafiei and Kazemi 2017a, Shafiei *et al.* 2017d, Azimi *et al.* 2018). Based on the Sinusoidal shear deformation beam theory, the following displacement fields are considered:

$$\begin{aligned} u_x &= u - z\frac{\partial w}{\partial x} + \\ &\left(\frac{(D_o - D_i)}{2\pi}\right) sin\big(2\pi z/(D_o - D_i)\big)\left(\psi + w_{,x}\right) \\ u_y &= 0 \\ u_z &= w \end{aligned} \tag{1}$$

where ‘u’, ‘ψ’, and ‘w’ are the axial, bending, and lateral displacement, respectively (Shafiei and She 2018, Shafiei *et al.* 2019, Shafiei *et al.* 2020). Also, ‘u_x’, ‘u_y’, and ‘u_z’ are the displacement fields along the x-/, y-/, and z-axis, moreover, ‘D_i=2R_i’, and ‘D_O=2R_O’ are the internal and external radius of the nanoblade (nanotube). Based on the defined displacement fields, the virtual Kinetic energy (*δK*) of the rotating nanoblade carrying the nanomedicine is defined as follows:

$$\begin{aligned} \delta K = \int_0^L &\left\{ I_1\frac{\partial \dot{w}}{\partial x}\delta\left(\frac{\partial \dot{w}}{\partial x}\right) + I_0(\dot{w}\delta\dot{w} + \dot{u}\delta\dot{u}) \right. \\ &+ I_3\begin{bmatrix} \frac{\partial \dot{w}}{\partial x}\delta\left(\frac{\partial \dot{w}}{\partial x}\right) + \varsigma^2 r\,cos(\theta)\,\delta(\dot{\psi}) \\ + \frac{\partial \dot{w}}{\partial x}\delta(\dot{\psi}) + \dot{\psi}\delta\left(\frac{\partial \dot{w}}{\partial x}\right) + \dot{\psi}\delta(\dot{\psi}) \end{bmatrix} \Bigg\} dx \\ &- I_2\left[\dot{\psi}\delta\left(\frac{\partial \dot{w}}{\partial x}\right) + 2\frac{\partial \dot{w}}{\partial x}\delta\left(\frac{\partial \dot{w}}{\partial x}\right) + \frac{\partial \dot{w}}{\partial x}\delta(\dot{\psi})\right] \end{aligned} \tag{2}$$

where

$$\begin{pmatrix} I_0 \\ I_1 \\ I_2 \\ I_3 \end{pmatrix} = \int \rho \begin{pmatrix} 1 \\ z^2 \\ z\,sin\left(\frac{\pi z}{R_O - R_i}\right)\frac{R_O - R_i}{\pi} \\ \left[sin\left(\frac{\pi z}{R_O - R_i}\right)\frac{R_O - R_i}{\pi}\right]^2 \end{pmatrix} rdrd\theta \tag{3}$$

where, ‘z=r sin(θ), ‘ρ’ is density, and ‘ζ’ is the angular velocity. Then, according to the implicit theory, the potential energy (P) is computed as follows (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):

$$P = 0.5\iiint \sigma\colon \varepsilon dv \tag{4}$$

where ‘ε’ is the strains tensor, and according to the displacement fields defined as follows (Ji *et al.* 2020, Zhuo *et al.* 2020, Ji *et al.* 2021, Jiang *et al.* 2021, Lai *et al.* 2021, Obireddy and Lai 2021, Shi *et al.* 2022, Xue *et al.* 2022):

$$\begin{aligned} \varepsilon_{xx} &= u_{,x} - zw_{,xx} + \\ &\left(sin\left(\frac{\pi z}{R_O - R_i}\right)\frac{R_O - R_i}{\pi}\right)\left(w_{,xx} + \psi_{,x}\right) \\ 2\varepsilon_{xy} &= \left(sin\left(\frac{\pi z}{R_O - R_i}\right)\frac{R_O - R_i}{\pi}\right)_{,y}\left(w_{,x} + \psi\right) \\ 2\varepsilon_{xz} &= \left(sin\left(\frac{\pi z}{R_O - R_i}\right)\frac{R_O - R_i}{\pi}\right)_{,z}\left(w_{,x} + \psi\right) \end{aligned} \tag{5}$$

