

Computer modeling for frequency performance of viscoelastic magneto-electro-elastic annular micro/nanosystem via adaptive tuned deep learning neural network optimization

Xu Guo^{1a}, Yixian Liu² and Guanzhuo Wang^{*3}

¹College of Electronics and Information, Shanghai Dianji University, Shanghai 201306, China

²School of Electrical and Computer Engineering, Nanfang College of Sun Yat-sen University, Conghua 510970, Guangdong, China

³Jiamusi School, Heilongjiang University of Chinese Medicine, Harbin 150040, Heilongjiang, China

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Abstract. The presented paper is the first attempt to apply deep learning for predicting the frequency characteristics of a magneto-electro-elastic (MEE) annular nano/microdisk (MEEAD). The optimum amount of the factors participating in the mechanism of the fully connected neural network are achieved through the optimizer based on the momentum. The positive side of the mentioned approach employed in this investigation would be due to its high accuracy along with lower epochs required for training the multi-layered network. This scrutinization would be semi-computational research that estimates the vibrational behavior of a MEEAD employing a non-classical continuum model known as the modified couple stress (MCS) model. First-order shear deformation theory (FSDT) and shell model would be provided for presenting their displacement fields. Then, Kelvin-Voight theory has been applied to model the viscoelastic foundation. Its non-classical governing equations, as well as related boundary conditions (BCs) of small-scaled MEEAD, would be achieved by considering the symmetric spinning gradient along with higher-order stress tensors for the strain energy. The provided non-classical theory would be able to capture the small scale in the MEEAD employing just one length scale of a material factor, then, the mathematical modeling of MEEAD according to the classical theory would be able to be recovered from the provided model by eliminating the material length scale factor. Ultimately, the non-classical governing equations would be solved by applying the generalized differential quadrature (GDQ) approach for multifarious BCs. Moreover, parametric research has been conducted to analyze the influences of the viscoelastic foundation, length scale factor, geometry of MEE, radial and circumferential mode number, radius ratio, and BCs on the frequency behavior of the MEEAD by applying MCST. The outcomes reveal that there would be a crucial radius ratio in which the relationship between these elements and crucial inserted voltage alters from direct to indirect relation.

Keywords: adaptive learning-rate optimization; deep-learning; higher-order stress tensors; frequency simulation; MEEAD

1. Introduction

One of the practical intelligent materials would be MEE. This kind of material is a smart composite material, and the electric and magnetic properties that created this material a tool to design a wide range of smart structures specifically, MEMS, actuators, NEMS, and sensors (Arefi and Zenkour 2017, 2018, 2019). This kind of material can be used in various systems (Li *et al.* 2020, Liu *et al.* 2020e, Wang *et al.* 2020, Yang *et al.* 2020). Moreover, there is a broad range of applications in analyzing wave propagation, including structural health monitoring. Thereby, recently an exciting research field has been taken into consideration by researchers and scientists known as wave propagation analysis (Arefi and Zenkour 2017). The electro-thermo-mechanical vibrational behavior of functionally graded

piezoelectric plates with porosities via a refined four-variable plate theory was explored by Ref. Barati and Zenkour (2018). Zenkour and El-Shahrany (2020a) presented the frequency performance of a viscoelastic simply-supported sandwich magnetostrictive plate on the Pasternak substrate. Vibration suppression analysis of a simply-supported laminated composite beam with magnetostrictive layers resting on visco-Pasternak's foundation was studied by Ref. Zenkour and El-Shahrany (2020a). Sobhy and Zenkour (2018) investigated the effect of the magnetic field on the thermomechanical buckling and vibration of viscoelastic sandwich nanobeams in a humid environment. In another work, Sobhy and Zenkour (2020) studied the bending of viscoelastic nanobeams laying on visco-Pasternak elastic foundations based on a new shear and normal deformations beam theory. Damping and vibration response of viscoelastic smart sandwich plate reinforced with non-uniform graphene platelet with magnetorheological fluid core was presented by Ref. Eyvazian *et al.* (2019). The presented approach in the previous reference can be a good tool for analysis of complex systems (Abd El Aziz *et al.* 2017, Devaraj *et al.*

