UNIVERSITI PUTRA MALAYSIA

NUMERICAL ANALYSIS OF FREQUENCY AND ELECTRICAL RESPONSE IN PIEZOELECTRIC-COVERED COMPONENTS FOR ENERGY HARVESTING

ERFAN SHAMSADDINI LORI

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By

ERFAN SHAMSADDINI LORI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Doctor of Philosophy

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Chairman : Associate Professor Eris Elianddy bin Supeni, PhD
Faculty : Engineering

In recent years there has been an increased interest in scavenging energy using alternative sources. One of these sources is vibration which can be harvested and converted to electrical energy. Piezoelectric materials can be used to capture vibration, motion or acoustic noise, to be converted into electrical output. Due to the never-ending human attitude towards technology for improving the mechanical properties and operation of the structures, GPL reinforcements gain the attention of scientists for providing an enthusiastic enhancement in the design of the existing composite structures. This study presents the electrical response of piezoelectric for two different components (microdisk and cantilever beam). In the first part of this research, the frequency analysis of a Graphene Nanoplatelets Reinforced Composite (GPLRC) microdisk is investigated for three different boundary conditions (simply-simply, simply-clamped and clamped-clamped). The issue rises since at nanoscale no experimental work has been done before. To overcome this problem, nonlocal strain gradient theory (NSGT) is employed which introduces two size-dependent length scale (l) and nonlocal (μ). The present study is done in the framework of numerical based generalized differential quadrature method (GDQM). The stresses and strains are obtained using the higher-order shear deformable theory (HOSDT). The rule of the mixture is employed to obtain varying mass density and Poisson's ratio, while the module of elasticity is computed by a modified Halpin-Tsai model. Governing equations and boundary conditions of the GPLRC microdisk covered with the piezoelectric layer are obtained by implementing Hamilton's principle. Regarding perfect bonding between the piezoelectric layer and core, the compatibility conditions are derived. Also, due to the existence of the piezoelectric layer, Maxwell's equation is derived. MATLAB software is used and results show that the ratio of the outer to the inner radius (R_o/R_i), ratios of length scale and nonlocal to thickness (l/h and μ/h), the ratio of piezoelectric to core thickness (h_p/h), applied voltage, and GPL weight fraction (g_{GPL}) have a significant influence

on the frequency characteristics of the GPLRC micro-disk. Another important consequence is that as well as the nonlinear indirect effects of applied voltage on the natural frequency of the GPLRC micro-disk covered with piezoelectric for each specific value of R_o/R_i, the impact of the R_o/R_i on the natural frequency is indirect. In addition, four different patterns of GPL distribution in the microdisk are investigated. For all patterns, the relation between g_{GPL} parameter and critical voltage is linear. It was also found that when the boundary conditions of S–S is considered, patterns 4 and 1 have not shown any significant effect on the critical voltage of the structure. A useful suggestion of this research is that, for designing the GPLRC circular microplate at the low value of the R_o/R_i, more attention should be given to the g_{GPL} and R_o/R_i, simultaneously.

For the second component, a cantilever beam with one fixed end which is covered with a piezoelectric layer is studied under two different vibrational sources. The effect of thickness ratio of the piezoelectric layer, different geometric shapes (trapezoidal, rectangular and triangular) of the beam and a tip mass on output voltage in both sources of vibration is carried using COMSOL Multiphysics. For the case of vibration under body load, a swept sine excitation source of 200 mV which creates a harmonic body load is investigated. The simulation is carried on in a frequency range of 0-800 Hz. The highest voltage output has been achieved by the triangular shape (14.4 V) of the beam and the lowest value belongs to the trapezium (3.3 V). For the effect of the thickness ratio of the piezoelectric layer to the base (R_p/R_b), the best result is achieved when the piezoelectric layer and the base layer have the same thickness. The simulation is continued with the second source of vibration which is coming from rain droplets and acts as a point load on the surface of the beam. Different rain droplets with various range of radius size, speed and impact force are used in the study. Besides, three different impact point along the beam was selected and the findings reveal that the closer the impact point to the free end of the beam the higher the output voltage generated. The highest voltage output occurs for the triangular beam where the droplet has a diameter of 5 mm and a terminal velocity of 9 m/s. It was found that by changing the shape of the beam from rectangular to triangular the voltage output had been more than doubled (increased from 5.7 V to 14.4 V). Attaching a tip mass on the cantilever beam results in decreasing the voltage output but it increases the duration of oscillation. In conclusion, the piezoelectric specimen which is cut into a triangular shape results in a significant increase in the output voltage compared to other geometrical shapes upon the impact of rain droplets. However, to utilize this more effectively in real applications there must be arrays of these specimens to cover a larger surface area; therefore, resulting in great power.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

ANALISIS BERANGKA FREKUENSI DAN TINDAKBALAS ELEKTRIK DALAM KOMPONEN BERLAPIS PIEZOELEKTRIK UNTUK PENUAIAN TENAGA

Oleh

ERFAN SHAMSADDINI LORI

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Dalam tahun-tahun kebelakangan ini, ada peningkatan minat untuk mengumpul tenaga menggunakan sumber alternatif. Salah satu sumbernya ialah getaran yang dapat diambil dan ditukarkan menjadi tenaga elektrik. Bahan piezoelektrik dapat digunakan untuk menangkap getaran, gerakan atau suara akustik, untuk diubah menjadi output elektrik oleh kerana sikap mausia ferhadap teknologi yang tidak pernah putus-putus untuk meningkatkan sifat mekanik dan operasi struktur. Pengukuhan GPL mendapat perhatian para saintis kerana memberikan peningkatan yang memberasangkan dalam reka bentuk struktur komposit yang sedia ada. Kajian ini menunjukkan tindak balas elektrik piezoelektrik untuk dua komponen yang berbeza (cakera mikro dan rasuk kantilever). Pada bahagian pertama penyelidikan ini, analisis frekuensi mikrodisk Graphene Nanoplatelets Reinforced Composite (GPLRC) disiasat untuk tiga keadaan sempadan yang berbeza (sederhana-sederhana, hanya diapit dan diapit-diapit). Masalahnya adalah, kerana ini dilakukan pada skala nano belum ada kerja eksperimen yang dilakukan sebelumnya. Untuk mengatasi masalah ini, teori kecerunan regangan nonlokal (NSGT) digunakan yang memperkenalkan dua skala panjang bergantung pada ukuran (l) dan nonlokal (μ). Kajian ini dilakukan dalam rangka kaedah kuadratur pembezaan generalisasi berdasarkan berangka (GDQM). Tekanan dan ketegangan diperoleh menggunakan teori ubah bentuk ricih tertib tinggi (HOSDT). Peraturan campuran digunakan untuk memperoleh kepadatan jisim dan nisbah Poisson yang berbeza-beza, sedangkan modul keanjalan dihitung dengan model Halpin-Tsai yang diubahsuai. Persamaan dan keadaan sempadan mikrodisk GPLRC yang ditutup dengan lapisan piezoelektrik diperoleh dengan menerapkan prinsip Hamilton. Mengenai ikatan sempurna antara lapisan dan teras piezoelektrik, syarat keserasian diperoleh. Juga, kerana wujudnya lapisan piezoelektrik, persamaan Maxwell diturunkan. Perisian MATLAB digunakan dan hasilnya menunjukkan bahawa nisbah jejari luaran ke dalam (R_o/R_i), nisbah skala panjang dan ketebalan tidak lokal ke (l/h and μ/h) nisbah ketebalan

piezoelektrik ke teras (h_p/h), voltan gunaan, dan pecahan berat GPL (g_{GPL}) mempunyai pengaruh yang signifikan terhadap ciri frekuensi cakera mikro GPLRC. Satu akibat penting lain adalah bahawa selain kesan tidak langsung voltan gunaan pada frekuensi semula jadi cakera mikro GPLRC yang ditutup dengan piezoelektrik untuk setiap nilai tertentu R_o/R_i, kesan R_o/R_i pada frekuensi semula jadi tidak langsung. Sebagai tambahan, empat corak taburan GPL yang berbeza dalam cakera mikro disiasat. Untuk semua corak, hubungan antara parameter g_{GPL} dan voltan kritikal adalah linear. Ia juga didapati bahawa apabila keadaan batas S-S dipertimbangkan, corak 4 dan 1 tidak menunjukkan kesan yang signifikan terhadap voltan kritikal struktur. Cadangan berguna dari penyelidikan ini adalah bahawa, untuk merancang plat mikro pekeliling GPLRC pada nilai rendah R_o/R_i, perhatian lebih harus diberikan kepada g_{GPL} dan R_o/R_i, secara serentak.

Untuk komponen kedua, rasuk kantilever dengan satu hujung tetap yang ditutup dengan lapisan piezoelektrik dikaji di bawah dua sumber getaran yang berbeza. Kesan nisbah ketebalan lapisan piezoelektrik, bentuk geometri yang berbeza (trapezoid, segi empat tepat dan segitiga) rasuk dan jisim hujung pada voltan keluaran di kedua-dua sumber getaran dibawa menggunakan COMSOL Multiphysics. Untuk kes getaran di bawah beban badan, sumber pengujaan sinus menyapu 200 mV yang membuat beban badan harmonik disiasat. Simulasi dijalankan dalam julat frekuensi 0-800 Hz. Output voltan tertinggi telah dicapai dengan bentuk segitiga (14.4 V) rasuk dan nilai terendah tergolong dalam trapezium (3.3 V). Untuk kesan nisbah ketebalan lapisan piezoelektrik ke dasar (R_p/R_b), hasil terbaik dicapai apabila lapisan piezoelektrik dan lapisan dasar mempunyai ketebalan yang sama. Simulasi diteruskan dengan sumber getaran kedua yang berasal dari titisan hujan dan bertindak sebagai muatan titik pada permukaan rasuk. Titisan hujan yang berbeza dengan pelbagai ukuran ukuran, kelajuan dan kekuatan hentaman digunakan dalam kajian ini. Di samping itu, tiga titik hentaman yang berbeza di sepanjang rasuk dipilih dan penemuan menunjukkan bahawa, semakin dekat titik hentaman ke hujung rasuk bebas, semakin tinggi voltan keluaran yang dihasilkan. Output voltan tertinggi berlaku untuk rasuk segitiga di mana titisan mempunyai diameter 5 mm dan halaju terminal 9 m/s. Didapati bahawa dengan mengubah bentuk rasuk dari segi empat tepat menjadi segitiga output voltan telah meningkat dua kali ganda (meningkat dari 5.7 V menjadi 14.4 V). Melampirkan jisim hujung pada rasuk kantilever akan menurunkan output voltan tetapi meningkatkan jangka masa ayunan. Kesimpulannya, spesimen piezoelektrik yang dipotong menjadi bentuk segitiga menghasilkan peningkatan voltan keluaran yang ketara dibandingkan dengan bentuk geometri lain pada kesan titisan hujan. Walau bagaimanapun, untuk menggunakan ini dengan lebih berkesan dalam aplikasi sebenar mesti ada susunan spesimen ini untuk menutup luas permukaan yang lebih besar; oleh itu, menghasilkan kuasa yang besar.

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LIST OF SYMBOLS

R_o	Outer radius
R_i	Inner radius
h	Core thickness
h_p	Piezoelectric thickness
l	Length scale
μ	Nonlocal scale
g_{GPL}	GPL weight fraction
V_{GPL}	GPL volume fraction
V_M	Matrix volume fraction
ρ_{GPL}	Mass densities of the GPL
ρ_M	Mass densities of polymer matrix
E_M	Young's modulus of polymer matrix
E_{GPL}	Young's modulus of GPL
L_{GPL}	Average length of GPL
t_{GPL}	Average thickness of GPL
w_{GPL}	Average width of GPL
ρ_c	Mass density of GPL/polymer nanocomposite
ν_c	Poisson's ratio of GPL/polymer nanocomposite
u^c	Displacement in core plate along *x*
v^c	Displacement in core plate along θ
w^c	Displacement in core plate along *z*
u^p	Displacement in piezoelectric layer along *x*
v^p	Displacement in piezoelectric layer along θ
w^p	Displacement in piezoelectric layer along *z*
Q_{ij}	Elasticity matrix
e_{mij}	Piezoelectric constant
s_{im}	Dielectric constant
D_i	Electric displacement of the piezoelectric
E_m	Electric fields strength of the piezoelectric

E_R	Electric fields strength along R
E_θ	Electric fields strength along θ
E_z	Electric fields strength along z
U^i	Strain energy of the microdsik
T^i	Kinetic energy of the microdisk
W^i	External work on the microdisk
N_i^P	External electric load
t_{ij}	Nonlocal strain gradient stress tensor
ε_{ck}	Strain tensor
C_{ijck}	Elasticity tensor
V	Volt
R	Load resistance
W1	fix end's width of the beam
W2	free end's width of the beam
r	Droplet radius
ρ_w	Density of water
v	Droplet velocity
L	Length of the beam

LIST OF ABBREVIATIONS

2D	Two dimensional
AC	Alternative current
CNT	Carbon nanotube
CWCVD	Cockcroft Walton Cascade Voltage Doubler
DC	Direct current
DQ	Differential quadrature
DWCNT	Double-walled carbon nanotube
EH	Energy harvesting
FG	Functionally graded
FGM	Functionally graded material
FSD	First-order shear deformation
FSDT	First-order shear deformation theory
GDQ	General differential quadrature
GDQM	Generalized differential quadrature method
GNPRC	Graphene nanoplatelet reinforced composite
GPL	Graphene nanoplatelet
GPLRC	Graphene nanoplatelets reinforced composite
HOSDT	Higher order shear deformable theory
KFCVD	Karthaus Fisher Cascade Voltage Doubler
MCS	Modified couple stress
MWCNT	Multi-walled carbon nanotube
NSGT	Nonlocal strain gradient theory
PEH	Piezoelectric energy harvesting
PIAC	Piezoelectric actuator
PMN- PT	Lead Magnesium Niobate-Lead Titanate
PVDF	Zinc Oxide and Polyvinylidene Difluoride
PZN- PT	Lead Zinc Niobate-Lead Titanate
PZT	Lead Zirconated Titanate
SWCNT	Single-walled carbon nanotube

CHAPTER 1

INTRODUCTION

1.1 Background

Over the past few years, the demand for renewable energy sources has significantly increased. Renewable energy sources are extensively used due to some of the disadvantages of fossil fuels such as, environmental damage, territorial imbalances and fossil fuel depletion which caused this global shift towards clean energy (Afsharzade et al., 2016; Candela et al., 2007; Di Dio et al., 2007; Shamsadini Lori & Leman, 2016). One of the potential sources of renewable energy that draws the researcher's attention is rain. Rain is a natural phenomenon that exists and occurs in day-to-day life. The potential energy that the raindrops carry out at high altitude is converted to kinetic energy upon impact on any surface which creates vibration. This vibration, even though might be weak but at large volume, can be harvested and can be used efficiently (Vatansever et al., 2011). There are of course some limitations to this idea since this method of harvesting relies strongly on frequency and volume of rainfall. Those regions, which have heavy rainy seasons, are suitable for this method. Malaysia is one of the countries which is located in equatorial and because of that it receives massive rainfall throughout the year (Mohtar et al., 2015). This makes it suitable to apply this technology especially in remote areas where the accessibility to electricity is difficult. It is seen that the demand has increased rapidly in self-powered electronic devices such as wireless sensors, industrial automation, and electronic devices.

