Structural Engineering and Mechanics, *Vol. 74, No. 5 (2020) 611-633*
DOI: https://doi.org/10.12989/sem.2020.74.5.611

A comprehensive review on the modeling of smart piezoelectric nanostructures

Farzad Ebrahimi*[1], S.H.S. Hosseini[1] and Abhinav Singhal[2]

[1]*Department of Mechanical Engineering, Faculty of Engineering, Imam Khomeini International University, 3414916818, Qazvin, Iran*
[2]*Department of mathematics, Madanapalle Institute of technology and sciences, Madanapalle-517325, Andhra Pradesh, India*

(Received April 2, 2019, Revised May 21, 2019, Accepted August 26, 2019)

Abstract. In this paper, a comprehensive review of nanostructures that exhibit piezoelectric behavior on all mechanical, buckling, vibrational, thermal and electrical properties is presented. It is firstly explained vast application of materials with their piezoelectric property and also introduction of other properties. Initially, more application of material which have piezoelectric property is introduced. Zinc oxide (ZnO), boron nitride (BN) and gallium nitride (GaN) respectively, are more application of piezoelectric materials. The nonlocal elasticity theory and piezoelectric constitutive relations are demonstrated to evaluate problems and analyses. Three different approaches consisting of atomistic modeling, continuum modeling and nano-scale continuum modeling in the investigation atomistic simulation of piezoelectric nanostructures are explained. Focusing on piezoelectric behavior, investigation of analyses is performed on fields of surface and small scale effects, buckling, vibration and wave propagation. Different investigations are available in literature focusing on the synthesis, applications and mechanical behaviors of piezoelectric nanostructures. In the study of vibration behavior, researches are studied on fields of linear and nonlinear, longitudinal and transverse, free and forced vibrations. This paper is intended to provide an introduction of the development of the piezoelectric nanostructures. The key issue is a very good understanding of mechanical and electrical behaviors and characteristics of piezoelectric structures to employ in electromechanical systems.

Keywords: piezoelectric; boron nitride; nanostructure; continuum modeling; mechanical properties

1. Introduction

The earliest knowledge of electric effects goes back to ancient Greece, where it was found that rubbing fur on amber caused an attraction between the two. Piezoelectricity was first discovered by Pierre and Jacques Curie brothers (1880), who found that by compressing certain crystals, electric charges were produced. The charges are proportional to the pressure and disappear when the pressure is by dawn. This phenomenon, known as the direct piezoelectric effect. The converse piezoelectric effect is the deformation of piezoelectric crystal under an applied electric field, which was predicted by Lippmann (1881) based on thermodynamic principles. The converse piezoelectric effect was later verified by the Curies. Nowadays, piezoelectric nanostructures have a wide range of potentials for engineering applications due to their exceptional mechanical and electrical properties. In recent years, piezoelectric materials and also piezoelectric nanomaterials (PNMs) have received significant interests among scientists because of their unique property. Many researchers had presented nice works to quantitatively explain the piezoelectric phenomenon. The main objective of this paper is to review nanostructures that exhibit piezoelectric properties. Different methods of synthesis and modeling which have been employed in the piezoelectric nanostructures are introduced and then their applications are demonstrated. Finally, mechanical analyses which have been achieved in this nanostructures are investigated.

*Corresponding author, Professor
E-mail: febrahimy@eng.ikiu.ac.ir

2. Nanostructures that exhibit piezoelectric properties

There are many materials which naturally have piezoelectricity, such as tourmaline, Rochelle salt, topaz, quartz, cane sugar, etc. However, the weakness of the electromechanical coupling effect in these natural materials strongly limits the application of piezoelectricity in the early days (Yan 2013). Nowadays, widespread application of the piezoelectric effect attributes to the introduction of artificial piezoelectric ceramics in the 1950’s, including lead zirconate titanate (PZT), barium titanate (BaTiO3), lead titanate (PbTiO3), etc (Yan 2013). But in general, zinc oxide (ZnO), boron nitride (BN) and gallium nitride (GaN) respectively are three key technological materials.

2.1 Zinc oxide

Zinc oxide is a unique material that exhibits semiconducting and piezoelectric dual properties. Using a solid–vapor phase thermal sublimation technique, nanocombs, nanorings, nanohelixes/ nanosprings, nanobelts, nanowires and nanocages of ZnO have been synthesized

http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

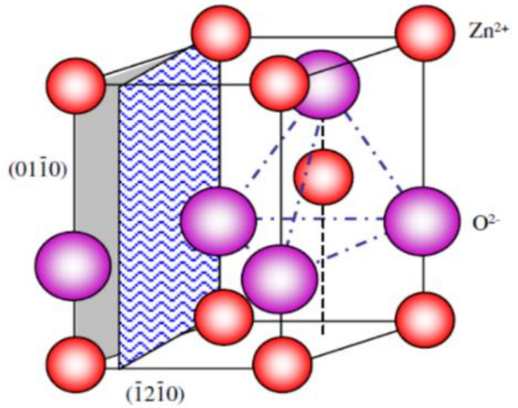


Fig. 1 The Wurtzite structure model of ZnO. The tetrahedral coordination of Zn–O is shown (Wang 2004).

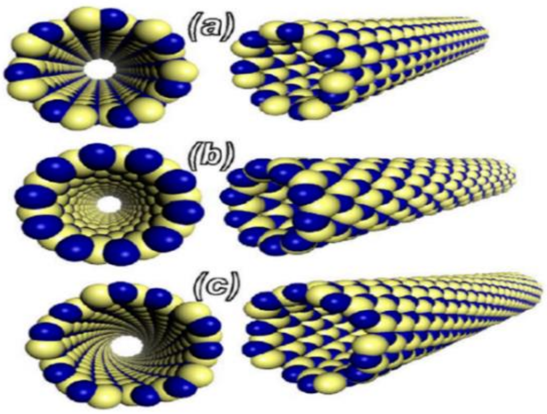


Fig. 2 Atomic models of (a) (7,7) arm-chair BNNT; (b) (10,0) zig-zag BNNT and (c) (10,5) chiral BNNT (Zhi *et al*. 2010).

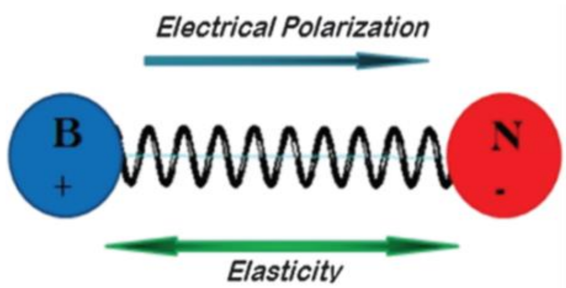


Fig. 3 Axial piezoelectric effect due to electrical polarization (Jafari *et al*. 2012).

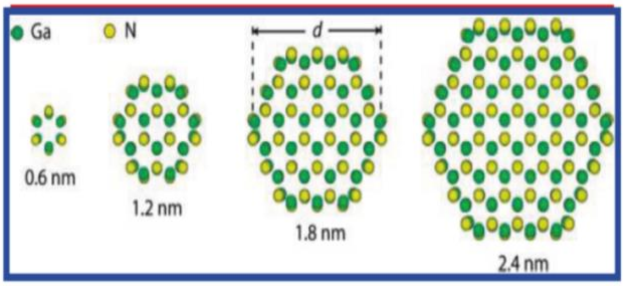


Fig. 4 Cross sections of modeled GaN nanowires. (Agrawal and Espinosa 2011)

under specific growth conditions (Wang 2004). Crystal and surface structure of ZnO are presented graphically in Figure. 1. Wurtzite zinc oxide has a hexagonal structure (space group C6mc) with lattice parameters a = 0.3296 and c = 0.520 65 nm. The structure of ZnO can be simply described as a number of alternating planes composed of tetrahedrally coordinated O^{2-} and Zn^{2+} ions, stacked alternately along the c-axis Fig. 1 (Wang 2004).

2.2 Boron nitride

Boron nitride formed B and N atoms in various nanostructures. In recent years, more application of boron nitride nanostructures in articles and papers have been nanotubes and nanowires. A boron nitride nanotube (BNNT) can be imagined as a rolled up hexagonal BN layer or as a carbon nanotube (CNT) in which alternating B and N atoms entirely substitute for C atoms Figure. 2 (Zhi *et al*. 2010).

In 1981, Ishii *et al*. (1981) reported on a discovery of one-dimensional BN nanostructures, which possess bamboo-like structure. These were named BN whiskers. In spite of structure similarity, BNNTs possess totally different electronic structures with CNTs. With a constant wide band gap at 5.0–6.0 eV, unmodified BNNTs can be considered as insulating materials. A dielectric constant of 5.90 was predicted by theoretical calculations, which is universal for all BNNTs, regardless of their radius and chirality. BNNTs are mainly insulating materials (Ishii *et al*. 1981). Also, BNNTs usually have a semiconducting behavior. Figure. 3 shows a schematic axial piezoelectric effect due to electrical polarization for B and N atoms.

2.3 Gallium nitride

Gallium nitride (GaN) nanostructures are the most attractive materials because of its potential for new visible and UV optoelectronic applications. One-dimensional GaN nanostructure, GaN nanowire, has been successfully synthesized using various methods such as carbon nanotube-confined reaction (Han *et al.* 1997), and chemical vapor deposition (CVD) (Cheng *et al.* 1999). Han *et al.* (2000) produced the GaN nanorods by arc discharge in a nitrogen atmosphere. Duan *et al*. (2000) formed the GaN nanorods by laser-assisted catalytic growth. Nanowire cross sections as a function of wire diameter are shown in Figure 4 together with the relaxed atomic positions by Agrawal and Espinosa (2011).

3. Synthesis and fabrication

A variety of methods, such as laser ablation, chemical vapor deposition (CVD), ball-milling, substitution reaction were invented and adopted to synthesize BNNTs. On field of BN nanostructures, initially the growth of hexagonal BNNTs and nanocages from the liquid flow of iron boride (FeB) nanoparticles has been achieved by the nitrogen plasma treatment of FeB nanoparticles at temperature close to the eutectic melting point of the alloy (Loh *et al*. 2004). BN nanotubes synthesized by annealing an iron thin film evaporated on boron pellets at 1000 °C in nitrogen gas atmosphere (Oku *et al*. 2008). Also, Hexagonal boron nitride nanotubes (BNNTs) synthesized at low substrate temperatures on nickel (Ni)-orcobalt by decomposition and reaction of gas mixtures consisting of B2 H6–N H3–H2 (Guo *et al*. 2009). Furthermore, over 1.0 mm BNNTs synthesized by an optimized ball milling and annealing method by Chen *et al*. (2008). Besides, Kumar *et al*. (2011) reported Controlled Growth of Semiconducting nanowire, nanowall, and hybrid nanostructures on graphene for piezoelectric nanogenerators. From the 1960s, synthesis of ZnO thin films has been an active field (Wang 2008). Hughes and Wang (2004) studied on the structural of nanorings and nanobows formed by bending single-crystal, PSD ZnO nanobelts. As a result, they reported the growth of PSD nanobelts into piezoelectric nanorings and nanobows of single-crystal ZnO. Xi *et al.* (2009) experimented the growth of hexagonal ZnO nanotube arrays using a solution chemical method by varying the growth temperature, time and solution concentration. Pandya and Chandra (2011) reported the preparation and characterization of nanostructured ZnO film prepared by a novel technique of oxidation of zinc film. In 2009, Gupta *et al.* (2009) investigated piezoelectric characterization of solution grown flower-like ZnO nanocrystal. Wang (2004), Xu and Wang (2011), Fan and Lu (2005) also investigated the growth and Synthesis of Zinc oxide nanostructures. GaN nanowires fabricated on Si substrates coated with gold and nickel catalyst using a thermally assisted chemical vapor deposition method by Djurisic *et al.* (2007). Furthermore, formation of thin BN coating on multiwall carbon nanotube (MWCNT) surfaces reported by Mohai *et al.* (2011). Jolandan *et al.* (2011) reported that on the strong shear piezoelectricity in individual single-crystal GaN nanowires quantified using the lateral PFM technique. Hocevar *et al.* (2013) presented a systematic red shift of the band-edge of passivated core-shell nanowires with increasing shell thickness up to 100 nm. In resumption, ZnO nanorods also synthesized on CNT yarns by an electrochemical deposition method (Seo *et al.* 2013). Atomic force microscopy manipulation of the nanostructures demonstrates their mechanical toughness and flexibility (Hughes *et al.* 2013). Xu *et al.* (2012) experimented the fabrication and characterization of novel piezoelectric nanofibers.

4. Application

Piezoelectric nanostructures are often used as sensors and actuators in vibration control systems. For this purpose, transducer are utilized as either a sensors to monitor structural vibrations, or as actuators to add damping to the structure (Moheimani and Fleming 2006).

4.1 Piezoelectric Sensor

When a piezoelectric transducer is mechanically stressed, it generates a voltage (Moheimani and Fleming 2006). This phenomenon is governed by the direct piezoelectric effect; this property makes piezoelectric transducers suitable for sensing applications (Moheimani and Fleming (2006), Baima *et al.* 2016).

4.2 Piezoelectric Actuator

The purpose of actuators is to generate bending in the beam by applying a moment to them (Moheimani and Fleming 2006). This is done by applying equal voltages, of 180° phase difference, to the two patches. Therefore, when one patch expands, the other contracts. Due to the phase difference between the voltages applied to the two actuators, only pure bending of the beam will occur, without any excitation of longitudinal waves (Moheimani and Fleming (2006), Croft *et al.* 2016, Bailey and Ubbard (1985)). In 2008, Wang *et al.* (2008) also studied piezoelectric nanogenerators for self-powered nanodevices. However, until now both theoretical and experimental studies have suggested that, for a given mechanical force, lateral bending of piezoelectric nanowires (PNWs) results in lower output electric potentials than vertical compression. Liu *et al.* (2010) also studied the first piezoelectric potential gated hybrid field-effect transistors based on nanotubes and nanowires. Newly, Hiralal *et al.* (2012) demonstrated the multiple ways in which they have been exploited for energy generation, from photovoltaics to piezoelectric generators. Recently, Araneo and Falconi (2013) demonstrated that this result only applies to nanostructures with a constant cross-section. The results provide guidelines for designing high-performance piezo-nano-devices for energy harvesting, mechanical sensing, piezotronics, piezo-phototronics, and piezo-controlled chemical reactions, among others. In another work, Chen *et al.* (2010) used PZT nanofibers for mechanical energy harvesting. PNW and nanofiber-based generators have potential uses for powering such devices through a conversion of mechanical energy into electrical energy. In order to eliminate the influence of the bioelectric field of the human body and the electromagnetic interference from the testing equipment, a free vibration test using the PZT nanogenerator as a damper was conducted Fig 5a. The output voltage from the nanogenerator was measured when a Teflon cantilever, placed on top of the nanogenerator, was subjected to free vibration, as shown in Fig 5b (Chen *et al.* 2010). Boughey *et al.* (2016) reported modeling a piezoelectric nanogenerator fabricated using ZnO nanowires. In order to consider the widespread application of piezoelectric nanomaterials, Maity *et al*. (2017), Lee *et al.* (2017) and Wu (2016) studied piezoelectric nanogenerators as portable and flexible energy harvesting devices.

Lahiri *et al.* (2011) proposed BNNT reinforced hydroxyapatite (HA) as a novel composite material for orthopedic implant applications. In recently years, several investigation done in field of piezoelectric effect such as medicine (Ciofani *et al.* 2009, Zhou *et al.* 2006), biosensor applications (Arya, *et al.* 2012, Sadek *et al.* 2010), photonic and optoelectronic applications (Djurišić *et al.* 2010, Wang 2007), actuators (Badr and Ali 2009, Aphale *et al.* 2007, Aphale *et al.* 2009), nanodevices (Wang and Shi 2012, Li *et al.* 2008), energy scavenging and energy harvesting applications (Chang *et al.* 2012, Kumar and Kim 2012, Majidi *et al.* 2010) and semiconducting (Kumar and Kim 2012, Gao and Wang 2005). In another work, the potential applications and novel nanodevices were demonstrated for ZnO and SnO2 nanostructures (Wang 2004).

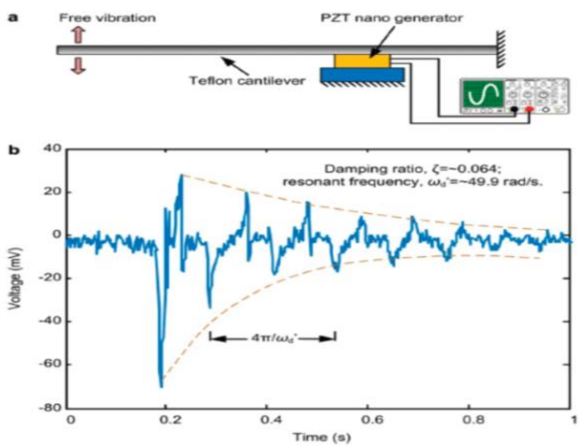


Fig. 5 Energy harvested from the free vibration of a Teflon cantilever. (a) Schematic of the experimental setup. (b) The open circuit voltage output when the cantilever was under free vibration (Chen *et al.* 2010).

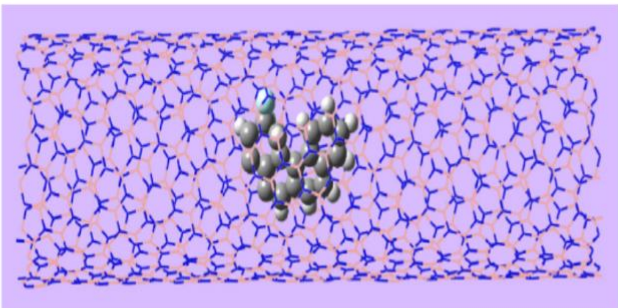


Fig. 6 The D molecule inside a (15,6) SWBNNT (Meng *et al.* 2014).

5. Modeling technique

The modeling methods of nanostructures can be categorized in three categories as atomistic modeling, continuum modeling and nano-scale continuum modeling (Rafiee and Moghadam 2014).

5.1 Atomistic modeling

Atomistic modeling techniques can be classified into three main categories. This categories are molecular dynamics (MD), Monte Carlo (MC) and ab initio (Rafiee and Moghadam 2014).

