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Impact of the geometric properties of intracranial vascular bifurcation and the mechanism of aneurysm occurrence and rupture

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Abstract. One factor that can heighten the risk of the rapture intracranial aneurysm (IA) is bifurcations, which can cause the IA to evaluate. This study presents the effect of geometric of intracranial vascular on the bifurcation analysis of the aneurysm occurrence. The aneurysm mechanism is mathematically modeled based on the nano pipe structures under the thermal stresses, and the impact of the aneurysm geometric on the stability and bifurcation points is analyzed. Because of the dimension of these structures, the classical theories could not predict their behavior perfectly, so the nonclassical and nonlocal theories are required for the mechanical modeling of the aneurysm. The presented results show that the bifurcation point of the aneurysm mechanism is dependent on the environment temperature, and the temperature change plays an essential role in the stability of these structures.

Keywords: aneurysm mechanism; bifurcation; buckling behavior; dynamic characteristics; mechanical analysis

1. Introduction

Intracranial aneurysms are known to affect a small population of people, with the average age being around 0.2 to 9% (Kim *et al*. 2016). The prevalence of this disease is also low in adults, around 3% (Vlak *et al*. 2011). A part of the artery wall will be like a dilatation balloon, leading to a rupture. This condition can cause subarachnoid hemorrhage, which can cause death at a rate of up to 30% (Nieuwkamp *et al*. 2009). Sometimes, an intracranial aneurysm can occur on an artery that has a bifurcation or curvature (Lai *et al*. 2020, 2021, Yan *et al*. 2020, Tang *et al*. 2021, Cao *et al*. 2022, Liu *et al*. 2022, Zhang *et al*. 2022a, b, c). This condition has the most complex and unclear pathophysiology (Valencia *et al*. 2013). There are also various unknown points in the management of this disease (Sadasivan *et al*. 2013, Valen-Sendstad *et al*. 2013). Some studies have shown that the risk of a rupture is increased with the presence of specific geometric parameters. These include the height and width ratio, aspect ratio, and size ratio (Nair *et al*. 2016). Then, a few examinations guaranteed that the aneurysms with bigger sizes have more opportunities for crack (Wermer *et al*. 2007, Ishibashi *et al*. 2009) which obviously, the legitimacy of this guarantee was dismissed by different investigations which obviously, the legitimacy of this guarantee was dismissed by different investigations (Weir 2002, Raghavan *et al*. 2005). A few different examinations showed that the chance of burst is higher in the aneurysms with sizes less than 5 mm (Wiebers 2003, Bijlenga *et al*. 2013) or less than10 mm (Gholampour and Mehrjoo 2021). In any case, these studies were dismissed by a few different scholars (Weir *et al*. 2003, Tominari *et al*. 2015). These inconsistencies demonstrate that exploring the morphology of the aneurysm alone can’t be a successful component for the expectation of rapture for the aneurysm, and unquestionably, different elements are engaged with this present circumstance too (Brunozzi *et al*. 2019). Xiang *et al*. (2011) exhibited that the blood hemodynamic is basically as significant and viable as the morphology boundaries in the rapture status of the IA patients. Consequently, various examinations have been performed on the job and adequacy of the blood hemodynamics in the IA assessment. Shojima *et al*. (2004), utilizing the computational fluid dynamics, have demonstrated that the IA crack happens not just in the high hemodynamic factors. Also, in low qualities, for example, the low wall shear pressure. Additionally, by employing fluid-structure interaction, the impact related to hemodynamic parameters was investigated by Hajirayat *et al*. (2017). In addition, various investigations studied the influence of such factors as age, natural history, as well as impingement regions on the rupture risk of the aneurysm (Duan *et al*. 2018, Hussein *et al*. 2020).

Temperature difference as one of the environmental factors can affect such mechanical behavior as vibration (Zhao *et al*. 2021, Kumaravel *et al*. 2007, Huang *et al*. 2021b, Jiao *et al*. 2021, Moradi *et al*. 2021, Xu *et al*. 2021), stability (Wang *et al*. 2008), and buckling (Sun *et al*. 2016) of any structure of any size. Thus, this factor has been included in various experimental as well as theoretical studies. Given this, it can refer to a work in which the thermal buckling as well as vibrational analysis associated with a nanobeam placed on a size-dependent foundation were investigated (Fakher *et al*. 2020). Next, Wattanasakulpong *et al*. (2011) explored the vibration and