Currently, three methods are being used to convert the mechanical energy from vibration into electrical energy namely as electromagnetic induction (Sari et al., 2007), electrostatic induction (Asanuma et al., 2013; Richards et al., 2004) and piezoelectric effect (Jackson et al., 2014; Lanbo et al., 2014). The studies on piezoelectric materials have been most widely investigated since they provide higher density and can be readily integrated into a system (Steven R Anton & Sodano, 2007; Li et al., 2014; S Roundy & Wright, 2004).

Reinforced laminated composites are increasingly used in various applications due to its outstanding features, namely high tensile strength, high modulus, and lightweight (Habibi et al., 2018; Habibi et al., 2016; Habibi, Hashemi et al., 2018). Sun & Zhao (2018) compared the fracture behavior of the functionally graded (FG) cemented carbide reinforced with and without the graphene nanoplatelet (GPL). They claimed that the property of GPLs in the nanocomposites is worked as a stopper for micro cracks. Besides, with the aid of an experimental study, Rafiee et al. (2009) reported that the composite structures which are reinforced with GPL agree with much stronger than the reinforced structures with single-walled carbon nanotube (SWCNT), double-walled carbon nanotube (DWCNT), and multi-walled carbon nanotube (MWCN). In their result presented the effect of different kinds of reinforcement to improving the vibrational behavior of the micro circular shell.

Gholami et al. (2018) focused on the modeling and instability analysis of the FG circular micro-shell based on a more applicable gradient elasticity theory which it can consider the size effect and high order parameters and that was a novelty in this field. They showed that the size effect and radius to thickness parameters could play an important role in the nonlinear instability of the microstructure. Mohammadimehr et al. (2018) presented static and dynamic stability of the circular composite plate which they solved this problem with the aid of first-order shear deformation (FSD) theory and general differential quadrature (GDQ) method.

Therefore, this study was conducted to investigate the frequency characteristics of a graphene nanoplatelet composite (GPLRC) as well as the critical voltage for circular micro-disk. Also, the effect of covering graphene with a layer of piezoelectric and its electrical properties are analyzed. These results are used in a bigger scale for the application of harvesting energy from raindrops. It is shown by simulation that how by varying design configurations an optimum output can be obtained.

1.2 Problem Statements

Due to the never-ending need of technology for improving the mechanical properties (Habibi et al., 2018; Habibi et al., 2016) and operation of the structures (Habibi et al., 2017), GPL reinforcements gain the attention of scientists for providing an enthusiastic enhancement in design of the applicable composite structures (Ebrahimi et al., 2018; Esmailpoor Hajilak et al., 2019a; Habibi et al., 2019b; Pourjabari et al., 2019a).

In the field of the vibrational and buckling characteristics of the piezoelectric circular micro/nanoplate, Wang et al. (2017) focused on the nonlinear dynamic responses of the size-dependent circular plate which is actuated with piezoelectric part and considered a thermal environment. They showed that nonlinear geometric effects on the dynamic responses are more significant. Mahinzare et al. (2019) presented a vibration response of an effected size functionally graded material (FGM) circular plate with the aid of nonlocal strain gradient theory (NSGT), first-order shear deformation theory (FSDT), Hamilton’s principle, and the differential quadrature (DQ) method. They considered rotation, thermal, and electro–elastic impact in their mathematical modeling. They found that rotational speed plays an important role in the vibration characteristics of the nanostructure. In another work, Mahinzare et al. (2018) played the attention on the vibrational behaviors of the rotating two-directional FG piezoelectric size-dependent circular plate based on the FSDT, DQM, and Hamilton’s principle. They showed that the dynamic behavior of the plate is depended on the externally applied voltage and rotating loads. Shojaeefard et al. (2018) illustrated the natural frequency of a rotating tapered size-dependent circular plate based on the DQM, and Hamilton’s principle. They modeled the material of the structure as 2D-FGM. They found out the critical angular velocity for the structure in diffract conditions. To the best of authors’ knowledge, frequency analysis of a GPLRC microdisk covered with a piezoelectric layer based on NSGT has not been issued in the published literature. In this study, modified Halpin-Tsai micromechanics is employed to approximate effective elastic properties. A numerical solution to differential governing equations is presented in the case of various boundary conditions. Special attentions are given to explore the effects of the R_o/R_i, l/h, μ/h, h/h_p, applied voltage and g_{GPL} on the frequency characteristics of a GPLRC micro-disk covered with piezoelectric layer.

In terms of harvesting energy from potential energy possessed in rain droplets, many types of research have been over the past decade. In a study done in Italy made a comparison between the two most commonly used piezoelectric material (PZT and PVDF) with a simple cantilever beam with one fix end. Various droplets have been used and it was concluded that PZT material generates a higher amount of output voltage compared to PVDF (Vatansever et al., 2011). In another research, they (Viola et al., 2014) used a rectangular membrane made of PVDF which was clamped at four edges and a droplet was released on the center. Their findings show that a membrane is not a suitable design for harvesting energy from rain droplets compared to cantilever since the output power was extremely low. Wong et al. (2014) used a cantilever beam with fixing the two ends (cantilever bridge) while using two different materials (PVDF, PZT). Their findings were in parallel with previous literature and proved that PZT provides a higher output. However, a cantilever beam with one fix end gives a more promising result compared to cantilever bridge. An experiment conducted by Wu et al. (2014) tried to achieve the best efficiency by varying the thickness of the cantilever and they have the best thickness for cantilever but not the ratio to the base beam.

Many of these researchers limited their study on mainly three basic designs (cantilever, cantilever bridge, and membrane) for two different widely used piezoelectric material (PVDF, PZT) until recently were new designs are suggested and investigated. An investigation by Viola (2018) on implementing a floating disk was a new approach. Three sets of the experiment (single cantilever, disk supported by two cantilevers, disk supported by four cantilevers) were conducted and the results were compared. It was found that in the case of one single droplet the single cantilever without the disk generates a higher output voltage. In another research, the cantilever has been modified to the spoon shape cantilever (Doria et al., 2019). This design achieved a slightly higher output. They investigated further the effect of wetness on the efficiency of the system and according to their finding a wet surface can produce an output voltage up to three times more than a dry surface.

In this research, a new way of harvesting energy from raindrops by employing piezoelectric material is modeled and simulated. This new approach not only brings more durability to the system because of implementing copper as the base material but also generates higher voltage output due to the truncated shape of the beam.

1.3 Research Objective

This research aims to investigate and evaluate the effects of using piezoelectric material combined with graphene Nanoplatelets reinforced composite (GPLRC).

Also, one practical application of it which is harvesting energy using raindrop is analyzed and a new design is proposed. Towards achieving the main objective, the related aims associated are identified as follows:

1. To investigate frequency characteristics of a GPL reinforced composite microdisk covered with piezoelectric layer;
2. To find the critical voltage for different patterns of GPL reinforced composite microdisk covered with a piezoelectric layer;
3. To obtain the optimal piezoelectric cantilever beam harvester under body load vibration;
4. To enhance the current method of harvesting energy from raindrop by implementing a new shape configuration.

1.4 Significance of the Study

The main objective of this project is to develop the potential of the smart material application using PZT incorporated with GPLRC from the impact of the raindrop that enables to harvest energy-based numerical model.

The significant of the study are briefly explained as follows:

1. This research works on the frequency analysis of a graphene nanoplatelets composite (GPLRC) microdisk which is integrated with a piezoelectric layer in the framework of numerical approach;
2. The findings of this research give a useful suggestion for designing of the GPLRC circular microplate;
3. The modified cantilever beam with a layer of piezoelectric is simulated under two types of excitation from different sources to find the optimum design;
4. This research exposes the potentials of using piezoelectric material as a self-powered sensor in remote areas of Malaysia by proposing a new design configuration.

1.5 Scope and Limitations of the Study

The scope of this study is focused on two main topics:

1. A numerical approach for finding the electrical characteristics (voltage and frequency) based on the generalized differential quadrature method (GDQM) is presented. To derive the equations related to motion, nonlocal strain gradient theory is used. In deriving some of the equations as well as designing the shape of the circular micro-disk layered with piezoelectric MATLAB and ABAQUS software's are used respectively. One of the limitations could be

regarding a perfect bonding between the piezoelectric layer and core which the compatibility conditions for that are derived.

2. A complete and detailed review is done on studying the possible factors which may have any effect on harvesting raindrop using a piezoelectric material. The focus is narrowed down to the impact of a raindrop on the surface of the material. The most well-known piezoelectric material, which is widely used, is PZT (Lead Zirconate Titanate) is used but due to its nature which is extremely brittleness, it causes some limitations. To overcome this copper is used as the base material and the simulation is done with the aid of COMSOL Multi-Physics software.

1.6 Structure of the Thesis

This thesis is structured into 5 chapters by the thesis format of Universiti Putra Malaysia. The details of the thesis structure are presented as follows:

Chapter 1

Problem statements and objectives are presented in this chapter. The significance of the research work and the scope of research are also presented in this chapter.

Chapter 2

This chapter presents a comprehensive literature review on the areas related to the topic of this research. Besides, the research gaps obtained from the review were also clarified within the chapter.

Chapter 3

The methodology used in this research for the preparation of materials, modeling and simulation procedures is presented in this chapter.

Chapter 4

This chapter starts with showing the validations and making a comparison with previous literature. After that, the data analysis is done and discussed in three sections. In the first section the effect of parameters such as ratio of the outer to the inner radius (R_o/R_i), ratios of length scale and nonlocal to thickness (l/h and μ/h), the ratio of piezoelectric to core thickness (h_p/h), microdisk pattern, and GPL weight fraction (g_{GPL}) on critical voltage is shown and discussed. In the second section, the effect of various geometry and tip mass on the voltage output of a cantilever beam supported at one end under body load excitation is presented. In the last part of this chapter, the impact force of various rain droplets is calculated and the corresponding output voltage for each one is presented.

Chapter 5

This chapter presents the overall conclusions from the whole study as well as future recommendations for further improvement of this study.

REFERENCES

Abidin, N. A. K. Z., Nayan, N. M., Azizan, M. M., & Ali, A. (2018). Analysis of voltage multiplier circuit simulation for rain energy harvesting using circular piezoelectric. *Mechanical Systems and Signal Processing, 101*, 211-218.

Abualnour, M., Houari, M. S. A., Tounsi, A., & Mahmoud, S. (2018). A novel quasi-3D trigonometric plate theory for free vibration analysis of advanced composite plates. *Composite Structures, 184*, 688-697.

Afsharzade, N., Papzan, A., Ashjaee, M., Delangizan, S., Van Passel, S., & Azadi, H. (2016). Renewable energy development in rural areas of Iran. *Renewable and Sustainable Energy Reviews, 65*, 743-755.

Al-Basyouni, K., Tounsi, A., & Mahmoud, S. (2015). Size dependent bending and vibration analysis of functionally graded micro beams based on modified couple stress theory and neutral surface position. *Composite Structures, 125*, 621-630.

Al Ahmad, M. (2014). Piezoelectric water drop energy harvesting. *Journal of Electronic Materials, 43*(2), 452-458.

Alimirzaei, S., Mohammadimehr, M., & Tounsi, A. (2019). Nonlinear analysis of viscoelastic micro-composite beam with geometrical imperfection using FEM: MSGT electro-magneto-elastic bending, buckling and vibration solutions. *Structural Engineering and Mechanics, 71*(5), 485-502.

Alipour, M. (2018). Transient forced vibration response analysis of heterogeneous sandwich circular plates under viscoelastic boundary support. *Archives of Civil and Mechanical Engineering, 18*(1), 12-31.