*Corresponding author, Ph.D.,

E-mail: guox@sdju.edu.cn

^a Ph.D., E-mail: 2003020229@st.btbu.edu.cn

2020, Elhoseny *et al.* 2014, Metawa *et al.* 2016, Tharwat *et al.* 2018). In the scope of dynamics of various structures, Liu and Jeffers (2017) presented stress distribution of the laminated composite and functionally graded sandwich plates based on a layerwise displacement theory within the framework of isogeometric analysis. The analysis of the Kirchhoff plate using rational Bézier triangles in isogeometric analysis coupled with a feature-preserving automatic meshing algorithm was performed by Ref. Liu and Jeffers (2018a). In another work, Liu *et al.* (2019) did research about the nonlinear response of functionally graded material structures via isogeometric continuum shell element (Liu *et al.* 2020d). Some researchers used computer modeling for analysis of various systems (Elhoseny *et al.* 2017, Elsayed *et al.* 2018, Hosseinabadi *et al.* 2019, Krishnaraj *et al.* 2021, Mohanty *et al.* 2020, Rizk-Allah *et al.* 2018). A framework for conducting heat transfer analysis of non-uniformly heated plates using isogeometric analysis (IGA) was presented by Liu *et al.* (2019). Adaptive isogeometric analysis in structural frames using a layer-based discretization to model spread of plasticity was studied by Ref. Liu and Jeffers (2018a). Liu and Jeffers (2019) presented the computational approach of modeling smeared damage with quadrilateral elements in isogeometric analysis. In their work, the solution algorithm was initialized with the cylindrical arc-length control and switches to a dissipation-based arc-length control for better numerical stability as the damage evolves.

Considering the dynamic analysis of an annular plate, Civalcik and Baltacıoğlu (2019) applied the first-order-shear-deformation (FOSD) model and a semi computational technique for analyzing the vibrational characteristics of a part of the annular plate that the supposed material would be FG. Mohammadimehr *et al.* (2019) reported a paper on the dynamics and statics behavior of an FG annular thin system subjected to primary stress and lied in a viscoelastic condition. Their mathematical model for the mentioned system has been extracted with a classical model, and the solver was GDQ approach. This kind of materials can be used in many applications such as (Niu *et al.* 2020, Zhang *et al.* 2019, 2020a). Arshid *et al.* (2019) presented research to analyze the vibration behavior of an FG smart annular system subject to three types of physical load through employing a semi-computational approach and thick model. Their mathematical manipulations were modeling magneto-electro-elastic system, and they took into account that the annular smart structure is in a thermal condition. Their outcome disclosed that by raising the magnetic field, the system would become stiffer, so it would be a reason for enhancing the structure's frequency. Employing an FE technique, Vinyas (2020) reported research on the magneto-electro-elastic annular and circular FG plate's dynamics through applying higher-order shear deformation theory (HSDT) approach, and there was a study regarding the influences of imperfections on the mode shape and highest deflection. The mentioned solution procedure as a strong solver can be used in many systems such as (Chen *et al.* 2020, Hu *et al.* 2020b, c, Zhang and Wang 2019). Safarpour *et al.* (2019) made a formulation on the GPLs filled FG shell, conical shell, and annular plate employing 3D-

elasticity approach for providing dynamic and static characteristics of the system. They selected the GDQ technique as an equation solver, and they revealed that the configurational factors of the GPLs contribute significantly to the frequency and bending behaviors of the systems. Also, this kind of analysis can be used in many systems (Ding *et al.* 2020, Hu *et al.* 2020a, Qiao *et al.* 2021, Yin *et al.* 2021). Dai *et al.* (2019) provided research in the area of dynamics of a spinning CNTs filling annular structure by supposing the influences of natural porosity, aggregation phenomenon in the material, along with the hygro-thermal condition. They selected the GDQ approach as an equation solver, and they disclosed that spinning velocity and moisture would contribute considerably to the annular system's frequency. Eshraghi and Dag (2020) employed the boundary element approach as a beneficial technique for analyzing the annular FG system's forced vibration. Bemani Khouzestani and Khorshidvand (2019) analyzed the frequency and bending behavior of the Axisymmetric imperfect annular structure through using basic shear-deformation approach and variational method. Their outcomes revealed that as the imperfection rises, the stress and frequency field decline. Due to new demand in technology (Cai *et al.* 2020, Jing *et al.* 2021, Zhang *et al.* 2018, Zhao *et al.* 2020) FG structures can be used as the main materials in the future (Cai *et al.* 2021, Dong *et al.* 2021, Liu *et al.* 2020a, Zhang *et al.* 2020a). Javani *et al.* (2020) reported a research in the area of thermal buckling investigation of a part of GPLs filling FG annular structure by applying FSDT and a semi computational approach. Moreover, they assumed nonlinear geometry through considering the von Kármán theory. As they disclosed in their paper, GPLs would be able to enhance the critical temperature and buckling load of the imperfected annular structure. The used method of previous reference can be a good tool for solving the complex problems such as (Abdel-Basset *et al.* 2019b, Elhoseny *et al.* 2019a, Krishnaraj *et al.* 2020, Lakshmanaprabu *et al.* 2019, Zaher *et al.* 2020). Heshmati and Jalali (2019) extracted a formulation of a annular sandwich panel supposing porosity in that material and analyzed the free vibration analysis applying the FSDT and Chebyshev theory. They reported that porosity's density in the core of the annular sandwich panel would be able to indirectly affect on the structure's frequency. Many researchers showed that mechanical properties analysis of the structures can make a marvelous influence on the stability analysis of the systems (Eyvazian *et al.* 2020b, Talebizadehsardari *et al.* 2020a).

