natural frequencies of the nonlocal double-nanobeam-system. Also Eltaher *et al.* (2012), have presented free vibration analysis of functionally graded (FG) size-dependent nanobeams using finite element method. Also in recent years the mechanical behavior of FG nanoplates is investigated based on various plate shear deformation plate theories (Ebrahimi and Barati 2016a, b, c, d, e, Ebrahimi *et al.* 2016a, Ebrahimi and Dabbagh 2016, Ebrahimi and Hosseini 2016a, b) while the analysis of nano-structure's mechanical behaviors is one of recent interesting research topics. (Ebrahimi and Barati 2016f, g, h, i, j, k, l, m, n, Ebrahimi and Barati 2017).

Because the nanobeams has the high proportion of the surface to volume, the surface stress effects has important role in their mechanics behavior of these structures (Ebrahimi *et al.* 2016a, 2015, Ebrahimi and Boreiry 2015). Hence, Gurtin and Murdach (1978) have considered surface stress effects. In this theory the surface is considered as a part of (nonphysical) the two-dimensional with zero thickness (mathematically) which has covered the total volume. This theory has used in many researches about nanobeams. Surface elasticity and residual stress effect on the elastic field of a nanoscale elastic layer is presented by Intarit *et al.* (2011). The nonlinear flexural vibrations of small scale beams in presence of surface properties have been studied by Gheshlaghi and Hasheminejad (2011). Nevertheless, nonlinear free vibration of functionally graded nanobeams with surface effects has been investigated by Sharabiani and Haeri (2013). In addition, Sahmani *et al.* (2014) have investigated Surface energy effects on the free vibration of post buckled third-order shear deformable nanobeams. And they have studied Surface properties on the nonlinear forced vibration response of third-order shear deformable nanobeams (Sahmani *et al.* 2015). In these papers they have been used to Gurtin-Murdach elasticity theory. Furthermore, the nonlinear free vibration of nanobeams with considering surface properties has been studied by Nazemnezhad *et al.* (2012). However, Hosseini-Hashemi and Nazemnezhad (2013) have presented nonlinear free vibration of functionally graded nanoscale beams with surface properties. As well as, Ansari *et al.* (2014) have investigated nonlinear forced vibration characteristics of nanobeams including surface stress effect. In this study, a new formulation of the Timoshenko beam theory has been developed through the Gurtin-Murdoch elasticity theory in which the effect of surface stress has been incorporated. Moreover, the surface and nonlocal effects on the nonlinear flexural free vibrations of elastically supported non-uniform cross section nanobeams have been investigated by Malekzadeh and Shojaee (2013) simultaneously. Vibration and buckling characteristics of FG nanobeams subjected to thermal effects are investigated by Ebrahimi and Salari (2015a, b, c) and Ebrahimi *et al.* (2015b, c). Ebrahimi and Barati (2016o, p, q) have also analyzed buckling behavior of smart piezoelectrically actuated nanobeams and plates in thermal environment.

In the field of elastic foundation there are linear and nonlinear which is named as Winkler and Pasternak respectively. Elastic foundation has employed in the size of macro and nanobeams in many recent researches as explained below. Zhao *et al.* (2015), have investigated the axial buckling of a nanowire resting on Winkler-Pasternak substrate medium with the Timoshenko beam theory. However, free vibration analysis of tapered beam-column with pinned ends embedded in Winkler-Pasternak elastic foundation is presented by Civalek (2010). In addition, Simple analytical expressions have been presented by Fallah and Aghdam (2011) for large amplitude free vibration and post-buckling analysis of functionally graded beams rest on nonlinear elastic foundation. Furthermore, Jang *et al.* (2011), have presented a new method of analyzing the non-linear deflection behavior of an infinite beam on a non-linear elastic foundation. Also, Niknam and Aghdam (2015) have obtained a closed form solution for both natural frequency and buckling load of nonlocal functionally graded beams resting on nonlinear elastic foundation. Moreover, the static instability of a nanobeam with geometrical imperfections with elastic foundation has been investigated by Mohammadi *et al.* (2014).

In this paper, Size-dependent effect is included in the nonlinear model. Nevertheless, differential transformation method has been used to predict the buckling behavior of single walled carbon nanotube on Winkler foundation under various boundary conditions by Pradhan and Reddy (2011).