The more technique used is MD method. In 2005, Hwang *et al.* (2005) investigated a nonvolatile nano memory element based on BN nanopeapods using MD simulations and they several switching processes investigated for external force fields using MD simulations. A feature of chiral transition of a difluorobenzo phenanthrene molecule confined in a BNNT based on MD simulations were studied by Meng *et al.* (2014); They found that feature of chiral transition in the confined environment and suggesting an alternative to conventional first-principles calculations to determine the complex potential energy surface of intermolecular interactions. The MD simulations have been performed for the D molecule in the (15,6) single-walled boron nitride nanotubes (SWBNNT) at various temperatures, and the structure is shown in Figure 6 (Meng *et al.* 2014). In resumption of MD simulations performed to study the composition-dependent elastic modulus and thermal conductivity for carbon/silicon core/shell nanowires (NWs) (Jing *et al.* 2012). Wang and Lee (2010) studied the application of atomistic field theory (AFT) in modelling and simulation of polarization and phase transformation in multi-element crystalline materials. They described atomistic field theory and its corresponding cluster-based numerical implementation. In 2012, Mortazavi and Re´mond (2012) employed classical MD simulations using the Tersoff potential for the Evaluation of thermal conductivity and tensile response of single-layer boron-nitride sheets (SBNS). Wang *et al.* (2008) performed atomistic simulations of $[0\ 0\ 1]-$, $[1\ \bar{1}\ 0]-$ and $[1\ 1\ 0]-$oriented GaN nanowires. Dai and Park (2013) utilized classical MD to study surface effects and Momeni *et al.* (2012) studied the Six MD models of ZnO nanobelts are constructed and simulated with lengths of $150.97\ \mathring{A}$ and lateral dimensions ranging between $8.13\ \mathring{A}$ and $37.37\ \mathring{A}$. Shokuhfar and Ebrahimi (2013) investigated the buckling of armchair BNNTs using MD simulation.

The second technique used is MC method. The physisorption of hydrogen storage in single walled boron nitride nanotube arrays (SWBNNTA) is simulated by the grand canonical MC method on the condition of moderate pressure at room temperature (Cheng *et al.* 2007a). Moreover, the properties of hydrogen physisorption in SWBNNTs investigated in detail by the grand canonical MC simulations by Cheng *et al.* (2007b).

Eventually, the third class is ab-initio. Using ab-initio, the Young’s modulus of double-wall boron nitride nanotubes (DWBNNT) were investigated by Fakhrabad and Shahtahmassebi (2013). In other researches (Mirnezhad *et al.* 2013, Zhukovskii *et al.* 2009), the mechanical properties of multilayer BN are characterized by ab initio simulations. Other atomistic modeling technique is density functional theory (DFT) (Rafiee and Moghadam 2014). Using DFT, the Young’s modulus of DWBNNTs were studied by Fakhrabad and Shahtahmassebi (2013) and Ansari *et al.* (2015). Recently, Bagheri *et al.* (2014) have studied electronic properties of zigzag DWBNNTs within DFT. In field of ZnO nanostructures, in 2006, Zhang and Huang (2006) simulated ZnO nanoplates according to DFT and Simulation of BN nanoribbons utilizing DFT. In another work, to estimate the bulk constant and the surface constant, Dai *et al.* (2011) compared both the DFT and MD results. Other atomistic methods such as tight bonding molecular dynamic, local density, density functional theory, Morse potential model and modified Morse potential model are also available which are in need of intensive calculations (Zhukovskii *et al.* 2009).

5.2 Continuum modeling

The second method used in modeling technique is continuum modeling (Zhukovskii *et al.* 2009). Continuum modeling (CM) were utilized by many engineers to investigate properties of PNS. Wang and Lee (2010)

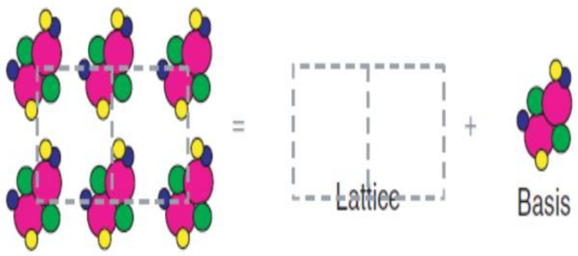


Fig. 7 Atomistic view of crystal structure (Wang and Lee 2010)

modelled and simulated the dynamic process of polarization and phase transformation in BaTiO3 through coarse-grained finite element method (FEM) simulations. A continuous collection of lattice cells and a group of discrete atoms situated within each lattice cell as shown in Figure 7 (Wang and Lee 2010).

Generalized Finite Element Method (GFEM) was utilized to formulate a nanocube made of cubic phase (BaTiO3) (Chen and Lee 2010). The FE simulation approach was used to analyze the effect of point defects like single atom vacancies (VB-boron vacancy and VN-nitrogen vacancy) and divacancies (VBN) (Panchal and Upadhyay 2013). In resumption, a finite element model for free vibrations of piezoelectric nanowires (NWs) was developed based on the non-local Euler-Bernoulli beam (EBB) model (Haghpanahi *et al.* 2013). Also, this simulation extended by many other researchers used CM for investigation and analysis as EBB model (Maraghi *et al.* 2013, Gheshlaghi and Hasheminejad 2012, Song *et al.* 2011), Timoshenko beam (TB) model (Ansari *et al.* 2014) various plate models (Yan and Jiang 2012, Asemi and Farajpour 2014, Zhang *et al.* 2014) and continuum shell model (Arani *et al.* 2013a, Kolahchi and Ghorbanpour 2012, Arani *et al.* 2012a).

5.3 Nano-scale continuum modeling

Since the continuum modeling is employed at the scale of nano, therefore the modeling is called as nano-scale continuum modeling (CM). Contrary to CM, nano-scale continuum modeling (NCM) provides a rationally acceptable compromise in the modeling process (Rafiee and Moghadam 2014).

The buckling behavior of BNNT-based structures was investigated with Nano-scale continuum (NCM) simulation (Salehi-Khojin and Jalili 2008). Jiang and Guo (2011), Freitas *et al.* (2013) and Panchal *et al.* (2013) extended a molecular mechanics model. They presented NCM modeling for simulation of SWBNNTs. Panchal *et al.* studied resonant frequency based analysis of SWBNNT with different types of point defect is performed using NCM modeling based on molecular structural mechanics. To evaluate the elastic properties of SWBNNTs, Jiang and Guo (2011) used NCM modeling.

6. Nonlocal continuum theory

Although the classical continuum method has given a simple description of nanotubes, it cannot present the small scale effects. Therefore, this method is limited for practical calculation. However, in the nonlocal continuum theory presented by Eringen (Salehi-Khojin and Jalili 2008, Meitzler *et al.* 1988), the stress at a reference point is considered as a function of the strain at every point in the body. Based on the nonlocal continuum theory, the constitutive relation of the nonlocal elasticity can be presented with the form of the integral equation as (Salehi-Khojin and Jalili 2008, Meitzler *et al.* 1988):

$$\sigma_{\mathfrak{k}l,\mathfrak{k}} - \rho \ddot{u}_l = 0 \quad (1)$$

$$\sigma_{\mathfrak{k}l}(x) = \int_V \alpha\,(x, x')\ \tau_{\mathfrak{k}l}(x')\ dV(x') \quad (2)$$

$$\varepsilon_{\mathfrak{k}l} = \frac{1}{2}(u_{\mathfrak{k},l} + u_{l,\mathfrak{k}}) \quad (3)$$

where $\sigma_{\mathfrak{k}l}$ is the nonlocal stress tensor, $\varepsilon_{\mathfrak{k}l}$ the strain tensor, ρ the mass density, u_l the displacement vector, $\tau_{\mathfrak{k}l}$ the classical (i.e. local) stress tensor, $\alpha\,(x, x')$ the kernel function which describes the influence of the strains at various location x' on the stress at a given location x and V the entire body. For the partial differential forms, the nonlocal constitutive relation can be expressed as

$$\sigma_x - (e_0 a)^2 \nabla^2 \sigma_x = \frac{E}{1-\nu^2}\left(\varepsilon_x + \nu\varepsilon_y + \nu\varepsilon_z\right) \quad (4)$$

$$\sigma_y - (e_0 a)^2 \nabla^2 \sigma_y = \frac{E}{1-\nu^2}\left(\varepsilon_y + \nu\varepsilon_x + \nu\varepsilon_z\right) \quad (5)$$

$$\sigma_z - (e_0 a)^2 \nabla^2 \sigma_z = \frac{E}{1-\nu^2}\left(\varepsilon_z + \nu\varepsilon_y + \nu\varepsilon_x\right) \quad (6)$$

$$\sigma_{xy} - (e_0 a)^2 \nabla^2 \sigma_{xy} = \frac{E}{2(1+\nu)}\gamma_{xy} \quad (7)$$

$$\sigma_{yz} - (e_0 a)^2 \nabla^2 \sigma_{yz} = \frac{E}{2(1+\nu)}\gamma_{yz} \quad (8)$$

$$\sigma_{zx} - (e_0 a)^2 \nabla^2 \sigma_{zx} = \frac{E}{2(1+\nu)}\gamma_{zx} \quad (9)$$

where $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ is the Laplacian operator, E the Young's modulus, the Poisson's ratio, the shear strain, e_0 the material constant to be determined from experiments or other methods, a the internal characteristic length (e.g. the length of C—C bond, the lattice spacing and granular distance) and $e_0 a$ the scale coefficient which denotes the small scale effect. Majority of before studies are based on Eringen's nonlocal elasticity theory.

7. Piezoelectric constitutive equations

Piezoelectric Constitutive Equations are presented based on the IEEE standard for piezoelectricity (Meitzler *et al.* 1988) which is widely accepted as being a good representation of piezoelectric material properties. The IEEE standard assumes that piezoelectric materials are

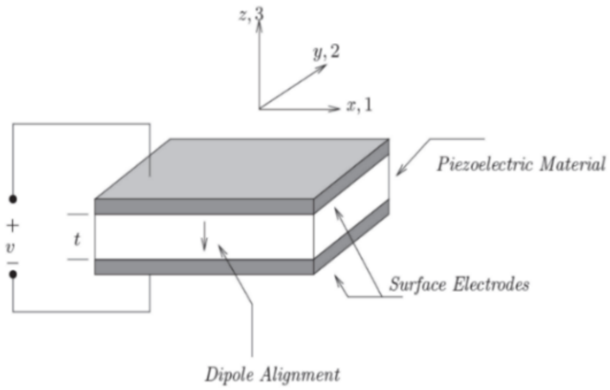
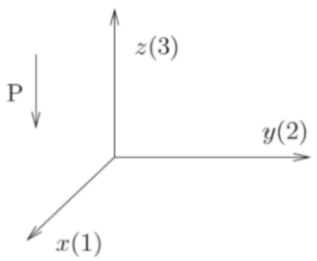


Fig. 8 Schematic diagram of a piezoelectric transducer (Meitzler *et al.* 1988)



	Axis
1	x
2	Y
3	z
4	Shear around x
5	Shear around y
6	Shear around z

Fig. 9 Axis nomenclature (Meitzler *et al.* 1988)

linear. Schematic diagram of a piezoelectric transducer is presented in Figure 8.

The constitutive equations describing the piezoelectric property are based on the assumption that the total strain in the transducer is the sum of mechanical strain induced by the mechanical stress and the controllable actuation strain caused by the applied electric voltage (Meitzler *et al.* 1988). The axes are identified by numerals rather than letters. In Figure 9, 1 refers to the x axis, 2 corresponds to the y axis, and 3 corresponds to the z axis. Axis 3 is assigned to the direction of the initial polarization of the piezoceramic, and axes 1 and 2 lie in the plane perpendicular to axis 3. This is demonstrated more clearly in Figure 9.

The describing electromechanical equations for a linear piezoelectric material can be written as:

$$\varepsilon_i = S_{ij}\,\sigma_j + d_{mi}\,E_m \tag{10}$$

$$D_m = d_{mi}\,\sigma_i + \zeta_{ik}\,E_k \tag{11}$$

where, the indexes $i, j = 1,2,\ldots,6$ and m, k = 1, 2, 3 refer to different directions within the material coordinate system, as shown in Figure 10. The above equations can be re-written in the following form, which is often used for applications that involve sensing (Meitzler *et al.* 1988):

$$\varepsilon_i = S_{ij}\,\sigma_j + g_{mi}\,D_m \tag{12}$$

$$E_i = g_{mi}\,\sigma_i + \beta_{ik}\,D_k \tag{13}$$

where,

σ: Stress vector($\mathrm{N/m^2}$)

ε: Strain vector (m/m)

E: Vector of applied electric field (v/m)

ζ: Permittivity (F/m)

d: Matrix of piezoelectric strain constants (m/V)

S: Matrix of compliance coefficients ($\mathrm{m^2/N}$)

D: Vector of electric displacement ($\mathrm{C/m^2}$)

g: Matrix of piezoelectric constants ($\mathrm{m^2/C}$)

β: Impermitivity component (m/F)

Furthermore, the superscripts D, E, and σ represent measurements taken at constant electric displacement, constant electric field and constant stress. Equations (10) and (12) express the converse piezoelectric effect, which describe the situation when the device is being used as an actuator. Eqs. 11 and 13, on the other hand, express the direct piezoelectric effect, which deals with the case when the transducer is being used as a sensor. The converse effect is often used to determine the piezoelectric coefficients (Meitzler *et al.* 1988).

8. Properties and behavior of piezoelectric nanostructures

In recent years, investigation of properties and behavior of PNSs has acquired very important in articles. Considerable efforts have been done by different researchers to evaluate mechanical and electrical properties of PNS. Many articles considered these properties such as Young's modulus (Zhang and Huang 2006, Jiang and Guo 2011, Chopra and Zettl 1998, Chen *et al.* 2006, Chen *et al.* 2010, Bo *et al.* 2014), Poisson's ratio (Jiang and Guo 2011, Mirnezhad *et al.* 2013), optical absorption (Rezania 2014, Mirnezhad *et al.* 2013), stability characteristics (Ansari *et al.* 2015, Lu *et al.* 2006), stress analysis (Fakrach *et al.* 2009, Arani *et al.* 2013a, Fang and Liu 2011).

In the study of ZnO nanostructures, Fan and Lu (2005) obtained physical properties and their values. Table 1 demonstrates the basic physical properties of bulk ZnO.

The elastic properties of BNNTs have been investigated in several work. Different results presented but all calculated values indicate a very high, but slightly smaller Young's modulus than for CNTs as shown in Table 2 (Zhi *et al.* 2010) Compared with the numbers of 1.22–1.25 TPa in CNTs, BNNTs possess a Young's modulus ranging from 0.837 to 0.912 TPa. The yield strength is also slightly smaller than that of CNTs (Zhi *et al.* 2010). Mechanical properties of hybrid nanocomposites consisting BN and multiwall carbon nano-tubes (MWCNT) embedded in epoxy resin were investigated by Ulus *et al.* (2013). Figure 11 shows the tensile strengths of epoxy resin reinforced with boron nitride nanoparticles (BNNPs) (Ulus *et al.* 2013). Figure 12 shows the elasticity moduli of neat epoxy, and epoxyresin modified by BNNP, MWCNT and BNNP/MWCNT (Ulus *et al.* 2013).

Table 1 Physical properties of wurtzite ZnO (Fan and Lu 2005)

properties	value
Lattice constants (T=300K)	0.32469 nm
a_0	0.52069 nm
C_0	5.606 g/cm^3
Density	2248 K
Melting point	8.66
Relative dielectric constant	3.4 eV, direct
Gap Energy	$< 10^6 cm^{-3}$
Intrinsic carrier concentration	60 meV
Exciton binding Energy	0.24
Electron effective mass	200 cm^2/Vs
Electron mobility (T=300 K)	0.59
Hole effective mass	5-50 cm^2/Vs
Hole	0.32469 nm

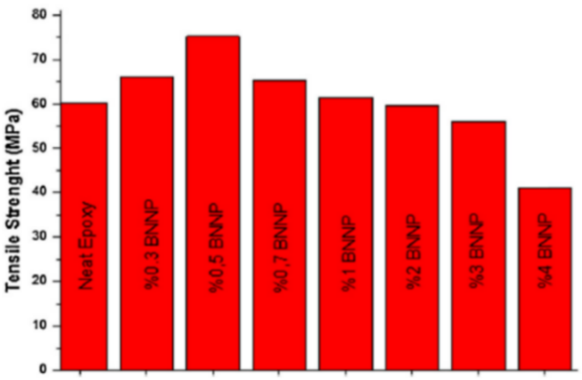


Fig. 10 Tensile stress charts of BNNP/Epoxy nanocomposites with different BN nanoplates loading (Ulus *et al.* 2013)

Freitas *et al.* (2013) investigated the effect of a transverse electric field on the properties of SW/DW/TW BNNTs. The obtained results indicated that significant reduction on the Formation and gap energies were observed for single-wall tubes with diameter greater than $10° A$.

Focusing on Young's modulus, in 1998, Chopra and Zettl (1998) reported the elastic properties of MWBNNTs. As an axial Young's modulus to be $1.22 \pm 0.24\ TPa$, a value consistent with theoretical estimates. In contrast, Chen *et al.* (2006) obtained the Young's modulus of piezoelectric NWs observed to increase with the decrease of NW diameter at the nanoscale. Young's moduli of ZnO nanoplates developed by Zhang and Huang (2006). Chen *et al.* (2010) investigated the nanoscale mechanical behaviors of (NKBT) piezoelectric nanofibers and thin film. In comparison with the reduced modulus (158.2 GPa) and hardness (7.3 GPa) of NKBT thin film, the reduced modulus and hardness are 107.6 GPa and 4.9 GPa for the nanofibers. In 2013,

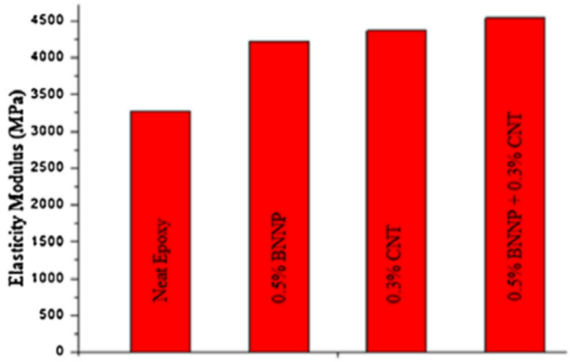


Fig. 11 Elasticity Modulus charts of epoxy nanocomposites with different nanoparticle loadings (Ulus *et al.* 2013).

Mirnezhad *et al.* (2013) studied the mechanical properties of multilayer BN. This investigation shown that Young's modulus and Poisson's ratio of multilayer BN are lower than those of monolayer BN. Bo *et al.* (2008) considered PZT piezoelectric composites incorporating zinc oxide nanowhiskers (ZnOw). They considered a significant enhancement in the mechanical properties such as Young's modulus. Electrical field-assisted thermal decomposition of BNNT were investigated by Xu *et al.* (2009), as well as they proposed a model that due to the partially ionic nature of the BN bond, the decomposition energy is both temperature and electrical field-related. Jiang and Guo (2011) obtained Young's modulus as functions of the nanotube diameter. Aydin (2013) calculated IR, nonresonance Raman spectra and vertical electronic transitions of the zigzag SW/DW BNNTs. Two-dimensional electro-mechanical analysis of a composite rotating shaft subjected to nonaxisymmetric internal pressure and applied voltage was investigated where hollow piezoelectric shaft reinforced by BNNTs (Arani *et al.* 2012a). An analytical study for the elastic properties of SWBNNTs were presented by Guo and Jiang (2011). As a result, Poisson's ratio and surface shear modulus were derived as functions of the nanotube diameter. Bando *et al.* (2001) reported the results on structural and chemical analysis of insulating BNNTs. Soltani *et al.* (2013) demonstrated the adsorption behavior of the CN radical (CRN) on the external surface of zigzag SWBNNT. The results indicated that BNNT could be a suitable sensor. Rezania *et al.* (2014) investigated the behavior of optical absorption of BNNT in the base of Hubbard model. A three-dimensional FEM proposed in which the nanotubes were modeled using the principles of structural mechanics. The results shown that at the same radius, longer nanotubes are less stable. However, for sufficiently long nanotubes the effect of side length decreases (Ansari *et al.* 2015). It is named as electrical field-assisted thermal decomposition. Structural and electronic properties of zigzag SWBNNTs investigated within density functional theory (Bagheri *et al.* 2014). Fakrach *et al.* (2009), using the spectral moments method, investigated the calculations of the Raman spectra of SWBNNTs. It is shown that the modes in the low frequency region are very sensitive to the nanotube diameter variation.