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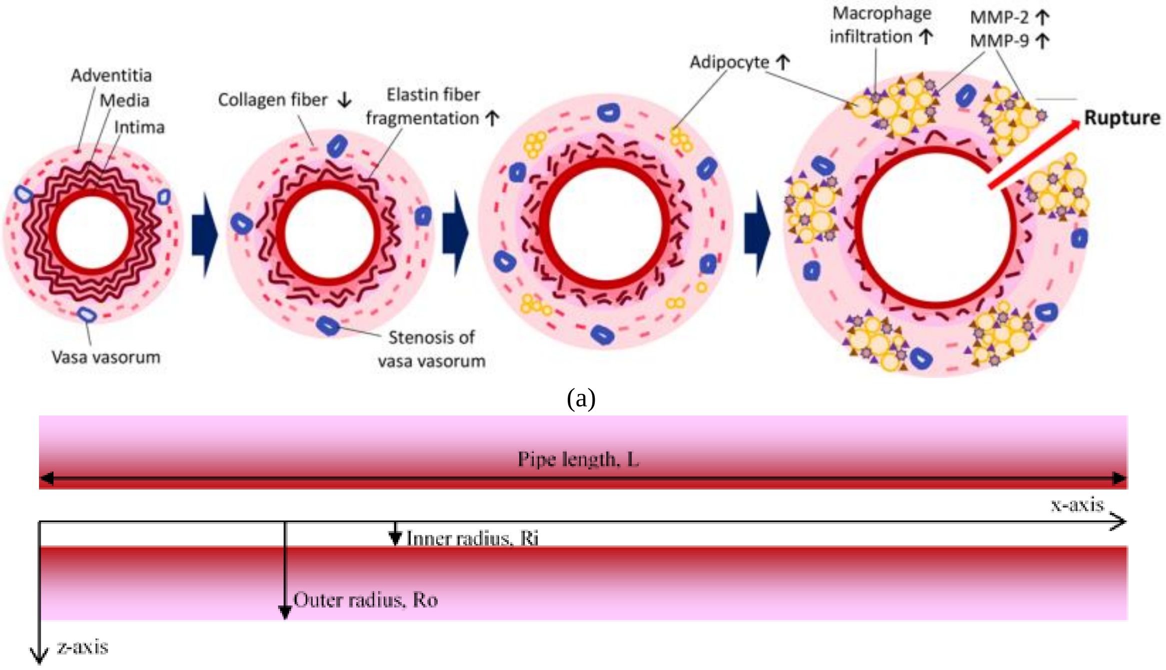

(a)

(b)

Fig. 1 (a) schematic of abdominal aortic aneurysm rupture (Kugo *et al*. 2018), (b) Schematic aneurysm modeled in this study via pipe structures

buckling related to an FG beam which was affected by a thermal load through the Ritz method. Also, by using Timoshenko theory, the vibrational as well as buckling responses associated with a beam made of FG composites were conducted by means of the Navier solution procedure (Ebrahimi and Salari 2015). Next, it can refer to a paper which deals with the vibration and buckling of reinforced composite plates (Wang *et al*. 2021b). The formulations were attained through the moving least square method and solved by using the mesh less procedure. Wang *et al*. (2022) extracted the formulation of vibration response associated with a disk whose material was reinforced composites through HSDT. In the abovementioned article, the results are obtained with the help of GDQM. The parameters that can affect the vibration of a small-sized plate, modeled via NSGT, placed in hygro-thermal surroundings were examined using the Galerkin method (Ebrahimi and Barati 2018). Also, based on a finite element model, the nonlinear vibration, buckling, and static bending of microplates affected by thermal loads were investigated utilizing classic plate theory along with von Kármán (Kazemi and Vatankhah 2021). They modeled the microplate in the framework of modified couple stress theory. By implementing FSDT as the plate theory and von Kármán theory to consider the effect of nonlinearity, Park and Kim (2006) managed to present an investigation on the vibrational chrachtristics of thermally influenced FG plates.

In order to reach a better understanding of intracranial aneurysm rupture, one of the critical phenomena is its bifurcation. As one of the most determining phases, bifurcation has been investigated for different structures. For instance, the bifurcation analysis associated with a member which was built via elastic-plastic based on the generalised beam theory was investigated (Gonçalves and Camotim 2007). Additionally, AminPour and Rizzi (2015) presented a paper on the bifurcation as well as stability of carbon nanotubes with one wall. In this area, the work in which the bifurcation corresponded to a nanotube with thick walls was investigated can be cited (Ma *et al*. 2021, Haughton and Ogden 1979, Hou *et al*. 2021, Huang *et al*. 2021d, Liu *et al*. 2021c, Yu *et al*. 2022). The presented paper studied two modes of this phenomenon. Also, the dynamic stability together with the bifurcation of nanotubes that were under thermal loading was conducted by using L-P method as the solution procedure (Liu *et al*. 2019).

The stability analysis of the abdominal aortic aneurysm, which is modeled as a microtube with varying sections, is explored in this paper. The vibrational frequency as well as critical temperature are obtained for the system. By using Timoshenko's beam theory, MCST, and the energy method, the formulations of the problem are acquired. Then, GDQM is implemented to discretize and rewrite the formulation in an eigenvalue form. The obtained results' accuracy is proven through some comparative tables. The effect of such factors as the small-scale factor, the rate of radius change, and end conditions on the system's stability are investigated.

2. Mathematical modeling of aneurysm mechanism

In this paper, the mechanism of an aneurysm was mathematically simulated via pipe structures with 'L' as the pipe length, 'Ri' as the inner radius, and 'Ro' as the outer radius (Fig. 1). The aneurysm mechanism is composed of several materials, which are presented in Fig. 1(a) The geometric impact of micro pipe is investigated in this paper, so the external radius (Ro) is varied along the pipe length according to the following mathematical equation.

$$Ro = Ro_L(1 - \eta x/L) \tag{1}$$

where 'η' is the rate of radius change. According to the first-order beam theory, the governing equations of the temperature-dependent aneurysm mechanism are generated based on the Hamilton principle regarding the following form (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).

