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Radial breathing-mode frequency of elastically confined spherical nanoparticles subjected to circumferential magnetic field

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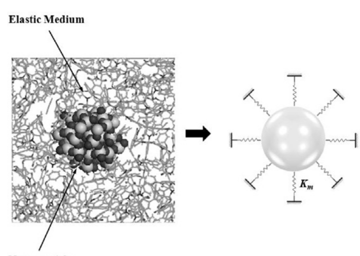
HIGHLIGHTS

- New formulation based on the nonlocal elasticity theory is proposed to investigate radial vibrations of the nanoparticles subjected to magnetic field.
- The influences of small scale and elastic foundation on the radial frequencies of several spherical nanoparticles are investigated.
- The transcendental equation for estimating the eigenfrequencies of the nanoparticles is developed.

GRAPHICAL ABSTRACT

An analytical model is presented for studying the effects of a circumferential magnetic field on the radial breathing-mode frequency of a magnetically sensitive nanoparticle. The transcendental equation for estimating the frequency of the breathing-mode of the elastically confined nanoparticles is developed based on nonlocal continuum mechanics.



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ABSTRACT

Knowledge of the vibrational properties of nanoparticles is of fundamental interest since it is a signature of their morphology, and it can be utilized to characterize their physical properties. In addition, the vibration characteristics of the nanoparticles coupled with surrounding media and subjected to magnetic field are of recent interest. This paper develops an analytical approach to study the radial breathing-mode frequency of elastically confined spherical nanoparticles subjected to magnetic field. Based on Maxwell's equations, the nonlocal differential equation of radial motion is derived in terms of radial displacement and Lorentz's force. Bessel functions are used to obtain a frequency equation. The model is justified by a good agreement between the results given by the present model and available experimental and atomic simulation data. Furthermore, the model is used to elucidate the effect of nanoparticle size, the magnetic field and the stiffness of the elastic medium on the radial breathing-mode frequencies of several nanoparticles. Our results reveal that the effects of the magnetic field and the elastic medium are significant for nanoparticle with small size.

1. Introduction

In the fields of modern materials science and technology, nanoparticles have been extremely interesting nano-objects due to their enormous technological importance. Understanding their structure and physical properties is crucial for many of their future

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novel applications. Knowledge of elastic vibrations is required to describe various mechanical, thermal and electrical properties of nanoparticles and efficient design of devices. In addition, the vibrations can be used to characterize nanoparticles. Therefore, various theoretical and experimental approaches have been developed to gain insight into these vibrations. The vibrations can be observed by inelastic scattering based optical techniques such as low frequency Raman scattering [1,2], Brillouin scattering [3] and time resolved femtosecond spectroscopy [4,5].

Voisin et al. [6] employed classical continuum mechanics to derive expressions for the breathing acoustic mode of noble metal nanoparticles embedded in an elastic medium. The analytically obtained results were compared to the experimental data obtained from a glass embedded with silver nanoparticles and gold colloids using a time-resolved pump–probe technique. Using a microscopic valence-force field model, the Raman intensities of low-frequency phonon modes of spherical germanium nanoparticles with various diameters were studied [7]. In another work, the vibration mode frequencies of spherical germanium were obtained by using an atomistic approach based on the Stillinger–Weber interaction potential and also utilizing the continuum theory [8]. The vibration of elastically anisotropic nanoparticles has been recently investigated [9,10]. Ng and Chang [11] investigated the laser-induced breathing vibration of gold and silver nanospheres with size ranging from 5.8 to 46.2 nm. In this way, the molecular dynamics and group theory were utilized. Recently, the elastic vibration of spherical nanoparticles was investigated by including the surface stress and the surface mass effects that can be captured by the surface elasticity [12]. Radial vibration characteristics of anisotropic spherical nanoparticles were analytically investigated by Ghavanloo and Fazelzadeh [13] using nonlocal continuum mechanics. More recently, the radial vibrations of spherical nanoparticles immersed in a fluid medium was investigated based on the nonlocal elasticity theory [14].