In recent years vibration of curved nanobeams and nanorings, have been worked in many empirical experiments and dynamic molecular simulations (Wang and Duan 2008). Hence some researchers are interested in studding of vibration curved nanobeams and nanorings. Yan and Jiang (2011) have investigated the electromechanical response of a curved piezoelectric nanobeam with the consideration of surface effects. In addition, a new numerical technique, the differential quadrature method has been developed for dynamic analysis of the nanobeams in the polar coordinate system by Kananipour *et al.* (2014). Moreover, Khater *et al.* (2014) have investigated the effect of surface energy and thermal loading on the static stability of nanowires. In this research, nanowires has been considered as curved fixed-fixed Euler-Bernoulli beams and has been used Gurtin-Murdoch theory to represent surface effects. The model has taken into account both von Kármán strain and axial strain. Wang and Duan (2008) have surveyed the free vibration problem of nanorings/arches. In this research the problem was formulated on the framework of nonlocal elasticity theory. Nevertheless, explicit solution has been shown for size and geometry dependent free vibration of curved nanobeams with including surface effects by Assadi and Farshi (2011).

To the best of the author's knowledge, there has been no record or any study regarding the curved nanobeams with surface effects and elastic foundation. Therefore, there is strong scientific need to understand the dynamic behavior of curved nanobeam with surface effects in considering the effect of elastic foundations. The aim of this research is to survey the effects of Winkler and Pasternak elastic foundation on vibrations and natural frequencies of curved nanobeams. In this regard, the curved nanobeams have been used in framework Euler-Bernoulli beam theory. So the paper has investigated the effects of surface density, surface elasticity and surface residual stress.

2. Problem statements

In plane free vibration of curved nanobeam is considered. As it shown in Fig. 1, the radius curvature and thickness are considered R and h respectively. Additional surface effects are supposed for all the external surfaces.

The dynamic equilibrium equations for a curved Euler-Bernoulli beam, are given as

$$\begin{aligned}
&\frac{\partial V}{\partial \theta}+P=\rho A R\,\frac{\partial^2 u_r}{\partial t^2}+Rb\rho^s\left(\frac{\partial^2 u_r^+}{\partial t^2}+\frac{\partial^2 u_r^-}{\partial t^2}\right)-fR\\
&\frac{\partial P}{\partial \theta}-V=\rho A R\,\frac{\partial^2 u_\theta}{\partial t^2}+Rb\rho^s\left(\frac{\partial^2 u_\theta^+}{\partial t^2}+\frac{\partial^2 u_\theta^-}{\partial t^2}\right)-pR\\
&\frac{\partial M}{\partial \theta}+RV=0
\end{aligned} \tag{1}$$

Where $F(\theta, t)$ is the shearing force, $P(\theta, t)$ is the tensile force, A is the cross sectional area, ρ is the mass density, ρ^s is the surface density of the nanoring and b is the width of nanoring In Eq. (1). It should be notice the displacement components of the surface property must satisfy the following relations (Rao 2007).

$$\ddot{u}_r^+=\ddot{u}_r^-=\ddot{u};\qquad \ddot{u}_\theta^+ +\ddot{u}_\theta^- =2\ddot{u}_\theta \tag{2}$$

By employing Eq. (2) and substituting into Eq. (1) the equilibrium equations can be determined as follow.

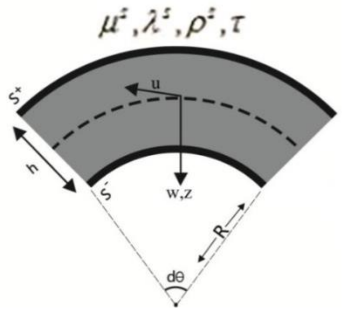


Fig. 1 Geometry of an element of a circular curved nanobeam with surface layers

$$P-\frac{1}{R}\frac{\partial^2 M}{\partial\theta^2}=\left(\rho AR+2Rb\rho^s\right)\frac{\partial^2 u_r}{\partial t^2}-fR$$
$$\frac{\partial P}{\partial\theta}+\frac{1}{R}\frac{\partial M}{\partial\theta}=\left(\rho AR+2Rb\rho^s\right)\frac{\partial^2 u_\theta}{\partial t^2}-pR \tag{3}$$