Table 2 Structural and elastic properties of nanotubes obtained from the tight-binding calculations. Young's modulus values given in parentheses were obtained from first-principles calculations (Zhi *et al.* 2010)

BxCyNz	(n,m)	Deq (nm)	σ	Ys(TPa nm)	Y (TPa)
C	(10,0)	0.791	0.275	0.416	1.22
	(6.6)	0.820 (0.817)	0.247	0.415(0.371)	1.22 (1.09)
	(10,5)	1.034	0.265	0.426	1.25
	(10,7)	1.165	0.266	0.422	1.24
	(10,10)	1.360	0.256	0.423	1.24
	(20,0)	1.571	0.270	0.430	1.26
	(15,15)	2.034	0.256	0.425	1.25
BN	(10,0)	0.811	0.232	0.284	0.837
	(6,6)	0.838 (0.823)	0.268	0.296 (0.267)	0.870 (0.784)
	(15,0)	1.206	0.246	0.298	0.876
	(10,10)	1.390	0.263	0.306	0.901
	(20,0)	1.604	0.254	0.301	0.884
	(15,15)	2.081	0.263	0.310	0.912
Bd	(5,0)	0.818	0.301	0.308	0.906
	(3,3)	0.850	0.289	0.311	0.914
	(10,0)	1.630	0.282	0.313	0.922
	(6,6)	1.694	0.279	0.315	0.925
BC2N II	(7,0)	1.111	0.289	0.336	0.988
	(5,5)	1.370	0.287	0.343	1.008

Hanifi Hachemi Amar *et al.* (2017) and Hadji *et al.* (2016c) studied size-dependent behavior of FG micro-beams. In 2011, Song *et al.* (2011) demonstrated the importance of accounting for the effects of initial stresses in NWs that are caused by deformation due to surface stresses. They noted that such initial stresses have previously been neglected in most existing continuum models. By considering the local geometrical nonlinearity of strains, a new formulation of EBB model for nanowires was developed through the incremental deformation theory. Under electro-elastic waves, the dynamic stress of a cylindrical piezoelectric nano-fiber in piezoelectric nanocomposites were studied by Fang and Liu (2011). The results shows that the dynamic stress decreases due to the electro-elastic coupling at the interface. In another work, electro-thermo-elastic stress analysis of piezoelectric thick-walled cylinder reinforced by BNNTs subjected to electro-thermo-mechanical fields was investigated by Arani *et al.* (2013b). Figure 12 presents dimensionless effective stress versus the radius of the smart composite cylinder for different voltages.

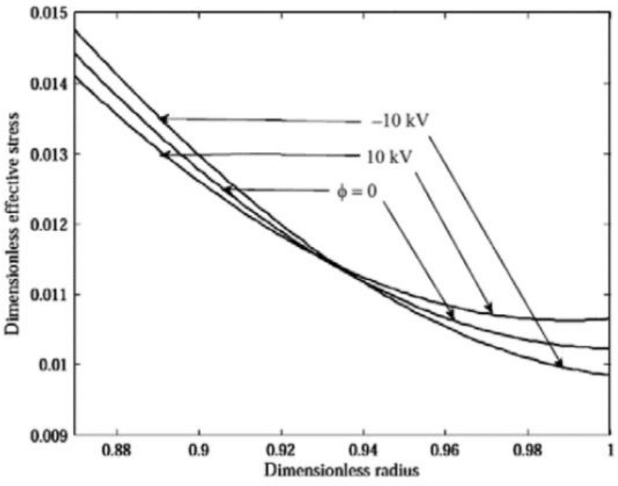


Fig. 12. present dimensionless effective stress versus the radius of the smart composite cylinder for different voltages (Arani *et al.* 2013a)

Figure 13 demonstrates the dimensionless effective stress versus the radius of the smart composite cylinder for different internal temperatures, with external temperature at 30℃ (Arani *et al.* 2013b). The tensile strength and strain of the end-to-end joint was obtained by Kim *et al.* (2012). Panchal *et al.* (2013) studied the dynamic response analysis of SWBNNTs. In another work, (Lin *et al.* 2008), PZT-based nanocomposites embedded with ZnO nanowhiskers (ZnOw) was Compared with monolithic PZT. Recently, Seo *et al.* (2013), Scrymgeour and Hsu (2008), Chowdhury *et al.* (2010), Kong and Wang (2003) have reported the elastic and piezoelectric properties of ZnO nanostructures. Liu *et al.* (2012) investigated Effect of flexoelectricity on electrostatic potential in a bent piezoelectric nanowire. It was shown that the electric potential in the NW does not have electromechanical effects of NWs analyzed with fully coupled models of electroelasticity (Patil *et al.* 2009). Strain distributions were obtained using analytical expressions derived from the Eshelby formulation. The effect of nitrogen content on microstructure, mechanical behaviors and thermal stability were investigated by X-ray diffraction (XRD), plan-view high resolution transmission electron microscopy (HRTEM) and X-ray photoelectron spectroscopy (XPS) and microindentation methods (Lu *et al.*

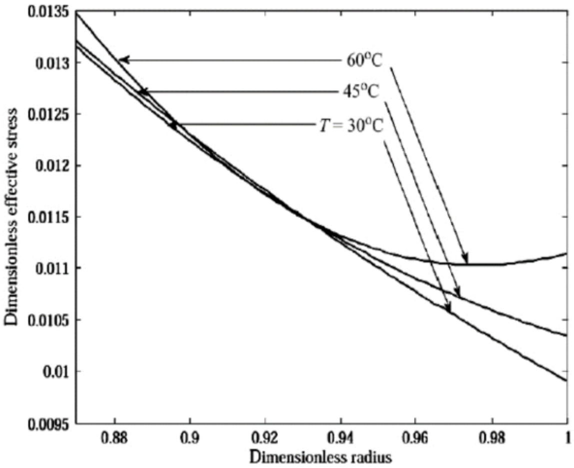


Fig. 13 Dimensionless effective stress versus the radius of the smart composite cylinder for different internal temperatures (Arani *et al.* 2013a)

2006). The electrical and piezoelectric properties of the M/C composite was demonstrated by Yun and Kim (2011). Additionally, piezoelectric response of in $Sm\,Fe_3(Bo_3)_4$ was studied by Kolodyazhnaya and Zvyagina (2017).

Sun *et al.* (2010) investigated the potential, the output power and the energy conversion efficiency of PNS, including NWs. The possibility of piezoelectric nano composites without using piezoelectric materials are studied by Sharma *et al.* (2007). Ganji and Mohammadi-Nejad (2007) considered a SW (5,0) BNNT sandwiched between an Au substrate to study the electrical transport properties of BNNTs. In 2012, Qi *et al.* (2012) reported that the band gap of zigzag BN nanoribbons can be significantly tuned under uniaxial tensile strain. The influence of polarization mode on the piezoelectric behavior of BT was studied by Capsal *et al.* (2010). Wang *et al.* (2006) studied piezoelectric behaviors of individual single NW under direct axial electric biasing. In 2012, Minary *et al.* (2012) considered GaN NWs exhibit strong piezoelectricity in three demensional. The mechanical responses of a piezoelectric composite nanotube subject to an axial strain and electrical voltage were investigated by Zhang *et al.* (2012). Zhang *et al.* (2010) studied Strain effect on ferroelectric behaviors of BaTiO3 NWs. In this paper, complementary to the earlier work by Wang *et al.* (2006), Zhang *et al.* (2010) found that size effects influences in the piezoelectric coefficient of the BaTiO3 NWs. Zemri *et al.* (2015) demonstrated a mechanical response for FG nanobeams. Focusing on piezoelectric characteristics, some papers have recently reported new results in considering the mechanical and electrical properties of nanomaterials zinc oxide (ZnO) nanowires and poly (vinylidene fluoride) (PVDF) polymer (Choi *et al.* 2017, Arefi and Zenkour 2017, Liu and Wang 2017).

It is worth mentioning that Asemi and Farajpour (2014) investigated the effect of non-uniform voltage distribution on combinational thermo-electro-mechanical vibration of piezoelectric nanoplates. They modeled a coupled piezo nanostructure. Arani and Haghparast (2011) modeled a piezoelectric annular plate reinforced with BNNTs. This piezoelectric nanostructure was used to analyze thermal environment on electro-mechanical buckling. To study dynamic stress and electric displacement caused by electro-elastic waves, Fang and Liu (2011) modeled piezoelectric nanocomposites reinforced with nanofibers. Recently, Rahmati and Mohammadimehr (2014) presented a non-uniform and non-homogeneous model based on boron nitride nanorods embedded in an elastic medium. It was subjected to combined loadings to analyze vibration behavior. Further, Razavi *et al.* (2017) modeled a functionally graded piezoelectric cylindrical nanoshell to investigate free vibration.

9. Mechanical analyses

This section intend administrate the investigation of the mechanical behavior of the piezoelectric nanostructures. These analyses can be divided on four categories: 1) surface and small scale effects, 2) buckling, 3) vibration and 4) wave propagation. In the following, it is paid to study each one of them.

9.1 surface and small scale effects

"Small is different", materials of nanostructured piezoelectric exhibit size-dependent properties, which are different from their bulk counterparts (Yan 2013) as well as the small-scale effect depends on the crystal structure in lattice dynamics and the nature of physics under investigation. For piezoelectric nanomaterials, based on the surface elasticity model, in 2006, a relation to electric field dependent surface stress, or alternatively surface piezoelectricity, was proposed. Based on such relation, a piezoelectric ring under prescribed potential was studied by Huang *et al.* (2006) and the results shown that the surface piezoelectricity may play an important role in the electromechanical behavior of piezoelectric nanostructures also, Huang *et al.* (2006) presented the constitutive equations for the surface are expressed as:

$$\sigma^{S}_{\alpha\beta} = \sigma^{0}_{\alpha\beta} + C^{S}_{\alpha\beta\gamma\delta}\varepsilon_{\alpha\beta} - e^{S}_{\alpha\beta k}\,E_{k} \tag{14}$$

$$D^{S}_{i} = D^{0}_{\alpha\beta} + e^{S}_{\alpha\beta i}\varepsilon_{\alpha\beta} - \kappa^{S}_{ij}\,E_{j} \tag{15}$$

which $C^{S}_{\alpha\beta\gamma\delta}$, $e^{S}_{\alpha\beta k}$ and κ^{S}_{ij} being the surface elastic constants, surface piezoelectric constants and surface dielectric constants tensors.

$\sigma^{0}_{\alpha\beta}$ and $D^{0}_{\alpha\beta}$ can be termed as residual surface stress and surface electric displacement without applied strain and electric field. The constitutive relations in the bulk are the same as traditional piezoelectric materials, which are written in the form,

$$\sigma_{ij} = C_{ijkl}\,\varepsilon_{kl} - e_{ijk}\,E_{k} \tag{16}$$

$$D_{i} = e_{kli}\,\varepsilon_{kl} + \kappa_{ij}\,E_{j} \tag{17}$$

with C_{ijkl}, e_{ijk} and κ_{ij} being the bulk elastic constants,

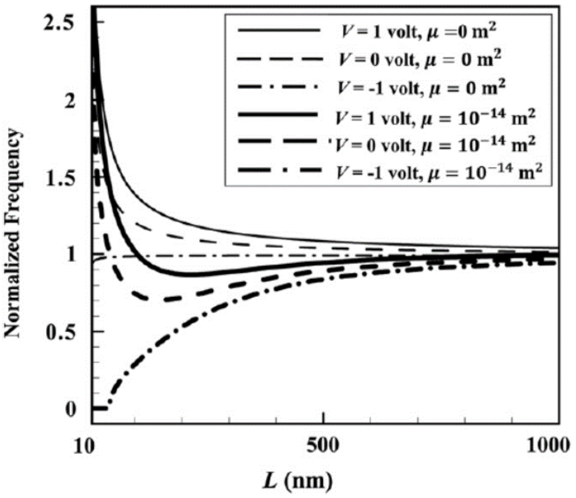


Fig. 14 Variation of the normalized fundamental natural frequency with NW length for selected input voltages and non-local parameters (Gheshlaghi and Hasheminejad 2012).

bulk piezoelectric constants and bulk dielectric constants tensors.

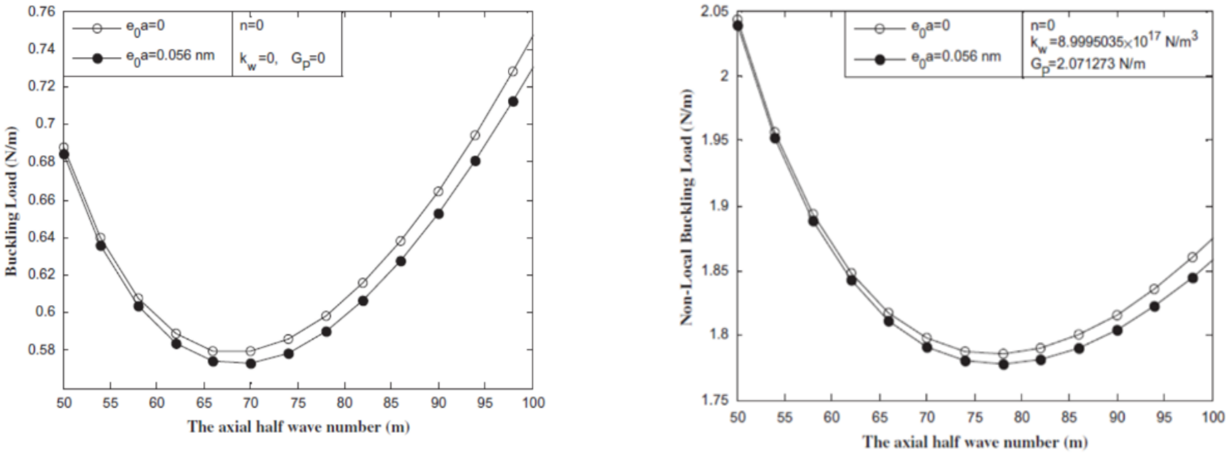
Dai *et al.* (2011) studied Size effects in nanostructures. Nanostructures of certain non-piezoelectric materials may also exhibit piezoelectric behavior and also the renormalization of apparent piezoelectric behavior at small scales, as mentioned by Dai *et al.* (2011). Yan and Jiang (2011a) investigated surface effects of a curved piezoelectric nanobeam (PNB). The results indicated that the surface effects play a significant role in the electroelastic fields and the piezoelectric response of the curved piezoelectric nanobeam. Dai and Park (2013), Yan and Jiang (2011b), Gheshlaghi and Hasheminejad (2012), Momeni *et al.* (2012), He and Lilley (2008a, b) studied surface effects on the piezoelectric properties of NWs. In addition, Gheshlaghi and Hasheminejad (2012) considered both surface and non-local effects. Mercan and Civalek (2017) and Youcef *et al.* (2018) studied surface stress effects on nanobeams made of Silicon carbide nanotubes (SiCNTs) and nanoplates.

Figure 14 displays variation of the normalized fundamental natural frequency of the piezoelectric NW with its length for selected input voltages and non-local parameters.

Dai and Park (2013) studied surface effects on the piezoelectric properties of ZnO nanowires as calculated under uniaxial loading. Momeni *et al.* (2012) also studied the size scale effect on the piezoelectric response of NWs. Yan and Jiang (2011b) studied the static bending of a cantilever piezoelectric NW. The surface effects were found to significantly influence the stiffness and electric field distribution in the NW. He and Lilley (2008a) investigated the influence of surface effects on the elastic behavior of static bending of NWs with different boundary conditions and also, they investigated the influence of surface effects on the resonant frequencies of NWs (He and Lilley 2008b). Recently, Wang *et al.* (2012) have investigated the influence of the surface and small-scale effects on electromechanical coupling behavior of a piezoelectric NW. One of the results was that the inclusion of the nonlocal effect in the model produces a significant difference from the past model which ignores the nonlocal effect in the prediction of the EMC coefficient and the electric field in the nanowire, confirming the significance of including the surface and small-scale effects in the analysis of piezoelectric NWs. The influence of surface effects, including residual surface stress, surface elasticity and surface piezoelectricity, on the vibrational and buckling behaviors of piezoelectric nanobelts (PNBs) was investigated by Yan and Jiang (2011c). Zheng *et al.* (2010) considered the influence of the residual stress and surface elasticity on the vibration and buckling behaviors of piezoelectric NWs using the EBB model. Yan and Jiang (2011b) investigated the electromechanical coupling coefficient and they found that the electromechanical coupling coefficient could be increased due to the surface effects. Also, in field of piezoelectric nanoplates (PNPs), Zhang *et al.* (2014) considered their surface effects. Numerical results show that the surface piezoelectricity have significant influence on the size-dependent properties of dispersion behaviors. In another work, surface effects on the clamped-clamped PNP were investigated using Kirchhoff plate theory with the incorporation of the surface piezoelectricity model and the generalized Young-Laplace equations (Yan and Jiang 2012a). In the study of one double-layer piezoelectric nanoplates under thermo-electro-mechanical loadings, residual surface stresses were studied by Karimi *et al.* (2017).

9.2 Buckling analysis

The term "buckling" means a deformation process in which a structure subjected to high stress undergoes a sudden change in morphology at a critical load (Brush and Almroth 1975). In the study of buckling behavior, Arani and Haghparast (2011) first reviewed axisymmetric buckling behavior of piezoelectric fiber, nonlinear buckling response of DWBNNT (Barzoki *et al.* 2013), then electro-thermo-torsional buckling of DWBNNT (Ghorbanpour Arani *et al.* 2013a, Ghorbanpour Arani *et al.* 2012a, Barzoki *et al.* 2012), axial buckling of DWBNNTs (Ghorbanpour Arani *et al.* 2012b), electro-thermomechanical buckling (Ghorbanpour Arani *et al.* 2012a). They also indicated how the buckling resistance of composite shell may vary by applying thermal and electrical loads. The results reported by Barzoki *et al.* (2012) were validated as far as possible by the axial buckling of cylindrical shell with an elastic core in the absence of an electric field, as presented by Ye *et al.* (2011). The effects of parameter small scale is demonstrated on the buckling behavior of the DWBNNTs Figure 15. In addition, Mokhtar *et al.* (2018a,b), Yazid *et al.* (2018), Younsi *et al.* (2018), Abdelaziz *et al.* (2017), Attia *et al.* (2018), Hebali *et al.* (2014), Bennoun *et al.* (2016), Abualnour *et al.* (2018), Draiche *et al.* (2016), El-Haina *et al.* (2017), Menasria *et al.* (2017), Chikh *et al.* (2017), Meksi *et al.* (2019), Meziane *et al.* (2014), Zaoui *et al.* (2019), Houari *et al.* (2016), Aissani *et al.* (2015) and Demir *et al.* (2016) in their research works, have developed mechanical behavior including buckling and bending of FG plate as well as composite plate structures. Their results are



(a) (b)

Fig. 15 Small scale effect on the buckling load for n = 0, (a) without elastic medium (b) with elastic medium (Ghorbanpour Arani *et al.* 2012b)

considered as benchmark in developing micro/nano electromechanical systems.