Also, ‘σ’ is the stresses tensors and defined as follows:

$$\begin{aligned} \sigma_{ij} &= G\varepsilon_{ij}, i \neq j \\ \sigma_{ij} &= E\varepsilon_{ij} i = j \end{aligned} \tag{6}$$

where ‘E’ is the Youngs modulus, ‘G=0.5E/(1+ν)’ is the Lame constant, and ‘ν’ is the Poison ratio. Utilizing the defined equations, the virtual potential energy (*δP*) is represented 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 P = &-\int_0^L \frac{\partial}{\partial x}\left(Q_{11}\frac{\partial u}{\partial x}\right)dx\,\delta(u) \\ &+ \int_0^L \frac{\partial^2}{\partial x^2}\left(Q_{21}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(w) - \frac{\partial}{\partial x}\left(Q_{23}\frac{\partial \psi}{\partial x}\right)\Big|_0^L \delta(w) \\ &+ Q_{21}\frac{\partial^2 w}{\partial x^2}\Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - \frac{\partial}{\partial x}\left(Q_{21}\frac{\partial^2 w}{\partial x^2}\right)\Big|_0^L \delta(w) \\ &+ Q_{11}\frac{\partial u}{\partial x}\Big|_0^L \delta(u) + Q_{23}\frac{\partial \psi}{\partial x}\Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) \\ &+ \int_0^L \frac{\partial^2}{\partial x^2}\left(Q_{23}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(w) - \frac{\partial}{\partial x}\left(Q_{23}\frac{\partial^2 w}{\partial x^2}\right)\Big|_0^L \delta(w) \\ &+ Q_{12}\psi|_0^L\delta(w) - \int_0^L \frac{\partial}{\partial x}\left(Q_{23}\frac{\partial \psi}{\partial x}\right)dx\,\delta(\psi) \\ &- \int_0^L \frac{\partial}{\partial x}\left(Q_{23}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(\psi) - \int_0^L \frac{\partial}{\partial x}\big(Q_{12}(\psi)\big)dx\,\delta(w) \\ &+ Q_{23}\frac{\partial \psi}{\partial x}\Big|_0^L \delta(\psi) + Q_{23}\frac{\partial^2 w}{\partial x^2}\Big|_0^L \delta(\psi) \\ &+ \int_0^L \frac{\partial^2}{\partial x^2}\left(Q_{23}\frac{\partial \psi}{\partial x}\right)dx\,\delta(w) + Q_{12}\frac{\partial w}{\partial x}\Big|_0^L \delta(w) \\ &- 2\,Q_{22}\frac{\partial^2 w}{\partial x^2}\Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - 2\int_0^L \frac{\partial^{2\psi}}{\partial x^2}\left(Q_{22}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(w) \\ &+ 2\frac{\partial}{\partial x}\left(Q_{22}\frac{\partial^2 w}{\partial x^2}\right)\Big|_0^L \delta(w) + \int_0^L \frac{\partial}{\partial x}\left(Q_{22}\frac{\partial^2 w}{\partial x^2}\right)dx\,\delta(\psi) \\ &- \int_0^L \frac{\partial^2}{\partial x^2}\left(Q_{22}\frac{\partial \psi}{\partial x}\right)dx\,\delta(w) - Q_{22}\frac{\partial^2 w}{\partial x^2}\Big|_0^L \delta(\psi) \\ &- Q_{22}\frac{\partial \psi}{\partial x}\Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial x}\left(Q_{22}\frac{\partial \psi}{\partial x}\right)\Big|_0^L \delta(w) \\ &+ Q_{23}\frac{\partial^2 w}{\partial x^2}\Big|_0^L \delta\left(\frac{\partial w}{\partial x}\right) - \int_0^L \frac{\partial}{\partial x}\left(Q_{12}\frac{\partial w}{\partial x}\right)dx\,\delta(w) \\ &+ \int_0^L Q_{12}\psi\delta(\psi) + Q_{12}\frac{\partial w}{\partial x}\delta(\psi)\,dx \end{aligned} \tag{7}$$

where

$$\begin{pmatrix} Q_{11} \\ Q_{12} \\ Q_{21} \\ Q_{22} \\ Q_{23} \end{pmatrix} = \int \begin{pmatrix} E \\ K_S G\left(\kappa_{,z}{}^2 + \kappa_{,y}{}^2\right) \\ Er^2\,sin^2(\theta) \\ \kappa(r\,sin(\theta)) \\ \kappa^2 \end{pmatrix} rdrd\theta \tag{8}$$

where

$$\kappa = sin(\pi r\,sin(\theta)\,(R_O - R_i)^{-1})\,(R_O - R_i)\pi^{-1} \tag{9}$$