$$\int_{t_1}^{t_2} \delta H dt = 0 \tag{2}$$

where

$$H = V - U - W \tag{3}$$

In which U, W, and V represent strain energy, the energy of the external works, and the kinetic energy (Liu *et al*. 2020b, Habibi *et al*. 2021, He *et al*. 2021, Huang *et al*. 2021a, Liu *et al*. 2021b, Zhang *et al*. 2021). Using the modified couple stress theory, the strain energy of the micropipe can be extracted as the following form (Yang *et al*. 2002):

$$U = \iiint u dv = 1/2 \iiint (m{:}\chi + \sigma{:}\varepsilon) dv \tag{4}$$

where 'ε' is the microtube's strain. Also, the displacements on the basis of Timoshenko theory are (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020b, Zare *et al*. 2020, Dai *et al*. 2021b):

$$\varepsilon_{xx} = u_{1_{,x}} = u_{,x} + z\psi_{,x} + 1/2\left(w_{,x}\right)^2 \tag{5a}$$

$$\varepsilon_{xy} = 0 \tag{5b}$$

$$2\varepsilon_{xz} = \left(u_{1,z} + u_{3,x}\right) = \left(\psi + w_{,x}\right) \tag{5c}$$

where

$$\begin{aligned} u_1(t,x,y,z) &= z\psi(x,t) + u(x,t) \\ u_2(t,x,y,z) &= 0 \\ u_3(t,x,y,z) &= w(x,t) \end{aligned} \tag{6}$$

In which w and u denote the fluxeral and axial displacments, and the rotation is represented by ψ. The stress of the system can be given as (Al-Furjan *et al*. 2020c, d, e, Bai *et al*. 2020, Li *et al*. 2020a, Zhang *et al*. 2020, Guo *et al*. 2021c, Liu *et al*. 2021a):

$$\sigma_{ij} = E\varepsilon_{ij}, i = j \tag{7a}$$

$$\sigma_{ij} = G\varepsilon_{ij}, i \neq j \tag{7b}$$

$$2G = E/(1 + \nu) \tag{7c}$$

The deviatoric matrices *m*', according to modified couple stress theory, can be written:

$$m = 2l^2\mu\chi \tag{8}$$

where 'μ' "*l*" are Lamé constants well as the length-scale parameter. Additionally, 'χ' is as follows (Ebrahimi *et al*. 2019b, c, 2020b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Shariati *et al*. 2020, Shokrgozar *et al*. 2020):

$$2\chi = (\nabla\theta)^T + \nabla\theta \tag{9}$$

where

$$2\theta = curl(u) \tag{10}$$

Using the Eqs. (8), (9) and (10), the the deviatoric and symmetric curvature are:

$$\chi_{11} = \chi_{22} = \chi_{33} = \chi_{23} = \chi_{32} = \chi_{13} = \chi_{31} = 0 \tag{11a}$$

$$2\chi_{12} = 2\chi_{21} = 0.5\left(\psi_{,x} + w_{,xx}\right) - w_{,xx} \tag{11b}$$

Now, the strain energy (Habibi *et al*. 2017, 2019c, Safarpour *et al*. 2018, 2020, Ghazanfari *et al*. 2020) of the microtube can be written as (Guo *et al*. 2021b, Li *et al*. 2021, Wang *et al*. 2021a, Zhao and Yu 2021, Zhong and Liang 2022):

$$\begin{aligned}
S = &\iiint \delta s dv = -\int_0^L D_{11}w_{,xxx} dx\, \delta(\psi) \\
&-\int_0^L D_{11}\psi_{,xx} dx\, \delta(\psi) - \int_0^L A_{11}u_{,xx} dx\, \delta(u) + A_{11}u_{,x}\Big|_0^L\delta(u) \\
&-D_{11}w_{,xxx}\Big|_0^L\delta(w) + D_{11}w_{,xx}\Big|_0^L\delta\left(w_{,x}\right) \\
&+\int_0^L D_{11}w_{,xxxx} dx\, \delta(w) + C_{10}w_{,x}\Big|_0^L\delta(w) - D_{11}w_{,xxx}\Big|_0^L\delta(w) \\
&+D_{11}w_{,xx}\Big|_0^L\delta\left(w_{,x}\right) + A_{11}u_{,x}w_{,x}\Big|_0^L\delta(w) + D_{11}w_{,xx}\Big|_0^L\delta(\psi) \\
&+\int_0^L D_{11}\psi_{,xxx} dx\, \delta(w) - D_{11}\psi_{,xx}\Big|_0^L\delta(w) + D_{11}\psi_{,x}\Big|_0^L\delta\left(w_{,x}\right) \\
&-2\int_0^L D_{11}w_{,xxxx} dx\, \delta(w) - D_{11}w_{,xx}\Big|_0^L\delta(\psi) \\
&-2D_{11}w_{,xx}\Big|_0^L\delta\left(w_{,x}\right) + 2D_{11}w_{,xxx}\Big|_0^L\delta(w) \\
&+\int_0^L D_{11}w_{,xxx} dx\, \delta(\psi) - \int_0^L D_{11}\psi_{,xxx} dx\, \delta(w) \\
&-D_{11}\psi_{,x}\Big|_0^L\delta\left(w_{,x}\right) + D_{11}\psi_{,xx}\Big|_0^L\delta(w) \\
&-\frac{1}{2}\int_0^L \frac{\partial}{\partial x}\left(A_{11}\left(w_{,x}\right)^3\right) dx\, \delta(w) + \frac{A_{11}}{2}\left(w_{,x}\right)^2\Big|_0^L \delta(u) \\
&+C_{10}\psi|_0^L\delta(w) + \int_0^L C_{10}\psi\delta(\psi)\, dx \\
&-A_{11}\int_0^L \frac{\partial}{\partial x}\left(u_{,x}w_{,x}\right) dx\, \delta(w) - 0.5A_{11}\int_0^L \frac{\partial}{\partial x}\left({w_{,x}}^2\right) dx\, \delta(u) \\
&+0.5A_{11}\left(w_{,x}\right)^3\Big|_0^L \delta(w) - C_{10}\int_0^L w_{,xx} dx\, \delta(w) \\
&+\int_0^L C_{10}w_{,x}\delta(\psi)\, dx + D_{11}\psi_{,x}\Big|_0^L\delta(\psi) \\
&+\int_0^L D_{11}w_{,xxxx\psi} dx\, \delta(w) \\
&-l^2 0.5A_{10}\left[\left[\int_0^L \frac{\partial}{\partial x}\left[0.5\left(\psi_{,x} + w_{,xx}\right)\right.\right.\right. \\
&\left.\left.- w_{,xx}\right] dx\, \delta(\psi)\right] l^2\frac{1}{4}A_{10}\left[\left(\left(\psi_{,x} + w_{,xx}\right) - 0.5w_{,xx}\right)\Big|_0^L \delta(\psi)\right. \\
&\left.- A_{10}\left[0.5w_{,xxx}\right]\Big|_0^L\delta(w)\right] l^2 A_{10}\int_0^L \left[-0.25\left(\psi_{,xxx} + w_{,xxxx}\right)\right. \\
&\left.+ 0.5w_{,xxxx}\right] dx\, \delta(w) \\
&-\int_0^L \frac{\partial}{\partial x}\left(C_{10}(\psi)\right) dx\, \delta(w) l^2 A_{10}\left[0.25\left(\psi_{,xx} + w_{,xxx}\right)\right]\Big|_0^L\delta(w)
\end{aligned} \tag{12}$$