Alipour, M., Torabi, M. A., Sareban, M., Lashini, H., Sadeghi, E., Fazaeli, A., Hashemi, R. (2020). Finite element and experimental method for analyzing the effects of martensite morphologies on the formability of DP steels. *Mechanics Based Design of Structures and Machines, 48*(5), 525-541.

Anton, S. R. (2011). *Multifunctional piezoelectric energy harvesting concepts.* PhD Thesis, Virginia Tech, USA.

Anton, S. R., & Sodano, H. A. (2007). A review of power harvesting using piezoelectric materials (2003–2006). *Smart Materials and Structures, 16*(3), 1-21.

Asanuma, H., Oguchi, H., Hara, M., & Kuwano, H. (2013). *Ferroelectric dipole electrets prepared from soft and hard PZT ceramics in electrostatic vibration energy harvesters.* Paper presented at the 13th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, London, UK

Atmane, H. A., Tounsi, A., & Bernard, F. (2017). Effect of thickness stretching and porosity on mechanical response of a functionally graded beams resting on elastic foundations. *International Journal of Mechanics and Materials in Design, 13*(1), 71-84.

Attariani, H., Rezaei, S. E., & Momeni, K. (2018). Defect engineering, a path to make ultra-high strength low-dimensional nanostructures. *Computational Materials Science, 151*, 307-316.

Attariani, H., Rezaei, S. E., & Momeni, K. (2019). Mechanical property enhancement of one-dimensional nanostructures through defect-mediated strain engineering. *Extreme Mechanics Letters, 27*, 66-75.

Ayed, S. B., Najar, F., & Abdelkefi, A. (2009). *Shape improvement for piezoelectric energy harvesting applications.* Paper presented at the 2009 3rd International Conference on Signals, Circuits and Systems (SCS), Tunisia.

Baker, J., Roundy, S., & Wright, P. (2005). *Alternative geometries for increasing power density in vibration energy scavenging for wireless sensor networks.* Paper presented at the 3rd International Energy Conversion Engineering Conference, California.

Bakhadda, B., Bouiadjra, M. B., Bourada, F., Bousahla, A. A., Tounsi, A., & Mahmoud, S. (2018). Dynamic and bending analysis of carbon nanotube-reinforced composite plates with elastic foundation. *Wind and Structures, 27*(5), 311-324.

Barooti, M. M., Safarpour, H., & Ghadiri, M. (2017). Critical speed and free vibration analysis of spinning 3D single-walled carbon nanotubes resting on elastic foundations. *The European Physical Journal Plus, 132*(1), 1-21.

Beard, K. V., & Chuang, C. (1987). A new model for the equilibrium shape of raindrops. *Journal of the Atmospheric sciences, 44*(11), 1509-1524.

Bellifa, H., Benrahou, K. H., Bousahla, A. A., Tounsi, A., & Mahmoud, S. (2017). A nonlocal zeroth-order shear deformation theory for nonlinear postbuckling of nanobeams. *Structural Engineering and Mechanics, 62*(6), 695-702.

Bellman, R., & Casti, J. (1971). Differential quadrature and long-term integration. *Journal of mathematical analysis and Applications*, *34*(2), 235-238

Benchohra, M., Driz, H., Bakora, A., Tounsi, A., Adda Bedia, E., & Mahmoud, S. (2018). A new quasi-3D sinusoidal shear deformation theory for functionally graded plates. *Structural Engineering and Mechanics, 65*(1), 19-31.

Berghouti, H., Adda Bedia, E., Benkhedda, A., & Tounsi, A. (2019). Vibration analysis of nonlocal porous nanobeams made of functionally graded material. *Advances in Nano Research, 7*(5), 351-364.

Bisheh, H., Alibeigloo, A., Safarpour, M., & Rahimi, A. (2019). Three-dimensional static and free vibrational analysis of graphene reinforced composite circular/annular plate using differential quadrature method. *International Journal of Applied Mechanics, 11*(08), 1950073.

Biswas, P., Uddin, M., Islam, M., Sarkar, M., Desa, V., Khan, M., & Huq, A. (2009). *Harnessing raindrop energy in Bangladesh.* Paper presented at the 4th International Conference on Mechanical Engineering, Bangladesh.

Bouadi, A., Bousahla, A. A., Houari, M. S. A., Heireche, H., & Tounsi, A. (2018). A new nonlocal HSDT for analysis of stability of single layer graphene sheet. *Advances in Nano Research, 6*(2), 147-162.

Bouhadra, A., Tounsi, A., Bousahla, A. A., Benyoucef, S., & Mahmoud, S. (2018). Improved HSDT accounting for effect of thickness stretching in advanced composite plates. *Structural Engineering and Mechanics, 66*(1), 61-73.

Boukhlif, Z., Bouremana, M., Bourada, F., Bousahla, A. A., Bourada, M., Tounsi, A., & Al-Osta, M. A. (2019). A simple quasi-3D HSDT for the dynamics analysis of FG thick plate on elastic foundation. *Steel and Composite Structures, 31*(5), 503-516.

Boulefrakh, L., Hebali, H., Chikh, A., Bousahla, A. A., Tounsi, A., & Mahmoud, S. (2019). The effect of parameters of visco-Pasternak foundation on the bending and vibration properties of a thick FG plate. *Geomechanics and Engineering, 18*(2), 161-178.

Bounouara, F., Benrahou, K. H., Belkorissat, I., & Tounsi, A. (2016). A nonlocal zeroth-order shear deformation theory for free vibration of functionally graded nanoscale plates resting on elastic foundation. *Steel and Composite Structures, 20*(2), 227-249.

Bousahla, A. A., Houari, M. S. A., Tounsi, A., & Bedia, E. A. (2014). A novel higher order shear and normal deformation theory based on neutral surface position for bending analysis of advanced composite plates. *International Journal of Computational Methods, 11*(06), 1350082.

Boutaleb, S., Benrahou, K. H., Bakora, A., Algarni, A., Bousahla, A. A., Tounsi, A., Mahmoud, S. (2019). Dynamic analysis of nanosize FG rectangular plates based on simple nonlocal quasi 3D HSDT. *Advances in Nano Research, 7*(3), 191.

Candela, R., Di Dio, V., Sanseverino, E. R., & Romano, P. (2007). *Reconfiguration techniques of partial shaded PV systems for the maximization of electrical energy production.* Paper presented at the 2007 International Conference on Clean Electrical Power, Italy.

Cecati, C., Genduso, F., Miceli, R., & Galluzzo, G. R. (2011). *A suitable control technique for fault-tolerant converters in distributed generation.* Paper presented at the 2011 IEEE International Symposium on Industrial Electronics, Poland.

Chin-Hong, W., Dahari, Z., Manaf, A. A., Sidek, O., Miskam, M. A., & Mohamed, J. J. (2013). *Simulation of piezoelectric raindrop energy harvester.* Paper presented at the IEEE 2013 Tencon-Spring, Sydney, Australia.

Cipriani, G., Corpora, M., Di Dio, V., Musolino, A., Rizzo, R., & Sani, L. (2016). A comparison among different kinds of stator lamination in tubular linear machines. *Progress In Electromagnetics Research, 50*, 95-104.

Crandall, S. H. (1968). *Dynamics of Mechanical and Electromechanical Systems*: McGraw-Hill.

D. Vatansever, Siores, E., & Shah, T. (2012). Alternative Resources for Renewable Energy : Piezoelectric and Photovoltaic Smart Structures. In B. R. Singh (Ed.), *Global Warming Impacts and Future Perspective,* pp 263-290. Janeza Trdine 9, 51000 Rijeka, Croatia: InTech,.

Dagdeviren, C., Yang, B. D., Su, Y., Tran, P. L., Joe, P., Anderson, E., Feng, X. (2014). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. *Proceedings of the National Academy of Sciences, 111*(5), 1927-1932.

De Villoria, R. G., & Miravete, A. (2007). Mechanical model to evaluate the effect of the dispersion in nanocomposites. *Acta Materialia*, *55*(9), 3025-3031.

Deterre, M., Lefeuvre, E., Zhu, Y., Woytasik, M., Boutaud, B., & Dal Molin, R. (2013). Micro blood pressure energy harvester for intracardiac pacemaker. *Journal of Microelectromechanical Systems, 23*(3), 651-660.

Dezfuli, A. A., Shokouhmand, A., Oveis, A. H., & Norouzi, Y. (2018). Reduced complexity and near optimum detector for linear-frequency-modulated and phase-modulated LPI radar signals. *IET Radar, Sonar & Navigation, 13*(4), 593-600.

Di Dio, V., Miceli, R., & Trapanese, M. (2007). *The use of sea waves for generation of electrical energy: a linear tubular asynchronous electrical generator*. Paper presented at the OCEANS 2007, Aberdeen, Scotland.

Di, L., Zhang, X., & Xu, Z. (2014). Preparation of Copper Nanoparticles Using Dielectric Barrier Discharge at Atmospheric Pressure and its Mechanism. *Plasma Science and Technology, 16*(1), 41-44.

Dimarogonas, A. D. (1996). *Vibration for Engineers*: Prentice Hall.

Doria, A., Fanti, G., Filipi, G., & Moro, F. (2019). Development of a novel piezoelectric harvester excited by raindrops. *Sensors, 19*(17), 3653-3674.

Draiche, K., Tounsi, A., & Mahmoud, S. (2016). A refined theory with stretching effect for the flexure analysis of laminated composite plates. *Geomechanics and Engineering, 11*(5), 671-690.

Draoui, A., Zidour, M., Tounsi, A., & Adim, B. (2019). *Static and dynamic behavior of nanotubes-reinforced sandwich plates using (FSDT). Nano Research*, 57, 117-135.

Du, H., Lim, M. K., & Lin, R. (1994). Application of generalized differential quadrature method to structural problems. *International Journal for Numerical Methods in Engineering*, *37*(11), 1881-1896

Ebrahimi-Mamaghani, A., Mirtalebi, S. H., & Ahmadian, M.-T. (2020). Magneto-mechanical stability of axially functionally graded supported nanotubes. *Materials Research Express*, *6*(12), 1250-1255.

Ebrahimi-Mamaghani, A., Sotudeh-Gharebagh, R., Zarghami, R., & Mostoufi, N. (2020). Thermo-mechanical stability of axially graded Rayleigh pipes. *Mechanics Based Design of Structures and Machines*, 48(5), 1-30.

Ebrahimi, F., & Daman, M. (2016a). Dynamic modeling of embedded curved nanobeams incorporating surface effects. *Coupled Syst. Mech, 5*(3), 255-267.

Ebrahimi, F., & Daman, M. (2016b). Investigating surface effects on thermomechanical behavior of embedded circular curved nanosize beams. *Journal of Engineering,* 2016, 1-11 .

Ebrahimi, F., & Daman, M. (2016c). An investigation of radial vibration modes of embedded double-curved-nanobeam-systems. *Çankaya Üniversitesi Bilim ve Mühendislik Dergisi, 13*(1), 58-79.

Ebrahimi, F., & Daman, M. (2017a). Analytical investigation of the surface effects on nonlocal vibration behavior of nanosize curved beams. *Advances in Nano Research, 5*(1), 35-47.

Ebrahimi, F., & Daman, M. (2017b). Dynamic characteristics of curved inhomogeneous nonlocal porous beams in thermal environment. *Struct Eng Mech, 64*(1), 121-133.

Ebrahimi, F., & Daman, M. (2017c). Nonlocal thermo-electromechanical vibration analysis of smart curved FG piezoelectric Timoshenko nanobeam. *Smart Structures and Systems, 20*(3), 351-368.

Ebrahimi, F., Daman, M., & Fardshad, R. E. (2017). Surface effects on vibration and buckling behavior of embedded nanoarches. *Struct Eng Mech, 64,* 1-10.

Ebrahimi, F., Daman, M., & Mahesh, V. (2019). Thermo-mechanical vibration analysis of curved imperfect nano-beams based on nonlocal strain gradient theory. *Adv Nano Res, 7,* 249-263.

Ebrahimi, F., Habibi, M., & Safarpour, H. (2019a). On modeling of wave propagation in a thermally affected GNP-reinforced imperfect nanocomposite shell. *Engineering with Computers, 35*(4), 1375-1389.

Ebrahimi, F., Hajilak, Z. E., Habibi, M., & Safarpour, H. (2019b). Buckling and vibration characteristics of a carbon nanotube-reinforced spinning cantilever cylindrical 3D shell conveying viscous fluid flow and carrying spring-mass systems under various temperature distributions. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science, 233*(13), 4590-4605.

Ebrahimi, F., Hashemabadi, D., Habibi, M., & Safarpour, H. (2019c). Thermal buckling and forced vibration characteristics of a porous GNP reinforced nanocomposite cylindrical shell. *Microsystem Technologies, 26*(2), 461-473.

Ebrahimi, F., Mohammadi, K., Barouti, M. M., & Habibi, M. (2019d). Wave propagation analysis of a spinning porous graphene nanoplatelet-reinforced nanoshell. *Waves in Random and Complex Media,* 29(4), 1-27.

Ebrahimi, F., & Rastgo, A. (2008a). An analytical study on the free vibration of smart circular thin FGM plate based on classical plate theory. *Thin-Walled Structures, 46*(12), 1402-1408.

Ebrahimi, F., & Rastgoo, A. (2008b). Free vibration analysis of smart annular FGM plates integrated with piezoelectric layers. *Smart Materials and Structures, 17*(1), 015044.