Moreover, the virtual energy of centrifugal force of rotation ($T^{Rotation}$) and the energy of blood flow (T^{Blood}) is considered as the virtual energy of external forces (δE) as defined as follows (Hashemi *et al.* 2019, Moayedi *et al.* 2019, 2020a, c, Oyarhossein *et al.* 2020, Shariati *et al.* 2020b):

$$\delta E = \int_V T^{Blood} dV\,\delta(w) + \delta\left[0.5\int_0^L T^{Rotation}\left(w_{,x}\right)^2 dx\right] \tag{10}$$

where

$$T^{Rotation} = \int_x^L \int_A \rho\varsigma^2 (x+\chi)\,dA\,dx \tag{11}$$

where ‘χ’ is hub radius, and

$$T^{Blood} = T \times \iota\, sin(\frac{n\pi}{L}x)\, sin(\tau t) \tag{12}$$

In which ‘T’ is the dynamic external bending load, and the ‘τ’ is the external excitation frequency of blood flow, and ‘ι’ is the length of the beam under the loading. By applying the nonlocal theory (Eringen 1972) to the stress-strain component of virtual Kinetic energy (Eq. (2)), potential energy (Eq. (7)), and energy of external forces (Eq. (10)), and using the following energy method of the Hamilton principle:

$$\int_{t_1}^{t_2} \delta\Pi dt = \int_{t_1}^{t_2} \delta(P+E-K)dt = 0 \tag{13}$$

The following Euler-Lagrange nonlocal governing equations and related boundary conditions will be obtained.

Nonlocal governing equations:

$$\delta(u):\ Q_{11}\frac{\partial^2 u}{\partial x^2} = I_0\ddot{u} - (ea)^2 I_0 \frac{\partial^2 \ddot{u}}{\partial x^2} \tag{14}$$

$$\begin{gathered}\delta(\psi): \\ -Q_{12}\left(\frac{\partial w}{\partial x}+\psi\right) - Q_{22}\frac{\partial^3 w}{\partial x^3} + Q_{23}\left(\frac{\partial^3 w}{\partial x^3}+\frac{\partial^2 \psi}{\partial x^2}\right) = \\ -(ea)^2 I_3 \frac{\partial^2 \ddot{\psi}}{\partial x^2} + (I_3 - I_2)\frac{\partial \ddot{w}}{\partial x} + (ea)^2 (I_2 - I_3)\frac{\partial^3 \ddot{w}}{\partial x^3} + I_3\ddot{\psi}\end{gathered} \tag{15}$$

$$\begin{gathered}\delta(w): \\ \frac{(Q_{23} - 2Q_{22} + Q_{21})\partial^4 w}{\partial x^4} + (Q_{23} - Q_{22})\frac{\partial^3 \psi}{\partial x^3} \\ -Q_{12}\left(\frac{\frac{\partial \psi}{\partial x} + \partial^2 w}{\partial x^2}\right) + T^{Blood} - T^{Rotation}\frac{\partial^2 w}{\partial x^2} \\ -T^{Rotation}{}_{,x}\frac{\partial w}{\partial x} - (ea)^2 T^{Blood}{}_{,xx} + (ea)^2 T^{Rotation}\frac{\partial^4 w}{\partial x^4} \\ +(ea)^2 T^{Rotation}{}_{,xxx}\frac{\partial w}{\partial x} + 3(ea)^2 T^{Rotation}{}_{,x}\frac{\partial^3 w}{\partial x^3} + \\ 3(ea)^2 T^{Rotation}{}_{,xx}\frac{\partial^2 w}{\partial x^2} = (I_3 - 2I_2 + I_1)\frac{\partial^2 \ddot{w}}{\partial x^2} \\ -I_0\ddot{w} + (I_3 - I_2)\frac{\partial \ddot{\psi}}{\partial x} - (ea)^2 (I_3 - 2I_2 + I_1)\frac{\partial^4 \ddot{w}}{\partial x^4} \\ -(ea)^2 (I_3 - I_2)\frac{\partial^3 \ddot{\psi}}{\partial x^3} + (ea)^2 I_0 \frac{\partial^2 \ddot{w}}{\partial x^2}\end{gathered} \tag{16}$$