The normal stress resultant *P* from Eq. (3) should be vanished. Therefore, obtains the relation between radial displacement and bending moment such as Eq. (4)

$$\frac{1}{R}\left(\frac{\partial^2 M}{\partial\theta^2}+\frac{\partial^4 M}{\partial\theta^4}\right)+R\left(\frac{\partial p}{\partial\theta}-\frac{\partial^2 f}{\partial\theta^2}\right)=\left(\rho AR+2Rb\rho^s\right)\left(\frac{\partial^2 u_r}{\partial t^2}-\frac{\partial^4 u_r}{\partial t^2\partial\theta^2}\right) \tag{4}$$

The stress components of the surface layers must satisfy the following equilibrium relations (Gurtin and Murdoch 1978)

$$\tau^{\pm}_{\alpha\beta}=\tau\delta_{\alpha\beta}+\left(\mu^s-\tau\right)\left(u^{\pm}_{\alpha\beta}+u^{\pm}_{\beta\alpha}\right)+\left(\lambda^s+\tau\right)u^{\pm}_{\gamma\gamma}\delta_{\alpha\beta}+\tau u^{\pm}_{\alpha\beta} \tag{5}$$

Where $\tau^{\pm}$ are residual surface tensions under unconstrained conditions, μ^s and λ^s are the surface Lamé constants for the surface material.

The strain in the curved element can be expressed as

$$\varepsilon_{\theta\theta}=\frac{1}{R}\left[-u_r+\frac{\partial u_\theta}{\partial\theta}-\frac{x}{R}\frac{\partial}{\partial\theta}\left(u_\theta+\frac{\partial u_r}{\partial\theta}\right)\right] \tag{6}$$

Considering inextensible deformation of the curved element at *x*=0, it can be concluded that $u_r=\partial u_\theta/\partial\theta$. The stress-strain relation for the surface material can be determined as

$$\tau^{\pm}_{\theta\theta}=\tau\pm\frac{h\left[2\mu^s+\lambda^s\left(1-\nu\right)-\nu\tau\right]}{2R^2}\left(u_r+\frac{\partial^2 u_r}{\partial\theta^2}\right) \tag{7}$$

Bending moment resultant *M* due to normal stress $\sigma_{\chi\chi}$ can be described by integrating the strain components on the cross section as follow as

$$\mathrm{M}=-\mathrm{b}\int_{-\frac{h}{2}}^{\frac{h}{2}}E\,\varepsilon_{\theta\theta}x\,dx+\frac{bh}{2}(\tau^{+}_{\theta\theta}-\tau^{-}_{\theta\theta}) \tag{8}$$

By substituting Eqs. (6) and (7) into Eq. (8), the bending moment of curved element, can be obtained as

$$M=\left\{\frac{EI}{R^2}+\frac{bh^2\left[2?^s+\lambda^s(1-\nu)-\nu\tau\right]}{2R^2}\right\}\left(u_r+\frac{\partial^2 u_r}{\partial\theta^2}\right) \tag{9}$$

Using Eq. (9) in Eq. (4) yields the governing equation for the curved nanobeam as

$$\frac{\lambda}{R}\left(\frac{\partial^6 u_r}{\partial\theta^6}+2\frac{\partial^4 u_r}{\partial\theta^4}+\frac{\partial^2 u_r}{\partial\theta^2}\right)+R\left(\frac{\partial p}{\partial\theta}-\frac{\partial^2 f}{\partial\theta^2}\right)=\left(\rho AR+2Rb\rho^s\right)\left(\frac{\partial^2 u_r}{\partial t^2}-\frac{\partial^4 u_r}{\partial\theta^2\partial t^2}\right) \tag{10}$$

Where *f* and λ, defined as follow

$$f=-K_w u+K_p\nabla^2 u \tag{11}$$

$$\lambda=\frac{(EI)+0.5bh^2\left(2\mu^s+\lambda^s(1-\upsilon)-\upsilon\tau\right)}{R^2} \tag{12}$$