The structural properties such as bond length, diameter dilation of smaller nanotubes, bucking of B–N bonds, and strain energy were investigated by Moon and Hwang (2004). As a result, the buckling decreases with increasing the nanotube diameter, but does not depend on nanotube helicity. In 2007, Salehi-Khojin and Jalili (2008) modeled the buckling of BNNT reinforced piezoelectric polymeric composites subject to combined electro-thermo-mechanical loadings. Akgoz and Civalek (2013), Semmah *et al.* (2019), Ahouel *et al.* (2016) and Civalek and Demir (2011) investigated linear and nonlinear postbuckling of nanobeams. The multi-walled structure of BNNT was considered as elastic media and a set of concentric cylindrical shells with van der Waals interaction between them. Shokuhfar and Ebrahimi-Nejad (2013) examined the buckling of perfect and defective armchair BNNTs with three types of vacancy defects. Results shown that reduction in the buckling strength of the nanotube due to the presence of more than one B-vacancy defect depends on their distribution and also vacancy defects play a critical role in the buckling of BNNTs. Using FEM, Taghizadeh *et al.* (2015) investigated bending in beams. Wang *et al.* (2011) studied the buckling behaviors of copper–filled SWBNNTs under axial Compression. Yan and Jiang (2011c, 2012b) considered the buckling behaviors of piezoelectric nanobeams and nanoplates. The axial buckling of the ZnO-CNTs nanotubes (ZCNTs) was investigated using a composite model. Analytical solutions were also obtained based on the theory of three- dimensional elasticity and piezoelectricity (Zhang *et al.* 2012). Wang and Feng (2010) explained the effect of surface stress on the buckling of piezoelectric nanowires using the surface elasticity model ignoring the surface piezoelectricity effect. Mechanical and dynamic behavior of FG micro/nano scale beams have also been conducted by Larbi Chaht *et al.* (2015), Al-Basyouni *et al.* (2015), Tlidji *et al.* (2019), Zidi *et al.* (2017), Li *et al.* (2017), Akgoz *et al.* (2017), Akbas *et al.* (2018) and Numanoglu *et al.* (2018).

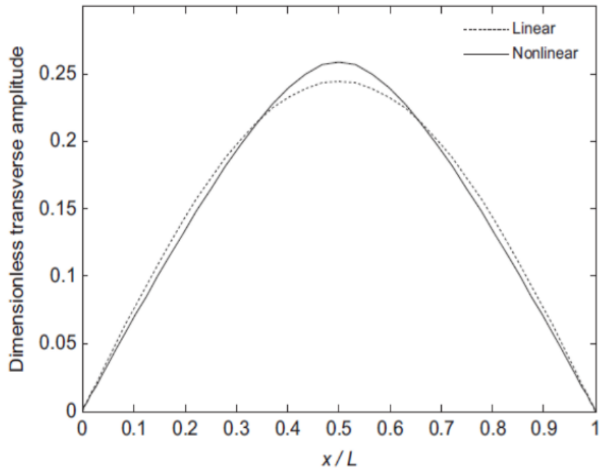


Fig. 16 Distribution of transverse amplitude along the SWBNNT (Arani *et al.* 2012b)

Size-dependent buckling and postbuckling behavior of piezoelectric cylindrical nanoshells has been recently studied by Sahmani *et al.* (2016) and Sahmani *et al.* (2017). In order to study buckling response, Ebrahimi and Barati (2017a, b) modeled smart nanobeams made of functionally graded piezoelectric materials. Ebrahimi and Salari (2015) also studied the buckling of functionally graded piezoelectric nanobeams under applied electric voltage. In another work, Liang *et al.* (2016) studied the flexoelectric effect on the buckling behaviors of piezoelectric nanofilms. Recently, using modified couple stress theory, Malikan (2017) has shown that how an external electric voltage can affect the buckling behavior of a piezoelectric nanoplate. Using the strain gradient and modified couple stress theories, Mercan and Civalek (2016) and also Akgöz and Civalek (2011) analyzed buckling of carbon CNTs and BNNTs.

9.3 Vibration analysis

Mechanical behaviors of PNSs such as vibrations are important in many applications among sensors. In fact,

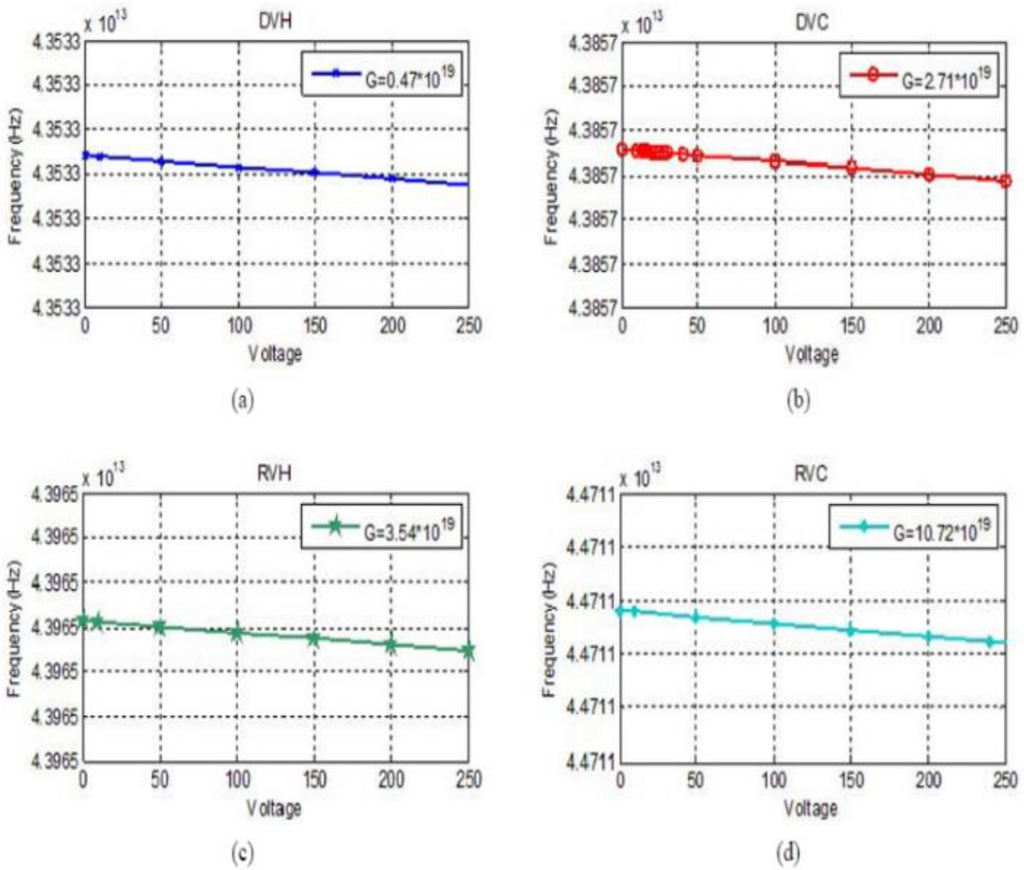


Fig. 17 The effect of elastic medium module G on the natural frequency versus flow velocity of embedded DWBNNT: (a) DVH; (b) DVC; (c) RVH; (d) DVC (Arani *et al.* 2012d)

vibration characteristics play a significant role to identify the performance of sensors. Initially, Zhang *et al.* (2008) proposed a continuum model to compute the long-wave length optical phonons of SWBNNTs. The effect of the polarity in the BNNTs on optical vibrations was considered by this model. In the study of vibration behavior of PNSs, Arani and his co-workers considered linear vibration behavior (Ghorbanpour Arani *et al.* 2013a, Arani *et al.* 2012b, Ghorbanpour Arani and Amir 2013), nonlinear vibration (Ghorbanpour Arani *et al.* 2012c, Arani *et al.* 2012c, Ghorbanpour Arani *et al.* 2013b, Khodami Maraghi *et al.* 2013) as well as longitudinal and transverse vibrations (Ghorbanpour Arani and Roudbari 2013, Ghorbanpour Arani *et al.* 2013b, Arani *et al.* 2012d) of PNSs such as a single layer and multilayer boron nitrides. Mouffoki *et al.* (2017) reported vibration characteristics of nanobeams in hygro-thermal environment. Cherif *et al.* (2018) investigated vibration behavior of nanobeams including thermal effect.

In another work, Ansari *et al.* (2014) studied the effects of geometric nonlinearity, elastic foundation modulus, electric potential field, temperature change and nonlocal parameter on the frequency of the SWBNNT studied in detail. Results reported by Ghorbanpour Arani *et al.* (2013b) indicated that the internal moving fluid is very important in the instability of the cylindrical shell and also in 2012, the results reported by Ghorbanpour Arani *et al.* (2012c) explained that increasing mean flow velocity in BNNTs remarkably increases the nonlinearity effects but small scale and temperature change effects become negligible. Demir and Civalek (2017) presented a new nonlocal FEM for thermal vibration of nanobeams. The amplitude of transverse vibration along the SWBNNT for linear and nonlinear analysis is shown in Figure 16 (Arani *et al.* 2012b).

SWBNNT embedded in Bundle of CNTs which is simulated as Pasternak foundation was investigated by Arani *et al.* (2012d). The influences of nonlocal parameter, geometrical aspect ratio, mechanical boundary condition, elastic medium constant, temperature gradient, orientation angle and volume fraction of DWBNNTs on the nonlinear frequency and nonlinear-to-linear frequency ratio were studied by Arani *et al.* (2012c). In order to study the effect of the van der Waals (vdW) forces, electro-thermo nonlinear vibration and instability of embedded DWBNNTs conveying viscose fluid was studied by Maraghi *et al.* (2013). Buckling and vibration of FG sandwich plate was analyzed by Tounsi *et al.* (2016).

In addition, Ghorbanpour Arani and Roudbari (2013), the detailed parametric study was conducted, focusing on the remarkable effects of the small scale parameter, aspect ratio, surface stress and visco-Pasternak coefficients on the vibration behavior of the coupled BNNT system. The influence of the intelligent controller was demonstrated on the nondimensional fundamental longitudinal frequency.

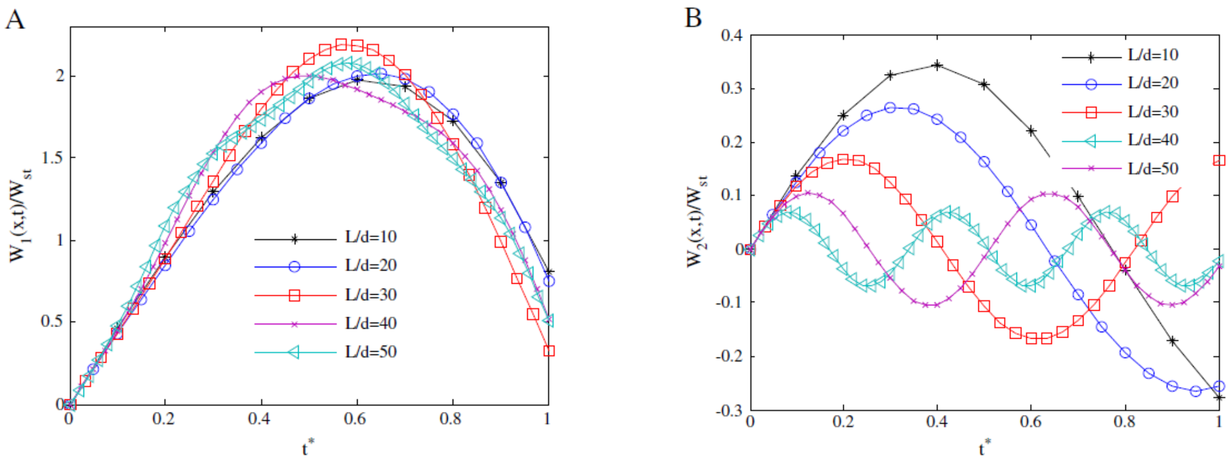


Fig. 18 A. Variation of the normalized dynamic deflections with the dimensionless time for primary nanotube. B. Variation of the normalized dynamic deflections with the dimensionless time for secondary nanotube (Panchal *et al.* 2013)

The results of Maraghi *et al.* (2013) indicated that the frequency and critical fluid velocity increases when considering the small scale parameter. Figure 17 shows the influence of applied voltage on the natural frequencies for four cases of DVH, DVC, RVH and RVC (Arani *et al.* 2012d).

DVH, DVC, RVC and RVH are four states of electro-thermal loading (Arani *et al.* 2012d). Variation of the normalized dynamic deflections with the dimensionless time for primary and secondary nanotube is illustrated in Figure 18 A and B. Since Arani, also other articles investigated the vibration behavior in piezoelectric nanostructures. Vibrational characteristics of SWBNNT were explored considering point defects (single atom vacancies and di-vacancies) to use SWBNNTs as nano mechanical mass sensors (Panchal *et al.* 2013). The results indicated that the mass sensitivity limit of 10^{-25} kg can be obtained. Recently, electro-thermo-nonlocal axial vibration analysis of SWBNNRs under electric excitation has been reported by Mohammadimehr and Rahmati (2013). The size-dependent nonlinear free vibration and instability of fluid-conveying SWBNNTs embedded in thermal environment were studied by Ansari *et al.* (2014).

Electro-thermo-mechanical vibration analysis of non-uniform and non-homogeneous boron nitride nanorod (BNNR) embedded in elastic medium was presented by Rahmati and Mohammadimehr (2014). Using Maxwell's equation and nonlocal elasticity theory, the coupled displacement and electrical Potential equations were presented. Wang *et al.* (2011) developed a mechanics model to quantify the pressure dependence of the NT vibration and then investigated the physics of the pressure-dependent vibration. An analytical model for predicting surface effects on the free transverse vibrations of piezoelectric nanowires (PNWs) was developed based on the non-local EBB theory by Gheshlaghi and Hasheminejad (2012). Asemi and Farajpour (2014) developed thermo-electro-mechanical free vibration of PNPs based the nonlocal theory and Kirchhoff theory. In another study presented by Liu *et al.* (2013), it was found that: (1) the increase in the nonlocal parameter is tending to decrease the natural frequencies; (2) the natural

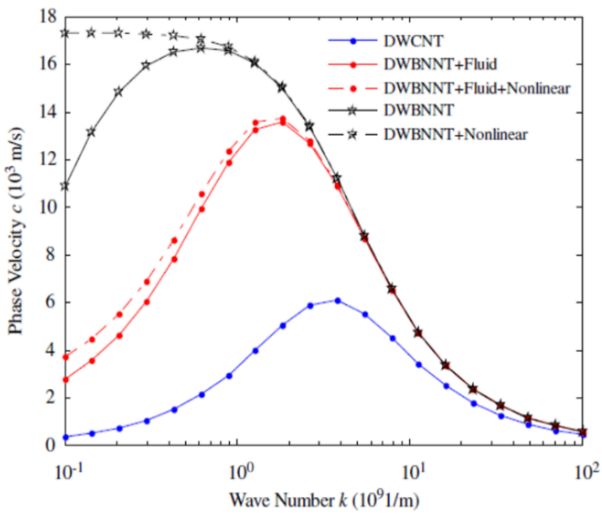


Fig. 19 The downstream phase velocity versus wave number for Eringen's nonlocal theory (Ghorbanpour Arani *et al.* 2012e)

frequencies of PNPs are very sensitive to the electro-mechanical loadings and insensitive to the thermal loading. Moreover, Haghpanahi *et al.* (2013) developed a finite element model for free vibrations of NWs based on the nonlocal theory and Galerkin method. Just recently, other researchers have studied vibration characteristics of diverse kinds of nano structures such as nanoplates (Zenkour, A. M. and Sobhy, M. 2017, Ebrahimi and Barati 2017c, Li *et al.* 2017, Wang *et al.* 2016), nanobeams (Ansari *et al.* 2016), nanoshells (Farajpour *et al.* 2017, Razavi *et al.* 2017), nanotubes (Kheibari and Beni 2017, Dehkordi and Beni 2017), single and double layered and functionally graded (Hosseini *et al.* 2017, Razavi *et al.* 2017, Refaeinejad *et al.* 2017, Zenkour and Arefi 2017) and porous (Shahverdi and Barati 2017) nanostructures. In each one of them, it has been tried to consider the effect of vibration behaviors on various nanomaterials.

The nonlinear vibration of PNBs based on the nonlocal theory were investigated by Ke *et al.* (2012). Besides, Ke and Wang (2012) investigated thermoelectric-mechanical vibration of the piezoelectric nanobeams based on the nonlocal theory. Nonlinear free vibration of FG nanobeams with immovable ends, i.e. simply supported-simply supported (SS) and simply supported-clamped (SC) was studied using the nonlocal elasticity (Nazemnezhad and Hosseini-Hashemi 2014). The surface effects including surface elasticity, surface stress and surface density on the nonlinear free vibration analysis of simply-supported FG_EB nanobeams using nonlocal elasticity theory were investigated by Hashemi *et al.* (2014). The influence of the flexoelectric effect on the static bending and free vibration of a simply supported piezoelectric nanobeam (PNB) was modeled based on the extended linear piezoelectricity theory by Zhang and Wang (2012). In this work, the vibration analysis of the PNB indicated that the flexoelectricity, rotary inertia and shear deformation tend to reduce the resonant frequency of the beams. In another work, the influence of the flexoelectric effect on free vibration of a simply supported piezoelectric nanobeam was investigated based on the extended linear piezoelectricity theory by Yan and Jiang (2013). Simulation results also indicated that the influence of the flexoelectricity on the vibration behavior of the PNB is more prominent for beams with smaller thickness. Zhou *et al.* (2007) studied the nonlinear vibration of a ZnO NW driven by an external electric field. Also, the thermo-electro-mechanical vibration characteristics of a piezoelectric nanoplate system (PNPS) embedded in a polymer matrix were studied. The governing equations were solved for various boundary conditions using differential quadrature method (DQM). With a focus on thermal and surface effect, nonlinear vibration of flexoelectric nanobeams is investigated by Barati (2017). Moreover, in order to analyze the surface energy effect on the vibration, nonlinear vibration of nonhomogeneous nanoshell covered with a piezoelectric nanolayer was developed by Fang and Zhu (2017).