$$+A_{10}\left(\psi_{,x} + w_{,xx} + 0.5w_{,xx}\right)\Big|_0^L \delta\left(w_{,x}\right)$$

In which

$$(A_{10}, A_{11}, C_{10}, D_{11}) \ = \int_A (G, E, GK_S, E(r\,sin(\theta))^2)\,dA \tag{13}$$

Here, ‘K_S’ is the shear correction factor for the shear deformation theory of circular beams that is calculated as follows (Ma *et al*. 2020):

$$K_S = \frac{K_{SA}}{K_{SB}}, \tag{14a}$$

$$K_{SA} = 6(1+\varsigma^2)^2(1+\nu)^2 \tag{14b}$$

$$\varsigma = \frac{R_i}{R_O} \tag{14c}$$

$$\begin{aligned} K_{SB} &= (7+14\nu+8\nu^2)(1+\varsigma^2)^2 \\ &+4\varsigma^2(5+10\nu+4\nu^2) \end{aligned} \tag{14d}$$

Also, the work associated with the external foces is (Habibi *et al*. 2019a, Safarpour *et al*. 2019b, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Chen *et al*. 2022):

$$\delta W = \iiint F^T w_{,x}\delta\left(w_{,x}\right)dv \tag{15}$$

where

$$F^T = \iint E\alpha \Delta T dA \tag{16}$$

And the kinetic energy is presented as follows (Habibi *et al*. 2018a, 2019b, d, e, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a).

$$\begin{aligned} \delta V = 1/2\delta \int_0^L \iint_A \rho\left({\dot u_1}^2 + {\dot u_2}^2 + {\dot u_3}^2\right)dA\,dx = \\ 1/2\delta \int_0^L \iint_A \rho\left(\dot u^2 + z^2\dot\psi^2 + \dot w^2\right)dA\,dx \end{aligned} \tag{17}$$

The final Euler-Lagrange equation using the Hamilton method is performed by substitution of Eqs. (12), (15) and (17) into Eq. (2), and putting the variation of ‘u’, ‘w’ and ‘ψ’ to zero (Habibi *et al*. 2016, 2018b, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019).

$$\delta(u): 1/2A_{11}\frac{\partial}{\partial x}\left(w_{,x}\right)^2 + \frac{A_{11}\partial}{\partial x}\left(u_{,x}\right) += m_0\ddot u \tag{18a}$$

$$\begin{aligned} &\delta(\psi): C_{10}\left(\psi + w_{,x}\right) - 0.25l^2A_{10}\left(\psi_{,x} - w_{,xx}\right) \\ &-\frac{\partial}{\partial x}\left(D_{11}\psi_{,x}\right) = m_2\ddot\psi \end{aligned} \tag{18b}$$

$$\begin{aligned} &\delta(w): \\ &-0.25l^2A_{10}\frac{\partial^2}{\partial x^2}\left(\left(\psi_{,x} - w_{,xx}\right)\right) - \frac{C_{10}\partial}{\partial x}\left(\psi + w_{,x}\right) \\ &-0.5A_{11}\frac{\partial}{\partial x}\left(\left(w_{,x}\right)^2 w_{,x} + 2u_{,x}w_{,x}\right) - F^T w_{,xx} = m_0\ddot w \end{aligned} \tag{18c}$$