In some new applications of nanotechnology, the investigation on dynamic characteristic of the nanostructures under magnetic field is useful [15]. Hence, in recent years, research interest has grown on studying behavior of the nanostructures subjected to an external magnetic field. Li et al. [16] investigated the effects of a magnetic field on the dynamic characteristics of multi-walled carbon nanotubes (MWNTs). The resonance frequencies and stability of a nanobeam subjected to a longitudinal magnetic field were investigated by Firouz-Abadi and Hosseinian [17]. Murmu et al. [18] developed an analytical model for studying the effects of a longitudinal magnetic field on the vibration of a magnetically sensitive double-walled carbon nanotube system. Dynamic response of an embedded conducting nanowire subjected to an axial magnetic shock was investigated by Kiani [19]. He also studied free vibrations of conducting nano-plates subjected to unidirectional in-plane magnetic fields [20].

From the above discussions it is understood that the study of the mechanical behavior of nanostructures subjected to an external magnetic field is important and requires attention. In spite of the extensive researches in the area of the dynamic characteristics of nanostructures subjected to magnetic field, there has been no attempt to tackle the problem described in the present paper. The aim of this study is to investigate the radial breathing-mode frequency of spherical nanoparticles subjected to the magnetic field and embedded in an infinite elastic matrix. The radial breathing-mode of nanoparticles is identified as the excitation of A_{1g} mode with in-phase radial displacement of atoms in the nanoparticles. This mode may be of interest in many experiments based on the inelastic scattering of light. Actually it has been well established that it is the fundamental radial vibration that is excited in time resolved femtosecond pump-probe experiments [21,22]. It should be noted that the breathing-mode is also Raman active.

In this investigation, the nonlocal elasticity theory which was first proposed by Eringen [23] is used to modify the classical elasticity theory. A nonlocal governing equation of the nanoparticles in the radial direction under a magnetic field is derived with considering the Lorentz magnetic force obtained from Maxwell's relation. The external medium is generally modeled as Winkler-type foundation. The foundation modulus is represented by stiffness of the springs. A Bessel function method is used to obtain an analytical frequency relation for the radial breathing-mode frequency of the nanoparticles with consideration of the small scale effect, magnetic field and external medium stiffness. To validate the accuracy of the present method, the results are compared with solutions found in the literature. In addition, the effects of the crucial parameters on the radial breathing-mode frequency are elucidated.

2. Basic equation of nanoparticles under magnetic field

Consider a perfectly conducting spherical nanoparticle with radius R and density ρ which is placed in a circumferential magnetic field $\vec{\mathbf{H}} = (0, 0, H_{\varphi})$. It is convenient to choose the origin at the center of the nanoparticle and use spherical coordinates r, θ and φ. The nanoparticle has been embedded in an infinite elastic matrix. The radial stiffness of the surrounding matrix of the nanoparticle is represented by K_m (Fig. 1). Under pure radial deformation, the nonzero component of displacement can be denoted as $u = u(r, t)$. Based on the nonlocal continuum mechanics, the constitutive relations are [13]

$$\sigma_{\theta\theta} - \mu^2\left(\frac{\partial^2\sigma_{\theta\theta}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{\theta\theta}}{\partial r} - \frac{2\sigma_{\theta\theta}}{r^2} + \frac{2\sigma_{rr}}{r^2}\right) = (c_{11} + c_{12})\frac{u}{r} + c_{13}\frac{\partial u}{\partial r} \tag{1}$$

$$\sigma_{\varphi\varphi} - \mu^2\left(\frac{\partial^2\sigma_{\varphi\varphi}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{\varphi\varphi}}{\partial r} - \frac{2\sigma_{\varphi\varphi}}{r^2} + \frac{2\sigma_{rr}}{r^2}\right) = (c_{12} + c_{22})\frac{u}{r} + c_{23}\frac{\partial u}{\partial r} \tag{2}$$

$$\sigma_{rr} - \mu^2\left(\frac{\partial^2\sigma_{rr}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{rr}}{\partial r} - \frac{4\sigma_{rr}}{r^2} + \frac{2(\sigma_{\theta\theta} + \sigma_{\varphi\varphi})}{r^2}\right)$$
$$= (c_{13} + c_{23})\frac{u}{r} + c_{33}\frac{\partial u}{\partial r} \tag{3}$$