For free vibration of curved nanobeam or nanoring, the radial displacement can be considered as

$$u_r=\bar{u}_r(\theta)e^{i(\omega_n t+\varphi)} \tag{13}$$

In which ω_n is the natural frequency of the nanoring. By substituting Eq. (13) into Eq. (10) the following equation can be determined

$$\begin{aligned}&\frac{\partial^6\bar{u}_r}{\partial\theta^6}+2\frac{\partial^4\bar{u}_r}{\partial\theta^4}+\frac{\partial^2\bar{u}_r}{\partial\theta^2}+\beta_n\left(\bar{u}_r-\frac{\partial^2\bar{u}_r}{\partial\theta^2}\right)=0\\&\beta_n^2=\frac{2\rho AR^4+4R^4b\rho^s}{2EI+Ah\left(2\mu^s+\lambda^s(1-\nu)-\nu\tau\right)}\omega_n^2\end{aligned} \tag{14}$$

3. Numerical results

In this section, The bulk elastic properties are E=177.3 Gpa, ρ=7000 g/m^3 the surface elastic properties are λ^s=−8 N/m, μ^s =2.5 N/m, τ=1.7 N/m and ρ^s=7×10-^{6} Kg/m^2. To validating results, Assume β_n^* and ω_n^* be the corresponding parameters for a curved beam with vanished surface properties and ignored Winkler and Pasternak foundation. Next employing Eq. (14) in which β_n reflects the effects of mode shapes with consideration of surface effects and obtaining the relation for β_n/β_n^* it can be concluded that

$$\left(\frac{R}{R^*}\right)^4=\frac{\rho Eh^3+6\rho h^2\left[2\mu^s+\lambda^s-\nu\left(\lambda^s+\tau\right)\right]}{Eh^{*2}\left(\rho h+2\rho^s\right)} \tag{15}$$

Where h^* and R^* are the thickness and radius of curved nanobeams without surface properties, respectively. It is detected in Table 1, the results are in good agreement with reference (Assadi and Farshi 2011). The nanorings with total central angle α and simply-simply supported, the Navier solution can be written as

Table 1 Geometric comparison of curved beams for the same natural frequency with and without surface effects

$h^*(nm)$	$\frac{h}{h^*}=0.9$		$\frac{h}{h^*}=0.95$		$\frac{h}{h^*}=1$		$\frac{h}{h^*}=1.05$		$\frac{h}{h^*}=1.1$	
	$(R/R^*)^4$		$(R/R^*)^4$		$(R/R^*)^4$		$(R/R^*)^4$		$(R/R^*)^4$	
	Present	(Assadi and Farshi 2011)	Present	(Assadi and Farshi 2011)	Present	(Assadi and Farshi 2011)	Present	(Assadi and Farshi 2011)	Present	(Assadi and Farshi 2011)
10	0.6595	0.6595	0.7421	0.7421	0.8297	0.8297	0.9222	0.9222	1.0197	1.0197
20	0.7272	0.7272	0.8147	0.8147	0.9071	0.9071	1.0045	1.0045	1.1069	1.1069
30	0.7529	0.7529	0.8420	0.8420	0.9361	0.9361	1.0352	1.0352	1.1393	1.1393
40	0.7664	0.7664	0.8564	0.8564	0.9513	0.9513	1.0513	1.0513	1.1562	1.1562
50	0.7748	0.7748	0.8652	0.8652	0.9607	0.9607	1.0611	1.0611	1.1666	1.1666
60	0.7804	0.7804	0.8712	0.8712	0.9670	0.9670	1.0678	1.0678	1.1736	1.1736
70	0.7845	0.7845	0.8756	0.8756	0.9716	0.9716	1.0726	1.0726	1.1787	1.1787
80	0.7876	0.7876	0.8788	0.8788	0.9751	0.9751	1.0763	1.0763	1.1825	1.1825
90	0.7900	0.7900	0.8814	0.8814	0.9778	0.9778	1.0791	1.0791	1.1855	1.1855
100	0.7920	0.7920	0.8835	0.8835	0.9800	0.9800	1.0814	1.0814	1.1879	1.1879

Table 2 Radius of curvatures and opening angle effect on first three dimensionless frequency of an S-S curved nanobeam with surface effects (h=10 nm)