Nonlocal Boundary conditions:

$$\delta(u):\ Q_{11}\frac{\partial u}{\partial x} - (ea)^2 I_0 \frac{\partial \ddot{u}}{\partial x} = 0 \tag{17}$$

$$\begin{gathered}\delta(\psi):\ Q_{23}\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + (ea)^2 (I_2 - I_3)\frac{\partial^2 \ddot{w}}{\partial x^2} \\ -Q_{22}\frac{\partial^2 w}{\partial x^2} - (ea)^2 I_3 \frac{\partial \ddot{\psi}}{\partial x} = 0\end{gathered} \tag{18}$$

$$\begin{gathered}\delta(w):\ Q_{12}\left(\frac{\partial w}{\partial x} + \psi\right) - (Q_{23} - Q_{22})\left(\frac{\partial^3 w}{\partial x^3} + \frac{\partial^2 \psi}{\partial x^2}\right) \\ +(Q_{22} - Q_{21})\frac{\partial^3 w}{\partial x^3} + T^{Blood}\frac{\partial w}{\partial x} + (ea)^2 I_0 \frac{\partial \ddot{w}}{\partial x} \\ -(ea)^2 \frac{T^{Blood}\partial^2 w}{\partial x^2} - (ea)^2 (I_3 - 2I_2 + I_1)\frac{\partial^3 \ddot{w}}{\partial x^3} \\ -(ea)^2 T^{Blood}{}_{,x}\frac{\partial w}{\partial x} + (ea)^2 (I_2 - I_3)\frac{\partial^2 \ddot{\psi}}{\partial x^2} = 0\end{gathered} \tag{19}$$

$$\begin{gathered}\delta(w_{,x}):\ (Q_{23} - Q_{22})\left(\frac{\partial \psi}{\partial x} + \frac{\partial^2 w}{\partial x^2}\right) + (ea)^2 I_0 \ddot{w} \\ -(Q_{22} - Q_{21})\frac{\partial^2 w}{\partial x^2} + (ea)^2 (I_2 - I_3)\frac{\partial \ddot{\psi}}{\partial x} \\ -(ea)^2 (I_3 - 2I_2 + I_1)\frac{\partial^2 \ddot{w}}{\partial x^2} = 0\end{gathered} \tag{20}$$

where ‘*ea*’ is the nonlocal parameter based on the nonlocal theory of Eringen and Wegner (2003).

3. Methodology of solution approach

In this paper, the generalized differential quadrature method (GDQM) is employed to solve the nonlocal governing equation as well as associated boundary conditions for the stability analysis of rotating nanoblade carrying the nanomedicine based on the high-order theory of beam coupled to the nonlocal theory (Ebrahimi *et al.* 2019a, b, 2020, Mohammadgholiha *et al.* 2019, Mohammadi *et al.* 2019, Habibi *et al.* 2020, Shariati *et al.* 2020a, Shokrgozar *et al.* 2020). The GDQM defines the v-order derivative function of ‘*f*’ as follows:

$$\frac{\partial^v f}{\partial x^v} = \sum_{q=1}^{n} H_{pq}{}^{(v)} f(x_p) \tag{21}$$

where ‘H’ is the weighting coefficient which is defined as follows (Habibi *et al.* 2017, 2019b, Ghazanfari *et al.* 2020, Safarpour *et al.* 2018, 2020):

$$H_{pq}^{(v)} = v\left[H_{pq}^{(1)} H_{pq}^{(v-1)} + H_{pq}^{(v-1)}(x_p - x_q)\right] \tag{22}$$

where

$$H_{pq}^{(1)} = X(x_q)^{-1} X(x_p)(x_p - x_q)^{-1} \tag{23}$$

where

$$X(x_p) = \prod_{j=q,q\neq p}^{n} (x_p - x_q) \tag{24}$$

Also, the grid points (N points) are defined as follows (Wang *et al.* 2020a, 2022a, Li *et al.* 2021, Si *et al.* 2021, Lei *et al.* 2022, Tang *et al.* 2022):

$$x_p = 0.5L\left(1 - cos\left((p-1)(N-1)^{-1}\pi\right)\right) \tag{25}$$

Then the following definitions should be applied to the time-dependent governing equations:

$$\begin{pmatrix}\psi\\ w\\ u\end{pmatrix} = \begin{pmatrix}\bar{\psi}\\ \bar{w}\\ \bar{u}\end{pmatrix} exp(i\omega t) \tag{26}$$

where ‘ω’ is the natural frequency. Finally, using the GDQM and the modal analysis, the governing equations (Eqs. (14)-(16)) reform to the following eigenvalue problem.