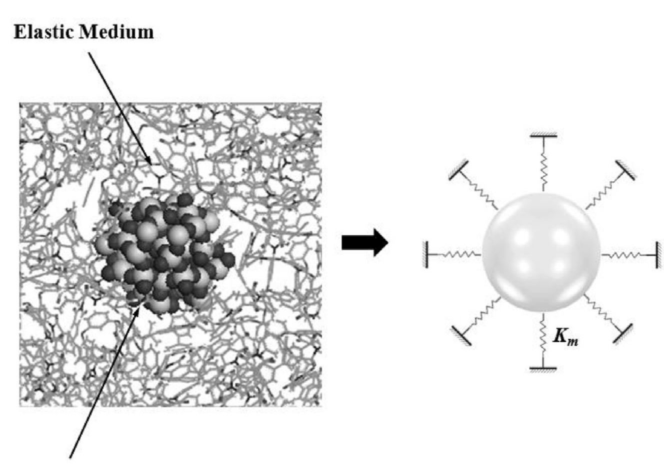

Fig. 1. Nanoparticle embedded in the elastic matrix.

wherein c_{11}, c_{12}, c_{13}, c_{22}, c_{23} and c_{33} are six independent elastic constants of anisotropic materials. The interested reader can find more detail about the elastic constants of the crystals in Ref. [24]. μ ($\mu = e_0 a$) is the nonlocal parameter revealing the small scale effect on the responses of nanoscale structures. e_0 is a material constant and a is the lattice constant. In this study, we use $e_0 \approx 0.39$ based on the Eringen results [25]. In the particular case of nanoparticles having cubic crystallinity, $c_{11} = c_{22} = c_{33}$ and $c_{12} = c_{13} = c_{23}$, the constitutive relations are

$$\sigma_{\theta\theta} - \mu^2\left(\frac{\partial^2\sigma_{\theta\theta}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{\theta\theta}}{\partial r} - \frac{2\sigma_{\theta\theta}}{r^2} + \frac{2\sigma_{rr}}{r^2}\right) = (c_{11} + c_{12})\frac{u}{r} + c_{12}\frac{\partial u}{\partial r} \tag{4}$$

$$\sigma_{\varphi\varphi} - \mu^2\left(\frac{\partial^2\sigma_{\varphi\varphi}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{\varphi\varphi}}{\partial r} - \frac{2\sigma_{\varphi\varphi}}{r^2} + \frac{2\sigma_{rr}}{r^2}\right) = (c_{12} + c_{11})\frac{u}{r} + c_{12}\frac{\partial u}{\partial r} \tag{5}$$

$$\sigma_{rr} - \mu^2\left(\frac{\partial^2\sigma_{rr}}{\partial r^2} + \frac{2}{r}\frac{\partial\sigma_{rr}}{\partial r} - \frac{4\sigma_{rr}}{r^2} + \frac{2(\sigma_{\theta\theta} + \sigma_{\varphi\varphi})}{r^2}\right) = 2c_{12}\frac{u}{r} + c_{11}\frac{\partial u}{\partial r} \tag{6}$$