Assuming the size dependency for predicting the thermomechanical characteristics of the nano-sized structure becomes a vital issue, due to nanotechnology development in multifarious industries, specifically in the area of the performance of NEMS, MEMS, and nano-scaled structures (Motezaker and Eyvazian 2020). According to the mentioned explanation, Mohammad-Rezaei Bidgoli and Arefi (2019), by applying the nonlocal-modified-strain-gradient, scrutinized the vibration behavior of a micro-scaled plate that would be supposed its material of the system is FG. Mahinzare *et al.* (2019) reported a complete study on the annular electrically FG system's dynamics in a

thermal condition through employing nonlocal-strain-gradient and FSDT. Moreover, they revealed the influences of nonlocal-strain-gradient and Eringen models on the smart structure's frequency. they selected the GDQ technique as an equation solver for publishing their outcomes. GDQ method can be used as a strong solver in many systems and structures such as (Lv *et al.* 2020, 2021c, Xiao *et al.* 2021). Arshid *et al.* (2020) applied FSDT and modified-strain-gradient models for analyzing frequency and buckling behavior of a GPLs filling annular micro-sized system. They, however, solved the extracted equations through applying the GDQ technique and disclosed that the thermal condition and viscoelastic foundation would be able to play prominent role on the behaviors of the small-scaled annular structure. Pal and Das (2020) made a formulation on the motion equation and BCs of a spinning annular FG micro-sized system through employing modified-couple-stress, Kirchhoff models, and variational approach. They supposed that the system is lied on a thermal condition and they disclosed the annular system's shape modes in a wide range of conditions. This kind of analysis can be used in many structures and systems such as (Cao *et al.* 2019, Dorri *et al.* 2019, Libo *et al.* 2019, Puri *et al.* 2019, Tang and Elhoseny 2019). Alipour and Shariyat (2019) devoted one of their studies for analyzing the static characteristics of a micro/nano annular sandwich structure applying a new nonlocal technique which is called the zigzag approach. Also, the optimization algorithm method can be a good tool for solving the complex structures and systems (Eassa *et al.* 2018, Hurrah *et al.* 2019, Muhammad *et al.* 2019, Murugan *et al.* 2019, Valayapalayam Kittusamy *et al.* 2019). Numerical solution procedure can have a marvelous influence on the dynamics/statics of the structures (Gaber *et al.* 2018, Yuan *et al.* 2018). Many researchers proved that the generalized differential quadrature method can be a good tool for solving complex systems (Madenci 2019, Madenci *et al.* 2020, Madenci and Ozutok 2020, Özütoğ and Madenci 2017). The analytical models and their features presented by Olia and Perić (2021) provided a fundamental, rational, mechanics-based framework for advancing the understanding of a load transfer mechanism and soil-structure interaction in energy geostructures, thus contributing directly toward better implementing these means of extracting renewable energy sources, which is step forward in reducing the greenhouse gases. In another work, Olia *et al.* (2021) developed a finite difference numerical model to further advance the seismic stability of geotechnical structures by proposing geometry and PGA-based seismic coefficient. Based on their analyses, an accurate prediction of seismic force in ground anchors is possible through a simple method. The presented approach in the previous reference can be a good tool for analysis of medical problems (Abdel-Basset *et al.* 2019a, Dutta *et al.* 2020, Elhoseny *et al.* 2019b, Elhoseny and Shankar 2019b, Shankar and Elhoseny 2019, Thakur *et al.* 2019).