δ(u):

$$Q_{11}\sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{u}_q = \omega^2 I_0 \bar{u} - \omega^2 (ea)^2 I_0 \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{u}_q \tag{27}$$

$$\begin{aligned}
&\delta(\psi){:}\ \ -Q_{12}\big(\textstyle\sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{w}_q + \bar{\psi}\big)_q \\
&+Q_{23}\left(\sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{w}_q + \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{\psi}_q\right) \\
&-Q_{22}\sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{w} = \omega^2 (I_3 - I_2) \sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{w}_q + \omega^2 I_3 \bar{\psi} \\
&-\omega^2 (ea)^2 I_3 \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{\psi}_q + \omega^2 (ea)^2 (I_2 - I_3) \sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{w}_q
\end{aligned} \tag{28}$$

$$\begin{aligned}
&\delta(w){:}\ \ (Q_{23} - 2Q_{22} + Q_{21}) \textstyle\sum_{q=1}^{n} H_{pq}{}^{(4)}\,\bar{w}_q \\
&+(Q_{23} - Q_{22}) \sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{\psi} \\
&-Q_{12}\left(\sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{\psi}_q + \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{w}_q\right) + T^{Blood} \\
&-T^{Rotation} \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{w}_q - T^{Rotation}{}_{,x} \sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{w}_q \\
&-(ea)^2 T^{Blood}{}_{,xx} + (ea)^2 T^{Rotation} \sum_{q=1}^{n} H_{pq}{}^{(4)}\,\bar{w}_q \\
&+(ea)^2 T^{Rotation}{}_{,xxx} \sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{w}_q \\
&+3(ea)^2 T^{Rotation}{}_{,x} \sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{w}_q + \\
&3(ea)^2 T^{Rotation}{}_{,xx} \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{w}_q \\
&= \omega^2 (I_3 - 2I_2 + I_1) \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{w}_q \\
&-\omega^2 I_0 \bar{w} + \omega^2 (I_3 - I_2) \sum_{q=1}^{n} H_{pq}{}^{(1)}\,\bar{\psi}_q \\
&+\omega^2 (ea)^2 I_0 \sum_{q=1}^{n} H_{pq}{}^{(2)}\,\bar{w}_q \\
&-\omega^2 (ea)^2 (I_3 - I_2) \sum_{q=1}^{n} H_{pq}{}^{(3)}\,\bar{\psi}_q \\
&-\omega^2 (ea)^2 (I_3 - 2I_2 + I_1) \sum_{q=1}^{n} H_{pq}{}^{(4)}\,\bar{w}_q
\end{aligned} \tag{29}$$

Eigenvalues of presented equations (Eqs. (27)-(29)) will obtain the natural frequency of rotating nanoblade while assembled to the boundary conditions equations (Eqs. (17), - (20)). Finally, using the Newmark-beta technique (Singh and Pal 2021), the time-dependent results will be calculated (Cao *et al.* 2022, Chang *et al.* 2022, Li *et al.* 2022, Zhang *et al.* 2022a, b).

4. Discussion of numerical results

The current paper studies the stability analysis of the nanodevice for drug-delivery purposes. In the previous section, the mathematical formulation for the theoretical modeling has been extracted, and according to the numerical procedure, the numerical results are obtained. As a result, the impact of sport and physical activities on drug delivery and the quality of drug delivery is also investigated in this paper as the main aim of this study. Before discussing outcomes, validating the results are compared to the published studies is necessary. So, the current results are compared to the results of Lu *et al.* (2006) (based on the local boundary condition), and Xu *et al.* (2016) (based on the nonlocal boundary conditions) in Fig. 2 for the bending vibration of the spinning nanotube, in which excellent agreement is seen. As mentioned, the primary purpose of the current study was to investigate the impact of sports and exercise on drug-delivery quality. Physical activities improve the blood flow and bloodstream of the vessels, which can enhance the frequency of blood flow. In other words, the exercise raises the blood flow frequency, the external parameter of the stability of nanodevices released in the blood (See Eq. (12)). In this paper, the impact of sport is shown by enhancing the excitation frequency. The exercise can delay the resonant frequency of the nanodevices because the physical activities improve the environmental frequency of nanodevices and delay the resonant happening. This parameter will be discussed in detail in the following. The following dimensionless parameters are necessary to introduce before the discussion of the results.