Ebrahimi, F., & Safarpour, H. (2018). Vibration analysis of inhomogeneous nonlocal beams via a modified couple stress theory incorporating surface effects. *Wind and Structures, 27*(6), 431-438.

Ehyaei, J., & Daman, M. (2017). Free vibration analysis of double walled carbon nanotubes embedded in an elastic medium with initial imperfection. *Advances in Nano Research, 5*(2), 179.

Elvin, N. G., Elvin, A. A., & Spector, M. (2001). A self-powered mechanical strain energy sensor. *Smart Materials and Structures, 10*(2), 293-299.

Erturk, A., & Inman, D. J. (2011). *Piezoelectric Energy Harvesting*: John Wiley & Sons.

Esmailpoor Hajilak, Z., Pourghader, J., Hashemabadi, D., Sharifi Bagh, F., Habibi, M., & Safarpour, H. (2019). Multilayer GPLRC composite cylindrical nanoshell using modified strain gradient theory. *Mechanics Based Design of Structures and Machines, 47*(5), 521-545.

Fazaeli, A., Habibi, M., & Ekrami, A. (2016). Experimental and finite element comparison of mechanical properties and formability of dual phase steel and ferrite-pearlite steel with the same chemical composition. *Metallurgical Engineering*. 19 (2), 84-93.

Gao, W., Dimitrov, D., & Abdo, H. (2018). Tight independent set neighborhood union condition for fractional critical deleted graphs and ID deleted graphs. *Discrete & Continuous Dynamical Systems-S, 12*(4&5), 711-721.

Gao, W., Guirao, J. L., Basavanagoud, B., & Wu, J. (2018). Partial multi-dividing ontology learning algorithm. *Information Sciences, 467*, 35-58.

Gao, W., Guirao, J. L. G., Abdel-Aty, M., & Xi, W. (2019). An independent set degree condition for fractional critical deleted graphs. *Discrete & Continuous Dynamical Systems*, *12*(4&5), 877-886.

Gao, W., Guirao, J. L. G., Basavanagoud, B., & Wu, J. (2018). Partial multi-dividing ontology learning algorithm. *Information Sciences*, *467*, 35-58.

Gao, W., Wang, W., Dimitrov, D., & Wang, Y. (2018). Nano properties analysis via fourth multiplicative ABC indicator calculating. *Arabian Journal of Chemistry*, *11*(6), 793-801.

Gao, W., Wu, H., Siddiqui, M. K., & Baig, A. Q. (2018). Study of biological networks using graph theory. *Saudi Journal of Biological Sciences, 25*(6), 1212-1219.

Gart, S., Mates, J. E., Megaridis, C. M., & Jung, S. (2015). Droplet impacting a cantilever: A leaf-raindrop system. *Physical Review Applied, 3*(4), 044019.

Ghabussi, A., Ashrafi, N., Shavalipour, A., Hosseinpour, A., Habibi, M., Moayedi, H., Safarpour, H. (2019). Free vibration analysis of an electro-elastic GPLRC cylindrical shell surrounded by viscoelastic foundation using modified length-couple stress parameter. *Mechanics Based Design of Structures and Machines*, 47(6), 1-25.

Ghadiri, M., & Safarpour, H. (2016). Free vibration analysis of embedded magneto-electro-thermo-elastic cylindrical nanoshell based on the modified couple stress theory. *Applied Physics A, 122*(9), 833-845.

Ghadiri, M., & SafarPour, H. (2017). Free vibration analysis of size-dependent functionally graded porous cylindrical microshells in thermal environment. *Journal of Thermal Stresses, 40*(1), 55-71.

Ghadiri, M., Shafiei, N., & Safarpour, H. (2017). Influence of surface effects on vibration behavior of a rotary functionally graded nanobeam based on Eringen's nonlocal elasticity. *Microsystem Technologies, 23*(4), 1045-1065.

Ghasemi, A. R., & Mohandes, M. (2020). Free vibration analysis of micro and nano fiber-metal laminates circular cylindrical shells based on modified couple stress theory. *Mechanics of Advanced Materials and Structures, 27*(1), 43-54.

Ghazanfari, A., Assempour, A., Habibi, M., & Hashemi, R. (2016). Investigation on the effective range of the through thickness shear stress on forming limit diagram using a modified Marciniak–Kuczynski model. *Modares Mechanical Engineering, 16*(1), 137-143.

Ghazanfari, A., Soleimani, S. S., Keshavarzzadeh, M., Habibi, M., Assempuor, A., & Hashemi, R. (2019). Prediction of FLD for sheet metal by considering through-thickness shear stresses. *Mechanics Based Design of Structures and Machines*, *48*(6), 755-772.

Gholami, R., Darvizeh, A., Ansari, R., & Pourashraf, T. (2018). Analytical treatment of the size-dependent nonlinear postbuckling of functionally graded circular cylindrical micro-/nano-shells. *Iranian Journal of Science and Technology, Transactions of Mechanical Engineering, 42*(2), 85-97.

Guigon, R., Chaillout, J.-J., Jager, T., & Despesse, G. (2008). Harvesting raindrop energy: experimental study. *Smart Materials and Structures, 17*(1), 015039.

Gusarova, E., Gusarov, B., Zakharov, D., Bousquet, M., Viala, B., Cugat, O., Gimeno, L. (2013). *An improved method for piezoelectric characterization of polymers for energy harvesting applications.* Paper presented at the 13th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications, London, UK.

Habibi, M., Ghazanfari, A., Assempour, A., Naghdabadi, R., & Hashemi, R. (2017). Determination of forming limit diagram using two modified finite element models. *Mech Eng, 48*(4), 141-144.

Habibi, M., Hashemabadi, D., & Safarpour, H. (2019a). Vibration analysis of a high-speed rotating GPLRC nanostructure coupled with a piezoelectric actuator. *The European Physical Journal Plus, 134*(6), 307-330.

Habibi, M., Hashemi, R., Ghazanfari, A., Naghdabadi, R., & Assempour, A. (2018). Forming limit diagrams by including the M–K model in finite element simulation considering the effect of bending. *Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 232*(8), 625-636.

Habibi, M., Hashemi, R., Sadeghi, E., Fazaeli, A., Ghazanfari, A., & Lashini, H. (2016). Enhancing the mechanical properties and formability of low carbon steel with dual-phase microstructures. *Journal of Materials Engineering and Performance, 25*(2), 382-389.

Habibi, M., Hashemi, R., Tafti, M. F., & Assempour, A. (2018). Experimental investigation of mechanical properties, formability and forming limit diagrams for tailor-welded blanks produced by friction stir welding. *Journal of Manufacturing Processes, 31*, 310-323.

Habibi, M., Mohammadgholiha, M., & Safarpour, H. (2019). Wave propagation characteristics of the electrically GNP-reinforced nanocomposite cylindrical shell. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41*(5), 1-15.

Habibi, M., Mohammadi, A., Safarpour, H., & Ghadiri, M. (2019a). Effect of porosity on buckling and vibrational characteristics of the imperfect GPLRC composite nanoshell. *Mechanics Based Design of Structures and Machines*, 47(6), 1-30.

Habibi, M., Mohammadi, A., Safarpour, H., Shavalipour, A., & Ghadiri, M. (2019b). Wave propagation analysis of the laminated cylindrical nanoshell coupled with a piezoelectric actuator. *Mechanics Based Design of Structures and Machines*, 47(5), 1-19.

Habibi, M., & Payganeh, G. (2018). Experimental and finite element investigation of titanium tubes hot gas forming and production of square cross-section specimens. *Aerospace Mechanics Journal*, 14, 88-98.

Habibi, M., Taghdir, A., & Safarpour, H. (2019c). Stability analysis of an electrically cylindrical nanoshell reinforced with graphene nanoplatelets. *Composites Part B: Engineering, 175*, 107125.

Hagood, N. W., Chung, W. H., & Von Flotow, A. (1990). Modelling of piezoelectric actuator dynamics for active structural control. *Journal of Intelligent Material Systems and Structures, 1*(3), 327-354.

Hamza-Cherif, R., Meradjah, M., Zidour, M., Tounsi, A., Belmahi, S., & Bensattalah, T. (2018). Vibration analysis of nano beam using differential transform method including thermal effect. *Journal of Nano Research*. 54, 1-14.

Han, J.-B., & Liew, K. (1999). Axisymmetric free vibration of thick annular plates. *International Journal of Mechanical Sciences, 41*(9), 1089-1109.

Harrison, J., & Ounaies, Z. (2002). *Encyclopedia of Smart Materials*. John Wiley & Sons.

Hashemi, H. R., Alizadeh, A. a., Oyarhossein, M. A., Shavalipour, A., Makkiabadi, M., & Habibi, M. (2019). Influence of imperfection on amplitude and resonance frequency of a reinforcement compositionally graded nanostructure. *Waves in Random and Complex Media*, 29(3), 1-27.

Horstmeyer, S. L. (2011). *The weather almanac: A reference guide to weather, climate, and related issues in the United States and its key cities*: John Wiley & Sons.

Hosseini, M., Bahaadini, R., & Makkiabadi, M. (2018). Application of the Green function method to flow-thermoelastic forced vibration analysis of viscoelastic carbon nanotubes. *Microfluidics and Nanofluidics, 22*(1), 1-15.

Hosseini, S., Habibi, M., & Assempour, A. (2018). Experimental and numerical determination of forming limit diagram of steel-copper two-layer sheet considering the interface between the layers. *Modares Mechanical Engineering, 18*(6), 174-181.

Hosseini, R., & Hamedi, M. (2015). Improvements in energy harvesting capabilities by using different shapes of piezoelectric bimorphs. *Journal of Micromechanics and Microengineering*, 25(12), 1-14.

Hu, H., Xue, H., & Hu, Y. (2007). A spiral-shaped harvester with an improved harvesting element and an adaptive storage circuit. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 54*(6), 1177-1187.

Ihlefeld, J. F. (2019). Fundamentals of Ferroelectric and Piezoelectric Properties. In *Ferroelectricity in Doped Hafnium Oxide: Materials, Properties and Devices* (pp. 1-24): Elsevier.

Ilyas, M. A., & Swingler, J. (2015). Piezoelectric energy harvesting from raindrop impacts. *Energy, 90*, 796-806.

Jackson, N., O'Keeffe, R., Waldron, F., O'Neill, M., & Mathewson, A. (2014). Evaluation of low-acceleration MEMS piezoelectric energy harvesting devices. *Microsystem Technologies*, *20*(4), 671-680.

Jafari, M., Moradi, G., SHIRAZI, R. S., & Mirzavand, R. (2017). Design and implementation of a six-port junction based on substrate integrated waveguide. *Turkish Journal of Electrical Engineering & Computer Sciences, 25*(3), 2547-2553.

Karami, B., Janghorban, M., Shahsavari, D., & Tounsi, A. (2018c). A size-dependent quasi-3D model for wave dispersion analysis of FG nanoplates. *Steel and Composite Structures, 28*(1), 99-110.

Karami, B., Janghorban, M., & Tounsi, A. (2017). Effects of triaxial magnetic field on the anisotropic nanoplates. *Steel and Composite Structures, 25*(3), 361-374.

Karami, B., Janghorban, M., & Tounsi, A. (2018a). Nonlocal strain gradient 3D elasticity theory for anisotropic spherical nanoparticles. *Steel and Composite Structures*, *27*(2), 201-216.

Karami, B., Janghorban, M., & Tounsi, A. (2018b). Variational approach for wave dispersion in anisotropic doubly-curved nanoshells based on a new nonlocal strain gradient higher order shell theory. *Thin-Walled Structures, 129*, 251-264.

Karami, B., Janghorban, M., & Tounsi, A. (2019a). Galerkin's approach for buckling analysis of functionally graded anisotropic nanoplates/different boundary conditions. *Engineering with Computers, 35*(4), 1297-1316.

Karami, B., Janghorban, M., & Tounsi, A. (2019b). On exact wave propagation analysis of triclinic material using three-dimensional bi-Helmholtz gradient plate model. *Structural Engineering and Mechanics, 69*(5), 487-497.

Karami, B., Janghorban, M., & Tounsi, A. (2019c). Wave propagation of functionally graded anisotropic nanoplates resting on Winkler-Pasternak foundation. *Structural Engineering and Mechanics, 70*(1), 55-66.

Karami, B., Shahsavari, D., Janghorban, M., & Tounsi, A. (2019d). Resonance behavior of functionally graded polymer composite nanoplates reinforced with graphene nanoplatelets. *International Journal of Mechanical Sciences, 156*, 94-105.

Karami, M. A., & Inman, D. J. (2011). Parametric study of zigzag microstructure for vibrational energy harvesting. *Journal of Microelectromechanical Systems, 21*(1), 145-160.

Ke, L., Wang, Y., & Reddy, J. (2014). Thermo-electro-mechanical vibration of size-dependent piezoelectric cylindrical nanoshells under various boundary conditions. *Composite Structures, 116*, 626-636.

Khalili, S. M. R., & Mohammadi, Y. (2012). Free vibration analysis of sandwich plates with functionally graded face sheets and temperature-dependent material properties: A new approach. *European Journal of Mechanics-A/Solids, 35*, 61-74.

Khiloun, M., Bousahla, A. A., Kaci, A., Bessaim, A., Tounsi, A., & Mahmoud, S. (2019). Analytical modeling of bending and vibration of thick advanced composite plates using a four-variable quasi 3D HSDT. *Engineering with Computers, 36*(3), 807-821.

Kostinski, A. B., & Shaw, R. A. (2009). Raindrops large and small. *Nature Physics, 5*(9), 624-625.