Assuming that the magnetic permeability, η, at the outer surface of the nanoparticle to be equal to the magnetic permeability of the matrix, and the matrix to be non-ferromagnetic and non-ferroelectric, and omitting the displacement electric currents, the Maxwell equations [26] for a perfectly conducting elastic body can be expressed as

$$\vec{\mathbf{J}} = \mathrm{Curl}\,\vec{\mathbf{h}} \tag{7}$$

$$\mathrm{Curl}\,\vec{\mathbf{e}} = -\eta\frac{\partial\vec{\mathbf{h}}}{\partial t} \tag{8}$$

$$\mathrm{div}\,\vec{\mathbf{h}} = 0 \tag{9}$$

$$\vec{\mathbf{e}} = -\eta\left(\frac{\partial\vec{\mathbf{U}}}{\partial t} \times \vec{\mathbf{H}}\right) \tag{10}$$

$$\vec{\mathbf{h}} = \mathrm{Curl}\left(\vec{\mathbf{U}} \times \vec{\mathbf{H}}\right) \tag{11}$$

in which $\vec{\mathbf{J}}$, $\vec{\mathbf{e}}$, $\vec{\mathbf{h}}$, and $\vec{\mathbf{U}}$ represent the current density, strength vectors of electric field, disturbing vectors of magnetic field and the vector of displacement. Applying an initial magnetic field vector $\vec{\mathbf{H}} = (0, 0, H_\varphi)$ to Eqs. (7)–(1), yields [27]

$$\vec{\mathbf{U}} = (u,\ 0,\ 0) \tag{12}$$

$$\vec{\mathbf{e}} = -\eta\left(0,\ H_\varphi\frac{\partial u}{\partial t},\ 0\right) \tag{13}$$

$$\vec{\mathbf{h}} = (0,\ 0,\ h_\varphi) \tag{14}$$

$$\vec{\mathbf{J}} = \left(0,\ -\frac{\partial h_\varphi}{\partial r},\ 0\right) \tag{15}$$

$$h_\varphi = -H_\varphi\left(\frac{\partial u}{\partial r} + \frac{2u}{r}\right) \tag{16}$$

Due to the applied magnetic field on the nanoparticle, a body force exerts on each element of the nanoparticle which is called Lorentz's force [27,28] and calculated by

$$f_r = \eta(\vec{\mathbf{J}} \times \vec{\mathbf{H}}) = \eta H_\varphi^2\frac{\partial}{\partial r}\left(\frac{\partial u}{\partial r} + \frac{2u}{r}\right) \tag{17}$$

It should be noted that in the present study the effective Lorentz force is a function of magnetic permeability and H_φ. In the absence of external body forces and taking into account Lorentz's force, the equation of motion for the nanoparticle is expressed as

$$\frac{\partial\sigma_{rr}}{\partial r} + \frac{2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\varphi\varphi}}{r} + f_r = \rho\frac{\partial^2 u}{\partial t^2} \tag{18}$$

Using Eqs. (4)–(6), the nonlocal equation of motion is obtained as

$$\begin{aligned}&\frac{\partial\sigma_{rr}}{\partial r} + \frac{2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\varphi\varphi}}{r}\\ &\quad - \mu^2\left[\left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2}{r^2}\right)\left(\frac{\partial\sigma_{rr}}{\partial r} + \frac{2\sigma_{rr} - \sigma_{\theta\theta} - \sigma_{\varphi\varphi}}{r}\right)\right]\\ &= c_{11}\left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2}\right)\end{aligned} \tag{19}$$

To eliminate the stress components in the governing Eq. (19), one can substitute the equation of motion in Eq. (18) into Eq. (19). The resultant equation is

$$\begin{aligned}&\rho\mu^2\left(\frac{\partial^4 u}{\partial r^2\partial t^2} + \frac{2}{r}\frac{\partial^3 u}{\partial r\partial t^2} - \frac{2}{r^2}\frac{\partial^2 u}{\partial t^2}\right) + c_{11}\left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2}\right) - \rho\frac{\partial^2 u}{\partial t^2}\\ &\quad + \eta H_\phi^2\left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2}\right)\\ &\quad - \mu^2\eta H_\varphi^2\left[\left(\frac{\partial^2}{\partial r^2} + \frac{2}{r}\frac{\partial}{\partial r} - \frac{2}{r^2}\right)\left(\frac{\partial^2 u}{\partial r^2} + \frac{2}{r}\frac{\partial u}{\partial r} - \frac{2u}{r^2}\right)\right] = 0\end{aligned} \tag{20}$$