Based on the authors' best knowledge, there would be no research in the published papers deriving the general mathematical formulation of small-scaled MEEAD based on the modified-couple-stress model. Moreover, this scrutinization applies algorithms corresponding to the

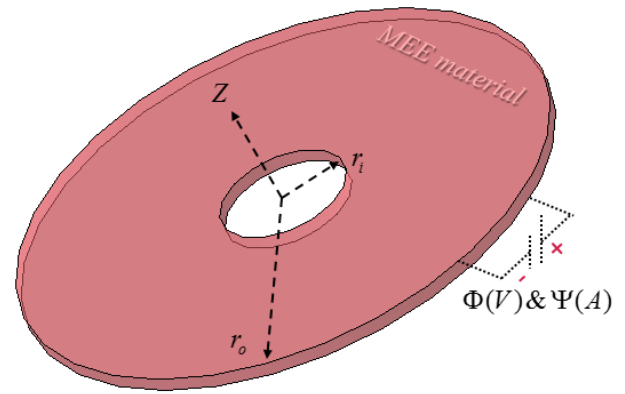


Fig. 1 A configuration of a MEEAD

machine learning approach to analyze a regression-based estimator mechanism for predicting the system's frequency at a swifter process. Thereby, the provided research aims to develop BCs and governing equations of MEEAD by incorporating the size dependency based on the modified-couple-stress model. By employing the variational method combined with the modified-couple-stress model, the pertained BCs and governing equation are extracted. Then, the declined forms of non-classical BCs are achieved in terms of the resultant forces and the middle surface displacement elements. Ultimately, the outcomes illustrate that length scale factor, radius ratio, radial and circumferential mode number, MEE geometry, and viscoelastic foundation contribute significantly to the frequency of the MEEAD by applying MCST.

2. Model, formulation and theories

A MEEAD is illustrated in Fig. 1.

2.1 Mathematical modeling of circular plate

According to the FSDT, the displacement fields are able to be explained as the following relations:

$$\begin{aligned} u(r, \theta, z, t) &= u_0(r, \theta, t) + zu_1(r, \theta, t) \\ v(r, \theta, z, t) &= v_0(r, \theta, t) + zv_1(r, \theta, t) \\ w(r, \theta, z, t) &= w_0(r, \theta, t) \end{aligned} \quad (1)$$

2.2 Strain-Stress of the structure

It could be mentioned noted that this panel system is likely to be polarized only through its thickness orientation. The constitutive relations of the MEE system would be able to be mathematically formulated as the next equations (Eringen 2002, Ke *et al.* 2014):

$$\begin{aligned} \sigma_{ij} &= c_{ijkl}\varepsilon_{kl} - q_{nij}H_n - e_{mij}E_m - \beta_{ij}\Delta T \\ D_i &= e_{ikl}\varepsilon_{kl} + d_{in}H_n + s_{im}E_m + p_i\Delta T \\ B_i &= q_{ikl}\varepsilon_{kl} + r_{in}H_n + d_{im}E_m + \lambda_i\Delta T \end{aligned} \quad (2)$$

In the aforementioned relations s_{im} , e_{mij} , and c_{ijkl} , would be the dielectric, piezo-electric constants, and elasticity

matrix, respectively. D_i and E_m would be electric displacements and electric fields strength, respectively. Moreover, other factors are pertained to the MEE structure's piezo-magnetic properties. The magnetic, and electric field strength, i.e., H_n and E_m where are provided in Eq. (2), could be written as below:

$$\begin{aligned} E_r &= -\frac{\partial\Phi}{\partial r}, E_\theta = -\frac{\partial\Phi}{\partial\theta}, E_z = -\frac{\partial\Phi}{\partial z} \\ H_r &= -\frac{\partial\Psi}{\partial r}, H_\theta = -\frac{\partial\Psi}{\partial\theta}, H_z = -\frac{\partial\Psi}{\partial z} \end{aligned} \quad (3)$$

Wang (2002) disclosed that, the magnetic and electric potential would be written as below:

$$\begin{aligned} \Phi(r, \theta, z, t) &= \frac{2z\phi_0}{\hbar} - \cos(\pi z/\hbar)\phi(r, \theta, t), \\ \Psi(r, \theta, z, t) &= \frac{2z\psi_0}{\hbar} - \cos(\pi z/\hbar)\psi(r, \theta, t) \end{aligned} \quad (4)$$

here ψ_0 and ϕ_0 denote the primary external magnetic and electric load, respectively. Furthermore, $\psi(r, \theta, t)$ and $\phi(r, \theta, t)$ explain a spatial variation relating to magnetic and electric potential in the directions of θ and r , respectively. Also, the strain elements could be given as (Ghiasi *et al.* 2014, Hosseini-Hashemi *et al.* 2010):

$$\begin{pmatrix} \varepsilon_{rr} \\ \varepsilon_{\theta\theta} \\ 2\gamma_{r\theta} \\ 2\gamma_{rz} \\ 2\gamma_{\theta z} \end{pmatrix} = \begin{pmatrix} \frac{\partial u}{\partial r} \\ \frac{\partial v}{\partial\theta} + \frac{u}{r} \\ \frac{\partial v}{\partial r} + \frac{1}{r}\frac{\partial u}{\partial\theta} - \frac{1}{r}v \\ \frac{\partial u}{\partial z} + \frac{\partial w}{\partial r} \\ \frac{\partial v}{\partial z} + \frac{1}{r}\frac{\partial w}{\partial\theta} \end{pmatrix} \quad (5)$$