In addition, the end conditions are (Shafiei and She 2018, Shafiei *et al*. 2019, 2020):

$$\delta(u): A_{11}u_{,x} + 0.5A_{11}\left(w_{,x}\right)^2 = 0 \tag{19a}$$

$$\delta(\psi): D_{11}\psi_{,x} + 0.25l^2A_{10}\left(\psi_{,x} - w_{,xx}\right) = 0 \tag{19b}$$

$$\begin{aligned} &\delta(w): +0.25l^2A_{10}\frac{\partial}{\partial x}\left(\psi_{,x} - w_{,xx}\right) + \\ &C_{10}\left(\psi + w_{,x}\right) + A_{11}\left(0.5\left(w_{,x}\right)^2 + w_{,x}\right)w_{,x} = 0 \end{aligned} \tag{19c}$$

where

$$(m_0, m_2) = \int_A (\rho, \rho r^2\,sin^2(\theta))dA \tag{20}$$

3. Methodology of solving procedure

The generalized differential quadrature method (GDQM) is employed to solve the governing equations (Eq.(18)), accordingly, the kth order derivative function of ‘*f*(*x*)’ will be changed to the following matrices form (Ebrahimi and Shafiei 2017, Ghadiri *et al*. 2017e, Mirjavadi *et al*. 2017a, Shafiei and Kazemi 2017a, Shafiei *et al*. 2017d, Azimi *et al*. 2018).

$$\left.\frac{\partial^k f(x)}{\partial x^k}\right|_{x=x_P} = \sum_{j=1}^{n} C_{ij}^{(k)} f(x_i) \tag{21a}$$

where ‘n’ represents the number of grid points which are dispersed as follows (Ehyaei *et al*. 2017, Ghadiri *et al*. 2017c, d, Mirjavadi *et al*. 2017d, Shafiei and Kazemi 2017b, Shafiei *et al*. 2017c):

$$x_i = L/2\left(1 + cos\left(\pi(1-i)/(n-1)\right)\right) \tag{21b}$$

And C_{ij} is defined as follows (Ghadiri *et al*. 2017a, b, Mirjavadi *et al*. 2017b, c, Shafiei *et al*. 2017a, b):

$$C_{ij}^{(k)} = k\left[C_{ij}^{(1)}C_{ij}^{(k-1)} + C_{ij}^{(k-1)}\left(x_j - x_i\right)^{-1}\right] \tag{21c}$$

$$C_{ii}^{(k)} = -\sum_{j=1, i\neq j}^{n} C_{ij}^{(k)}, i = j \tag{21d}$$

In which

$$C_{ij}^{(1)} = \Xi(x_i)\left[\left(x_i - x_j\right)\Xi\left(x_j\right)\right]^{-1}, i \neq j \tag{21e}$$

$$C_{ij}^{(1)} = -\sum_{j=1, i\neq j}^{n} C_{ij}^{(1)}, i = j \tag{21f}$$

where (Ebrahimi and Shafiei 2016, Shafiei *et al*. 2016c, d, f, Ebrahimi *et al*. 2017, Shivanian *et al*. 2017)

$$\Xi(x_i) = \prod_{j=1, j\neq i}^{k}\left(x_i - x_j\right) \tag{21h}$$

The following time-independent modal analysis will be obtained by implementing the derivative function of GDQM (Eq. (21)) to the governing equations (Eq. (18)) and boundary conditions ((19)) (Azimi *et al*. 2016, Ghadiri and Shafiei 2016c, Ghadiri and Shafiei 2016a, Shafiei *et al*. 2016a, e, g).

$$\omega = \sqrt{[K]/[M]}\{u \quad w \quad \psi\}^T \tag{22a}$$

Table 1 Comparison results of frequency of thermal vibration ($\omega L^2\sqrt{(A_{11}/D_{11})}$) of fully pinned and fully clamped microtube regarding the temperature change (ΔT) against the results of Huang *et al.* (2021c), L=40Ro=80Ri

	Clamped		Pinned	
	Present	Huang *et al.* (2021c)	Present	Huang *et al.* (2021c)
ΔT=0	22.346237	22.34646	9.8600074	9.860106
ΔT=10	22.240098	22.24032	9.6655613	9.665658
ΔT=20	22.131889	22.13211	9.4642774	9.464372
ΔT=30	22.02157	22.02179	9.2557074	9.2558
ΔT=40	21.909101	21.90932	9.0393496	9.03944
ΔT=50	21.794462	21.79468	8.8146299	8.814718
ΔT=60	21.677593	21.67781	8.5808892	8.580975
ΔT=70	21.558474	21.55869	8.3373716	8.337455
ΔT=80	21.437056	21.43727	8.0831922	8.083273
ΔT=90	21.313297	21.31351	7.8173108	7.817389

Table 2 Validity of thermal buckling of pinned small-scale pipe for different aspect ratio values (L/R)