R (nm)	n=1			n=2			n=3		
	Opening angle			Opening angle			Opening angle		
	$\pi/4$	$\pi/2$	π	$\pi/4$	$\pi/2$	π	$\pi/4$	$\pi/2$	π
10	8.5860	7.9899	10.4824	35.5131	34.3442	31.9595	80.4543	79.1681	75.1266
20	9.9584	14.5663	33.1482	36.7241	39.8337	58.2651	81.6298	84.1989	98.9823
30	12.5597	26.0609	70.3180	38.8763	50.2389	104.243	83.6543	93.4159	143.790
40	16.5435	42.3610	122.245	42.1267	66.1739	169.444	86.6159	107.609	210.267
50	21.9300	63.3998	188.974	46.6265	87.7200	253.599	90.6203	127.320	297.848
60	28.6895	89.1502	270.519	52.4893	114.758	356.601	95.7771	152.774	406.031
70	36.7900	119.601	366.884	59.7808	147.160	478.403	102.187	183.985	534.516
80	46.2081	154.746	478.071	68.5258	184.833	618.985	109.934	220.873	683.140
90	56.9286	194.584	604.080	78.7233	227.714	778.334	119.078	263.334	851.811
100	68.9415	239.111	744.914	90.3584	275.766	956.445	129.660	311.279	1040.47

$$u_r=\sin\left(\frac{n\pi}{\alpha}\theta\right)e^{i\omega_n t} \tag{16}$$

By employing Eq. (16) and substituting into Eq. (10), the dimensionless natural frequencies of the curved nanobeam with surface properties and elastic foundations determined as

$$\Omega_n^2=\frac{\frac{\lambda}{R}\left(\lambda_n^6-2\lambda_n^4+\lambda_n^2\right)+R\left(K_w\left(\lambda_n^2\right)+\frac{K_p}{R^2}\left(\lambda_n^4\right)\right)}{\left(\rho AR+2Rb\rho^s\right)\left(1+\lambda_n^2\right)}\frac{(R\alpha)^4\rho A}{EI};\qquad \lambda_n=\frac{n\pi}{\alpha} \tag{17}$$

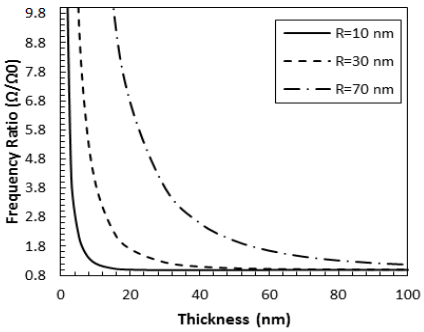


Fig. 2 Frequency ratio with and without surface effects versus thickness *h* for different radius of curvature

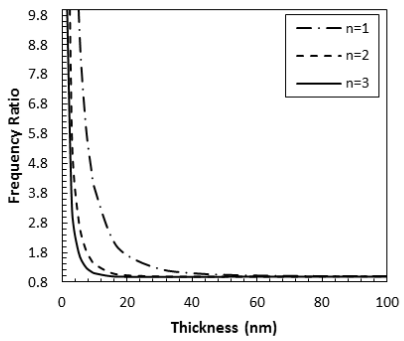


Fig. 3 Frequency ratio with and without surface effects versus thickness *h* for different mode numbers

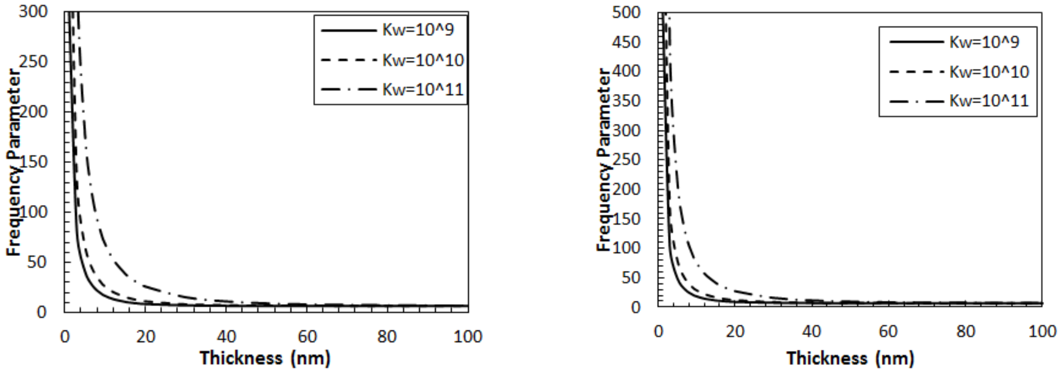
The dimensionless natural frequency of curved beam without surface effects and elastic foundation can be written as

$$\Omega_{n0}^2 = \frac{\mathrm{EI}\left(\lambda_n^6 - 2\lambda_n^4 + \lambda_n^2\right)}{\left(\rho A R^4\right)\left(1+\lambda_n^2\right)} \frac{\left(R\alpha\right)^4 \rho A}{EI}; \qquad \lambda_n = \frac{n\pi}{\alpha} \tag{18}$$