2.3 Variational method

According to the variational approach, there would be relations between motion equations and BCs which would be given as (Dehshahri *et al.* 2020, Ebrahimi and Jafari 2017, Ebrahimi *et al.* 2019a, b, 2020, Ebrahimi and Salari 2019, Ehyaei and Daman 2017, Emdadi *et al.* 2019, Ghannadpour and Moradi 2019, Hussain *et al.* 2019, Kumar 2018, Salari 2016, Shahsavari *et al.* 2019, Tounsi *et al.* 2013, Wu *et al.* 2018):

$$\int_{t_1}^{t_2} (\delta T - \delta U - \delta U_2 - \delta U_3 - \delta U_4 + \delta W) dt = 0 \quad (6)$$

Then, the pertained system's kinetic energy may be given as:

$$T = \int_V \frac{1}{2}\rho \left[\left(\frac{\partial u}{\partial t} \right)^2 + \left(\frac{\partial v}{\partial t} \right)^2 + \left(\frac{\partial w}{\partial t} \right)^2 \right] dV \quad (7)$$

here the kinetic energy's first variation would be defined as follows:

$$\delta T = \int_V \rho \left(\frac{\partial u}{\partial t} \frac{\delta u}{\partial t} + \frac{\partial v}{\partial t} \frac{\delta v}{\partial t} + \frac{\partial w}{\partial t} \frac{\delta w}{\partial t} \right) dV \quad (8)$$

Moreover, the presented composite system's strain energy could be determined as (Eyvazian *et al.* 2020a, Karami *et al.* 2020):

$$U_1 = \frac{1}{2} \iiint_V (\sigma_{ij} \varepsilon_{ij}^2) dV \quad (9)$$

The strain energy due to MCST may be explained as follows:

$$U_2 = \frac{1}{2} \iiint_V (m_{ij}^s \chi_{ij}^s) r dr d\theta dz \quad (10)$$

Here in Eq. (10) σ_{ij} and ε_{ij} denote the elements of a stress and strain tensor, which could be defined in Ref (Barooti *et al.* 2017). Moreover, χ_{ij}^s and m_{ij} would be the elements of a higher-order stress tensor and symmetric spinning gradient tensor.

Then, for MEE materials (Ghadiri and Safarpour 2016):

$$\delta U_3 = - \iiint_V (D_r \delta E_r + D_\theta \delta E_\theta + D_z \delta E_z) \quad (11)$$

$$\delta U_4 = - \iiint_V (B_r \delta H_r + B_\theta \delta H_\theta + B_z \delta H_z) \quad (12)$$

The external work conducted according to viscoelastic substrate, would be computed as follows:

$$\begin{aligned} \delta W &= \int_A \left[K_w w \delta w + K_p \left(\frac{\partial w}{\partial r} \frac{\delta w}{\partial r} + \frac{\partial w}{\partial \theta} \frac{\delta w}{\partial \theta} + \frac{\partial w}{\partial r} \frac{\delta w}{\partial r} \right) + C_d \dot{w} \delta \dot{w} \right] dA \end{aligned} \quad (13)$$

here K_p , K_w , and C_d denote Pasternak, Winkler, and damping factors, respectively. Then, corresponding BCs and governing equations would be extracted by inserting Eqs. (8)-(13) into the variational approach (Eq. (6)) that would be obtained.

3. Numerical method

The highlighted benefit of GDQ approach is its fast convergence regarding the lower number of grid points. It means, GDQ technique makes an accurate result with fewer computational operations. The GDQ method as the time dependent solution procedure can be used in many advance structures such as (He *et al.* 2020, Lv *et al.* 2021c, Weng *et al.* 2021). Hence, in this research, GDQ technique has been applied to achieve the computational solution to the natural frequency of viscoelastic FG-GPLRC annular plate. Due to this technique, r-th derivative of $f(x)$ would be computed as

$$\frac{\partial^r f(x)}{\partial x^r} \Big|_{x=x_p} = \sum_{j=1}^N g_{ij}^{(r)} f(\alpha_j) \quad (14)$$

here N is the number of grid-points distribution through the x-axis. Weighting factor C_{ij} are obtained from the first-order-derivative as follow