9.4 Wave propagation

For BN nanostructures based on Eringen's piezoelasticity theories and the strain gradient, the wave propagation of an embedded DWBNNT conveying fluid was investigated using an EBB model by Ghorbanpour Arani *et al.* (2012e). Figure 19 illustrates the downstream phase velocity versus wave number for Eringen's nonlocal theory.

Nonlocal electro-thermo-mechanical wave propagation in an embedded armchair three-walled boron nitride nanotube (TWBNNT) conveying viscous fluid under torsional load was investigated (Abdollahian *et al.* 2013). Further, wave propagation of nanoplates and nanobeams made of graphene was conducted by Ebrahimi and Dabbagh (2018), Fourn *et al.* (2018). Electric wave propagation of SWBNNTs induced by alternating current (AC) was proposed by Arani *et al.* (2013b). Moreover, the dispersion characteristics of elastic waves propagating in a monolayer PNP were investigated by Zhang *et al.* (2014). Ait Yahia *et al.* (2015) investigated wave propagation of FG plates. Numerical results shown that both the nonlocal scale parameter and surface piezoelectricity have significant influence on the size-dependent properties of dispersion behaviors. Arani *et al.* (2014) also considered PNB used in micro and nano electromechanical systems and the dynamic testing of such structures often produces stress wave propagation in them. The two PNBs were coupled by an enclosing elastic medium which is simulated by Pasternak foundation. Results indicated that the imposed external voltage is an effective controlling parameter for wave propagation of the coupled system. Furthermore, the phase velocity of in-phase wave propagation is independent of elastic medium stiffness. In 2013, the dispersion characteristics of elastic waves propagating in a monolayer PNP was studied by Zhang *et al.* (2014). Using both the Euler and Timoshenko nanobeam model, Ma *et al.* (2017) presented a report in wave propagation behavior magneto-electro-elastic nanobeams.

10. Summary and conclusion

Owing to their superior mechanical and electrical properties, PNSs hold many potential applications in the ever-growing nanotechnology industry. In this paper, a comprehensive review on the piezoelectric nanostructures to obtain mechanical and electrical properties is done. Initially, more application of material which have piezoelectric property is introduced. ZnO, BN and GaN respectively, are more application of piezoelectric materials. In the following, modeling of PNSs is classified. Generally, the modeling methods of nanostructures can be categorized in three main groups as atomistic modeling, CM and NSCM. Other atomistic methods such as tight bonding MD, local density, density functional theory, Morse potential model and modified Morse potential model are also available which are in need of intensive calculations. Investigation of analyses is performed on fields: 1) surface and small scale effects, 2) buckling, 3) vibration and 4) wave propagation. In the study of vibration behavior, researches reviewed on fields of linear and nonlinear, longitudinal and transverse and free and forced vibrations. Application of these nanostructures in nanodevice such as nanogenerators, transistors, nanosensors and actuators is studied and then, synthesis and growth of PNSs is investigated. Finally, this paper shows that in field of model of PNBs, has been performed and presented many researches, but in field of other nanostructures such as PNPs still exists research area. The key issue is a very good understanding of mechanical behaviors of PNSs to use in nanodevice. The development of PNSs is still developing and the ongoing subject of study. Further studies on PNSs will focus:

- Thermal effects on piezoelectric property.
- Effect of functionally graded materials on PNSs.
- Investigation of nonlinear behavior in piezoelectric nanoplates.
- Composition of functionally graded material and piezoelectric nanomaterial then investigation of their mechanical and electrical behavior can be another interesting research area.

The results of the present study may also be listed as follows,

1. The piezoelectric effect and flexoelectric effect of material tend to diminish nonlinear vibration.

2. An increase in the nonlocal parameter is tending to decrease the natural frequencies.

3. Natural frequency of PNPs are very sensitive to the electro-mechanical loadings and insensitive to the thermal loading.

4. Surface piezoelectricity in PNPs have significant influence on the size-dependent properties of dispersion behaviors.

5. With a constant wide band gap at 5.0–6.0 eV, unmodified BNNTs can be considered as insulating materials.

6. The results can be helpful as a benchmark for the design of the piezoelectric structures such as micro/nano electromechanical systems (MEMS/NEMS).

References

Abdelaziz, H.H., Meziane, M.A.A., Bousahla, A.A., Tounsi, A., Mahmoud, S.R. and Alwabli, A.S. (2017), "An efficient hyperbolic shear deformation theory for bending, buckling and free vibration of FGM sandwich plates with various boundary conditions", *Steel Compos. Struct.*, **25**(6), 693-704. https://doi.org/10.12989/scs.2017.25.6.693.

Abdollahian, M., Ghorbanpour Arani, A., Mosallaie Barzoki, A. A., Kolahchi, R. and Loghman, A. (2013), "Non-local wave propagation in embedded armchair TWBNNTs conveying viscous fluid using DQM", *Physica B: Condensed Matter*, **418**, 1-15. https://doi.org/10.1016/j.physb.2013.02.037.

Abualnour, M., Houari, M.S.A., Tounsi, A. and Mahmoud, S.R. (2018), "A novel quasi-3D trigonometric plate theory for free vibration analysis of advanced composite plates", *Compos. Struct.*, **184**, 688-697. https://doi.org/10.1016/j.compstruct.2017.10.047.

Agrawal, R. and Espinosa, H.D. (2011), "Giant piezoelectric size effects in zinc oxide and gallium nitride nanowires. A first principles investigation", *Nano letters,* **11**(2), 786-790. https://doi.org/10.1021/nl104004d

Ahouel, M., Houari, M.S.A., Adda Bedia, E.A. and Tounsi, A. (2016), "Size-dependent mechanical behavior of functionally graded trigonometric shear deformable nanobeams including neutral surface position concept", *Steel Compos. Struct*, **20**(5), 963-981. https://doi.org/10.12989/scs.2016.20.5.963.

Aissani, K., Bouiadjra, M. B., Ahouel, M. and Tounsi, A. (2015), "A new nonlocal hyperbolic shear deformation theory for nanobeams embedded in an elastic medium", *Struct. Eng. Mech.*, **55**(4), 743-763. https://doi.org/10.12989/sem.2015.55.4.743.

Akbas, S. D. (2018), "Bending of a cracked functionally graded nanobeam", *Adv. Nano Res.*, **6**(3), 219-242. https://doi.org/10.12989/anr.2018.6.3.219.

Akgoz, B. and Civalek, O. (2011), "Buckling analysis of cantilever carbon nanotubes using the strain gradient elasticity and modified couple stress theories", *J. Comput. Theroetical Nanosci.*, **8**, 1821-1827. https://doi.org/10.1166/jctn.2011.1888.

Akgoz, B. and Civalek, O. (2013), "Buckling analysis of linearly tapered micro-columns based on strain gradient elasticity", *Struct. Eng. Mech.*, **48**(2), 195-205. https://doi.org/10.12989/sem.2013.48.2.195.

Akgoz, B. and Civalek O. (2017), "Effects of thermal and shear deformation on vibration response of functionally graded thick composite microbeams", *Compos. Part B Eng.*, **129**, 77-87. https://doi.org/10.1016/j.compositesb.2017.07.024.

Al-Basyouni, K. S., Tounsi, A. and Mahmoud, S. R. (2015), "Size dependent bending and vibration analysis of functionally graded micro beams based on modified couple stress theory and neutral surface position", *Compos. Struct*, **125**, 621-630. https://doi.org/10.1016/j.compstruct.2014.12.070.

Ansari, R., Norouzzadeh, A., Gholami, R., Faghih Shojaei, M. and Hosseinzadeh, M. (2014), "Size-dependent nonlinear vibration and instability of embedded fluid-conveying SWBNNTs in thermal environment", *Physica E Low Dimensional Syst. Nanostruct.,* **61**, 148-157. https://doi.org/10.1016/j.physe.2014.04.004.

Ansari, R., Rouhi, S., Mirnezhad, M. and Aryayi, M. (2015), "Stability characteristics of single-walled boron nitride nanotubes", *Arch. Civil Mech. Eng.*, **15**(1), 162-170. https://doi.org/10.1016/j.acme.2014.01.008.

Ansari, R., Oskouie, M. F., Gholami, R. and Sadeghi, F. (2016), "Thermo-electro-mechanical vibration of postbuckled piezoelectric Timoshenko nanobeams based on the nonlocal elasticity theory", *Compos. Part B Eng.*, **89**, 316-327. https://doi.org/10.1016/j.compositesb.2015.12.029.

Aphale, S., Fleming, A.J. and Moheimani, S.O.R. (2007), "High speed nano-scale positioning using a piezoelectric tube actuator with active shunt control", *Micro Nano Lett.,* **2**(1), 9-12. https://doi.org/10.1049/mnl:20065075.

Araneo, R. and Falconi, C. (2013), "Lateral bending of tapered piezo-semiconductive nanostructures for ultra-sensitive mechanical force to voltage conversion", *Nanotechnology,* **24**(26), 265707. https://doi.org/10.1088/0957-4484/24/26/265707.

Arani, A. G. and Haghparast, E. (2011), "Electro-Mechanical Buckling of a Piezoelectric Annular Plate Reinforced with BNNTs Under Thermal Environment", *J. Solid Mech.*, **3**(4), 379-391.

Arani, A. G., Haghparast, E. and Amir, S. (2012a), "Analytical Solution for Electro-mechanical Behavior of Piezoelectric Rotating Shaft Reinforced by BNNTs under Non-axisymmetric Internal Pressure", *J. Solid Mech.,* **4**(4), 339-354.

Arani, A. G., Atabakhshian, V., Loghman, A., Shajari, A. R. and Amir, S. (2012b), "Nonlinear vibration of embedded SWBNNTs based on nonlocal Timoshenko beam theory using DQ method", *Physica B: Condensed Matter*, **407**(13), 2549-2555. https://doi.org/10.1016/j.physb.2012.03.065.

Arani, A. G., Vossough, H., Kolahchi, R. and Barzoki, A. M. (2012c), "Electro-thermo nonlocal nonlinear vibration in an embedded polymeric piezoelectric micro plate reinforced by DWBNNTs using DQM", *J. Mech. Sci. Technol.,* **26**(10), 3047-3057. https://doi.org/10.1007/s12206-012-0816-6.

Arani, A. G., Shokravi, M., Amir, S. and Mozdianfard, M. R. (2012d), "Nonlocal electro-thermal transverse vibration of embedded fluid-conveying DWBNNTs", *J. Mech. Sci. Technol.,* **26**(5), 1455-1462. https://doi.org/10.1007/s12206-012-0307-9.

Arani, A. G., Haghshenas, A., Amir, S., Mozdianfard, M. R. and Latifi, M. (2013a), "Electro-thermo-mechanical response of thick-walled piezoelectric cylinder reinforced by boron-nitride nanotubes", *Strength Mater.,* **45**(1), 102-115. https://doi.org/10.1007/s11223-013-9437-2.

Arani, A. G., Bidgoli, A. H., Ravandi, A. K., Roudbari, M. A., Amir, S., & Azizkhani, M. B. (2013b), "Induced nonlocal electric wave propagation of boron nitride nanotubes", *J. Mech. Sci. Technol.,* **27**(10), 3063-3071. https://doi.org/10.1007/s12206-013-0705-7.

Arani, A. G., Kolahchi, R. and Mortazavi, S. A. (2014), "Nonlocal piezoelasticity based wave propagation of bonded double-piezoelectric nanobeam-systems", *J. Mech. Mater. Design,* **10**(2), 179-191. https://doi.org/10.1007/s10999-014-9239-0.

Arefi, M. and Zenkour, A. M. (2017), "Nonlocal electro-thermo-mechanical analysis of a sandwich nanoplate containing a Kelvin–Voigt viscoelastic nanoplate and two piezoelectric layers", *Acta Mechanica*, **228**(2), 475-493. https://doi.org/10.1007/s00707-016-1716-0.

Arya, S. K., Saha, S., Ramirez-Vick, J. E., Gupta, V., Bhansali, S.

and Singh, S. P. (2012), "Recent advances in ZnO nanostructures and thin films for biosensor applications: Review", *Analytica Chimica Acta,* **737**, 1-21. https://doi.org/10.1016/j.aca.2012.05.048.

Asemi, S. R. and Farajpour, A. (2014), "Thermo-electro-mechanical vibration of coupled piezoelectric-nanoplate systems under non-uniform voltage distribution embedded in Pasternak elastic medium", *Current Appl. Phys.,* **14**(5), 814-832. https://doi.org/10.1016/j.cap.2014.03.012.

Attia, A., Bousahla, A. A., Tounsi, A., Mahmoud, S. R. and Alwabli, A. S. (2018), "A refined four variable plate theory for thermoelastic analysis of FGM plates resting on variable elastic foundations", *Struct. Eng. Mech.*, **65**(4), 453-464. https://doi.org/10.12989/sem.2018.65.4.453.

Aydin, M. (2013), "Vibrational and electronic properties of single-walled and double-walled boron nitride nanotubes", *Vib. Spectroscopy,* **66**, 30-42. https://doi.org/10.1016/j.vibspec.2013.01.011.

Badr, B. M. and Ali, W. G. (2010), "Nanopositioning fuzzy control for piezoelectric actuators", *J. Eng. Technol.,* **10**, 70-74.

Bagheri, M., Bahari, A., Amiri, M. and Dehbandi, B. (2014), "Electronic and structural properties of Au-doped zigzag boron nitride nanotubes: A DFT study", *Solid State Communications*, **189**, 1-4. https://doi.org/10.1016/j.ssc.2014.02.027.

Bailey, T. and Ubbard, J. E. (1985), "Distributed piezoelectric-polymer active vibration control of a cantilever beam", *J. Guidance Control Dynam.,* **8**(5), 605-611. https://doi.org/10.2514/3.20029.

Baima, J., Erba, A., Maschio, L., Zicovich-Wilson, C. M., Dovesi, R. and Kirtman, B. (2016), "Direct Piezoelectric Tensor of 3D Periodic Systems through a Coupled Perturbed Hartree–Fock/Kohn–Sham Method", *Z. Phys. Chem.*, **230**(5–7), 719–736. https://doi.org/10.1515/zpch-2015-0701.

Bando, Y., Ogawa, K. and Golberg, D. (2001), "Insulating nanocables: Invar Fe–Ni alloy nanorods inside BN nanotubes", *Chem. Phys. Lett.,* **347**(4), 349-354. https://doi.org/10.1016/S0009-2614(01)01075-2.

Barati, M.R. (2017), "On non-linear vibrations of flexoelectric nanobeams", *J. Eng. Sci.*, **121**, 143-153. https://doi.org/10.1016/j.ijengsci.2017.09.001.

Boughey, F. L., Davies, T., Datta, A., Whiter, R. A., Sahonta, S. L. and Kar-Narayan, S. (2016), "Vertically aligned zinc oxide nanowires electrodeposited within porous polycarbonate templates for vibrational energy harvesting", *Nanotechnology*, **27**(28), 28LT02. https://doi.org/10.1088/0957-4484/27/28/28LT02.

Brush, D. O. and Almroth, B. O. (1975), Buckling of Bars, Plates, And Shells, McGraw-Hill, NY, USA.

Capsal, J.F., Dantras, E., Laffont, L., Dandurand, J. and Lacabanne, C. (2010), "Nanotexture influence of BaTiO3 particles on piezoelectric behaviour of PA 11/BaTiO3 nanocomposites", *J. Non Crystalline Solids*, **356**(11-17), 629-634. https://doi.org/10.1016/j.jnoncrysol.2009.06.050.

Chang, J., Dommer, M., Chang, C. and Lin, L. (2012), "Piezoelectric nanofibers for energy scavenging applications", *Nano Energy,* **1**(3), 356-371. https://doi.org/10.1016/j.nanoen.2012.02.003.

Chen, C. Q., Shi, Y., Zhang, Y. S., Zhu, J. and Yan, Y. J. (2006), "Size dependence of Young's modulus in ZnO nanowires", *Physical Rev. Lett.,* **96**(7), 075505. https://doi.org/10.1103/PhysRevLett.96.075505.

Chen, H., Chen, Y., Liu, Y., Fu, L., Huang, C. and Llewellyn, D. (2008), "Over 1.0 mm-long boron nitride nanotubes", *Chem. Phys. Lett.,* **463**(1), 130-133. https://doi.org/10.1016/j.cplett.2008.08.007.

Chen, X., Xu, S., Yao, N. and Shi, Y. (2010), "1.6 V nanogenerator for mechanical energy harvesting using PZT nanofibers", *Nano Letters,* **10**(6), 2133-2137. https://doi.org/10.1021/nl100812k.

Chen, J. and Lee, J. D. (2010), "Atomic Formulation of Nano-Piezoelectricity in Barium Titanate", *Nanosci. Nanotechnol. Lett.,* **2**(1), 26-29. https://doi.org/10.1166/nnl.2010.1048.

Chen, Y. Q., Zheng, X. J. and Li, W. (2010), "Size effect of mechanical behavior for lead-free (Na0. 82K0. 18) 0.5 Bi0. 5TiO3 nanofibers by nanoindentation", *Mater. Sci. Eng. A Struct. Mater.,* **527**(21), 5462. https://doi.org/10.1016/j.msea.2010.05.066

Cheng, G. S., Zhang, L. D., Zhu, Y., Fei, G. T., Li, L., Mo, C. M. and Mao, Y. Q. (1999), "Large-scale synthesis of single crystalline gallium nitride nanowires", *Appl. Phys. Lett.,* **75**(16), 2455-2457. https://doi.org/10.1063/1.125046.

Cheng, J., Ding, R., Liu, Y., Ding, Z. and Zhang, L. (2007a), "Computer simulation of hydrogen physisorption in single-walled boron nitride nanotube arrays", *Comput. Mater. Sci.,* **40**(3), 341-344. https://doi.org/10.1016/j.commatsci.2007.01.006.

Cheng, J., Zhang, L., Ding, R., Ding, Z., Wang, X. and Wang, Z. (2007b), "Grand canonical Monte Carlo simulation of hydrogen physisorption in single-walled boron nitride nanotubes", *J. Hydrogen Energy,* **32**(15), 3402-3405. https://doi.org/10.1016/j.ijhydene.2007.02.037.

Cherif, R. H., Meradjah, M., Zidour, M., Tounsi, A., Belmahi, H. and Bensattalah, T. (2018), "Vibration analysis of nano beam using differential transform method including thermal effect", *J. Nano Res.*, 54, 1-14. https://doi.org/10.4028/www.scientific.net/JNanoR.54.1.

Chikh, A., Tounsi, A., Hebali, H. and Mahmoud, S.R. (2017), "Thermal buckling analysis of cross-ply laminated plates using a simplified HSDT", *Smart Struct. Syst.*, **19**(3), 289-297.

Choi, M., Murillo, G., Hwang, S., Kim, J. W., Jung, J. H., Chen, C. Y. and Lee, M. (2017), "Mechanical and electrical characterization of PVDF-ZnO hybrid structure for application to nanogenerator", *Nano Energy*, **33**, 462-468.

Chopra, N. G. and Zettl, A. (1998), "Measurement of the elastic modulus of a multi-wall boron nitride nanotube", *Solid State Communications,* **105**(5), 297-300.