Kötz, R., & Carlen, M. (2000). Principles and applications of electrochemical capacitors. *Electrochimica acta, 45*(15-16), 2483-2498.

Lanbo, D., Xiuling, Z., & Zhijian, X. (2014). Preparation of copper nanoparticles using dielectric barrier discharge at atmospheric pressure and its mechanism. *Plasma Science and Technology, 16*(1), 41-44.

Leo, D. J. (2007). *Active Material Systems: Analysis, Design, and Control*: Wiley new york.

Li, H., Tian, C., & Deng, Z. D. (2014). Energy harvesting from low frequency applications using piezoelectric materials. *Applied physics reviews, 1*(4), 041301.

Lim, B. (2006). Derivation of the Shape of Raindrops. *School of Applied and Engineering Physics,* Master Thesis. Cornell University. Ithaca, NY, 14853.

Liu, Y., Xie, X., Hu, Y., Qian, Y., Sheng, G., Jiang, X., & Liu, Y. (2016). A novel high-density power energy harvesting methodology for transmission line online monitoring devices. *Review of Scientific Instruments, 87*(7), 075119.

Mahinzare, M., Alipour, M. J., Sadatsakkak, S. A., & Ghadiri, M. (2019). A nonlocal strain gradient theory for dynamic modeling of a rotary thermo piezo electrically actuated nano FG circular plate. *Mechanical Systems and Signal Processing, 115*, 323-337.

Mahinzare, M., Ranjbarpur, H., & Ghadiri, M. (2018). Free vibration analysis of a rotary smart two directional functionally graded piezoelectric material in axial symmetry circular nanoplate. *Mechanical Systems and Signal Processing, 100*, 188-207.

Mahmoudi, A., Benyoucef, S., Tounsi, A., Benachour, A., Adda Bedia, E. A., & Mahmoud, S. (2019). A refined quasi-3D shear deformation theory for thermo-mechanical behavior of functionally graded sandwich plates on elastic foundations. *Journal of Sandwich Structures & Materials, 21*(6), 1906-1929.

Makki, N., & Pop-Iliev, R. (2012). Battery-and wire-less tire pressure measurement systems (TPMS) sensor. *Microsystem Technologies, 18*(7-8), 1201-1212.

Medani, M., Benahmed, A., Zidour, M., Heireche, H., Tounsi, A., Bousahla, A. A., Mahmoud, S. (2019). Static and dynamic behavior of (FG-CNT) reinforced porous sandwich plate using energy principle. *Steel and Composite Structures, 32*(5), 595-610.

Miceli, R., Romano, P., Spataro, C., & Viola, F. (2014). *Performances of rainfall energy harvester.* Paper presented at the Proceedings of the 20th IMEKO TC4 International Workshop on ADC Modelling and Testing Research on Electric and Electronic Measurement for the Economic Upturn, Benevento, Italy.

Mirtalebi, S. H., Ahmadian, M. T., & Ebrahimi-Mamaghani, A. (2019). On the dynamics of micro-tubes conveying fluid on various foundations. *SN Applied Sciences, 1*(6), 547-553.

Moayedi, H., Aliakbarlou, H., Jebeli, M., Noormohammadi Arani, O., Habibi, M., Safarpour, H., & Foong, L. Thermal buckling responses of a graphene reinforced composite micropanel structure. *International Journal of Applied Mechanics, 12*(01), 2050010.

Moayedi, H., Darabi, R., Ghabussi, A., Habibi, M., & Foong, L. K. (2020). Weld orientation effects on the formability of tailor welded thin steel sheets. *Thin-Walled Structures, 149*, 106669.

Moayedi, H., Habibi, M., Safarpour, H., Safarpour, M., & Foong, L. Buckling and frequency responses of a graphen nanoplatelet reinforced composite microdisk. *International Journal of Applied Mechanics*, 11(10), 1950102 .

Mohammadgholiha, M., Shokrgozar, A., Habibi, M., & Safarpour, H. (2019). Buckling and frequency analysis of the nonlocal strain–stress gradient shell reinforced with graphene nanoplatelets. *Journal of Vibration and Control, 25*(19-20), 2627-2640.

Mohammadi, A., Lashini, H., Habibi, M., & Safarpour, H. (2019a). Influence of viscoelastic foundation on dynamic behaviour of the double walled cylindrical inhomogeneous micro shell using MCST and with the aid of GDQM. *Journal of Solid Mechanics, 11*(2), 440-453.

Mohammadi, K., Barouti, M. M., Safarpour, H., & Ghadiri, M. (2019b). Effect of distributed axial loading on dynamic stability and buckling analysis of a viscoelastic DWCNT conveying viscous fluid flow. *Journal of the Brazilian Society of Mechanical Sciences and Engineering, 41*(2), 1-16.

Mohammadimehr, M., Atifeh, S. J., & Rousta Navi, B. (2018a). Stress and free vibration analysis of piezoelectric hollow circular FG-SWBNNTs reinforced nanocomposite plate based on modified couple stress theory subjected to thermo-mechanical loadings. *Journal of Vibration and Control, 24*(15), 3471-3486.

Mohammadimehr, M., Emdadi, M., Afshari, H., & Rousta Navi, B. (2018b). Bending, buckling and vibration analyses of MSGT microcomposite circular-annular sandwich plate under hydro-thermo-magneto-mechanical loadings using DQM. *International Journal of Smart and Nano Materials, 9*(4), 233-260.

Mohtar, Z. A., Yahaya, A. S., & Ahmad, F. (2015). Rainfall erosivity estimation for Northern and Southern peninsular Malaysia using Fourneir indexes. *Procedia Engineering, 125*, 179-184.

Mongruel, A., Daru, V., Tabakova, S., Stoilova, A., Feuillebois, F., & Radev, S. (2007). *Impact of drops on a solid and dry surface: short time study*. Paper presented at the 18th French Congress of Mechanics, Courbevoie, Paris.

Montazeri, A., & Rafii-Tabar, H. (2011). Multiscale modeling of graphene-and nanotube-based reinforced polymer nanocomposites. *Physics Letters A, 375*(45), 4034-4040.

Mortazavi, B., Benzerara, O., Meyer, H., Bardon, J., & Ahzi, S. (2013). Combined molecular dynamics-finite element multiscale modeling of thermal conduction in graphene epoxy nanocomposites. *Carbon, 60*, 356-365.

Mundo, C., Sommerfeld, M., & Tropea, C. (1995). Droplet-wall collisions: experimental studies of the deformation and breakup process. *International Journal of Multiphase Flow, 21*(2), 151-173.

Muthalif, A. G., & Nordin, N. D. (2015). Optimal piezoelectric beam shape for single and broadband vibration energy harvesting: Modeling, simulation and experimental results. *Mechanical Systems and Signal Processing, 54*, 417-426.

Nadri, S., Xie, L., Jafari, M., Alijabbari, N., Cyberey, M. E., Barker, N. S., Weikle, R. M. (2018). *A 160 GHz frequency Quadrupler based on heterogeneous integration of GaAs Schottky diodes onto silicon using SU-8 for epitaxy transfer*. Paper presented at the 2018 IEEE/MTT-S International Microwave Symposium-IMS, Philadelphia.

Nayfeh, A. H., & Pai, P. F. (2008). *Linear and Nonlinear Structural Mechanics*: John Wiley & Sons.

Perera, K., Sampath, B., Dassanayake, V., & Hapuwatte, B. (2014). Harvesting of kinetic energy of the raindrops. *International Journal of Energy and Power Engineering, 8*(2), 325-330.

Petersson, B. (1995). The Liquid drop impact as a source of sound and vibration. *Building Acoustics, 2*(4), 585-621.

Potts, J. R., Dreyer, D. R., Bielawski, C. W., & Ruoff, R. S. (2011). Graphene-based polymer nanocomposites. *Polymer, 52*(1), 5-25. .

Pourjabari, A., Hajilak, Z. E., Mohammadi, A., Habibi, M., & Safarpour, H. (2019). Effect of porosity on free and forced vibration characteristics of the GPL reinforcement composite nanostructures. *Computers & Mathematics with Applications, 77*(10), 2608-2626.

Qiao, W., Huang, K., Azimi, M., & Han, S. (2019). A novel hybrid prediction model for hourly gas consumption in supply side based on improved machine learning algorithms. *IEEE Access*. *7*, 88218-88230.

Qiao, W., Tian, W., Tian, Y., Yang, Q., Wang, Y., & Zhang, J. (2019). the forecasting of PM 2.5 using a hybrid model based on wavelet transform and an improved deep learning algorithm. *IEEE Access, 7*, 142814-142825.

Qiao, W., & Yang, Z. (2019a). Forecast the electricity price of US using a wavelet transform-based hybrid model. *Energy*, 193, 116704.

Qiao, W., & Yang, Z. (2019b). Modified dolphin swarm algorithm based on chaotic maps for solving high-dimensional function optimization problems. *IEEE Access, 7*, 110472-110486.

Qiao, W., & Yang, Z. (2019c). Solving large-scale function optimization problem by using a new metaheuristic algorithm based on quantum dolphin swarm algorithm. *IEEE Access, 7*, 138972-138989.

Qiao, W., Yang, Z., Kang, Z., & Pan, Z. (2020). Short-term natural gas consumption prediction based on Volterra adaptive filter and improved whale optimization algorithm. *Engineering Applications of Artificial Intelligence, 87*, 103323.

Rafiee, M., Rafiee, J., Yu, Z.-Z., & Koratkar, N. (2009). Buckling resistant graphene nanocomposites. *Applied Physics Letters, 95*(22), 223103.

Rafiee, M. A., Rafiee, J., Srivastava, I., Wang, Z., Song, H., Yu, Z. Z., & Koratkar, N. (2010). Fracture and fatigue in graphene nanocomposites. *Small*, *6*(2), 179-183.

Rafiee, M. A., Rafiee, J., Wang, Z., Song, H., Yu, Z.-Z., & Koratkar, N. (2009). Enhanced mechanical properties of nanocomposites at low graphene content. *ACS Nano, 3*(12), 3884-3890.

Rahimi, A., Alibeigloo, A., & Safarpour, M. (2020). Three-dimensional static and free vibration analysis of graphene platelet–reinforced porous composite cylindrical shell. *Journal of Vibration and Control*, 26(19-20), 1627-1645.

Range, K., & Feuillebois, F. (1998). Influence of surface roughness on liquid drop impact. *Journal of Colloid and Interface Science, 203*(1), 16-30.

Rashvand, K., & Madinei, H. (2014). Effect of length-scale parameter on pull-in voltage and natural frequency of a micro-plate. *International Journal of Engineering, 27*(3), 375-384.

Rashvand, K., Rezazadeh, G., Mobki, H., & Ghayesh, M. H. (2013). On the size-dependent behavior of a capacitive circular micro-plate considering the variable length-scale parameter. *International Journal of Mechanical Sciences, 77*, 333-342.

Reddy, J. N. (2004). *Mechanics of Laminated Composite Plates and Shells: Theory and Analysis*: CRC press.

Rein, M. (2002). Interactions between drops and hot surfaces. In *Drop-surface Interactions* (pp. 185-217): Springer.

Richards, C. D., Anderson, M. J., Bahr, D. F., & Richards, R. F. (2004). Efficiency of energy conversion for devices containing a piezoelectric component. *Journal of Micromechanics and Microengineering, 14*(5), 717-721.

Rizzo, R., Piegari, L., & Tricoli, P. (2012). A comparison between line-start synchronous machines and induction machines in distributed generation. *Prz. Elektrotech, 88*, 187-189.

Roscoe, N. M., & Judd, M. D. (2013). Harvesting energy from magnetic fields to power condition monitoring sensors. *IEEE Sensors Journal, 13*(6), 2263-2270.

Roundy, S., Leland, E. S., Baker, J., Carleton, E., Reilly, E., Lai, E., Sundararajan, V. (2005). Improving power output for vibration-based energy scavengers. *IEEE Pervasive computing, 4*(1), 28-36.

Roundy, S., & Wright, P. K. (2004). A piezoelectric vibration based generator for wireless electronics. *Smart Materials and structures, 13*(5), 1131-1142.

Roundy, S., Wright, P. K., & Rabaey, J. (2003). A study of low level vibrations as a power source for wireless sensor nodes. *Computer communications, 26*(11), 1131-1144.

Safarpour, H., Barooti, M., & Ghadiri, M. (2019a). Influence of rotation on vibration behavior of a functionally graded moderately thick cylindrical nanoshell considering initial hoop tension. *Journal of Solid Mechanics, 11*(2), 254-271.

SafarPour, H., & Ghadiri, M. (2017). Critical rotational speed, critical velocity of fluid flow and free vibration analysis of a spinning SWCNT conveying viscous fluid. *Microfluidics and Nanofluidics, 21*(2), 1-23.

SafarPour, H., Ghanbari, B., & Ghadiri, M. (2019b). Buckling and free vibration analysis of high speed rotating carbon nanotube reinforced cylindrical piezoelectric shell. *Applied Mathematical Modelling, 65*, 428-442.

Safarpour, H., Ghanizadeh, S. A., & Habibi, M. (2018a). Wave propagation characteristics of a cylindrical laminated composite nanoshell in thermal environment based on the nonlocal strain gradient theory. *The European Physical Journal Plus, 133*(12), 1-17.

Safarpour, H., Hajilak, Z. E., & Habibi, M. (2019c). A size-dependent exact theory for thermal buckling, free and forced vibration analysis of temperature dependent FG multilayer GPLRC composite nanostructures restring on elastic foundation. *International Journal of Mechanics and Materials in Design, 15*(3), 569-583.