Dimensionless frequency (Ξ):

$$\Xi = \omega^2 I_0 L^4 / Q_{11} \pi R_O{}^2 \tag{30a}$$

Dimensionless rotation speed (Λ):

$$\Lambda^2 Q_{11} = I_0 L^4 \Theta^2 \tag{30b}$$

Dimensionless nonlocal parameter (α):

$$\alpha^2 = (ea)^2 / L \tag{30c}$$

Sport impact or rate of excitation frequency (ϖ):

$$\varpi^{-1} = \omega / \tau \tag{30d}$$

Dimensionless deflection (λ):

$$\lambda = -w \times 10\pi^2 Q_{11} / T L^4 \tag{30e}$$

It is noted that the impact of the sport is shown via ‘ϖ’, and the results are prepared for ‘ ϖ^{-1}’, so the impact of exercise and physical activity is precisely reversed to ‘ ϖ’.

In the next part of the article, the investigation of the effect corresponded to various parameters and factors which play a role in the stability and dynamic response of the nanomotor used as a model of a drug delivery system is carried out. Initially, Table 1 and Table 2 are presented to investigate the effect of rotation speed and nonlocal parameters on the nondimensional vibration frequency. These tables, respectively, present the results by using local and nonlocal types of end conditions. These tables exhibit that increasing the rotation speed leads to a rise in the

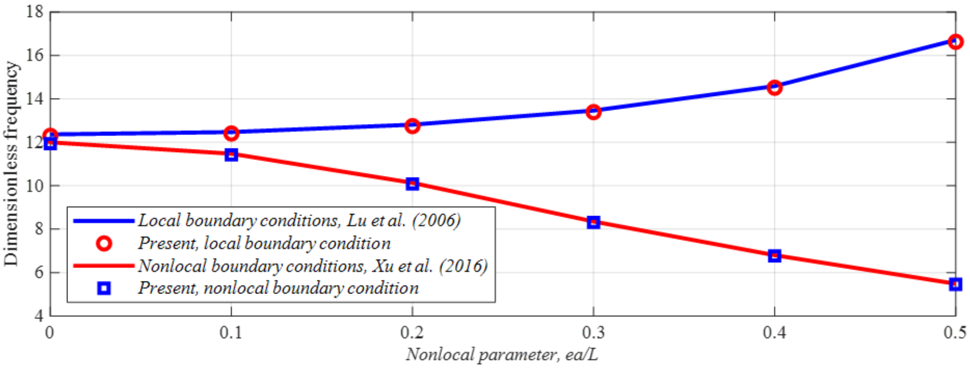

Fig. 2 The numerical presented results regarding the free bending frequency ($\omega^2L^4I_0/Q_{11}$) of the cantilever nanobeam compared to the results of Xu *et al*. (2016) for when the nonlocal boundary conditions are applied and Lu *et al*. (2006) for the local boundary conditions versus the different nonlocal parameters (*ea*/L)