Chowdhury, R., Adhikari, S. and Scarpa, F. (2010), "Elasticity and piezoelectricity of zinc oxide nanostructure", *Physica E Low Dimensional Syst. Nanostruct.,* **42**(8), 2036-2040. https://doi.org/10.1016/j.physe.2010.03.018.

Ciofani, G., Raffa, V., Menciassi, A. and Cuschieri, A. (2009), "Boron nitride nanotubes: An innovative tool for nanomedicine", *Nano Today,* **4**(1), 8-10. https://doi.org/10.1016/j.nantod.2008.09.001.

Civalek, O. and Demir C. (2011), "Buckling and bending analyses of cantilever carbon nanotubes using the Euler-Bernoulli beam theory based on non-local continuum model", *Asian J. Civil Eng.*, **12**(5), 651-661.

Croft, D., Stilson, S. and Devasia, S. (1999), "Optimal tracking of piezo-based nanopositioners", *Nanotechnology,* **10**(2), 201. https://doi.org/10.1088/0957-4484/10/2/316.

Curie, J. (1880), "Développement par compression de l'électricité polaire dans les cristaux hémièdres à faces inclinées", *Bull. Soc. Fr. Mineral.*, **3**(90). https://doi.org/10.3406/bulmi.1880.1564.

Dai, S., Gharbi, M., Sharma, P. and Park, H. S. (2011), "Surface piezoelectricity: size effects in nanostructures and the emergence of piezoelectricity in non-piezoelectric materials", *J. Appl. Phys.,* **110**(10), 104305. https://doi.org/10.1063/1.3660431.

Dai, S. and Park, H. S. (2013), "Surface effects on the piezoelectricity of ZnO nanowires", *J. Mech. Phys. Solids*, **61**(2), 385-397. https://doi.org/10.1016/j.jmps.2012.10.003.

Dehkordi, S. F. and Beni, Y. T. (2017), "Electro-mechanical free vibration of single-walled piezoelectric/flexoelectric nano cones using consistent couple stress theory", *Int. J. Mech. Sci.*, **128**, 125-139. https://doi.org/10.1016/j.ijmecsci.2017.04.004.

Demir, C., Mercan, K. and Civalek, O. (2016), "Determination of critical buckling loads of isotropic, FGM and laminated

truncated conical panel", *Composites Part B*, **94**, 1-10. https://doi.org/10.1016/j.compositesb.2016.03.031.
Demir, C. and Civalek, O. (2017), "A new nonlocal FEM via Hermitian cubic shape functions for thermal vibration of nano beams surrounded by an elastic matrix", *Compos Struct*, **168**, 872–884. https://doi.org/10.1016/j.compstruct.2017.02.091.
Djurišić, A. B., Tam, K. H., Hsu, Y. F., Zhang, S. L., Xie, M. H. and Chan, W. K. (2007), "GaN nanowires—influence of the starting material on nanowire growth", *Thin Solid Films,* **516**(2), 238-242. https://doi.org/10.1016/j.tsf.2007.06.031.
Djurišić, A. B., Ng, A. M. C. and Chen, X. Y. (2010), "ZnO nanostructures for optoelectronics: material properties and device applications", *Progress Quantum Electronics,* **34**(4), 191-259. https://doi.org/10.1016/j.pquantelec.2010.04.001.
Draiche, K., Tounsi, A. and Mahmoud, S. R. (2016), "A refined theory with stretching effect for the flexure analysis of laminated composite plates", *Geomech. Eng.*, **11**(5), 671-690. https://doi.org/10.12989/gae.2016.11.5.671.
Duan, X. and Lieber, C. M. (2000), "Laser-assisted catalytic growth of single crystal GaN nanowires", *J. American Chem. Society*, **122**(1), 188-189. https://doi.org/10.1021/ja993713u.
Ebrahimi, F. and Salari, E. (2015), "Size-dependent thermo-electrical buckling analysis of functionally graded piezoelectric nanobeams", *Smart Mater. Struct.*, **24**(12), 125007. https://doi.org/10.1088/0964-1726/24/12/125007.
Ebrahimi, F. and Barati, M. R. (2017a), "Buckling analysis of nonlocal third-order shear deformable functionally graded piezoelectric nanobeams embedded in elastic medium", *J. Brazilian Soc. Mech. Sci. Eng.,* **39**(3), 937-952. https://doi.org/10.1007/s40430-016-0551-5.
Ebrahimi, F. and Barati, M. R. (2017b), "Modeling of smart magnetically affected flexoelectric/piezoelectric nanostructures incorporating surface effects", *Nanomater. Nanotechnol.*, **7**, https://doi.org/10.1177/1847980417713106.
Ebrahimi, F. and Barati, M.R. (2017c), "Vibration analysis of size-dependent flexoelectric nanoplates incorporating surface and thermal effects", *Mech. Adv. Mater. Struct.*, 1-11. https://doi.org/10.1080/15376494.2017.1285464.
Ebrahimi, F. and Dabbagh, A. (2018), "Viscoelastic wave propagation analysis of axially motivated double-layered graphene sheets via nonlocal strain gradient theory", *Waves in Random Complex Media*, 1-20. https://doi.org/10.1080/17455030.2018.1490505.
El-Haina, F., Bakora, A., Bousahla, A.A., Tounsi, A. and Mahmoud, S.R. (2017), "A simple analytical approach for thermal buckling of thick functionally graded sandwich plates", *Struct. Eng. Mech.*, **63**(5), 585-595. https://doi.org/10.12989/sem.2017.63.5.585.
Fakrach, B., Rahmani, A., Chadli, H., Sbai, K. and Sauvajol, J. L. (2009), "Raman spectrum of single-walled boron nitride nanotube", *Physica E Low Dimensional Syst. Nanostruct.,* **41**(10), 1800-1805. https://doi.org/10.1016/j.physe.2009.07.002.
Fan, Z. and Lu, J. G. (2005), "Zinc oxide nanostructures: synthesis and properties", *J. Nanosci. Nanotechnol.,* **5**(10), 1561-1573. https://doi.org/10.1166/jnn.2005.182.
Fang, X. Q. and Liu, J. X. (2011), "Dynamic stress and electric displacement around a nano-fiber in piezoelectric nanocomposites under electro-elastic waves", *Philosophical Magazine Letters,* **91**(9), 621-631. https://doi.org/10.1080/09500839.2011.600258.
Fang, X. Q. and Zhu, C. S. (2017), "Size-dependent nonlinear vibration of nonhomogeneous shell embedded with a piezoelectric layer based on surface/interface theory", *Compos. Struct.*, **160**, 1191-1197. https://doi.org/10.1016/j.compstruct.2016.11.008.
Farajpour, A., Rastgoo, A. and Mohammadi, M. (2017), "Vibration, buckling and smart control of microtubules using piezoelectric nanoshells under electric voltage in thermal environment", *Physica B: Condensed Matter*, **509**, 100-114. https://doi.org/10.1016/j.physb.2017.01.006.
Fourn, H., Atmane, H. A., Bourada, M., Bousahla, A. A., Tounsi, A. and Mahmoud, S. R. (2018), "A novel four variable refined plate theory for wave propagation in functionally graded material plates", *Steel Compos. Struct.*, **27**(1), 109-122. https://doi.org/10.12989/scs.2018.27.1.109.
Freitas, A., Azevedo, S. and Kaschny, J. R. (2013), "Effects of a transverse electric field on the electronic properties of single-and multi-wall BN nanotubes", *Solid State Communications,* **153**(1), 40-45. https://doi.org/10.1016/j.ssc.2012.09.024.
Ganji, M. D. and Mohammadi-Nejad, A. (2008), "Simulation of STM technique for electron transport through boron-nitride nanotubes", *Physics Letters A,* **372**(27), 4839-4844. https://doi.org/10.1016/j.physleta.2008.05.038.
Gao, P. X. and Wang, Z. L. (2005), "Nanoarchitectures of semiconducting and piezoelectric zinc oxide", *J. Appl. Phys.,* **97**(4), 044304. https://doi.org/10.1063/1.1847701.
Gheshlaghi, B. and Hasheminejad, S. M. (2012), "Vibration analysis of piezoelectric nanowires with surface and small scale effects", *Current Appl. Phys.,* **12**(4), 1096-1099. https://doi.org/10.1016/j.cap.2012.01.014.
Ghorbanpour Arani, A., Shams, S., Amir, S. and Khoddami Maraghi, Z. (2012a), "Effects of Electro-Thermal Fields on Buckling of a Piezoelectric Polymeric Shell Reinforced with DWBNNTs", *J. Nanostruct.*, **2**(3), 345-355.
Ghorbanpour Arani, A., Amir, S., Shajari, A. R. and Mozdianfard, M.R. (2012b), "Electro-thermo-mechanical buckling of DWBNNTs embedded in bundle of CNTs using nonlocal piezoelasticity cylindrical shell theory", *Compos. Part B Eng.,* **43**(2), 195-203. https://doi.org/10.1016/j.compositesb.2011.10.012.
Ghorbanpour Arani, A., Shajari, A. R., Amir, S. and Loghman, A. (2012c), "Electro-thermo-mechanical nonlinear nonlocal vibration and instability of embedded micro-tube reinforced by BNNT, conveying fluid", *Physica E Low Dimensional Syst. Nanostruct.,* **45**, 109-121. https://doi.org/10.1016/j.compositesb.2011.10.012.
Ghorbanpour Arani, A., Roudbari, M. A. and Amir, S. (2012d), "Nonlocal vibration of SWBNNT embedded in bundle of CNTs under a moving nanoparticle", *Physica B Condensed Matter,* **407**(17), 3646-3653. https://doi.org/10.1016/j.physb.2012.05.043.
Ghorbanpour Arani, A., Kolahchi, R. and Vossough, H. (2012e), "Nonlocal wave propagation in an embedded DWBNNT conveying fluid via strain gradient theory", *Physica B: Condensed Matter,* **407**(21), 4281-4286. https://doi.org/10.1016/j.physb.2012.07.018.
Ghorbanpour Arani, A., Abdollahian, M., Kolahchi, R. and Rahmati, A. H. (2013a), "Electro-thermo-torsional buckling of an embedded armchair DWBNNT using nonlocal shear deformable shell model", *Compos. Part B Eng.,* **51**, 291-299. https://doi.org/10.1016/j.compositesb.2013.03.017.
Ghorbanpour Arani, A., Shajari, A. R., Atabakhshian, V., Amir, S. and Loghman, A. (2013a), "Nonlinear dynamical response of embedded fluid-conveyed micro-tube reinforced by BNNTs", *Compos. Part B Eng.,* **44**(1), 424-432. https://doi.org/10.1016/j.compositesb.2012.04.025.
Ghorbanpour Arani, A., Hashemian, M. and Kolahchi, R. (2013b), "Time discretization effect on the nonlinear vibration of embedded SWBNNT conveying viscous fluid", *Compos. Part B Eng.,* **54**, 298-306. https://doi.org/10.1016/j.compositesb.2013.05.031.
Ghorbanpour Arani, A. and Roudbari, M. A. (2013), "Nonlocal piezoelastic surface effect on the vibration of visco-Pasternak coupled boron nitride nanotube system under a moving nanoparticle", *Thin Solid Films,* **542**, 232-241. https://doi.org/10.1016/j.tsf.2013.06.025.

Ghorbanpour Arani, A. and Amir, S. (2013), "Electro-thermal vibration of visco-elastically coupled BNNT systems conveying fluid embedded on elastic foundation via strain gradient theory", *Physica B: Condensed Matter*, **419**, 1-6. https://doi.org/10.1016/j.physb.2013.03.010.

Guo, L. and Singh, R. N. (2009), "Catalytic growth of boron nitride nanotubes using gas precursors", *Physica E Low Dimensional Syst. Nanostruct.,* **41**(3), 448-453. https://doi.org/10.1016/j.physe.2008.09.009.

Gupta, M. K., Sinha, N., Singh, B. K., Singh, N., Kumar, K. and Kumar, B. (2009), "Piezoelectric, dielectric, optical and electrical characterization of solution grown flower-like ZnO nanocrystal", *Materials Lett.,* **63**(22), 1910-1913. https://doi.org/10.1016/j.matlet.2009.06.003.

Haghpanahi, M., Oveisi, A. and Gudarzi, M. (2013), "Vibration analysis of piezoelectric nanowires using the finite element method", *Int. Res. J. Appl. Basic Sci.*, **4**(1), 205-212.

Hai-Bo, L., Mao-Sheng, C., Jie, Y., Da-Wei, W., Quan-Liang, Z. and Fu-Chi, W. (2008), "Enhanced mechanical behaviour of lead zirconate titanate piezoelectric composites incorporating zinc oxide nanowhiskers", *Chinese Physics B,* **17**(11), 4323. https://doi.org/10.1088/1674-1056/17/11/060.

Han, W., Fan, S., Li, Q. and Hu, Y. (1997), "Synthesis of gallium nitride nanorods through a carbon nanotube-confined reaction", *Science,* **277**(5330), 1287-1289. https://doi.org/10.1126/science.277.5330.1287.

Han, W., Redlich, P., Ernst, F. and Rühle, M. (2000), "Synthesis of GaN–carbon composite nanotubes and GaN nanorods by arc discharge in nitrogen atmosphere", *Appl. Phys. Lett.,* **76**(5), 652-654. https://doi.org/10.1063/1.125848.

He, J. and Lilley, C. M. (2008a), "Surface effect on the elastic behavior of static bending nanowires", *Nano Letters,* **8**(7), 1798-1802. https://doi.org/10.1021/nl0733233.

He, J. and Lilley, C. M. (2008b), "Surface stress effect on bending resonance of nanowires with different boundary conditions", *Appl. Phys. Lett.,* **93**(26), 263108. https://doi.org/10.1063/1.3050108.

Hebali, H., Tounsi, A., Houari, M. S. A., Bessaim, A. and Bedia, E. A. A. (2014), "New quasi-3D hyperbolic shear deformation theory for the static and free vibration analysis of functionally graded plates", *J. Eng. Mech.*, **140**(2), 374-383. https://doi.org/10.1061/(ASCE)EM.1943-7889.0000665.

Hiralal, P., Unalan, H. E. and Amaratunga, G. A. (2012), "Nanowires for energy generation", *Nanotechnology,* **23**(19), 194002. https://doi.org/10.1088/0957-4484/23/19/194002.

Hocevar, M., Songmuang, R., Den Hertog, M., Besombes, L., Bleuse, J., Niquet, Y. M. and Pelekanos, N. T. (2013), "Residual strain and piezoelectric effects in passivated GaAs/AlGaAs core-shell nanowires", *Appl. Phys. Lett.,* **102**(19), 191103. https://doi.org/10.1063/1.4803685.

Hosseini, M., Maryam, A. Z. B. and Bahaadini, R. (2017), "Forced vibrations of fluid-conveyed double piezoelectric functionally graded micropipes subjected to moving load", *Microfluidics Nanofluidics*, **21**(8), 134. https://doi.org/10.1007/s10404-017-1963-y.

Hosseini-Hashemi, S., Nazemnezhad, R. and Bedroud, M. (2014), "Surface effects on nonlinear free vibration of functionally graded nanobeams using nonlocal elasticity", *Appl. Math. Modelling,* **38**(14), 3538-3553. https://doi.org/10.1016/j.apm.2013.11.068.

Houari, M. S. A., Tounsi, A., Bessaim, A. and Mahmoud, S. R. (2016), "A new simple three-unknown sinusoidal shear deformation theory for functionally graded plates", *Steel Compos. Struct.*, **22**(2), 257-276. https://doi.org/10.12989/scs.2016.22.2.257.

Huang, G. Y. and Yu, S. W. (2006), "Effect of surface piezoelectricity on the electromechanical behaviour of a piezoelectric ring", *Physica Status Solidi (b),* **243**(4), 22-24. https://doi.org/10.1002/pssb.200541521.

Hughes, W. L. and Wang, Z. L. (2004), "Formation of piezoelectric single-crystal nanorings and nanobows", *J. American Chem. Soc.,* **126**(21), 6703-6709. https://doi.org/10.1021/ja049266m.

Hughes, W. L. and Wang, Z. L. (2005), "Controlled synthesis and manipulation of ZnO nanorings and nanobows", *Appl. Phys. Lett.,* **86**(4), 043106. https://doi.org/10.1063/1.1853514.

Hwang, H. J., Choi, W. Y. and Kang, J. W. (2005), "Molecular dynamics simulations of nanomemory element based on boron-nitride nanotube-to-peapod transition", *Comput. Mater. Sci.,* **33**(1), 317-324. https://doi.org/10.1016/j.commatsci.2004.12.068.

Hanifi Hachemi Amar, L., Kaci, A., Tounsi, A. (2017), "On the size-dependent behavior of functionally graded micro-beams with porosities", *Struct. Eng. Mech.*, **64**(5), 527-541. https://doi.org/10.12989/sem.2017.64.5.527.

Hadji, L., Hassaine Daouadji, T., Ait Amar Meziane, M., Tlidji, Y., (2016c), "Analysis of functionally graded beam using a new first-order shear deformation theory", *Struct. Eng. Mech.*, **57**(2), 315-325. http://dx.doi.org/10.12989/sem.2016.57.2.315.

Ishii, T., Sato, T., Sekikawa, Y. and Iwata, M. (1981), "Growth of whiskers of hexagonal boron nitride", *J. Crystal Growth*, **52**, 285-289. https://doi.org/10.1016/0022-0248(81)90206-2.

Jafari, A., Khatibi, A. A. and Mashhadi, M. M. (2012), "Evaluation of Mechanical and Piezoelectric Properties of Boron Nitride Nanotube: A Novel Electrostructural Analogy Approach", *J. Comput. Theroetical Nanosci.,* **9**(3), 461-468. https://doi.org/10.1166/jctn.2012.2047.

Jiang, L. and Guo, W. (2011), "A molecular mechanics study on size-dependent elastic properties of single-walled boron nitride nanotubes", *J. Mech. Phys. Solids,* **59**(6), 1204-1213. https://doi.org/10.1016/j.jmps.2011.03.008.

Jing, Y. H., Yu, K. P., Qin, X. and Shen, J. (2012), "Composition-dependent mechanical and thermal transport properties of carbon/silicon core/shell nanowires", *J. Shanghai Jiaotong University (Science),* **17**, 743-747. https://doi.org/10.1007/s12204-012-1357-y.

Karimi, M., Shahidi, A. R. and Ziaei-Rad, S. (2017), "Surface layer and nonlocal parameter effects on the in-phase and out-of-phase natural frequencies of a double-layer piezoelectric nanoplate under thermo-electro-mechanical loadings", *Microsyst. Technol.*, **23**(10), 4903-4915. https://doi.org/10.1007/s00542-017-3395-8.

Ke, L. L., Wang, Y. S. and Wang, Z. D. (2012), "Nonlinear vibration of the piezoelectric nanobeams based on the nonlocal theory", *Compos. Struct.,* **94**(6), 2038-2047. https://doi.org/10.1016/j.compstruct.2012.01.023.