$$\begin{aligned} g_{ij}^{(1)} &= \frac{M(R_i)}{(R_i - R_j)M(R_j)} \\ i, j &= 1, 2, \dots, N \text{ and } i \neq j \end{aligned} \quad (15)$$

$$g_{ij}^{(1)} = - \sum_{j=1, i \neq j}^N C_{ij}^{(1)}$$

$$i = j$$

In which $M(R_i) = \prod_{j=1, j \neq i}^N (R_i - R_j)$. In order to achieve weighting factors of higher-order derivatives, the next equations could be employed

$$g_{ij}^{(r)} = r \left[g_{ij}^{(r-1)} g_{ij}^{(1)} - \frac{g_{ij}^{(r-1)}}{(R_i - R_j)} \right]$$

$$i, j = 1, 2, \dots, N, i \neq j \quad \text{and } 2 \leq r \leq N - 1 \quad (16)$$

$$g_{ii}^{(r)} = - \sum_{j=1, i \neq j}^N g_{ij}^{(r)}$$

$$i, j = 1, 2, \dots, N \text{ and } 1 \leq r \leq N - 1$$

In this paper, a non-uniform distribution of grid-points has been selected as the following equation

$$r_j = r_i + \frac{r_0 - r_i}{2} \left(1 - \cos \left(\frac{(j-1)\pi}{(N-1)} \right) \right), j = 1, 2, 3, \dots, N \quad (17)$$

The degrees of freedom would be supposed as:

$$\left\{ \begin{array}{l} u_0(r, \theta, t) \\ v_0(r, \theta, t) \\ w_0(r, \theta, t) \\ u_1(r, \theta, t) \\ v_1(r, \theta, t) \\ \Phi(r, \theta, t) \\ \Psi(r, \theta, t) \end{array} \right\} = \sum_{n=1}^{\infty} \left\{ \begin{array}{l} u_{0n}(r) \times \sin(n\theta) \\ v_{0n}(r) \times \cos(n\theta) \\ w_{0n}(r) \times \sin(n\theta) \\ u_{1n}(r) \times \sin(n\theta) \\ v_{1n}(r) \times \cos(n\theta) \\ \Phi_{0n}(r) \times \sin(n\theta) \\ \Psi_{0n}(r) \times \sin(n\theta) \end{array} \right\} e^{i\omega t} \quad (18)$$

rewriting the BCs and quadrature analogs of field equations into the basic generalized eigenvalue problem would be obtained

$$\left\{ \begin{array}{l} \left[\begin{array}{cc} [M_{dd}] & [M_{db}] \\ [M_{bd}] & [M_{bb}] \end{array} \right] \omega_n^2 + \left[\begin{array}{cc} [C_{dd}] & [C_{db}] \\ [C_{bd}] & [C_{bb}] \end{array} \right] \omega_n \\ + \left[\begin{array}{cc} [K_{dd}] & [K_{db}] \\ [K_{bd}] & [K_{bb}] \end{array} \right] \end{array} \right\} \left\{ \begin{array}{l} \delta_d \\ \delta_b \end{array} \right\} = 0 \quad (19)$$

Eq. (19) would be changed to a classical eigenvalue problem:

$$[K^* + iC^*] \{\delta_i\} = (\omega_n^2) [M^*] \{\delta_i\}$$

$$K^* = [K_{bd}] - [K_{bb}][K_{ab}]^{-1}[K_{dd}]$$

$$C^* = [C_{bd}] - [C_{bb}][K_{ab}]^{-1}[K_{dd}]$$

$$M^* = [M_{bd}] - [M_{bb}][K_{ab}]^{-1}[K_{dd}] \quad (20)$$

For decreasing the numerical complexity, the MEEAD's frequency should be non-dimensional as follows

