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

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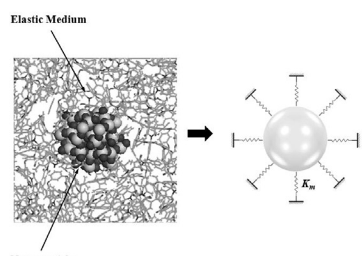
HIGHLIGHTS

- 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]

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

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

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

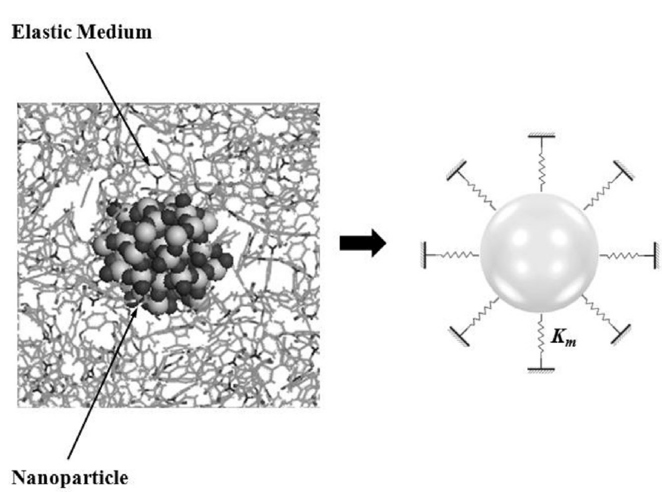

Fig. 1. Nanoparticle embedded in the elastic matrix.