3.1 Effect of thickness on frequency ratio with different radius of curvature

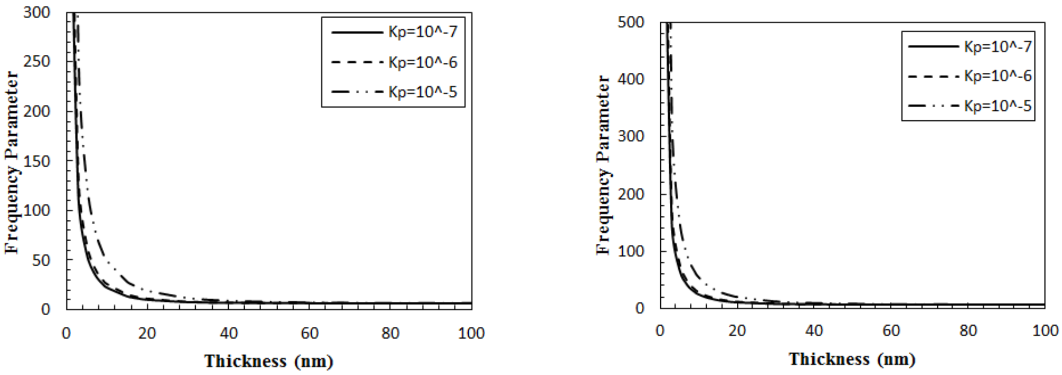
In this subsection, the effect of the thickness (*h*) with various curvature radiuses on frequency ratio with and without surface effects is examined. The same material and geometric parameters are selected is used for the results by the present model in Fig. 2. In addition the Winkler and Pasternak elastic foundation for this case, are 10^{10} N/m^2 and 10^{-6} N respectively. To highlight the surface properties effect, on the natural frequencies of the curved nanobeams, the dispersion curves are presented in Fig. 2. It is clearly seen that, at the low values of thickness *L*, the greater values of curved nanobeams with surface effects. Hence, it is shown that by increasing thickness *h*, the surface effects tend to vanished. However, the Fig. 2, reveals that, the surface effects play important role in higher curvature radiuses.

3.2 Analysis of higher modes on frequency ratio of curved beam with and without surface effects and elastic foundation



(a) With surface effects (b) Without surface effects

Fig. 4 Dimensionless natural frequency of curved nanobeam respect to thickness *h* for various Winkler elastic foundation



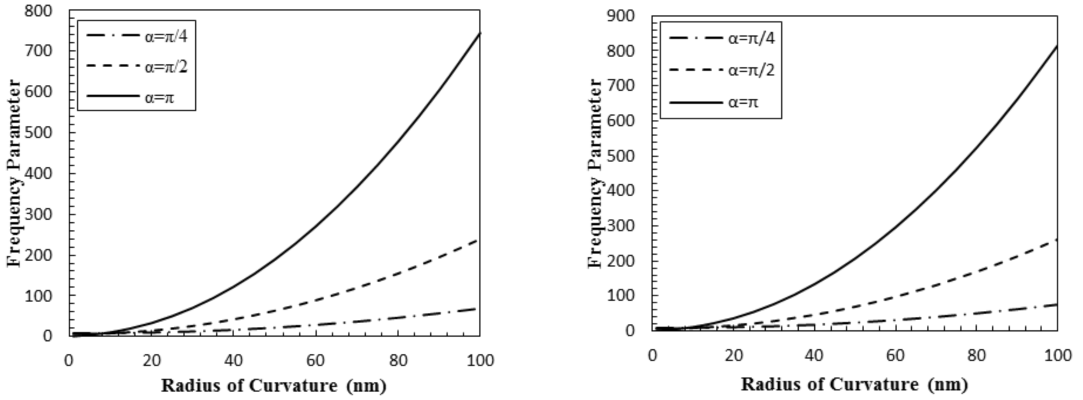
(a) With surface effects (b) Without surface effects