$$\bar{\omega}_n = \omega_n r_i^2 \sqrt{\frac{\rho_m}{E_m}} \quad (21)$$

3.1 A comparative study using the deep learning-based method

In recent years, a wide range of scientists has been

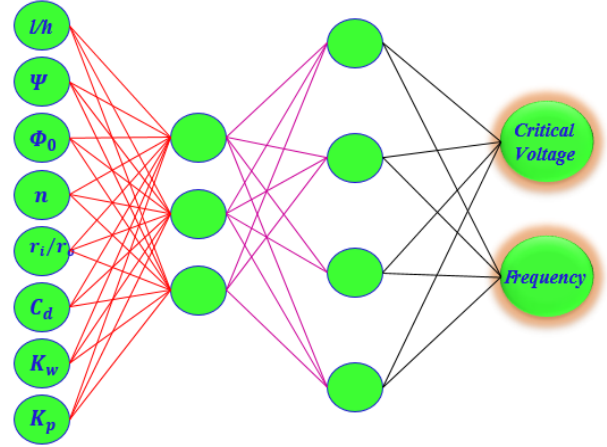


Fig. 2 Structure's schematic of fully-connected DNN

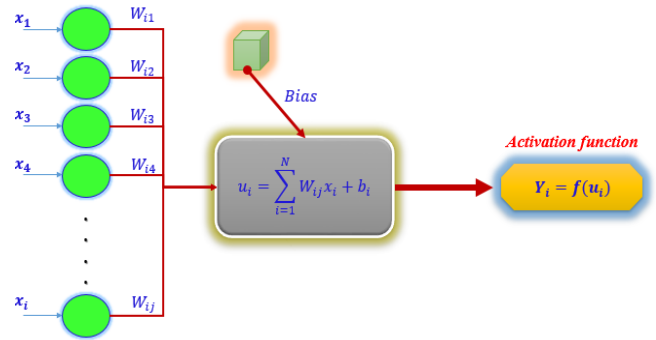


Fig. 3 Operation mechanism and elements of a perceptron

attracted by the deep learning approach to employ it as an applicable tool in multifarious fields, including regression, classification, and segmentation duties. Using optimization algorithm can solve the complex equations (Elhoseny *et al.* 2018, Ewees *et al.* 2017, Shankar *et al.* 2020, Xu *et al.* 2020). Thus, we applied a deep neural network (DNN) with optimized factors obtained by ADADELTA (an abbreviation for adaptive delta). DNN with optimized parameters achieved by ADADELTA as an accurate solver would be employed in multifarious systems, including (Liu *et al.* 2020b, c, Wu *et al.* 2018, Ye *et al.* 2020). The X set which could be defined as $X = \{l/h, C_d, K_w, K_p, \Phi_0, \Psi, r_i/r_0\}^T$ has been selected as the regression-based DNN input for estimating the natural frequency and critical voltage. Moreover, thanks to new needs in technology, DNN would be an accurate tool to solve multifarious complicated structures (Lou *et al.* 2021, Lv *et al.* 2021a, b, Zhou *et al.* 2021). The configuration of the mentioned DNN would be illustrated in Fig. 2.

Computer simulation is a strong tool for modeling a structure (Abdel-Basset *et al.* 2020, Ali *et al.* 2020, El-Hasnony *et al.* 2020, Saračević *et al.* 2020, Uthayakumar *et al.* 2020). All DNN's layers have numerical units called the perceptron. Fig. 3 demonstrates the operation details conducted in a perceptron.

The perceptron input would be the units constituting the last layer of the network output. To achieve the numerical unit output, the amount of each input should be mathematically operated with biases and weights. In order

to be more informed regarding the neural network technique basis, readers would check the reference (White 1992). Machine learning techniques may be employed in multifarious systems (Jiang *et al.* 2021, Li *et al.* 2021, Lou *et al.* 2021, Yu *et al.* 2021). As well as this, Genetic algorithm is a strong tool for simulating a structure (Elhoseny 2020a, b, Elhoseny and Shankar 2019b, Geetha *et al.* 2021, Lydia *et al.* 2021). The mean squared error (MSE) could be the metric chosen in the presented research to examine the DNN's accuracy in the estimation of the free vibrations. The next equation would explain MSE as the mean of the squared nuances between the estimated frequency and expected one.

$$\text{MSE} = \frac{1}{n} \sum_{i=1}^n (Y - \hat{Y})^2. \quad (22)$$

3.2 ADADELTA optimization to tune the DNN parameters

ADADELTA would be selected as the optimization technique to find suitable biases and weights for minimizing the MSE. The key benefit of ADADELTA could be listed as below:

- This technique sets the learning rate automatically
- ADADELTA would not sensitive to the amount of the hyperparameters
- This technique is able to be employed in the local condition along with the distributed one

To update the neural network factors (weights and biases) at all steps of iteration (epoch), one may apply the next equation

$$\begin{aligned} h_{t+1} &= h_t + \Delta h_t \\ \Delta \chi_t &= -\eta \frac{\partial f(\chi_t)}{\partial \chi_t} \end{aligned} \quad (23)$$

where, η denotes the primary learning rate. For simplifying the involved factors' gradient at the t^{th} epoch,

we employ G_t in the $\frac{\partial f(h_t)}{\partial h_t}$. To achieve the upgraded weights and biases, it would be needed to compute the mean root square of the gradient at the present epoch applying the following equation

$$\text{RMS}[\mathfrak{R}_t] = \sqrt{E[\mathfrak{R}_t^2] + \varepsilon} \quad (24)$$

where, ε would a constant. It could be mentioned that $E[\mathfrak{R}_t^2]$ implies to the expected amount of the squared gradient which may be obtained due to the subsequent definition

$$E[\mathfrak{R}_t^2] = \rho E[\mathfrak{R}_{t-1}^2] + (1 - \rho) \mathfrak{R}_t^2 \quad (25)$$