Ke, L. L. and Wang, Y. S. (2012), "Thermoelectric-mechanical vibration of piezoelectric nanobeams based on the nonlocal theory", *Smart Mater. Struct.,* **21**(2), 025018. https://doi.org/10.1088/0964-1726/21/2/025018.

Kheibari, F. and Beni, Y. T. (2017), "Size dependent electro-mechanical vibration of single-walled piezoelectric nanotubes using thin shell model", *Mater. Design*, **114**, 572-583. https://doi.org/10.1016/j.matdes.2016.10.041.

Khodami Maraghi, Z., Ghorbanpour Arani, A., Kolahchi, R., Amir, S. and Bagheri, M. R. (2013), "Nonlocal vibration and instability of embedded DWBNNT conveying viscose fluid", *Compos. Part B Eng.,* **45**(1), 423-432. https://doi.org/10.1016/j.compositesb.2012.04.066.

Kim, J. W., Núñez, J. C., Siochi, E. J., Wise, K. E., Lin, Y., Connell, J. W. and Smith, M. W. (2012), "In situ mechanical property measurements of amorphous carbon–boron nitride nanotube nanostructures", *Nanotechnology,* **23**(3), 035701. https://doi.org/10.1088/0957-4484/23/3/035701

Kolahchi, R. and Ghorbanpour, A. A. (2012), "Nonlinear Vibration and Instability Analysis of a PVDF Cylindrical Shell Reinforced with BNNTs Conveying Viscose Fluid Using HDQ Method", *J. Solid Mech.,* **4**(3), 267-276.

Kolodyazhnaya, M. P., Zvyagina, G. A., Gudim, I. A., Bilych, I. V., Burma, N. G., Zhekov, K. R. and Fil, V. D. (2017), "Piezoelectric response in SmFe3 (BO3) 4, a non-piezoactive configuration. The surface piezoelectric effect", *Low Temperature Physics*, **43**(8), 924-929. https://doi.org/10.1063/1.5001291.

Kong, X. Y. and Wang, Z. L. (2003), "Spontaneous polarization-induced nanohelixes, nanosprings, and nanorings of piezoelectric nanobelts", *Nano Letters,* **3**(12), 1625-1631. https://doi.org/10.1021/nl034463p.

Kumar, B., Lee, K. Y., Park, H. K., Chae, S. J., Lee, Y. H. and Kim, S. W. (2011), "Controlled growth of semiconducting nanowire, nanowall, and hybrid nanostructures on graphene for piezoelectric nanogenerators", *Acs Nano,* **5**(5), 4197-4204. https://doi.org/10.1021/nn200942s.

Kumar, B. and Kim, S. W. (2012), "Energy harvesting based on semiconducting piezoelectric ZnO nanostructures", *Nano Energy,* **1**(3), 342-355. https://doi.org/10.1016/j.nanoen.2012.02.001.

Lahiri, D., Singh, V., Benaduce, A. P., Seal, S., Kos, L. and Agarwal, A. (2011), "Boron nitride nanotube reinforced hydroxyapatite composite: Mechanical and tribological performance and *in-vitro* biocompatibility to osteoblasts", *J. Mech. Behavior Biomedical Mater.,* **4**(1), 44-56. https://doi.org/10.1016/j.jmbbm.2010.09.005.

Larbi Chaht, F., Kaci, A., Houari, M. S. A., Tounsi, A., Anwar Bég, O. and Mahmoud, S. R. (2015), "Bending and buckling analyses of functionally graded material (FGM) size-dependent nanoscale beams including the thickness stretching effect", *Steel. Compos. Struct*, **18**(2), 425-442. https://doi.org/10.12989/scs.2015.18.2.425.

Lee, Y. B., Han, J. K., Noothongkaew, S., Kim, S. K., Song, W., Myung, S. and An, K. S. (2017), "Toward Arbitrary-Direction Energy Harvesting through Flexible Piezoelectric Nanogenerators Using Perovskite PbTiO3 Nanotube Arrays", *Adv. Mater.*, **29**(6). https://doi.org/10.1002/adma.201604500.

Li, F. M., Hsieh, G. W., Dalal, S., Newton, M. C., Stott, J. E., Hiralal, P. and Milne, W. I. (2008), "Zinc oxide nanostructures and high electron mobility nanocomposite thin film transistors", *Electron Devices, IEEE Transactions on,* **55**(11), 3001-3011. https://doi.org/10.1109/TED.2008.2005180.

Li, C., Liu, J. J., Cheng, M. and Fan, X.L. (2017), "Nonlocal vibrations and stabilities in parametric resonance of axially moving viscoelastic piezoelectric nanoplate subjected to thermo-electro-mechanical forces", *Compos. Part B Eng.*, **116**, 153-169. https://doi.org/10.1016/j.compositesb.2017.01.071.

Li, X. B., Li, L., Hu, Y. J., Ding, Z. and Deng, W. M. (2017), "Bending, buckling and vibration of axially functionally graded beams based on nonlocal strain gradient theory", *Compos. Struct.*, **165**, 250-265. https://doi.org/10.1016/j.compstruct.2017.01.032.

Liang, X., Yang, W., Hu, S. and Shen, S. (2016), "Buckling and vibration of flexoelectric nanofilms subjected to mechanical loads", *J. Phys D Appl. Phys.*, **49**(11), 115307. https://doi.org/10.1088/0022-3727/49/11/115307.

Lin, H. B., Cao, M. S., Zhao, Q. L., Shi, X. L., Wang, D. W. and Wang, F. C. (2008), "Mechanical reinforcement and piezoelectric properties of nanocomposites embedded with ZnO nanowhiskers", *Scripta Materialia,* **59**(7), 780-783. https://doi.org/10.1016/j.scriptamat.2008.06.016.

Lippmann, G. (1881), "Principe de la conservation de l'électricité, ou second principe de la théorie des phénomènes électriques", *Journal de Physique Théorique et Appliquée*, **10**(1), 381-394. https://doi.org/10.1051/jphystap:0188100100038100.

Liu, W., Lee, M., Ding, L., Liu, J. and Wang, Z. L. (2010), "Piezopotential Gated Nanowire− Nanotube Hybrid Field-Effect Transistor", *Nano Letters,* **10**(8), 3084-3089. https://doi.org/10.1021/nl1017145.

Liu, C., Hu, S. and Shen, S. (2012), "Effect of flexoelectricity on electrostatic potential in a bent piezoelectric nanowire", *Smart Mater. Struct.,* **21**(11), 115024. https://doi.org/10.1088/0964-1726/21/11/115024.

Liu, C., Ke, L. L., Wang, Y. S., Yang, J. and Kitipornchai, S. (2013), "Thermo-electro-mechanical vibration of piezoelectric nanoplates based on the nonlocal theory", *Compos. Struct.,* **106**, 167-174. https://doi.org/10.1016/j.compstruct.2013.05.031

Liu, C. and Wang, J. (2017), "Size-dependent electromechanical properties in piezoelectric superlattices due to flexoelectric effect", *Theoretical Appl. Mech. Lett.*, **7**(2), 88-92. https://doi.org/10.1016/j.taml.2017.02.007.

Loh, K. P., Lin, M., Yeadon, M., Boothroyd, C. and Hu, Z. (2004), "Growth of boron nitride nanotubes and iron nanowires from the liquid flow of FeB nanoparticles", *Chem. Phys. Lett.,* **387**(1), 40-46. https://doi.org/10.1016/j.cplett.2004.01.093.

Lu, Y. H., Shen, Y. G., Li, K. Y. and Chen, H. (2006), "Effects of nitrogen content on nanostructure evolution, mechanical behaviors and thermal stability in Ti–B–N thin films", *Surface Coatings Technol.,* **201**(3), 1228-1235. https://doi.org/10.1016/j.surfcoat.2006.01.045.

Ma, L.H., Ke, L.L., Wang, Y.Z. and Wang, Y.S. (2017), "Wave propagation in magneto-electro-elastic nanobeams via two nonlocal beam models", *Physica E Low Dimensional Syst. Nanostruct.*, **86**, 253-261. https://doi.org/10.1016/j.physe.2016.10.036.

Maity, K., Mahanty, B., Sinha, T.K., Garain, S., Biswas, A., Ghosh, S.K. and Mandal, D. (2017), "Two-Dimensional Piezoelectric MoS2-Modulated Nanogenerator and Nanosensor Made of Poly (vinlydine Fluoride) Nanofiber Webs for Self-Powered Electronics and Robotics", *Energy Technol.*, **5**(2), 234-243. https://doi.org/10.1002/ente.201600419.

Majidi, C., Haataja, M. and Srolovitz, D.J. (2010), "Analysis and design principles for shear-mode piezoelectric energy harvesting with ZnO nanoribbons", *Smart Mater. Struct.,* **19**(5), 055027. https://doi.org/10.1088/0964-1726/19/5/055027.

Malikan, M. (2017), "Electro-mechanical shear buckling of piezoelectric nanoplate using modified couple stress theory based on simplified first order shear deformation theory", *Appl. Math. Model.*, **48**, 196-207. https://doi.org/10.1016/j.apm.2017.03.065.

Meitzler, A.W., A.H., Tiersten, H.F., Warner, A.W., Berlincourt, D., Couqin, G. A. and Welsh III, F. S. (1988), *IEEE Standard on Piezoelectricity*, IEEE, USA.

Meksi, R., Benyoucef, S., Mahmoudi, A., Tounsi, A., Adda Bedia, E. A. and Mahmoud, S. R. (2019), "An analytical solution for bending, buckling and vibration responses of FGM sandwich plates", *J. Sandwich Struct. Mater.*, **21**(2), 727-757. https://doi.org/10.1177%2F1099636217698443.

Menasria, A., Bouhadra, A., Tounsi, A., Bousahla, A.A. and Mahmoud, S. R. (2017), "A new and simple HSDT for thermal stability analysis of FG sandwich plates", *Steel Compos. Struct.*, **25**(2), 157-175. https://doi.org/10.12989/scs.2017.25.2.157.

Meng, Y., Xiu, P., Huang, B., Wang, Z., Zhang, R.Q. and Zhou, R. (2014), "A unique feature of chiral transition of a difluorobenzo [c] phenanthrene molecule confined in a boron-nitride nanotube based on molecular dynamics simulations", *Chem. Phys. Lett.,* **591**, 265-267. https://doi.org/10.1016/j.cplett.2013.11.052.

Mercan, K. and Civalek, O. (2016), "DSC method for buckling analysis of boron nitride nanotube (BNNT) surrounded by an elastic matrix", *Compos. Struct*. **143**, 300–309.

https://doi.org/10.1016/j.compstruct.2016.02.040.

Mercan K and Civalek, O. (2017), "Buckling analysis of Silicon carbide nanotubes (SiCNTs) with surface effect and nonlocalelasticity using the method of HDQ", *Compos. Part B*, **114**, 34-45. https://doi.org/10.1016/j.compositesb.2017.01.067.

Meziane, M. A. A., Abdelaziz, H. H. and Tounsi, A. (2014), "An efficient and simple refined theory for buckling and free vibration of exponentially graded sandwich plates under various boundary conditions", *J. Sandwich Struct. Mater.*, **16**(3), 293-318. https://doi.org/10.1177%2F1099636214526852.

Minary-Jolandan, M., Bernal, R.A. and Espinosa, H.D. (2011), "Strong piezoelectricity in individual GaN nanowires", *MRS Communications,* **1**(01), 45-48. https://doi.org/10.1557/mrc.2011.14

Minary-Jolandan, M., Bernal, R.A., Kuljanishvili, I., Parpoil, V. and Espinosa, H.D. (2012), "Individual GaN nanowires exhibit strong piezoelectricity in 3D", *Nano Letters,* **12**(2), 970-976. https://doi.org/10.1021/nl204043y.

Mirnezhad, M., Ansari, R. and Rouhi, H. (2013), "Mechanical properties of multilayer boron nitride with different stacking orders", *Superlattices Microstructures,* **53**, 223-231. https://doi.org/10.1016/j.spmi.2012.10.016.

Mohai, I., Mohai, M., Bertóti, I., Sebestyén, Z., Németh, P., Babievskaya, I.Z. and Szépvölgyi, J. (2011), "Formation of thin boron nitride coating on multiwall carbon nanotube surfaces" *Diamond Related Mater.,* **20**(2), 227-231. https://doi.org/10.1016/j.diamond.2010.12.001.

Mohammadimehr, M. and Rahmati, A.H. (2013), "Small scale effect on electro-thermo-mechanical vibration analysis of single-walled boron nitride nanorods under electric excitation", *Turkish J. Eng. Environ. Sci.*, **37**(1).

Moheimani, S.R. and Fleming, A.J. (2006), *Piezoelectric Transducers For Vibration Control And Damping*, Springer Science & Business Media, Germany.

Mokhtar, Y., Heireche, H., Bousahla, A.A., Houari, M.S.A., Tounsi, A. and Mahmoud, S.R. (2018a), "A novel shear deformation theory for buckling analysis of single layer graphene sheet based on nonlocal elasticity theory", *Smart Struct. Syst.*, **21**(4), 397-405. https://doi.org/10.12989/sss.2018.21.4.397.

Mokhtar, Y., Heireche, H., Bousahla, A.A., Houari, M.S.A., Tounsi, A. and Mahmoud, S.R. (2018), "A novel shear deformation theory for buckling analysis of single layer graphene sheet based on nonlocal elasticity theory", *Smart Struct. Syst.*, **21**(4), 397-405. https://doi.org/10.12989/sss.2018.21.4.397.

Momeni, K., Odegard, G.M. and Yassar, R.S. (2012), "Finite size effect on the piezoelectric properties of ZnO nanobelts: a molecular dynamics approach", *Acta materialia,* **60**(13), 5117-5124. https://doi.org/10.1016/j.actamat.2012.06.041.

Moon, W.H. and Hwang, H.J. (2004), "Molecular mechanics of structural properties of boron nitride nanotubes", *Physica E Low Dimensional Syst. Nanostruct.,* **23**(1), 26-30. https://doi.org/10.1016/j.physe.2003.11.273

Mortazavi, B. and Rémond, Y. (2012), "Investigation of tensile response and thermal conductivity of boron-nitride nanosheets using molecular dynamics simulations", *Physica E Low Dimensional Syst. Nanostruct.,* **44**(9), 1846-1852. https://doi.org/10.1016/j.physe.2012.05.007.

Mosallaie Barzoki, A.A., Ghorbanpour Arani, A., Kolahchi, R. and Mozdianfard, M.R. (2012), "Electro-thermo-mechanical torsional buckling of a piezoelectric polymeric cylindrical shell reinforced by DWBNNTs with an elastic core", *Appl. Math. Modelling,* **36**(7), 2983-2995. https://doi.org/10.1016/j.apm.2011.09.093.

Mosallaie Barzoki, A.A., Ghorbanpour Arani, A., Kolahchi, R., Mozdianfard, M.R. and Loghman, A. (2013), "Nonlinear buckling response of embedded piezoelectric cylindrical shell reinforced with BNNT under electro–thermo-mechanical loadings using HDQM", *Compos. Part B Eng.,* **44**(1), 722-727. https://doi.org/10.1016/j.compositesb.2012.01.052.

Mouffoki, A., Adda Bedia, E. A., Houari, M. S. A., Tounsi, A. and Mahmoud, S.R. (2017), "Vibration analysis of nonlocal advanced nanobeams in hygro-thermal environment using a new two-unknown trigonometric shear deformation beam theory", *Smart Struct. Syst.,* **20**(3), 369-383. https://doi.org/10.12989/sss.2017.20.3.369.

Nazemnezhad, R. and Hosseini-Hashemi, S. (2014), "Nonlocal nonlinear free vibration of functionally graded nanobeams", *Compos. Struct.,* **110**, 192-199. https://doi.org/10.1016/j.compstruct.2013.12.006.

Numanoglu, H.M., Akgöz, B. and Civalek, O. (2018), "On dynamic analysis of nanorods", *J. Eng. Sci.*, **130**, 33-50. https://doi.org/10.1016/j.ijengsci.2018.05.001.

Oku, T., Koi, N. and Suganuma, K. (2008), "Synthesis and nanostructure of boron nitride nanotubes grown from iron-evaporated boron", *Diamond Related Mater.,* **17**(7), 1805-1807. https://doi.org/10.1016/j.diamond.2008.01.009.

Panchal, M.B. and Upadhyay, S.H. (2013), "Cantilevered single walled boron nitride nanotube based nanomechanical resonators of zigzag and armchair forms", *Physica E Low Dimensional Syst. Nanostruct.,* **50**, 73-82. https://doi.org/10.1016/j.physe.2013.02.018

Panchal, M.B., Upadhyay, S.H. and Harsha, S.P. (2013), "Vibrational characteristics of defective single walled BN nanotube based nanomechanical mass sensors: single atom vacancies and divacancies", *Sensors Actuators A Physical,* **197**, 111-121. https://doi.org/10.1016/j.sna.2013.04.011.

Pandya, H.J. and Chandra, S. (2011), "Zinc oxide nanostructures by oxidation of zinc films deposited on oxidized silicon substrate", *J. Nano-Electron. Phys.,* **3**(1), 409-413.

Patil, S.R. and Melnik, R.V. (2009), "Coupled electromechanical effects in II–VI group finite length semiconductor nanowires", *J. Physics D Appl. Phys.,* **42**(14), 145113. https://doi.org/10.1088/0022-3727/42/14/145113.

Pour, H.R., Vossough, H., Heydari, M.M., Beygipoor, G. and Azimzadeh, A. (2015), "Nonlinear vibration analysis of a nonlocal sinusoidal shear deformation carbon nanotube using differential quadrature method", *Struct. Eng. Mech.*, **54**(6), 1061-1073. https://doi.org/10.12989/sem.2015.54.6.1061.

Qi, J., Qian, X., Qi, L., Feng, J., Shi, D. and Li, J. (2012), "Strain-engineering of band gaps in piezoelectric boron nitride nanoribbons", *Nano Letters,* **12**(3), 1224-1228. https://doi.org/10.1021/nl2035749.

Rafiee, R. and Moghadam, R.M. (2014), "On the modeling of carbon nanotubes: A critical review", *Compos. Part B Eng.,* **56**, 435-449. https://doi.org/10.1016/j.compositesb.2013.08.037

Rahmati, A.H. and Mohammadimehr, M. (2014), "Vibration analysis of non-uniform and non-homogeneous boron nitride nanorods embedded in an elastic medium under combined loadings using DQM", *Physica B: Condensed Matter,* **440**, 88-98. https://doi.org/10.1016/j.physb.2014.01.036.

Razavi, H., Babadi, A.F. and Beni, Y.T. (2017), "Free vibration analysis of functionally graded piezoelectric cylindrical nanoshell based on consistent couple stress theory", *Compos. Struct.*, **160**, 1299-1309. https://doi.org/10.1016/j.compstruct.2016.10.056.

Refaeinejad, V., Rahmani, O. and Hosseini, S.A.H. (2017), "Evaluation of nonlocal higher order shear deformation models for the vibrational analysis of functionally graded nanostructures", *Mech. Adv. Mater. Struct.*, **24**(13), 1116-1123. https://doi.org/10.1080/15376494.2016.1227496.