Fig. 5 Dimensionless natural frequency of curved nanobeam respect to thickness *h* for various Pasternak elastic foundation

The frequency ratio with and without surface properties has been illustrated in Fig. 3. In this case, the following parameters are selected as, R=30 nm, $K_w=10^{10}$ N/m^2, $K_p=10^{-6}$ N. he trends of Fig. 3 is similar to Fig. 2. It is noted that with an increase of thickness in curved nanobeam h in Fig. 3, the frequency ratios tend to one at three natural frequency mode numbers. It is revealed that in high values of thickness the influences of surface effects have been diminished in all mode numbers.

3.3 Effect of Winkler foundation on frequency parameter

In this subsection, the effect of the Winkler elastic foundations of curved nanobeams with and without surface effects on the vibration frequencies is investigated respect to thickness of curved nanobeam with and without surface properties. For this aim, the variation of fundamental dimensionless natural frequency respect to thickness with various Winkler elastic foundations is considered as shown in Fig. 4. In the case, the Pasternak elastic foundation assume constant and it is equal to 10^{-6} N. From Fig. 4, it is seen that the Winkler elastic foundation can significantly influence the vibration of curved nanobeam with and without surface effects. It is also observed that as



(a) With surface effects (b) Without surface effects

Fig. 6 Dimensionless natural frequency of curved nanobeam respect to radius of curvature for various curvature angles

thickness of curved nanobeam heightens, the fundamental frequencies decrease, which indicates that the Winkler elastic foundation has an important role in dimensionless frequencies. As it shown in Fig. 4, as Winkler values increase, the dimensionless natural frequencies also increase.

3.4 Effect of Pasternak foundation on frequency parameter of curved nanobeam

To evaluate the influence of the Pasternak elastic foundation on vibration of curved nanobeam with and without surface effects, Fig. 5 presents the natural frequency of the Euler-Bernoulli model with respect to different values of Pasternak elastic foundation. For this aim, the variation of fundamental dimensionless natural frequency respect to thickness with various Pasternak elastic foundations is considered as shown in Fig. 5. In the case, the Winkler elastic foundation assume constant and it is equal to 10^{10} N/m^2. It is seen from Fig. 5 that the dimensionless frequency is more sensitive to low thicknesses. As the thickness of curved nanobeam increases, the dimensionless frequency decreases. However it is observed from that as Pasternak values increase, the dimensionless natural frequencies also increase.

3.5 Effect of radius of curvature with different curvature angle on frequency parameter

To understand the influence of the radius change R on the first dimensionless natural frequency of curved nanobeam with and without surface effects Fig. 6. Present the natural frequencies of curved nano beam with respect to curvature radius for different angles of curvatures. Effects of the curvature radius change on the natural frequencies of curved nanobeams are shown in Fig. 6. In this case, the following parameters are selected: h=10 nm, K_w=10^{10} N/m^2, K_p=10^{-6}. In Fig. 6, it is noted that with an increase of radius of curvature R, the dimensionless natural frequency increase. Meanwhile, it is also found that at the same curvature radius, the frequency at higher angle of curvature is greater than other frequencies. According to Table 2, it can be seen that the dimensionless frequency increase with increasing radius of curvatures. It is interesting to say that natural frequencies also increase with increase opening angles. These observations can be used for the design of curved nanobeams and nanorings.

4. Conclusions

Derived herein are the governing equations for the free vibration of circular nanorings/arches including surface elasticity, surface density and surface tension. The Winkler and Pasternak elastic foundations were considered on vibration behavior of the curve nanobeam. In addition, the simply-simply boundary conditions were assumed for this case. Hence, the Navier method was employed to solve the governing equation to satisfied boundary conditions. The effects of the thickness of curved nanobeam, Winkler elastic foundation, Pasternak elastic foundation, opening angle and radius of curvature, on the frequency parameters of the circular curved beams were investigated. It is observed that by increasing thickness h, the surface effects tend to vanished. Furthermore, it is shown that the elastic foundations and surface effects play an important role in dynamics behavior of circular curved nanobeams.

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