3. Frequency equation

For the vibration analysis, it is assumed that the displacement u varies harmonically with respect to the time variable t as follows:

$$u(r, t) = U(r)\sin(\omega t) \tag{21}$$

where ω is angular frequency related to natural frequency f by $\omega = 2\pi f$. Substituting Eq. (21) into Eq. (20), the following equation is derived:

$$\begin{aligned}&-\omega^2\rho\mu^2\left(\frac{d^2U}{dr^2} + \frac{2}{r}\frac{dU}{dr} - \frac{2U}{r^2}\right)\\ &\quad + c_{11}\left(\frac{d^2U}{dr^2} + \frac{2}{r}\frac{dU}{dr} - \frac{2U}{r^2}\right) + \rho\omega^2 U\\ &\quad + \eta H_\varphi^2\left(\frac{d^2U}{dr^2} + \frac{2}{r}\frac{dU}{dr} - \frac{2U}{r^2}\right)\\ &-\mu^2\eta H_\varphi^2\left[\left(\frac{d^2}{dr^2} + \frac{2}{r}\frac{d}{dr} - \frac{2}{r^2}\right)\left(\frac{d^2U}{dr^2} + \frac{2}{r}\frac{dU}{dr} - \frac{2U}{r^2}\right)\right] = 0\end{aligned} \tag{22}$$

It should be noted that the solution of Eq. (22) can be obtained through solving

$$\frac{d^2U}{dr^2} + \frac{2}{r}\frac{dU}{dr} + \left(\left(\frac{\lambda}{R}\right)^2 - \frac{2}{r^2}\right)U = 0 \tag{23}$$

Here, λ is an eigenvalue corresponding to boundary conditions and given by local model. Therefore, analytical frequency relation for the radial breathing-mode frequency of the nanoparticles is obtained. This relationship is

$$\omega^2 = \frac{\mu^2 M(\lambda/R)^4 + (c_{11} + M)(\lambda/R)^2}{\rho + \rho\mu^2(\lambda/R)^2} \tag{24}$$

where

$$M = \eta H_\varphi^2 \tag{25}$$

Eq. (23) is a Bessel equation and the general solution of the Bessel equation corresponding to it is given by

$$U(r) = A_1 \frac{J_{3/2}}{\sqrt{r}}\left(\lambda \frac{r}{R}\right) + A_2 \frac{Y_{3/2}}{\sqrt{r}}\left(\lambda \frac{r}{R}\right) \tag{26}$$

where A_1 and A_2 are unknown constants, $J_{3/2}$ and $Y_{3/2}$ are Bessel functions of first- and second-kind, of order 3/2 respectively. As the displacement must remain finite at the center of the nanoparticle, we must set $A_2=0$ to remove the infinite value of $Y_{3/2}(\lambda r/R)/\sqrt{r}$ when $r=0$. The resultant equation becomes

$$U(r) = \frac{A_1}{\sqrt{r}} J_{3/2}\left(\lambda \frac{r}{R}\right) \tag{27}$$

The nanoparticle has been confined in an infinite elastic medium with Young's modulus E_m and Poisson's ratio ν_m. It can be proved that the radial stiffness of the surrounding medium is determined by

$$K_m = \frac{E_m}{2R(1 + \nu_m)} \tag{28}$$

Therefore, the boundary conditions of Eq. (27) or the interaction of the nanoparticle with its surrounding medium are given by

$$\sigma_{rr}(R, t) = -K_m u(R, t) \tag{29}$$

Substituting Eqs. (21) and (27) into boundary condition, the frequency equation is obtained as below:

$$J_{3/2}(\lambda)\left[1 + \frac{2c_{12}}{c_{11}} + \frac{K_m R}{c_{11}} + \frac{\mu^2 K_m R}{R^2 c_{11}}\left(\lambda^2 + \frac{11}{4}\right)\right] - \lambda J_{5/2}(\lambda) = 0 \tag{30}$$