SafarPour, H., Hosseini, M., & Ghadiri, M. (2017a). Influence of three-parameter viscoelastic medium on vibration behavior of a cylindrical nonhomogeneous microshell in thermal environment: An exact solution. *Journal of Thermal Stresses, 40*(11), 1353-1367.

Safarpour, H., Mohammadi, K., & Ghadiri, M. (2017b). Temperature-dependent vibration analysis of a FG viscoelastic cylindrical microshell under various thermal distribution via modified length scale parameter: a numerical solution. *Journal of the Mechanical Behavior of Materials, 26*(1-2), 9-24.

Safarpour, H., Mohammadi, K., Ghadiri, M., & Barooti, M. M. (2018b). Effect of porosity on flexural vibration of CNT-reinforced cylindrical shells in thermal environment using GDQM. *International Journal of Structural Stability and Dynamics, 18*(10), 1850123.

SafarPour, H., Mohammadi, K., Ghadiri, M., & Rajabpour, A. (2017c). Influence of various temperature distributions on critical speed and vibrational characteristics of rotating cylindrical microshells with modified lengthscale parameter. *The European Physical Journal Plus, 132*(6), 1-19.

Safarpour, H., Pourghader, J., & Habibi, M. (2019d). Influence of spring-mass systems on frequency behavior and critical voltage of a high-speed rotating cantilever cylindrical three-dimensional shell coupled with piezoelectric actuator. *Journal of Vibration and Control, 25*(9), 1543-1557.

Safarpour, M., Ebrahimi, F., Habibi, M., & Safarpour, H. (2020a). On the nonlinear dynamics of a multi-scale hybrid nanocomposite disk. *Engineering with Computers*, 36(1), 1-20.

Safarpour, M., Ghabussi, A., Ebrahimi, F., Habibi, M., & Safarpour, H. (2020b). Frequency characteristics of FG-GPLRC viscoelastic thick annular plate with the aid of GDQM. *Thin-Walled Structures, 150*, 106683.

Safarpour, M., Rahimi, A., & Alibeigloo, A. (2019e). Static and free vibration analysis of graphene platelets reinforced composite truncated conical shell, cylindrical shell, and annular plate using theory of elasticity and DQM. *Mechanics Based Design of Structures and Machines*, 1-29.

Safarpour, M., Rahimi, A., Alibeigloo, A., Bisheh, H., & Forooghi, A. (2019f). Parametric study of three-dimensional bending and frequency of FG-GPLRC porous circular and annular plates on different boundary conditions. *Mechanics Based Design of Structures and Machines*, 1-31.

Sajadi, B., Alijani, F., Goosen, H., & van Keulen, F. (2018). Effect of pressure on nonlinear dynamics and instability of electrically actuated circular micro-plates. *Nonlinear Dynamics, 91*(4), 2157-2170.

Santawitee, O., Grall, S., Chayasombat, B., Thanachayanont, C., Hochart, X., Bernard, J., & Debéda, H. (2019). Processing of printed piezoelectric microdisks: effect of PZT particle sizes and electrodes on electromechanical properties. *Journal of Electroceramics*, *44*(1), 41-51.

Sari, I., Balkan, T., & Kulah, H. (2007). *A wideband electromagnetic micro power generator for wireless microsystems.* Paper presented at the 2007 International Solid-State Sensors, Actuators and Microsystems Conference, Lyon.

Sari, I., Balkan, T., & Kulah, H. (2008). An electromagnetic micro power generator for wideband environmental vibrations. *Sensors and Actuators A: Physical*, *145-146*, 405-413.

Sarparast, H., & Ebrahimi-Mamaghani, A. (2019). Vibrations of laminated deep curved beams under moving loads. *Composite Structures*, *226*, 111262.

Sebald, G., Kuwano, H., Guyomar, D., & Ducharne, B. (2011). Experimental Duffing oscillator for broadband piezoelectric energy harvesting. *Smart Materials and Structures, 20*(10), 102001.

Shahgholian-Ghahfarokhi, D., Safarpour, M., & Rahimi, A. (2019). Torsional buckling analyses of functionally graded porous nanocomposite cylindrical shells reinforced with graphene platelets (GPLs). *Mechanics Based Design of Structures and Machines*, 47(5), 1-22.

Shahgholian, D., Safarpour, M., Rahimi, A., & Alibeigloo, A. (2020). Buckling analyses of functionally graded graphene-reinforced porous cylindrical shell using the Rayleigh–Ritz method. *Acta Mechanica*, 231(2), 1-16.

Shamloofard, M., & Assempour, A. (2019). Development of an inverse isogeometric methodology and its application in sheet metal forming process. *Applied Mathematical Modelling*, *73*, 266-284.

Shamloofard, M., & Movahhedy, M. R. (2015). Development of thermo-elastic tapered and spherical superelements. *Applied Mathematics and Computation*, *265*, 380-399.

Shamsaddini Lori, E., & Leman, Z. (2016). Renewable energy sources and analyzing the wind turbine performance; A Review. *Ciência e Natura*, *38*(2), 780-802.

Shetty, S., Kishore, V., Pinto, S. R., & Bommegowda, K. B. (2020). Energy Harvesting Using Raindrops Through Solar Panels: A Review. In *Advances in Communication, Signal Processing, VLSI, and Embedded Systems*, 614, 289-298.

Shojaeefard, M., Googarchin, H. S., Mahinzare, M., & Ghadiri, M. (2018). Free vibration and critical angular velocity of a rotating variable thickness two-directional FG circular microplate. *Microsystem Technologies*, *24*(3), 1525-1543.

Shojaeefard, M., Mahinzare, M., Safarpour, H., Googarchin, H. S., & Ghadiri, M. (2018). Free vibration of an ultra-fast-rotating-induced cylindrical nano-shell resting on a Winkler foundation under thermo-electro-magneto-elastic condition. *Applied Mathematical Modelling*, *61*, 255-279.

Shokrgozar, A., Ghabussi, A., Ebrahimi, F., Habibi, M., & Safarpour, H. (2020a). Viscoelastic dynamics and static responses of a graphene nanoplatelets-reinforced composite cylindrical microshell. *Mechanics Based Design of Structures and Machines*, 48(1), 1-28.

Shokrgozar, A., Safarpour, H., & Habibi, M. (2020b). Influence of system parameters on buckling and frequency analysis of a spinning cantilever cylindrical 3D shell coupled with piezoelectric actuator. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, *234*(2), 512-529.

Shu, C. (2012). *Differential Quadrature and Its Application in Engineering*: Springer Science & Business Media.

Shu, C., & Richards, B. E. (1992). Application of generalized differential quadrature to solve two- dimensional incompressible Navier- Stokes equations. International Journal for Numerical Methods in Fluids, 15(7), 791-798.

Šikalo, Š., Tropea, C., & Ganić, E. (2005). Impact of droplets onto inclined surfaces. *Journal of Colloid and Interface Science*, *286*(2), 661-669.

Sivakumar, D., Katagiri, K., Sato, T., & Nishiyama, H. (2005). Spreading behavior of an impacting drop on a structured rough surface. *Physics of Fluids*, *17*(10), 100608.

Sodano, H. A. (2003). *Macro-fiber composites for sensing, actuation and power generation.* PhD Thesis, Virginia Tech, USA.

Song, M., Kitipornchai, S., & Yang, J. (2017). Free and forced vibrations of functionally graded polymer composite plates reinforced with graphene nanoplatelets. *Composite Structures*, *159*, 579-588.

Spataro, C., Viola, F., Romano, P., & Miceli, R. (2014). *Performances of rainfall energy harvester*. Paper presented at the Proceedings of the 20th IMEKO TC4 International Symposium and 18th International Workshop on ADC Modelling and Testing Research on Electric and Electronic Measurement for the Economic Upturn, Benevento, Italy.

Sun, J., & Zhao, J. (2018). Multi-layer graphene reinforced nano-laminated WC-Co composites. *Materials Science and Engineering: A, 723*, 1-7.

Tanaka, T., Mizutani, F., & Yasukawa, T. (2016). Dielectrophoretic tweezers for pickup and relocation of individual cells using microdisk electrodes with a microcavity. *Electrochemistry, 84*(5), 361-363.

Tang, L., & Yang, Y. (2012). A nonlinear piezoelectric energy harvester with magnetic oscillator. *Applied Physics Letters, 101*(9), 094102.

Tashiro, K., Wakiwaka, H., Inoue, S.-i., & Uchiyama, Y. (2011). Energy harvesting of magnetic power-line noise. *IEEE Transactions on Magnetics, 47*(10), 4441-4444.

Umeda, M., Nakamura, K., Takahashi, S., & Ueha, S. (2001). Waveforms of the vibration velocity and the current of a piezoelectric transducer in the transient state. *Japanese Journal of Applied Physics, 40*(Part 1, No. 9B), 5735-5739.

Valentín, D., Roehr, C., Presas, A., Heiss, C., Egusquiza, E., & Bosbach, W. A. (2019). Experimental-Numerical Design and Evaluation of a Vibration Bioreactor Using Piezoelectric Patches. *Sensors*, *19*(2), 436-455.

Vafamehr, A., Khodayar, M. E., & Abdelghany, K. (2017). Oligopolistic competition among cloud providers in electricity and data networks. *IEEE Transactions on Smart Grid, 10*(2), 1801-1812.

Van Boxel, J. (1998). Numerical model for the fall speed of rain drops in a rain fall simulator. *I.C.E Special Report, 1998*(1), 77-85.

Vatansever, D., Hadimani, R., Shah, T., & Siores, E. (2011). An investigation of energy harvesting from renewable sources with PVDF and PZT. *Smart Materials and Structures, 20*(5), 055019.

Viola, F. (2018). Comparison among different rainfall energy harvesting structures. *Applied Sciences, 8*(6), 1-15.

Viola, F., Romano, P., Miceli, R., & Acciari, G. (2013a). *Harvesting rainfall energy by means of piezoelectric transducer*. Paper presented at the 2013 International Conference on Clean Electrical Power (ICCEP), Alghero, Italy.

Viola, F., Romano, P., Miceli, R., & Acciari, G. (2013b). *On the harvest of rainfall energy by means of piezoelectric transducer*. Paper presented at the 2013 International Conference on Renewable Energy Research and Applications (ICRERA), Madrid, Spain.

Viola, F., Romano, P., Miceli, R., Acciari, G., & Spataro, C. (2014). *Piezoelectric model of rainfall energy harvester.* Paper presented at the 2014 Ninth International Conference on Ecological Vehicles and Renewable Energies (EVER), Monaco.

Von Wagner, U., & Hagedorn, P. (2002). Piezo–beam systems subjected to weak electric field: experiments and modelling of non-linearities. *Journal of Sound and Vibration, 256*(5), 861-872.

Vreeland, N. (1977). *Area Handbook for Malaysia* (Vol. 45): US Government Printing Office.

Walter, V., Delobelle, P., Le Moal, P., Joseph, E., & Collet, M. (2002). A piezo-mechanical characterization of PZT thick films screen-printed on alumina substrate. *Sensors and Actuators A: Physical, 96*(2-3), 157-166.

Wang, J., Zhou, L., Zhang, C., & Wang, Z. L. (2019). Small-scale energy harvesting from environment by triboelectric nanogenerators. In Manyala, R. (Ed), *Small-Scale Energy Harvesting* (pp.63-94): IntechOpen Publishers.

Wang, K., Wang, B., & Zhang, C. (2017). Surface energy and thermal stress effect on nonlinear vibration of electrostatically actuated circular micro-/nanoplates based on modified couple stress theory. *Acta Mechanica, 228*(1), 129-140.

Wang, Q. (2002). On buckling of column structures with a pair of piezoelectric layers. *Engineering Structures, 24*(2), 199-205.

Wang, S., Lin, L., & Wang, Z. L. (2015). Triboelectric nanogenerators as self-powered active sensors. *Nano Energy, 11*, 436-462.

Wang, Y., Yu, J., Dai, W., Song, Y., Wang, D., Zeng, L., & Jiang, N. (2015). Enhanced thermal and electrical properties of epoxy composites reinforced with graphene nanoplatelets. *Polymer Composites, 36*(3), 556-565.

Wang, Y., Zeng, R., & Safarpour, M. (2020). Vibration analysis of FG-GPLRC annular plate in a thermal environment. *Mechanics Based Design of Structures and Machines*, 48(1), 1-19.

Wang, Z.-W., Han, Q.-F., Nash, D. H., & Liu, P.-Q. (2017). Investigation on inconsistency of theoretical solution of thermal buckling critical temperature rise for cylindrical shell. *Thin-Walled Structures, 119*, 438-446.

Wang, Z. L. (2017). On Maxwell's displacement current for energy and sensors: the origin of nanogenerators. *Materials Today, 20*(2), 74-82.

Weaver Jr, W., Timoshenko, S. P., & Young, D. H. (1990). *Vibration Problems in Engineering*: John Wiley & Sons.

Wong, C.-H., Dahari, Z., Manaf, A. A., & Miskam, M. A. (2015). Harvesting raindrop energy with piezoelectrics: A review. *Journal of Electronic Materials, 44*(1), 13-21.

Wong, V. K., Ho, J. H., & Yap, E. H. (2014). Experimental study of a piezoelectric rain energy harvester. *Advanced Materials Research*, 1043, 263-267.

Wu, H., Kitipornchai, S., & Yang, J. (2017). Thermal buckling and postbuckling of functionally graded graphene nanocomposite plates. *Materials & Design, 132*, 430-441.