	Shan and Huang (2022)	Present study
L=60(Ro-Ri)	31.70918	31.67746583
L=50(Ro-Ri)	45.64677	45.60112223
L=40(Ro-Ri)	71.2816	71.2103144

where

$$[K]=\begin{bmatrix}[K_{11}] & 0 & [K_{13}]\\ 0 & [K_{22}] & [K_{23}]\\ [K_{31}] & [K_{32}] & [K_{33}]\end{bmatrix} \tag{22b}$$

$$[M]=\begin{bmatrix}m_0 & 0 & 0\\ 0 & m_2 & 0\\ 0 & 0 & m_0\end{bmatrix} \tag{22c}$$

$$[K_{11}]=A_{11}\sum_{j=1}^{n}C_{ij}^{(2)} \tag{22d}$$

$$[K_{13}]=0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(1)}\left(\sum_{j=1}^{n}C_{ij}^{(1)}w_j\sum_{j=1}^{n}C_{ij}^{(1)}w_j\right) \tag{22e}$$

$$[K_{22}]=C_{10}-D_{11}\sum_{j=1}^{n}C_{ij}^{(2)}-0.25l^2A_{10}\sum_{j=1}^{n}C_{ij}^{(1)} \tag{22f}$$

$$[K_{23}]=C_{10}\sum_{j=1}^{n}C_{ij}^{(1)}+0.25l^2A_{10}\sum_{j=1}^{n}C_{ij}^{(2)} \tag{22g}$$

$$[K_{31}]=-0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(2)}\sum_{j=1}^{n}C_{ij}^{(1)}w_j \tag{22h}$$

$$[K_{32}]=-0.25l^2A_{10}\sum_{j=1}^{n}C_{ij}^{(3)}-C_{10}\sum_{j=1}^{n}C_{ij}^{(1)} \tag{22i}$$

$$\begin{aligned}[K_{33}]&=0.25l^2A_{10}\sum_{j=1}^{n}C_{ij}^{(4)}-C_{10}\sum_{j=1}^{n}C_{ij}^{(2)}\\ &-F^T\sum_{j=1}^{n}C_{ij}^{(2)}-0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(1)}\sum_{j=1}^{n}C_{ij}^{(2)}u_j\\ &-0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(2)}\left(\sum_{j=1}^{n}C_{ij}^{(1)}w_j\sum_{j=1}^{n}C_{ij}^{(1)}w_j\right)\end{aligned} \tag{22j}$$

For the thermal buckling (ΔT_{CR}) analysis, the time-dependent terms assign to zero, and the Eq. (22).a reform to the following form to obtain the thermal buckling. (Ghadiri and Shafiei 2016b, Ghadiri *et al.* 2016a, b, c, d, Shafiei *et al.* 2016b)

$$\Delta T_{CR}=\sqrt{[K^T]/[M^T]}\{u\quad w\quad \psi\}^T \tag{23a}$$

where

$$[M^T]=\begin{bmatrix}0 & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & EA\alpha\end{bmatrix}\sum_{j=1}^{n}C_{ij}^{(2)} \tag{23b}$$

$$[K^T]=\begin{bmatrix}[K_{11}] & 0 & [K_{13}]\\ 0 & [K_{22}] & [K_{23}]\\ [K_{31}] & [K_{32}] & [K_{33}{}^T]\end{bmatrix} \tag{23c}$$

where

$$\begin{aligned}[K_{33}]&=0.25l^2A_{10}\sum_{j=1}^{n}C_{ij}^{(4)}-C_{10}\sum_{j=1}^{n}C_{ij}^{(2)}\\ &-0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(1)}\sum_{j=1}^{n}C_{ij}^{(2)}u_j\\ &-0.5A_{11}\sum_{j=1}^{n}C_{ij}^{(2)}\left(\sum_{j=1}^{n}C_{ij}^{(1)}w_j\sum_{j=1}^{n}C_{ij}^{(1)}w_j\right)\end{aligned} \tag{23d}$$

4. Results and discussions

Results validation as one of the essential parts of studies must be evaluated., in this regard, both thermal frequency and thermal buckling results should be compared with previously published reports. Since the frequency analysis and thermal buckling behavior of the aneurysm mechanism have not been investigated yet, the present results will validate via results of other microstructures, pipes, and tubes, so, Table 1 confirms the accuracy of the presented results compared to the results of Huang *et al.* (2021c) concerning the thermal vibration of microtube based on the modified couple stress theory. Moreover, Table 2 shows excellent agreement between the present study results compared to the outcomes of Shan and Huang (2022) regarding the thermal buckling of small-scale tubes.

The following dimension less parameter will be defined in order to better description of results, which 'Ω' is dimensionless frequency, and 'ϑ' is the size effect parameter.