By solving Eq. (30), we can obtain the radial frequencies of the nanoparticles. It should be noted that the lowest frequency is the breathing-mode which is critical to the characterization of the nanoparticles.

4. Numerical results and discussion

In this section, the capabilities of the proposed model in predicting the radial breathing-mode frequency of elastically confined spherical nanoparticles subjected to magnetic field are addressed. To determine the numerical results, basic quantities which have to be defined appropriately are the elastic constants of the nanoparticles. The parameters used in this work are given in Table 1 according to previous experimental and numerical investigations.

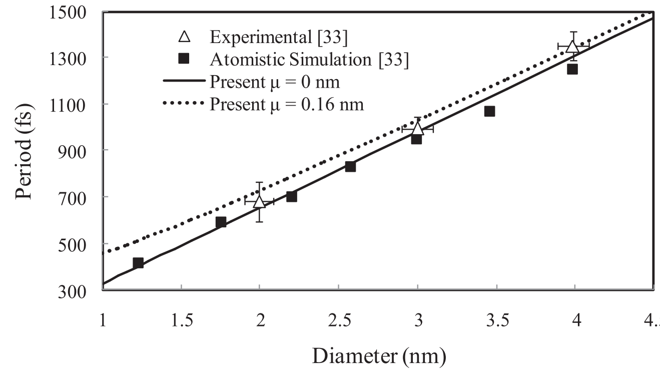

Fig. 2. Radial-breathing mode periods for free Au nanoparticles.

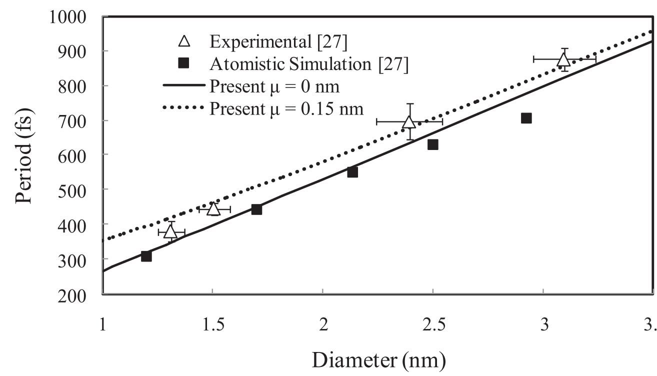

Fig. 3. Radial-breathing mode periods for free Pt nanoparticles.

To confirm the validity of the suggested model, we compare the present results with some existing experimental results. Fig. 2 shows the predicted radial breathing-mode period for free Au

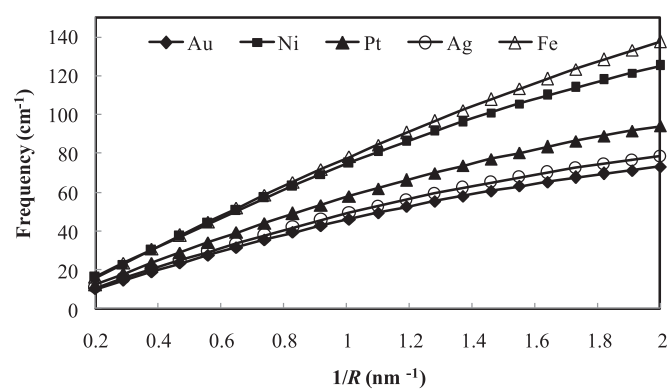

Fig. 4. Radial-breathing mode frequency of five free nanoparticles as a function of R^{-1}.