Wu, L., Chure, M.-C., Wu, K.-K., & Tung, C.-C. (2014). Voltage generated characteristics of piezoelectric ceramics cymbal transducer. *Journal of Materials Science and Chemical Engineering, 2*(10), 32-37.

Yang, B., & Yun, K.-S. (2011). *Efficient energy harvesting from human motion using wearable piezoelectric shell structures.* Paper presented at the 2011 16th International Solid-State Sensors, Actuators and Microsystems Conference, Beijing.

Yang, K., Li, Z., Jing, Y., Chen, D., & Ye, T. (2009). *Research on the resonant frequency formula of V-shaped cantilevers.* Paper presented at the 2009 4th IEEE International Conference on Nano/Micro Engineered and Molecular Systems, Shenzhen, China.

Yang, Y., Wang, Z., & Wang, Y. (2018). Thermoelastic coupling vibration and stability analysis of rotating circular plate in friction clutch. *Journal of Low Frequency Noise, Vibration and Active Control*, *38*(2), 558-573.

Yang, Y., Wang, Z., & Wang, Y. (2019). Thermoelastic coupling vibration and stability analysis of rotating circular plate in friction clutch. *Journal of Low Frequency Noise, Vibration and Active Control*, *38*(2), 558-573.

Youcef, D. O., Kaci, A., Benzair, A., Bousahla, A. A., & Tounsi, A. (2018). Dynamic analysis of nanoscale beams including surface stress effects. *Smart Structures and Systems, 21*(1), 65-74.

Younsi, A., Tounsi, A., Zaoui, F. Z., Bousahla, A. A., & Mahmoud, S. (2018). Novel quasi-3D and 2D shear deformation theories for bending and free vibration analysis of FGM plates. *Geomechanics and Engineering*, *14*(6), 519-532.

Zaoui, F. Z., Ouinas, D., & Tounsi, A. (2019). New 2D and quasi-3D shear deformation theories for free vibration of functionally graded plates on elastic foundations. *Composites Part B: Engineering, 159*, 231-247.

Zarga, D., Tounsi, A., Bousahla, A. A., Bourada, F., & Mahmoud, S. (2019). Thermomechanical bending study for functionally graded sandwich plates using a simple quasi-3D shear deformation theory. *Steel and Composite Structures, 32*(3), 389-410.

Zhang, H., Zhang, X.-S., Cheng, X., Liu, Y., Han, M., Xue, X., Zhang, H. (2015). A flexible and implantable piezoelectric generator harvesting energy from the pulsation of ascending aorta: in vitro and in vivo studies. *Nano Energy, 12*, 296-304.

Zhang, Z., Yao, C., Yu, Y., Hong, Z., Zhi, M., & Wang, X. (2016). Mesoporous piezoelectric polymer composite films with tunable mechanical modulus for harvesting energy from liquid pressure fluctuation. *Advanced Functional Materials, 26*(37), 6760-6765.

Zhong, R., Wang, Q., Tang, J., Shuai, C., & Qin, B. (2018). Vibration analysis of functionally graded carbon nanotube reinforced composites (FG-CNTRC) circular, annular and sector plates. *Composite Structures*, *194*, 49-67.

Zhou, S., Zhang, R., Zhou, S., & Li, A. (2019). Free vibration analysis of bilayered circular micro-plate including surface effects. *Applied Mathematical Modelling*, *70*, 54-66.

Zhu, D., Beeby, S. P., Tudor, M. J., White, N. M., & Harris, N. R. (2012). Novel Miniature Airflow Energy Harvester for Wireless Sensing Applications in Buildings. *IEEE Sensors Journal*, *13*(2), 691-700.

APPENDIX

The governing equations of the GPLRC microdisk are given as follows:

$\delta u^{i}{}_{0}:$

$$
(1-l^{2}\nabla^{2})\left[\begin{array}{l}
\dfrac{\partial}{\partial R}\left(\begin{array}{l}
\left[A^{i}{}_{11}\dfrac{\partial u^{i}{}_{0}}{\partial R^{i}}+B^{i}{}_{11}\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}-D^{i}{}_{11}c_{1}\left(\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}+\dfrac{\partial^{2} w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\
\left[A^{i}{}_{12}\dfrac{u^{i}{}_{0}}{R^{i}}+B^{i}{}_{12}\dfrac{u_{1}}{R}-D^{i}{}_{12}c_{1}\left(\dfrac{u^{i}{}_{1}}{R^{i}}+\dfrac{\partial w^{i}{}_{0}}{R^{i}\partial R^{i}}\right)\right]-X_{31}\phi
\end{array}\right)\\
-\dfrac{1}{R}\left(\begin{array}{l}
\left[A^{i}{}_{12}\dfrac{\partial u^{i}{}_{0}}{\partial R^{i}}+B^{i}{}_{12}\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}-D^{i}{}_{12}c_{1}\left(\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}+\dfrac{\partial^{2} w^{i}{}_{0}}{\partial R^{i2}}\right)\right]\\
+Q^{i}{}_{22}\left[A^{i}{}_{22}\dfrac{u^{i}{}_{0}}{R^{i}}+B^{i}{}_{22}\dfrac{u^{i}{}_{1}}{R^{i}}-D^{i}{}_{22}c_{1}\left(\dfrac{u^{i}{}_{1}}{R^{i}}+\dfrac{\partial w^{i}{}_{0}}{R^{i}\partial R^{i}}\right)\right]
\end{array}\right)
\end{array}\right] \qquad \text{(P-1)}
$$

$$
=(1-\mu^{2}\nabla^{2})\left[I^{i}{}_{0}\frac{\partial^{2}u^{i}{}_{0}}{\partial t^{2}}+I^{i}{}_{1}\frac{\partial^{2}u^{i}{}_{1}}{\partial t^{2}}-I^{i}{}_{3}c_{1}\left(\frac{\partial^{2}u^{i}{}_{1}}{\partial t^{2}}+\frac{\partial^{3}w^{i}{}_{0}}{\partial t^{2}\partial R^{i}}\right)\right]
$$

$;i=c,\,p$

$\delta w^{i}{}_{0}:$

$$(1-l^2\nabla^2)\left[\begin{array}{l} c_1\dfrac{\partial^2}{\partial R^{i2}}\left(\begin{array}{l}\left[D^{i}{}_{11}\dfrac{\partial u^{i}{}_{0}}{\partial R^{i}}+E^{i}{}_{11}\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}-G^{i}{}_{11}c_1\left(\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}+\dfrac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\ \left[D^{i}{}_{12}\dfrac{u^{i}{}_{0}}{R^{i}}+E^{i}{}_{12}\dfrac{u^{i}{}_{1}}{R^{i}}-G^{i}{}_{12}c_1\left(\dfrac{u^{i}{}_{1}}{R^{i}}+\dfrac{\partial w^{i}{}_{0}}{R^{i}\partial R^{i}}\right)\right]-X_{33}\phi\end{array}\right)\\ -c_1\dfrac{\partial}{R^{i}\partial R^{i}}\left(\begin{array}{l}\left[D^{i}{}_{12}\dfrac{\partial u^{i}{}_{0}}{\partial R^{i}}+E^{i}{}_{12}\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}-G^{i}{}_{12}c_1\left(\dfrac{\partial u^{i}{}_{1}}{\partial R^{i}}+\dfrac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\ Q^{i}{}_{22}\left[D^{i}{}_{22}\dfrac{u^{i}{}_{0}}{R^{i}}+E^{i}{}_{22}\dfrac{u^{i}{}_{1}}{R^{i}}-G^{i}{}_{22}c_1\left(\dfrac{u^{i}{}_{1}}{R^{i}}+\dfrac{\partial w^{i}{}_{0}}{R^{i}\partial R^{i}}\right)\right]\end{array}\right)\\ +\dfrac{\partial}{\partial R^{i}}\left((A^{i}{}_{55}-3C^{i}{}_{55}c_1)\left(u^{i}{}_{1}+\dfrac{\partial w^{i}{}_{0}}{\partial R^{i}}\right)+X_{11}\partial\phi/\partial R\right)\\ -3c_1\dfrac{\partial}{\partial R^{i}}\left((C^{i}{}_{55}-3E^{i}{}_{55}c_1)\left(u^{i}{}_{1}+\dfrac{\partial w^{i}{}_{0}}{\partial R^{i}}\right)+X_{12}\partial\phi/\partial R^{i}\right)-N_1^{p}w^{i}{}_{0,x^2}\end{array}\right] \quad \text{(P-2)}$$

$$=(1-\mu^2\nabla^2)\left[c_1 I^{i}{}_{3}\frac{\partial^3 u^{i}{}_{0}}{\partial R^{i}\partial t^2}+c_1 I^{i}{}_{4}\frac{\partial^3 u^{i}{}_{1}}{\partial R^{i}\partial t^2}-I^{i}{}_{6}c_1^{2}\left(\frac{\partial^3 u^{i}{}_{1}}{\partial R^{i}\partial t^2}+\frac{\partial^4 w^{i}_{0}}{\partial t^2\partial R^2}\right)+\left(I^{i}{}_{0}\frac{\partial^2 w^{i}{}_{0}}{\partial t^2}\right)\right]$$

$;i=c,p$

$\delta u^{i}{}_{1}:$

$$
\begin{aligned}
&(1-l^2\nabla^2)\left[\begin{aligned}
&\frac{\partial}{\partial R^i}\left(\begin{aligned}&\left[B^{i}{}_{11}\frac{\partial u^{i}{}_{0}}{\partial R^i}+C^{i}{}_{11}\frac{\partial u^{i}{}_{1}}{\partial R^i}-E^{i}{}_{11}c_1\left(\frac{\partial u^{i}{}_{1}}{\partial R^i}+\frac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\
&\left[B^{i}{}_{12}\frac{u^{i}{}_{0}}{R^i}+C^{i}{}_{12}\frac{u^{i}{}_{1}}{R^i}-E^{i}{}_{12}c_1\left(\frac{u^{i}{}_{1}}{R^i}+\frac{\partial w^{i}{}_{0}}{R^i\partial R^i}\right)\right]-X_{32}\phi\end{aligned}\right)\\
&-\frac{c_1\partial}{\partial R^i}\left(\begin{aligned}&\left[D^{i}{}_{11}\frac{\partial u^{i}{}_{0}}{\partial R^i}+E^{i}{}_{11}\frac{\partial u^{i}{}_{1}}{\partial R^i}-G^{i}{}_{11}c_1\left(\frac{\partial u^{i}{}_{1}}{\partial R^i}+\frac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\
&\left[D^{i}{}_{12}\frac{u^{i}{}_{0}}{R^i}+E^{i}{}_{12}\frac{u^{i}{}_{1}}{R^i}-G^{i}{}_{12}c_1\left(\frac{u^{i}{}_{1}}{R^i}+\frac{\partial w^{i}{}_{0}}{R^i\partial R^i}\right)\right]-X_{33}\phi\end{aligned}\right)\\
&-\frac{1}{R^i}\left(\begin{aligned}&\left[B^{i}{}_{12}\frac{\partial u^{i}{}_{0}}{\partial R^i}+C^{i}{}_{12}\frac{\partial u^{i}{}_{1}}{\partial R^i}-E^{i}{}_{12}c_1\left(\frac{\partial u^{i}{}_{1}}{\partial R^i}+\frac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]+\\
&Q^{i}{}_{22}\left[B^{i}{}_{22}\frac{u^{i}{}_{0}}{R^i}+C^{i}{}_{22}\frac{u^{i}{}_{1}}{R^i}-E^{i}{}_{22}c_1\left(\frac{u^{i}{}_{1}}{R^i}+\frac{\partial w^{i}{}_{0}}{R^i\partial R^i}\right)\right]\end{aligned}\right)\\
&+\frac{c_1}{R^i}\left(\begin{aligned}&\left[D^{i}{}_{12}\frac{\partial u^{i}{}_{0}}{\partial R^i}+E^{i}{}_{12}\frac{\partial u^{i}{}_{1}}{\partial R^i}-G^{i}{}_{12}c_1\left(\frac{\partial u^{i}{}_{1}}{\partial R^i}+\frac{\partial^2 w^{i}{}_{0}}{\partial R^{i2}}\right)\right]\\
&+Q^{i}{}_{22}\left[D^{i}{}_{22}\frac{u^{i}{}_{0}}{R^i}+E^{i}{}_{22}\frac{u^{i}{}_{1}}{R^i}-G^{i}{}_{22}c_1\left(\frac{u^{i}{}_{1}}{R^i}+\frac{\partial w^{i}{}_{0}}{R^i\partial R^i}\right)\right]\end{aligned}\right)\\
&-\left[(A^{i}{}_{55}-3C^{i}{}_{55}c_1)\left(u^{i}{}_{1}+\frac{\partial w^{i}{}_{0}}{\partial R^i}\right)+X_{11}\partial\phi/\partial R^i\right]\\
&+3c_1\left(S^{i}{}_{Rz}=(C^{i}{}_{55}-3E^{i}{}_{55}c_1)\left(u^{i}{}_{1}+\frac{\partial w^{i}{}_{0}}{\partial R^i}\right)+X_{12}\partial\phi/\partial R^i\right)
\end{aligned}\right] \qquad \text{(P-3)}\\
&=(1-\mu^2\nabla^2)\left[\begin{aligned}&I^{i}{}_{1}\frac{\partial^2 u^{i}{}_{0}}{\partial t^2}+I^{i}{}_{2}\frac{\partial^2 u^{i}{}_{1}}{\partial t^2}-I^{i}{}_{4}c_1\left(\frac{\partial^2 u^{i}{}_{1}}{\partial t^2}+\frac{\partial^3 w_0{}^{i}}{\partial t^2\partial R^i}\right)-c_1I^{i}{}_{3}\frac{\partial^2 u^{i}{}_{0}}{\partial t^2}\\
&-c_1I^{i}{}_{4}\frac{\partial^2 u^{i}{}_{1}}{\partial t^2}+I^{i}{}_{6}c_1{}^2\left(\frac{\partial^2 u^{i}{}_{1}}{\partial t^2}+\frac{\partial^3 w^{i}_{0}}{\partial t^2\partial R^i}\right)\end{aligned}\right]\\
&;i=c,p
\end{aligned}
$$