$$\Omega^2=\omega^2L^4\pi A_{11}/D_{11} \tag{24a}$$

$$\vartheta^2Ro=l^2 \tag{24b}$$

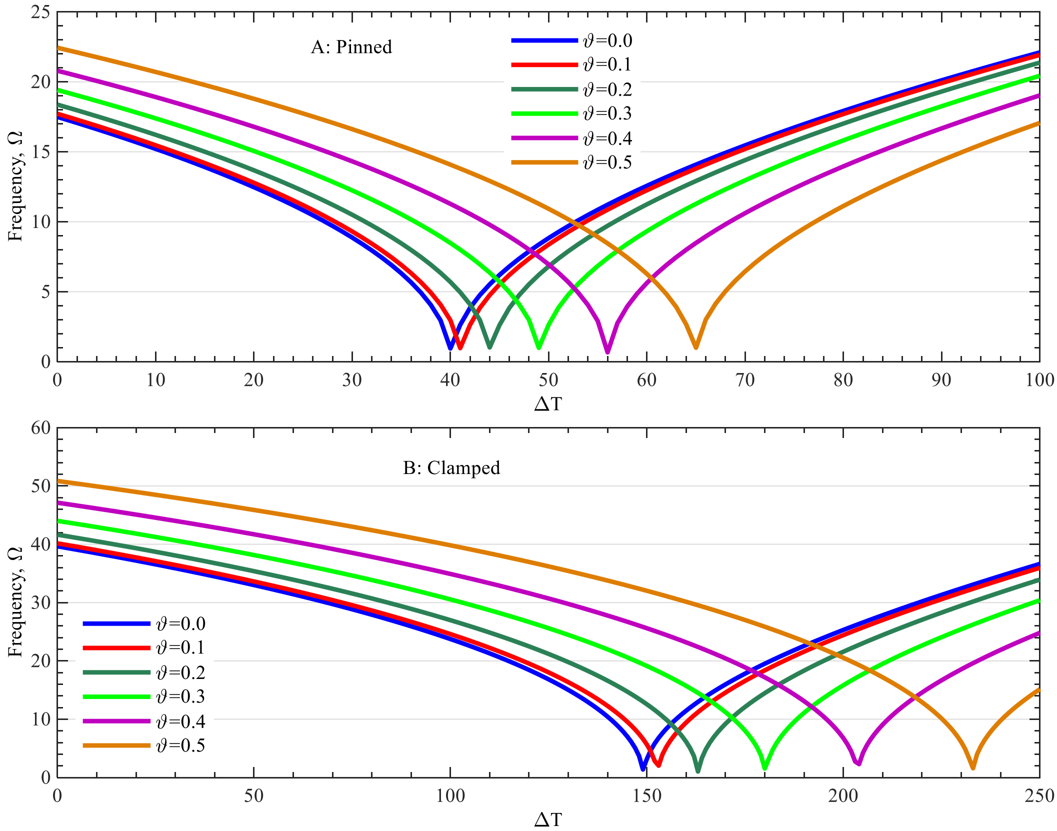

Fig. 2 Thermal vibration (Ω) aneurysm mechanism versus the small-scale parameter (ϑ) based on clamped and pinned boundary conditions, L=100Ro=200Ri

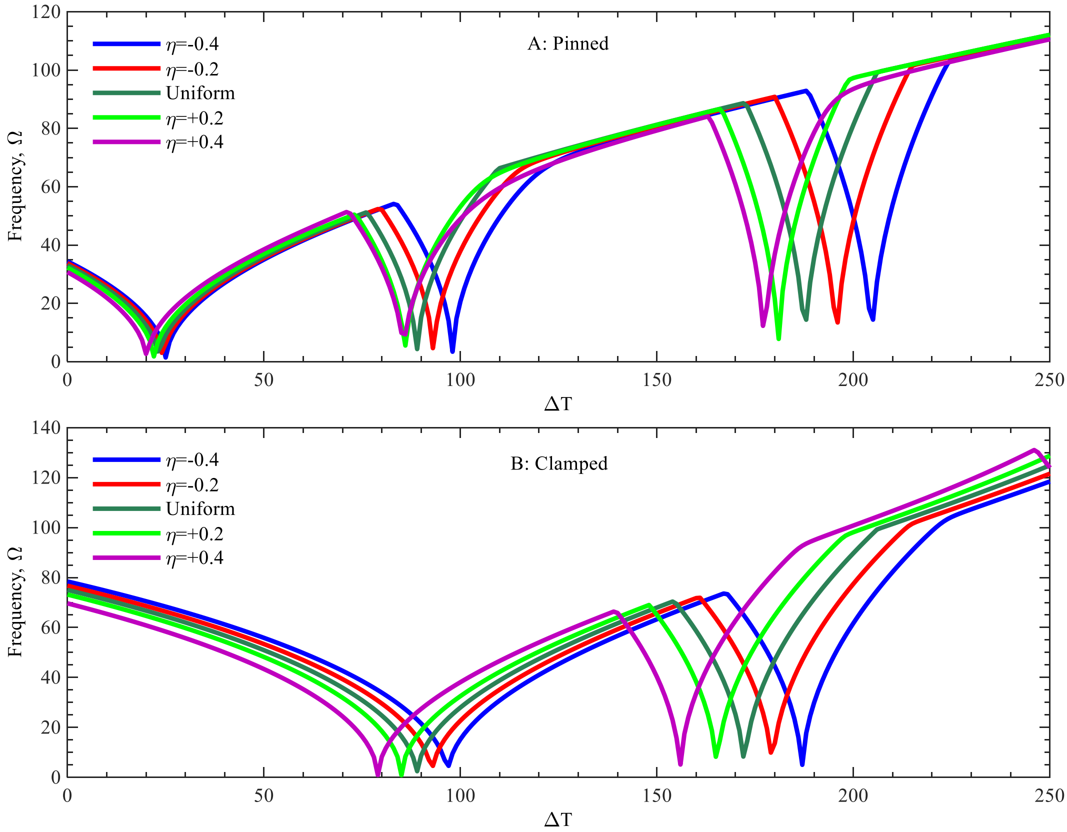

Fig. 3 Thermal vibration (Ω) behavior of aneurysm mechanism versus the rate of section change (η) for both clamped and pinned type of boundary conditions, L=200Ro, Ro=2Ri, ϑ=1.0