Table 1
Material properties of different nanoparticles.

Material	Formula	ρ/g cm^{-3}	Elastic constants (1011 N/m^2)		Temperature (K)	**Lattice constant (nm)**
			c_{11}	c_{12}		
Gold	Au	19.283	1.9234	1.6314	300	0.408
Nickel	Ni	8.91	2.481	1.549	298	0.352
Platinum	Pt	21.50	3.4670	2.5070	300	0.393
Silver	Ag	10.50	1.2399	0.9367	300	0.409
Iron	Fe	7.8672	2.26	1.40	298	0.287

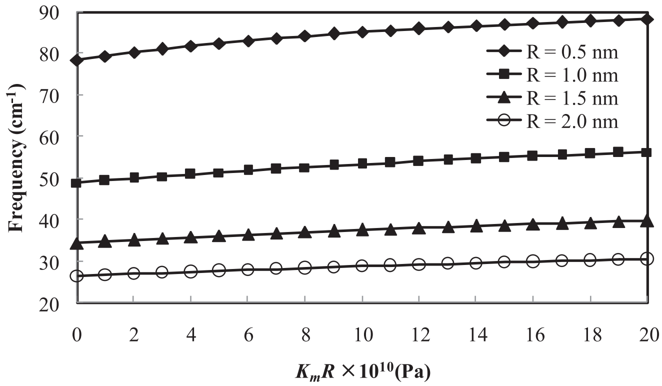

Fig. 5. Radial-breathing mode frequency of Ag nanoparticle as a function of elastic medium stiffness for several nanoparticle sizes.

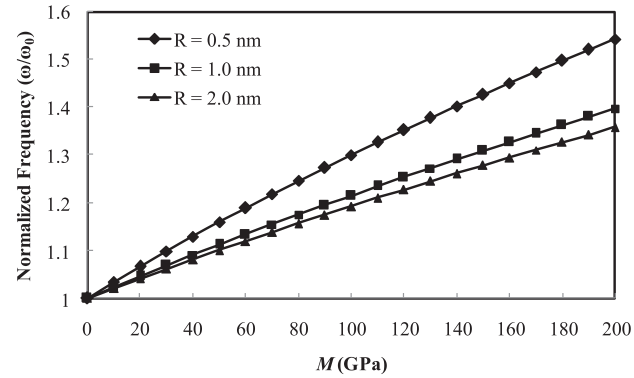

Fig. 7. Variations of normalized frequency of Ni nanoparticle as a function of *M* for several values of the nanoparticle size.

nanoparticles without magnetic field in the size range up to 4 nm along with the experimental data measured from time-resolved pump-probe spectroscopy and atomistic simulation [29]. The comparison of the calculated radial breathing-mode period for free Pt nanoparticles with experimental and atomistic simulation data is shown in Fig. 3. It can be seen that the nonlocal results are in good agreement with the results reported in Ref. [29]. Therefore, the nonlocal elasticity theory can be used for predicting the breathing-mode frequency of nanoparticles. After verifying the accuracy and reliability of the present formulation, we now proceed to the application of this method to various nanoparticles.

The variations of the radial breathing-mode frequency of different free nanoparticle without magnetic field including Au, Ni, Pt, Ag and Fe nanoparticles with respect to the inverse radius are plotted in Fig. 4. It is observed that the frequencies are not linear functions of nanoparticle radius. This behavior is related to the small scale effect.

To illustrate the effect of elastic medium, the radial breathing-mode frequencies of Ag nanoparticles without magnetic field are displayed in Fig. 5 for four different values of nanoparticle radius. As expected, the radial breathing-mode frequency slightly increases with an increase of stiffness of the elastic medium. The present results are quite consistent with the literature experimental results [30]. In addition, this figure reveals that the frequency strongly depends on the particle size and increases with decreasing size.