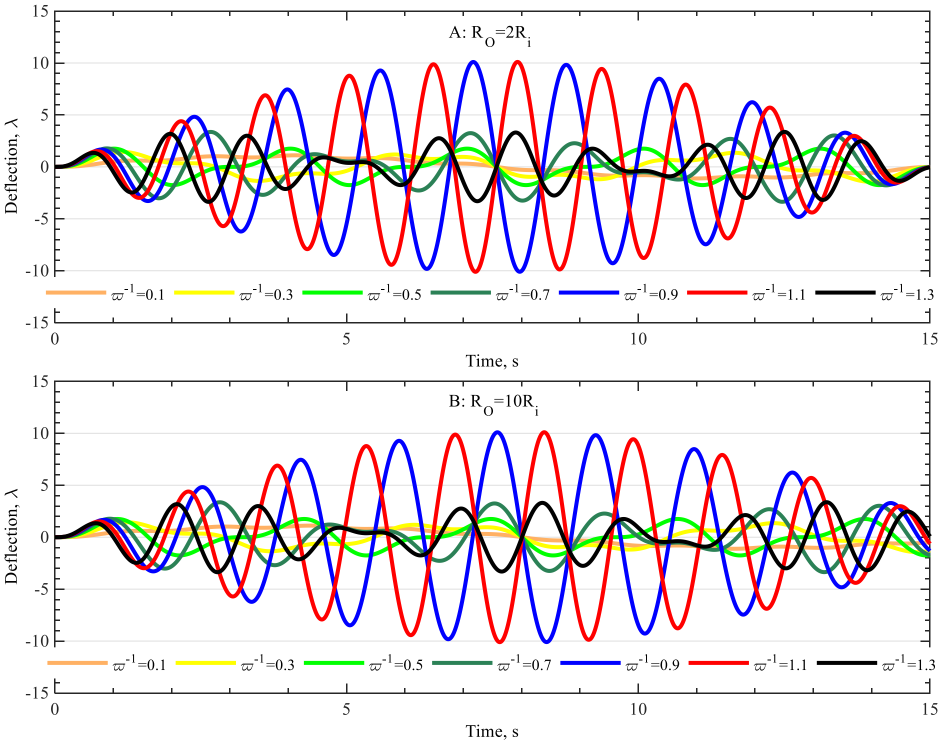

Fig. 3 Impact of sports and physical activities ‘ϖ’ on the dynamic stability of the drug-delivery mechanism for different radius aspect ratios (R_O/R_i), $L=25R_O$

Table 1 The fundamental frequency (Ξ) of spinning nanotube versus the angular velocity (Λ) for the different nonlocal parameters (α) regarding the local boundary conditions, $L=25R_O=50R$¬i

	‘α = 0’	‘α = 0.5’	‘α = 1.0’	‘α = 1.5’	‘α = 2.0’
Λ=0	4.150313	4.17074	4.235128	4.35319	4.553529
Λ=0.5	4.25609	4.282561	4.368595	4.528237	4.792996
Λ=1.0	4.571356	4.62021	4.77276	5.053784	5.520267
Λ=1.5	5.098682	5.183102	5.447752	5.933925	6.75794
Λ=2.0	5.837778	5.970913	6.392388	7.180731	8.523315
Λ=2.5	6.790224	6.985612	7.610334	8.812819	10.79915
Λ=3.0	7.958737	8.227631	9.099801	10.78653	13.83285
Λ=3.5	9.345458	9.700803	10.87836	13.22049	17.37467
Λ=4.0	10.95511	11.40714	12.93471	15.96771	21.51361
Λ=4.5	12.79382	13.35356	15.25716	19.18179	26.22548
Λ=5.0	14.87102	15.54448	17.9606	22.77487	31.62745

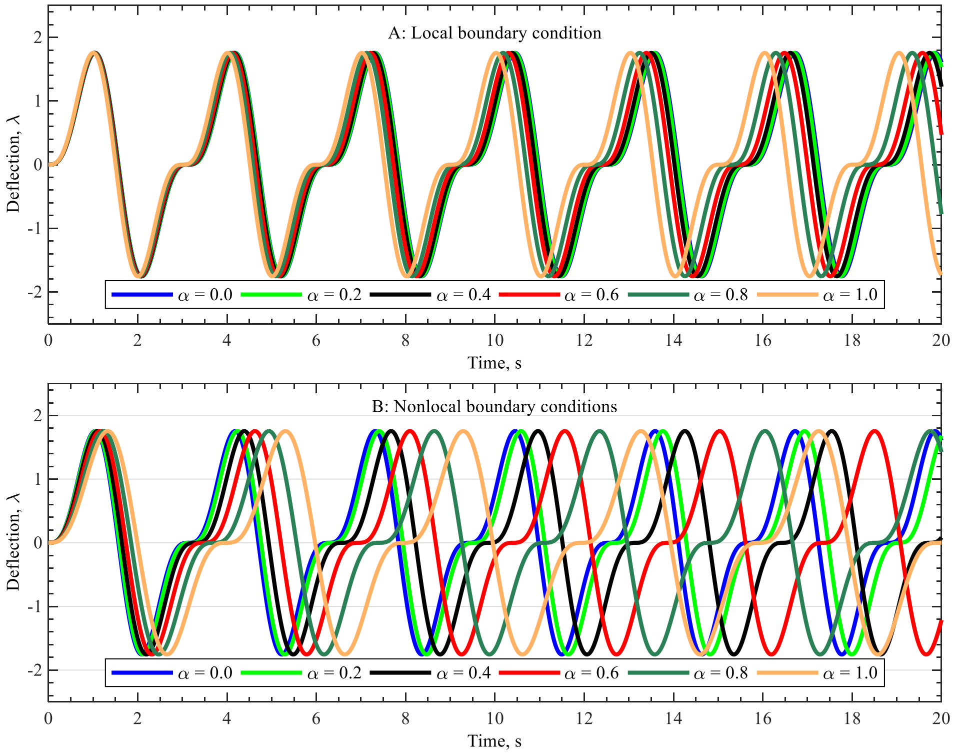

Fig. 4 Effect of nonlocal parameters (α) on the dynamic stability and deflection (λ) of flap-wise nano-blade concerning the local and nonlocal boundary conditions, $L=20R_O=60R_i$