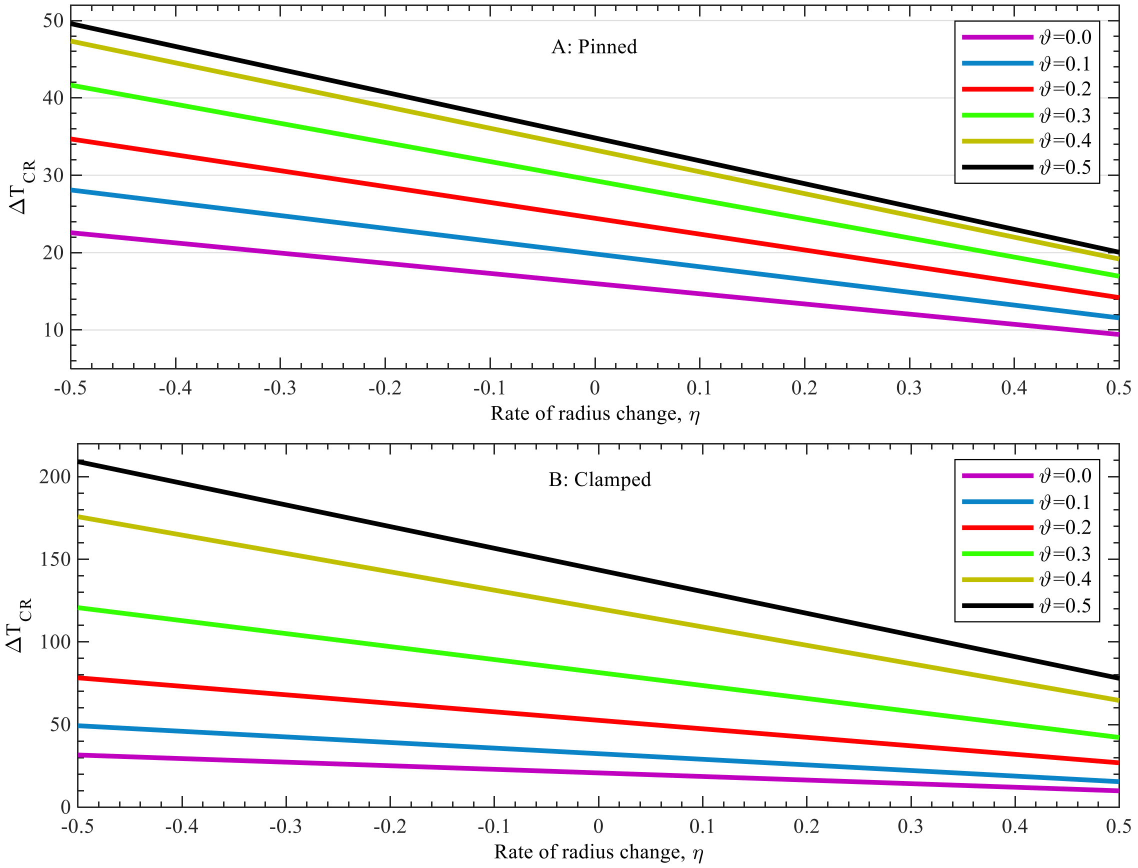

Fig. 4 Impact of small-scale parameters (ϑ) on the thermal buckling (ΔT_{CR}) of aneurysm mechanism versus the rate of radius change (η), L=20Ro, Ro=3Ri

Next, the impact of parameters on the stability response of a microtube affected by thermal loads is explored. Firstly, the influence related to the small scale parameter on the stability analysis of the microtube in Fig. 2 for two end conditions is investigated. in this figure, the variation of frequency associated with the microtube is plotted against the value of temperature difference. This figure demonstrates that the bifurcation points occur in a higher temperature difference, provided that the small-scale factor possesses a higher value, regardless of the boundary condition. In addition, the critical temperatures are higher in cases with stiffer end conditions.

Fig. 3, in a similar fashion, investigate the effect related to the rate of section change on bifurcation and dynamic stability of the system. The x-axis of these figures represents frequency, while the y-axis is the temperature difference. The figure indicates that, in any boundary condition, the system can have a higher critical temperature if the value of η is higher. Additionally, it can be seen that three bifurcation points for microtubes with pined and two points for microtubes with clamped conditions can happen in this range of temperature difference, showing the increasing effect of stiffer boundary conditions.

Lastly, the variation of critical temperature, or bifurcation points, is plotted versus the radius change rate for various small-scale factors in Fig. 4. The figures are extracted for two end conditions. As seen, the critical temperature intensifies by increasing the value of the small-scale parameter in both of the end conditions. Also, this value is diminished by increasing the rate of radius change. As a general conclusion, the cases with stiffer end conditions have a higher critical temperature.

5. Conclusions

The stability analysis of the abdominal aortic aneurysm, which is modeled as a microtube with varying sections, is explored in this paper. The vibrational frequency as well as critical tempreture are obtained for the system. By using Timoshenko's beam theory, MCST, and the energy method, the formulations of the problem are acquired. Then, GDQM is employed to discretize and rewrite the formulation in an eigenvalue form. The obtained results' accuracy is proven through some comparative tables. The effect of such factors as the small-scale factor, the rate of radius change, and end conditions on the system's stability are investigated. Here are some of the highlighted conclusions of the current article:

- The cases with stiffer end conditions have a higher critical temperature.
- The system can have a higher critical temperature if the value of η is higher.
- The bifurcation points occur in a higher temperature difference, provided that the small-scale factor possesses a higher value.

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