Rezania, H. (2014), "The effect of local electronic interaction on the optical properties of boron–nitride nanotubes", *Physica E*

Low Dimensional Syst. Nanostruct., **61**, 48-52. https://doi.org/10.1016/j.physe.2014.03.014.

Sadek, A.S., Karabalin, R.B., Du, J., Roukes, M.L., Koch, C. and Masmanidis, S. C. (2010), "Wiring nanoscale biosensors with piezoelectric nanomechanical resonators", *Nano letters,* **10**(5), 1769-1773. https://doi.org/10.1021/nl100245z.

Sahmani, S., Aghdam, M.M. and Akbarzadeh, A.H. (2016), "Size-dependent buckling and postbuckling behavior of piezoelectric cylindrical nanoshells subjected to compression and electrical load", *Mater. Design*, **105**, 341-351. https://doi.org/10.1016/j.matdes.2016.05.065

Sahmani, S. and Fattahi, A.M. (2017), "Thermo-electro-mechanical size-dependent postbuckling response of axially loaded piezoelectric shear deformable nanoshells via nonlocal elasticity theory", *Microsyst. Technol.*, **23**(10), 5105-5119. https://doi.org/10.1007/s00542-017-3316-x.

Salehi-Khojin, A. and Jalili, N. (2008), "Buckling of boron nitride nanotube reinforced piezoelectric polymeric composites subject to combined electro-thermo-mechanical loadings", *Compos. Sci. Technol.,* **68**(6), 1489-1501. https://doi.org/10.1016/j.compscitech.2007.10.024.

Scrymgeour, D.A. and Hsu, J.W. (2008), "Correlated piezoelectric and electrical properties in individual ZnO nanorods", *Nano Letters,* **8**(8), 2204-2209. https://doi.org/10.1021/nl080704n.

Semmah, A., Heireche, H., Bousahla, A.A. and Tounsi, A. (2019), "Thermal buckling analysis of SWBNNT on Winkler foundation by nonlocal FSDT", *Adv. Nano Res.*, **7**(2), 89-98. https://doi.org/10.12989/anr.2019.7.2.089.

Seo, M., Jung, Y., Lim, D., Cho, D. and Jeong, Y. (2013), "Piezoelectric and field emitted properties of controlled ZnO nanorods on CNT yarns", *Mater. Letters,* **92**, 177-180. https://doi.org/10.1016/j.matlet.2012.10.076.

Shahverdi, H. and Barati, M.R. (2017), "Vibration analysis of porous functionally graded nanoplates". *J. Eng. Sci.*, **120**, 82-99. https://doi.org/10.1016/j.ijengsci.2017.06.008.

Sharma, N.D., Maranganti, R. and Sharma, P. (2007), "On the possibility of piezoelectric nanocomposites without using piezoelectric materials", *J. Mech. Phys. Solids,* **55**(11), 2328-2350. https://doi.org/10.1016/j.jmps.2007.03.016.

Shokuhfar, A. and Ebrahimi-Nejad, S. (2013)' "Effects of structural defects on the compressive buckling of boron nitride nanotubes", *Physica E Low Dimensional Syst. Nanostruct.,* **48**, 53-60. https://doi.org/10.1016/j.physe.2012.11.024.

Sinha, N., Wabiszewski, G.E., Mahameed, R., Felmetsger, V.V., Tanner, S. M., Carpick, R. W. and Piazza, G. (2009), "Ultra-thin AlN piezoelectric nano-actuators", *Solid-State Sensors, Actuators and Microsystems Conference, 2009, TRANSDUCERS 2009. International*, Denver, Colorado, USA. 469-472. https://doi.org/10.1109/SENSOR.2009.5285460.

Soltani, A., Moradi, A.V., Bahari, M., Masoodi, A. and Shojaee, S. (2013), "Computational investigation of the electronic and structural properties of CN radical on the pristine and Al-doped (6, 0) BN nanotubes", *Physica B: Condensed Matter*, **430**, 20-26. https://doi.org/10.1016/j.physb.2013.07.032.

Song, F., Huang, G.L., Park, H.S. and Liu, X.N. (2011), "A continuum model for the mechanical behavior of nanowires including surface and surface-induced initial stresses", *J. Solids Struct.,* **48**(14), 2154-2163. https://doi.org/10.1016/j.ijsolstr.2011.03.021.

Sun, C., Shi, J. and Wang, X. (2010), "Fundamental study of mechanical energy harvesting using piezoelectric nanostructures", *J. Appl. Phys.,* **108**(3), 034309. https://doi.org/10.1063/1.3462468.

Taghizadeh, M., Ovesy, H.R. and Ghannadpour, S.A.M. (2015), "Nonlocal integral elasticity analysis of beam bending by using finite element method", *Struct. Eng. Mech.*, **54**(4), 755-769. https://doi.org/10.12989/sem.2015.54.4.755.

Tlidji, Y., Zidour, M., Draiche, K., Safa, A., Bourada, M., Tounsi, A., Bousahla, A.A. and Mahmoud, S.R. (2019), "Vibration analysis of different material distributions of functionally graded microbeam", *Struct. Eng. Mech.*, **69**(6), 637-649. https://doi.org/10.12989/sem.2019.69.6.637.

Tounsi, A., Houari, M.S.A. and Bessaim, A. (2016), "A new 3-unknowns non-polynomial plate theory for buckling and vibration of functionally graded sandwich plate", *Struct. Eng. Mech.*, **60**(4), 547-565. https://doi.org/10.12989/sem.2016.60.4.547.

Ulus, H., Üstün, T., Eskizeybek, V., Şahin, Ö.S., Avcı, A. and Ekrem, M. (2013), "Boron nitride-MWCNT/epoxy hybrid nanocomposites: Preparation and mechanical properties", *Appl. Surface Sci.*, 37-42. https://doi.org/10.1016/j.apsusc.2013.12.070.

Vahedi Fakhrabad, D. and Shahtahmassebi, N. (2013), "First-principles calculations of the Young's modulus of double wall boron-nitride nanotubes", *Mater. Chem. Phys.,* **138**(2), 963-966. https://doi.org/10.1016/j.matchemphys.2013.01.004.

Wang, Z.L. (2004), "Nanostructures of zinc oxide", *Mater. Today,* **7**(6), 26-33. https://doi.org/10.1016/S1369-7021(04)00286-X.

Wang, Z.L. (2004), "Zinc oxide nanostructures: growth, properties and applications", *J. Phys. Condensed Matter,* **16**(25), R829. https://doi.org/10.1088/0953-8984/16/25/R01.

Wang, Z.L. (2004), "Zinc oxide nanostructures: growth, properties and applications", *J. Phys. Condensed Matter*, **16**(25), R829. https://doi.org/10.1088/0953-8984/16/25/R01.

Wang, Z., Suryavanshi, A.P. and Yu, M.F. (2006), "Ferroelectric and piezoelectric behaviors of individual single crystalline BaTiO3 nanowire under direct axial electric biasing", *Appl. Phys. Lett.,* **89**(8), 082903. https://doi.org/10.1063/1.2338015.

Wang, Z. L. (2007), "Novel nanostructures of ZnO for nanoscale photonics, optoelectronics, piezoelectricity, and sensing", *Appl. Phys. A,* **88**(1), 7-15. https://doi.org/10.1007/s00339-007-3942-8.

Wang, Z., Zu, X., Yang, L., Gao, F. and Weber, W. J. (2008), "Molecular dynamics simulation on the buckling behavior of GaN nanowires under uniaxial compression", *Physica E Low Dimensional Syst. Nanostruct.,* **40**(3), 561-566. https://doi.org/10.1016/j.physe.2007.08.040.

Wang, X. and Lee, J.D. (2010), "Nano-Piezoelectricity in BaTiO3: An Atomistic/Continuum Simulation", *Adv. Sci. Lett.,*, **3**(4), 422-427. https://doi.org/10.1166/asl.2010.1164.

Wang, G.F. and Feng, X.Q. (2010), "Effect of surface stresses on the vibration and buckling of piezoelectric nanowires", *Europhys. Lett.,* **91**(5), 56007. https://doi.org/10.1209/0295-5075/91/56007

Wang, C.Y., Li, L.J. and Chew, Z.J. (2011), "Vibrating ZnO–CNT nanotubes as pressure/stress sensors", *Physica E Low Dimensional Syst. Nanostruct.,* **43**(6), 1288-1293. https://doi.org/10.1016/j.physe.2011.03.003.

Wang, J., Li, H., Li, Y., Yu, H., He, Y. and Song, X. (2011), "Deformation of copper-filled single-walled boron-nitride nanotubes under axial compression", *Physica E Low Dimensional Syst. Nanostruct.,* **44**(1), 286-289. https://doi.org/10.1016/j.physe.2011.08.024.

Wang, X. and Shi, J. (2012), "Piezoelectric nanogenerators for self-powered nanodevices", *Piezoelectric Nanomaterials for Biomedical Applications*, Springer Berlin Heidelberg, Berlin, Germany. 135-172. https://doi.org/10.1007/978-3-642-28044-3_5.

Wang, K.F. and Wang, B.L. (2012), "The electromechanical coupling behavior of piezoelectric nanowires: Surface and small-scale effects", *EPL (Europhysics Letters),* **97**(6), 66005. https://doi.org/10.1209/0295-5075/97/66005.

Wang, W., Li, P., Jin, F. and Wang, J. (2016), "Vibration analysis of piezoelectric ceramic circular nanoplates considering surface and nonlocal effects", *Compos. Struct.*, **140**, 758-775. https://doi.org/10.1016/j.compstruct.2016.01.035.

Wu, W. (2016), "High-performance piezoelectric nanogenerators for self-powered nanosystems: Quantitative standards and figures of merit", *Nanotechnology*, **27**(11), 112503. http://dx.doi.org/10.1088/0957-4484/27/11/112503.

Xi, Y., Song, J., Xu, S., Yang, R., Gao, Z., Hu, C. and Wang, Z.L. (2009), "Growth of ZnO nanotube arrays and nanotube based piezoelectric nanogenerators", *J. Mater. Chem.,* **19**(48), 9260-9264. https://doi.org/10.1039/B917525C.

Xu, Z., Golberg, D. and Bando, Y. (2009), "Electrical field-assisted thermal decomposition of boron nitride nanotube: experiments and first principle calculations", *Chem. Phys. Lett.,* **480**(1), 110-112. https://doi.org/10.1016/j.cplett.2009.08.072.

Xu, S. and Wang, Z.L. (2011), "One-dimensional ZnO nanostructures: solution growth and functional properties", *Nano Res.,* **4**(11), 1013-1098. https://doi.org/10.1007/s12274-011-0160-7.

Xu, S., Poirier, G. and Yao, N. (2012), "Fabrication and piezoelectric property of PMN-PT nanofibers", *Nano Energy,* **1**(4), 602-607. https://doi.org/10.1016/j.nanoen.2012.03.011.

Yahia, S.A., Atmane, H.A., Houari, M.S.A. and Tounsi, A. (2015), "Wave propagation in functionally graded plates with porosities using various higher-order shear deformation plate theories", *Struct. Eng. Mech*, **53**(6), 1143-1165. https://doi.org/10.12989/sem.2015.53.6.1143.

Yan, Z. and Jiang, L. (2011a), "Electromechanical response of a curved piezoelectric nanobeam with the consideration of surface effects", *J. Phys. D Appl. Phys.,* **44**(36), 365301. https://doi.org/10.1088/0022-3727/44/36/365301.

Yan, Z. and Jiang, L. (2011b), "Surface effects on the electromechanical coupling and bending behaviors of piezoelectric nanowires", *J. Phys. D Appl. Phys.,* **44**(7), 75404.

Yan, Z. and Jiang, L.Y. (2011c), "The vibrational and buckling behaviors of piezoelectric nanobeams with surface effects", *Nanotechnology,* **22**(24), 245703. https://doi.org/10.1088/0957-4484/22/24/245703.

Yan, Z. and Jiang, L.Y. (2012a), "Surface effects on the vibration and buckling of piezoelectric nanoplates", *EPL (Europhysics Letters),* **99**(2), 27007. https://doi.org/10.1209/0295-5075/99/27007.

Yan, Z. and Jiang, L.Y. (2012b), "Vibration and buckling analysis of a piezoelectric nanoplate considering surface effects and in-plane constraints", *Proceedings of the Royal Society A: Mathematical, Phys. Eng. Sci.*, https://doi.org/10.1098/rspa.2012.0214.

Yan, Z. (2013), "Continuum modeling on size-dependent properties of piezoelectric nanostructures", https://ir.lib.uwo.ca/etd/1322.

Yan, Z. and Jiang, L. (2013), "Size-dependent bending and vibration behaviour of piezoelectric nanobeams due to flexoelectricity", *J. Phys. D Appl. Phys.,* **46**(35), 355502.

Yazid, M., Heireche, H., Tounsi, A., Bousahla, A. A. and Houari, M. S. A. (2018), "A novel nonlocal refined plate theory for stability response of orthotropic single-layer graphene sheet resting on elastic medium", *Smart Struct. Syst.*., **21**(1), 15-25. https://doi.org/10.12989/sss.2018.21.1.015.

Ye, L., Lu, G. and Ong, L. S. (2011), "Buckling of a thin-walled cylindrical shell with foam core under axial compression", *Thin-walled struct.,* **49**(1), 106-111. https://doi.org/10.1016/j.tws.2010.08.011.

Youcef, D.O., Kaci, A., Benzair, A., Bousahla, A. A. and Tounsi, A. (2018), "Dynamic analysis of nanoscale beams including surface stress effects", *Smart Struct. Syst.*, **21**(1), 65-74. https://doi.org/10.12989/sss.2018.21.1.065.

Younsi, A., Tounsi, A., Zaoui, F.Z., Bousahla, A. A. and Mahmoud, S. R. (2018), "Novel quasi-3D and 2D shear deformation theories for bending and free vibration analysis of FGM plates", *Geomech. Eng.*, **14**(6), 519-532. https://doi.org/10.12989/gae.2018.14.6.519.

Yun, S. and Kim, J. (2011), "Mechanical, electrical, piezoelectric and electro-active behavior of aligned multi-walled carbon nanotube/cellulose composites", *Carbon,* **49**(2), 518-527. https://doi.org/10.1016/j.carbon.2010.09.051.

Zaoui, F. Z., Ouinas, D. and Tounsi, A. (2019), "New 2D and quasi-3D shear deformation theories for free vibration of functionally graded plates on elastic foundations", *Compos. Part B*, **159**, 231-247. https://doi.org/10.1016/j.compositesb.2018.09.051.

Zemri, A., Houari, M. S. A., Bousahla, A. A. and Tounsi, A. (2015), "A mechanical response of functionally graded nanoscale beam: an assessment of a refined nonlocal shear deformation theory beam theory", *Struct. Eng. Mech.*, **54**(4), 693-710. https://doi.org/10.12989/sem.2015.54.4.693.

Zenkour, A. M. and Sobhy, M. (2017), "Nonlocal piezo-hygrothermal analysis for vibration characteristics of a piezoelectric Kelvin–Voigt viscoelastic nanoplate embedded in a viscoelastic medium", *Acta Mechanica*, 1-17. https://doi.org/10.1007/s00707-017-1920-6.

Zenkour, A. M. and Arefi, M. (2017), "Nonlocal transient electrothermomechanical vibration and bending analysis of a functionally graded piezoelectric single-layered nanosheet rest on visco-Pasternak foundation", *J. Thermal Stresses*, **40**(2), 167-184. https://doi.org/10.1080/01495739.2016.1229146.

Zhang, L. and Huang, H. (2006), "Young's moduli of ZnO nanoplates: Ab initio determinations", *Appl. Phys. Lett.,* **89**(18), 183111. https://doi.org/10.1063/1.2374856.

Zhang, S., Liu, Y., Xia, M., Zhang, L., Zhang, E., Liang, R. and Zhao, S. (2008), "Long-wavelength optical phonons in single-walled boron nitride nanotubes", *Physica B Condensed Matter,* **403**(23), 4196-4201. https://doi.org/10.1016/j.physb.2008.09.010.

Zhang, Y., Hong, J., Liu, B. and Fang, D. (2010), "Strain effect on ferroelectric behaviors of BaTiO3 nanowires: A molecular dynamics study", *Nanotechnology,* **21**(1), 015701. https://doi.org/10.1088/0957-4484/21/1/015701.

Zhang, J., Wang, R. and Wang, C. (2012), "Piezoelectric ZnO-CNT nanotubes under axial strain and electrical voltage", *Physica E Low Dimensional Syst. Nanostruct.*, **46**, 105-112. https://doi.org/10.1016/j.physe.2012.09.001.

Zhang, J. and Wang, C. (2012), "Vibrating piezoelectric nanofilms as sandwich nanoplates", *J. Appl. Phys.,* **111**(9), 094303. https://doi.org/10.1063/1.4709754.

Zhang, L. L., Liu, J. X., Fang, X. Q. and Nie, G. Q. (2014)' "Effects of surface piezoelectricity and nonlocal scale on wave propagation in piezoelectric nanoplates", *Europ. J. Mech. A/Solids,* **46**, 22-29. https://doi.org/10.1016/j.euromechsol.2014.01.005.

Zheng, X. P., Cao, Y. P., Li, B., Feng, X. Q. and Wang, G. F. (2010), "Surface effects in various bending-based test methods for measuring the elastic property of nanowires", *Nanotechnology,* **21**(20), 205702. https://doi.org/10.1088/0957-4484/21/20/205702.

Zhi, C., Bando, Y., Tang, C. and Golberg, D. (2010), "Boron nitride nanotubes", *Mater. Sci. Eng. R: Reports,* **70**(3), 92-111. https://doi.org/10.1126/science.269.5226.966.

Zhou, J., Xu, N. S. and Wang, Z. L. (2006), "Dissolving behavior and stability of ZnO wires in biofluids: a study on biodegradability and biocompatibility of ZnO nanostructures", *Adv. Mater.,* **18**(18), 2432-2435. https://doi.org/10.1002/adma.200600200.

Zhou, J., Wang, Z., Grots, A. and He, X. (2007), "Electric field drives the nonlinear resonance of a piezoelectric nanowire", *Solid State Communications,* **144**(3), 118-123. https://doi.org/10.1016/j.ssc.2007.08.011.

Zhukovskii, Y. F., Piskunov, S., Pugno, N., Berzina, B., Trinkler, L. and Bellucci, S. (2009), "*Ab initio* simulations on the atomic and electronic structure of single-walled BN nanotubes and nanoarches", *J. Phys. Chem. Solids,* **70**(5), 796-803.

https://doi.org/10.1016/j.jpcs.2009.03.016.
Zidi, M., Houari, M. S. A., Tounsi, A., Bessaim, A. and Mahmoud, S. R. (2017), "A novel simple two-unknown hyperbolic shear deformation theory for functionally graded beams", *Struct. Eng. Mech.*, **64**(2), 145-153. https://doi.org/10.12989/sem.2017.64.2.145.

CC