Another crucial study is conducted to examine the influence of the magnetic field strength on the breathing-mode frequencies of the nanoparticles. Therefore, as last numerical examples, the influence of the magnetic field on the radial breathing-mode frequencies of nickel and iron nanoparticles are investigated. The variations of the radial breathing-mode frequency of free iron

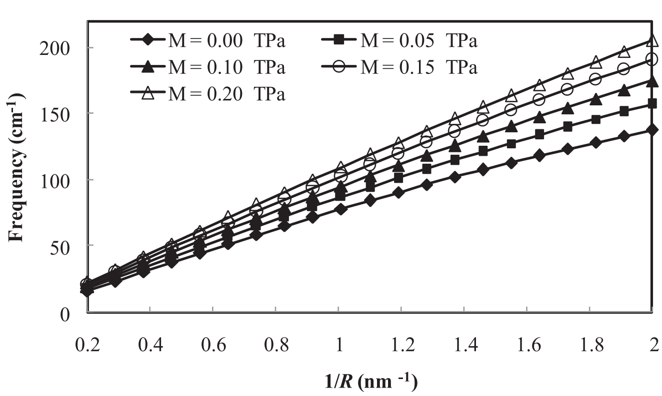

Fig. 6. Radial-breathing mode frequency of Fe nanoparticle as a function of R^{-1} for several values of the magnetic field strength.

nanoparticles with respect to the inverse radius are indicated in Fig. 6 for different values of the parameter $M = \eta H_\varphi^2$. From the figure, it is observed that the frequencies of iron nanoparticles have higher frequencies in the presence of magnetic field than without the magnetic field. The results show that the predicted breathing-mode frequencies generally magnify as the influence of the magnetic field strength becomes highlighted. Such a fact can be interpreted by Eq. (24). Finally, to illustrate the simultaneous effects of the magnetic field and external medium, the variations of the normalized frequencies of the Ni nanoparticles as a function of the parameter M are displayed in Fig. 7. The normalized frequency is defined as

$$\frac{\omega^2}{{\omega_0}^2} = \mu^2 \frac{M}{c_{11}} \left(\frac{\lambda}{R}\right)^2 + \left(1 + \frac{M}{c_{11}}\right) \tag{31}$$

where

$${\omega_0}^2 = \frac{(c_{11})(\lambda/R)^2}{\rho + \rho\mu^2(\lambda/R)^2} \tag{32}$$

In this figure, the stiffness of external elastic medium is set to 10^{20} (Pa/m). It can be seen from this figure that normalized frequency increases as the magnitude of the M increases. This physical means that the magnetic field would lead to an increase of the rigidity of the nanoparticles.

5. Concluding remarks

In this paper, an analytical model was presented for studying the effects of a magnetic field on the radial breathing-mode frequency of a magnetically sensitive nanoparticle. The transcendental equation for estimating the frequency of the breathing-mode of the elastically confined nanoparticles was developed based on nonlocal continuum mechanics. In spite of some previous works on vibration analysis of the nanoparticles, to our knowledge, there has been no attempt to address the problem described in the present investigation. Developing the nonlocal elastic model in conjunction with the magnetic effect is the main contribution of the present paper. The comparison of theoretical results from the present model with experiments and atomic simulation results indicated a good agreement for Au and Pt nanoparticles. The main results of the present work can be summarized as follows:

1) The frequency of breathing-mode is not inversely proportional to the radius of the nanoparticle as predicted by the classical elasticity.
2) We observed that the consideration of magnetic field may lead to an increase of the stiffness of nanoparticles.

3) The magnetic field and external elastic medium induce novel size-dependent vibration behavior of the nanoparticles, which is most significant for diameters below about 4 nm.

Finally, it should be noted that these results can be interesting since the radial breathing-mode determination could be used as a fingerprint to identify the nanoparticles diameter within such spectroscopy techniques such as Raman spectroscopy and time-resolved spectroscopy.

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