$\delta\phi;$

$$
(1-l^2\nabla^2)\left(\begin{aligned}&+X_{31}\frac{\partial u^{p}{}_{0}}{\partial R^p}+(X_{11}-3X_{12})\frac{\partial^2 w^{p}{}_{0}}{\partial R^{p2}}-X_{33}\frac{\partial^2 w^{p}{}_{0}}{\partial R^{p2}}\\
&-(-X_{11}+3X_{12})\frac{\partial u^{p}{}_{1}}{\partial R^p}+X_{32}\frac{\partial u^{p}{}_{1}}{\partial R^p}-X_{33}\frac{\partial u^{p}{}_{1}}{\partial R^p}\\
&-X_{41}\frac{\partial^2\phi}{\partial R^{p2}}+X_{42}\phi\end{aligned}\right)=0 \qquad \text{(P-4)}
$$

The GDQ form of the governing equations of the GPLRC microdisk are given as below:

$\delta u^i{}_0:$

$$
\left(1-l^2\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{1}{R^{\,i}}\end{array}\right)\right)
\left[\begin{array}{l}
\left(\begin{array}{l}
\left[\begin{array}{l} A^i{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^i{}_0+B^i{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^i{}_1\\ -D^i{}_{11}c_1\left(\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^i{}_1+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}w^i{}_0\right)\end{array}\right]+\\
\left[\begin{array}{l} A^i{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_0}{R_n{}^i}+B^i{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_1}{R_n{}^i}\\ -D^i{}_{12}c_1\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_1}{R^{\,i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\frac{w^i{}_0}{R_n{}^i}\right)\end{array}\right]-X_{31}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\phi_n
\end{array}\right)\\
-\frac{1}{R}\left(\begin{array}{l}
\left[\begin{array}{l} A^i{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_0}{R_n{}^i}+B^i{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_1}{R_n{}^i}-\\ D^i{}_{12}c_1\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{u^i{}_1}{R_n{}^i}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\frac{w^i{}_0}{R_n{}^i}\right)\end{array}\right]\\
+Q^i{}_{22}\left[\begin{array}{l} A^i{}_{22}\sum_{v=1}^{N_n}\frac{u^i{}_0}{R^2{}_n{}^i}+B^i{}_{22}\sum_{v=1}^{N_n}\frac{u^i{}_1}{R^2{}_n{}^i}-\\ D^i{}_{22}c_1\left(\sum_{v=1}^{N_n}\frac{u^i{}_1}{R^2{}_n{}^i}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{w^i{}_0}{R^2{}_n{}^i}\right)\end{array}\right]
\end{array}\right)
\end{array}\right] \tag{P-5}
$$

$$
=\left(1-\mu^2\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\frac{1}{R^{\,i}}\end{array}\right)\right)\left[I^i{}_0\sum_{v=1}^{N_n}\omega^2u^i{}_0I_v+I^i{}_1\sum_{v=1}^{N_n}\omega^2u^i{}_1I_v-I^i{}_3c_1\left(\sum_{v=1}^{N_n}\omega^2u^i{}_1I_v+\sum_{v=1}^{N_n}C^{(1)}{}_{n,v}\omega^2w^i{}_0I_v\right)\right]
$$

$;i=c,p$

$\delta w^{i}{}_{0}:$

$$
\begin{aligned}
&(1-l^{2}\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{1}{R^{i}}\end{array}\right))
\left[\begin{array}{l}
c_1\left(\begin{array}{l}
\left[\begin{array}{l}D^{i}{}_{11}\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}u^{i}{}_{0}+E^{i}{}_{11}\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}u^{i}{}_{1}\\ -G^{i}{}_{11}c_1\left(\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}u^{i}{}_{1}+\sum_{v=1}^{N_n} C^{(4)}{}_{n,v}w^{i}{}_{0}\right)\end{array}\right]+\\
\left[\begin{array}{l}D^{i}{}_{12}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+E^{i}{}_{12}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}\\ -G^{i}{}_{12}c_1\left(\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R_n{}^{i}}\right)\end{array}\right]-X_{33}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\phi
\end{array}\right)\\
-c_1\left(\begin{array}{l}
\left[\begin{array}{l}D^{i}{}_{12}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+E^{i}{}_{12}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}\\ -G^{i}{}_{12}c_1\left(\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R_n{}^{i}}\right)\end{array}\right]+\\
Q^{i}{}_{22}\left[\begin{array}{l}D^{i}{}_{22}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}+E^{i}{}_{22}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}\\ -G^{i}{}_{22}c_1\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}\right)\end{array}\right]
\end{array}\right)\\
+\left((A^{i}{}_{55}-3C^{i}{}_{55}c_1)\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}u^{i}{}_{1}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}w^{i}{}_{0}\right)+X_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\phi\right)\\
-3c_1\left(\begin{array}{l}(C^{i}{}_{55}-3E^{i}{}_{55}c_1)\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}u^{i}{}_{1}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}w^{i}{}_{0}\right)\\ +X_{12}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\phi\end{array}\right)-N_1^{p}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}w^{i}{}_{0}
\end{array}\right] \qquad \text{(P-6)}\\
&=(1-\mu^{2}\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{1}{R^{i}}\end{array}\right))
\left[\begin{array}{l}c_1I^{i}{}_{3}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\omega^{2}u^{i}{}_{0}I_v+c_1I^{i}{}_{4}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\omega^{2}u^{i}{}_{1}I_v\\ -I^{i}{}_{6}c_1{}^{2}\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\omega^{2}u^{i}{}_{1}I_v+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\omega^{2}w^{i}{}_{0}I_v\right)+\left(I^{i}{}_{0}\sum_{v=1}^{N_n}\omega^{2}w^{i}{}_{0}I_v\right)\end{array}\right]
\end{aligned}
$$

$;i=c,p$

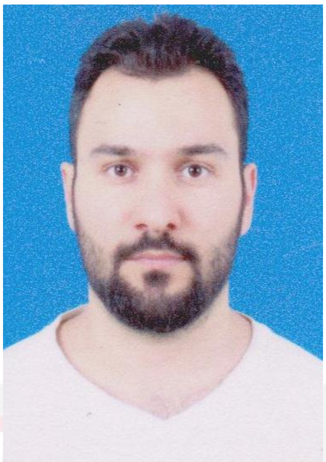
$\delta u^{i}_{1}:$

$$
\begin{aligned}
&\left(1-l^{2}\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{1}{R^{i}}\end{array}\right)\right)
\left[\begin{array}{l}
\left(\begin{array}{l}
\left[B^{i}{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{0}+C^{i}{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{1}-E^{i}{}_{11}c_{1}\left(\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{1}+\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}w^{i}{}_{0}\right)\right]+\\
\left[\begin{array}{l}B^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+C^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}-\\
E^{i}{}_{12}c_{1}\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R_n{}^{i}}\right)\end{array}\right]-X_{32}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\phi
\end{array}\right)\\
-c_{1}\left(\begin{array}{l}
\left[D^{i}{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{0}+E^{i}{}_{11}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{1}-G^{i}{}_{11}c_{1}\left(\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}u^{i}{}_{1}+\sum_{v=1}^{N_n} C^{(3)}{}_{n,v}w^{i}{}_{0}\right)\right]+\\
\left[\begin{array}{l}D^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+E^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}-\\
G^{i}{}_{12}c_{1}\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R_n{}^{i}}\right)\end{array}\right]-X_{33}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\phi
\end{array}\right)\\
-\left(\begin{array}{l}
\left[\begin{array}{l}B^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+C^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}\\
-E^{i}{}_{12}c_{1}\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R_n{}^{i}}\right)\end{array}\right]+\\
Q^{i}{}_{22}\left[B^{i}{}_{22}\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}+C^{i}{}_{22}\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}-E^{i}{}_{22}c_{1}\left(\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}\right)\right]
\end{array}\right)\\
+c_{1}\left(\begin{array}{l}
\left[\begin{array}{l}D^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{0}}{R_n{}^{i}}+E^{i}{}_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}\\
-G^{i}{}_{12}c_{1}\left(\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{u^{i}{}_{1}}{R_n{}^{i}}+\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\dfrac{w^{i}{}_{1}}{R_n{}^{i}}\right)\end{array}\right]\\
+Q^{i}{}_{22}\left[D^{i}{}_{22}\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}+E^{i}{}_{22}\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}-G^{i}{}_{22}c_{1}\left(\sum_{v=1}^{N_n}\dfrac{u^{i}{}_{1}}{R^{2}{}_{n}{}^{i}}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{w^{i}{}_{0}}{R^{2}{}_{n}{}^{i}}\right)\right]
\end{array}\right)\\
-\left[(A^{i}{}_{55}-3C^{i}{}_{55}c_{1})\left(\sum_{v=1}^{N_n} u^{i}{}_{0}I_{v}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}w^{i}{}_{0}\right)+X_{11}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\phi\right]\\
+3c_{1}\left((C^{i}{}_{55}-3E^{i}{}_{55}c_{1})\left(\sum_{v=1}^{N_n} u^{i}{}_{1}I_{v}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}w^{i}{}_{0}\right)+X_{12}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\phi\right)
\end{array}\right]\\
&=\left(1-\mu^{2}\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}+\\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{1}{R^{i}}\end{array}\right)\right)
\left[\begin{array}{l}
I^{i}{}_{1}\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{0}I_{v}+I^{i}{}_{2}\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{1}I_{v}-I^{i}{}_{4}c_{1}\left(\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{1}I_{v}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\omega^{2}w^{i}{}_{0}I_{v}\right)\\
-c_{1}I^{i}{}_{3}\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{0}I_{v}-c_{1}I^{i}{}_{4}\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{1}I_{v}\\
+I^{i}{}_{6}c_{1}{}^{2}\left(\sum_{v=1}^{N_n}\omega^{2}u^{i}{}_{1}I_{v}+\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\omega^{2}w^{i}{}_{0}I_{v}\right)
\end{array}\right];i=c,p
\end{aligned}
\qquad \text{(P-7)}
$$

$\delta\phi$:

$$(1-l^2\left(\begin{array}{l}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v} + \\ \sum_{v=1}^{N_n} C^{(1)}{}_{n,v}\dfrac{1}{R^{\,i}}\end{array}\right))\left(\begin{array}{l} +X_{31}\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}u^{p}{}_{0} + (X_{11}-3X_{12}-X_{33})\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}w^{p}{}_{0} \\ -(-X_{11}+3X_{12}-X_{32}+X_{33})\sum_{v=1}^{N_n} C^{(1)}{}_{n,v}u^{p}{}_{1} \\ -X_{41}\sum_{v=1}^{N_n} C^{(2)}{}_{n,v}\phi + X_{42}\sum_{v=1}^{N_n}\phi I_v \end{array}\right) = 0 \qquad \text{(P-8)}$$

BIODATA OF STUDENT



The student Erfan Shamsaddini Lori was born on the 9th September 1989 in Bandarabbas, Iran. He received his early primary education at Abu Ali Sina School, Kerman from 1996 to 2000. Then he completed his secondary school at ImamAli School and Olum Pezeshki School, Kerman from 2001 to 2006. Then, proceeded to pursue his foundation in Engineering in 2006 at Multimedia University, Melaka Campus (MMU), Melaka, Malaysia. Then proceeded to pursue his Bachelor's Degree in Mechanical Engineering in 2008 at Multimedia University (MMU). Upon completing his BSc (Hons) in 2013, he continued his learning journey by undertaking a Master degree in the field of manufacturing systems at Universiti Putra Malaysia (UPM). Immediately after his graduation on 2016 he became a PhD candidate in the field of Mechanical Engineering at Universiti Putra Malaysia (UPM). His main research interests are: (1) material engineering (polymer composites, smart materials, piezoelectric) and (2) sustainable energy. He has authored and published more than 6 citation indexed journals on piezoelectric materials with new approach of harvesting energy.

LIST OF PUBLICATIONS

Journal Articles

Erfan Shamsaddini Lori, Ebrahimi, F., Supeni, E. E. B., Habibi, M., & Safarpour, H. (2020). Frequency characteristics of a GPL-reinforced composite microdisk coupled with a piezoelectric layer. *The European Physical Journal Plus*, *135*(2), 144. (Published) [Q2, Impact factor: 2.24]

Lori, E. S., Ebrahimi, F., Supeni, E. E. B., Habibi, M., & Safarpour, H. (2020). The critical voltage of a GPL-reinforced composite microdisk covered with piezoelectric layer. *Engineering with Computers*, 1-20. (Published) [Q1, Impact factor: 2.76]

Erfan Shamsaddini Lori, Eris Elianddy Supeni. (2019). Harvesting energy from rain drop through application of PZT material; A Review. International Journal of Science and Research (IJSR) 8 (1), 2082 - 2089. (Published) [Scopus Indexed]

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