Table 2 The fundamental frequency (Ξ) of rotating nanotube versus the rotating speed (Λ) for the different nonlocal parameters (α) under the nonlocal boundary conditions, $L=25R_O=50Ri$

	‘α = 0’	‘α = 0.25’	‘α = 0.5’	‘α = 0.75’	‘α = 1.0’
Λ=0.0	4.150313	4.111369	4.005309	3.856491	3.690249
Λ=0.15	4.160215	4.119057	4.009998	3.856389	3.690152
Λ=0.3	4.18872	4.144501	4.024262	3.85453	3.688373
Λ=0.45	4.235679	4.185926	4.048375	3.852393	3.686328
Λ=0.6	4.302561	4.242747	4.080792	3.849718	3.683768
Λ=0.75	4.3875	4.317157	4.124163	3.84689	3.681062
Λ=0.9	4.492403	4.4077	4.177392	3.845138	3.679386
Λ=1.05	4.615827	4.515944	4.240332	3.844025	3.67832
Λ=1.2	4.757182	4.639713	4.314349	3.848337	3.682447
Λ=1.35	4.918248	4.78006	4.397668	3.853388	3.68728
Λ=1.5	5.098682	4.937365	4.493071	3.868093	3.701351

vibration frequency, regardless of the nonlocality of the system. In addition, the contractor results of these tables are that, providing that the local boundary condition is utilized, increasing the nonlocality cause the vibrational frequency to intensify, which is entirely opposite in Table 2. In other words, if the nonlocal boundary condition is used, the higher the nonlocality is, the softer the system is.

Now, Fig. 3 deals with the impact of sports and physical activities on the nanodevice’s stability and the forced vibration. The results are presented for two different radius aspect ratios. It is seen that the radius aspect ratio only causes the time history of the system to be shifted, while it cannot change the vibration amplitude. Additionally, it can be observed that the highest vibration amplitude is associated with the cases in which $\varpi^{-1}=0.9$ and 1.1. Also, when $\varpi^{-1}=0.1$, the lowest amplitude occurs. Generally, it can be said that increasing ϖ^{-1} from 0.1 to 1.3 leads to first increasing and then decreasing the vibration amplitude.

Finally, Fig. 4 plots the vibration time history of the system for various nonlocality with considering both local and nonlocal boundary conditions. It can be understood from this figure that the vibrational response of the nanomotor shifts to the left and right by intensifying the nonlocality if, respectively, the local and nonlocal type of end conditions are implemented. Additionally, it is notable that, in both boundary conditions, the vibration amplitude does not vary by increasing the nonlocality.

5. Conclusions

The dynamic stability of a nanomotor made of a rotating nanotube utilized as a drug delivery system is investigated in the current paper. The nanotube is modeled via nonlocal elasticity. The two types of boundary conditions, local and nonlocal, are presented for the current model. Also, the effect of physical activity on the behavior of the drug delivery system is formulated and examined. The formulation of the vibration response of this nanodevice is obtained via the energy method, and then solved numerically with the aid of GDQM. The validation study of the current formulation with local and nonlocal end conditions is presented. Finally, the impact of such factors as physical activity, boundary type, nonlocality, speed of nanomotor, and radius aspect ratio on the free and forced vibration of the current system is investigated, and the following are the highlighted conclusions:

• increasing ϖ^{-1} from 0.1 to 1.3 leads to increasing and then decreasing the vibration amplitude.

• The radius aspect ratio cannot change the vibration amplitude.

• The vibrational response of the nanomotor shifts to the left and right by intensifying the nonlocality if, respectively, the local and nonlocal type of end conditions are implemented.

• Increment in sports activities improves and enhances the blood flow, then raises the frequency of whole cells.

An increment in exercise intensifies (τ), and decreases the 'ϖ^{-1}', it can say the increment of sports activities delays the resonant frequency.

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