Then, ρ implies to the decay rate. Applying Eq. (24) and Eq. (25), one would achieve the updated mentioned factors as below

$$\nabla h_t = -\frac{\eta}{\text{RMS}[\mathfrak{R}_t]} \mathfrak{R}_t \quad (26)$$

4. Validation and convergence conditions

The convergence number of grid points concerning the various BCs is revealed in Table 1. Based on Table 1, it

Table 1 Convergence number of grid points concerning the various boundary conditions

Boundary conditions	N = 5	N = 7	N = 9	N = 11	N = 13	N = 15
Simply-Simply	0.0332	0.0385	0.0390	0.0391	0.0391	0.0391
Clamped-Simply	0.0948	0.0934	0.0936	0.0936	0.0936	0.0936
Clamped-Clamped	0.1300	0.1284	0.1285	0.1285	0.1285	0.1285

Table 2 Comparing dimensionless frequencies of the provided system with the published researches

	h/r_i	S-S				C-C			
		Mode number				Mode number			
		1	2	3	4	1	2	3	4
Ref. (Han and Liew 1999)	0.001	14.585	51.681	112.89	198.34	27.180	75.264	148.01	245.37
Current study	0.001	14.524	51.502	111.76	198.51	27.014	75.263	147.05	244.15
Ref. (Han and Liew 1999)	0.050	14.424	50.309	107.15	182.45	26.434	71.128	135.14	215.18
Current study	0.050	14.328	50.009	106.19	182.18	26.079	71.006	134.26	214.36
Ref. (Han and Liew 1999)	0.100	13.774	46.847	94.570	151.81	24.529	62.040	111.02	167.06
Current study	0.100	13.654	46.661	94.394	151.26	24.458	62.040	110.29	166.31
Ref. (Han and Liew 1999)	0.150	13.118	42.530	81.419	124.82	22.130	52.662	90.186	131.25
Current study	0.150	13.038	42.082	81.136	124.14	22.109	52.535	89.862	130.41
Ref. (Han and Liew 1999)	0.200	12.350	38.237	70.124	104.10	19.743	44.813	74.760	106.71
Current study	0.200	12.226	38.143	70.115	104.14	19.594	44.683	73.528	105.65

would be clear that the necessary and sufficient grid points to produce accurate results are eleven, and this is a fact for all BCs.

To evaluate the presented approach's validity, the annular plate's frequency elements extracted in this research have been compared with those reported in Ref. Han and Liew (1999) for a wide range of axisymmetric types of vibration modes through h/r_i assuming three multifarious BCs as illustrated in Table 2. Due to the tables provided in this paper, the presented scrutinization estimates the annular plate's frequency much nearer contrasting to those provided in Ref. Han and Liew (1999). The system's kinematics would be defined, supposing FSDT in Ref. Han and Liew (1999). As can be seen, the difference between the current results with the outcomes of Ref. Han and Liew (1999) is less than 1%.

5. Results

The MEE structure's material properties would be provided as follows (Lori *et al.* 2020)

A comparative analysis has been provided in Fig. 4 for analyzing the influences of the inserted ampere, various BCs, and applied voltage on the system's dynamics. Due to the provided information in Fig. 4, the influence of applied voltage on the system's dynamics would be more significant than the influence of inserted ampere and the mentioned issue would be more recognizable for simply BCs. Ultimately, in-plane (Φ_0, Ψ) , we would be able to find a triangular surface in which inserted ampere and applied voltage do not affect on the spinning system's frequency, and the triangular surface becomes smaller based on changing BCs from S-S to C-C.

The frequency of the MEEAD with respect to material length scale parameter (l/h) of the micro-scaled structure is demonstrated in Fig. 5 for different applied external voltages to the piezoelectric disk (Φ_0) .

According to Fig. 5, we would be able to conclude that raising the Φ_0 parameter declines the system's frequency, and the relationship would be highlighted at the primary amount of l/h parameter. Moreover, in the larger amounts of material length scale parameters, we would not be able to find any influence from the inserted external voltage on the smart system's dynamics. Moreover, l/h parameter and MEEAD's dynamic stability are directly related to each other. However, at the larger amount of l/h parameter, there would not be any change in the system's frequency due to the raising material length scale.

Fig. 6 would be reported for analyzing the impacts of inserted circumferential wave number and external voltage on the MEEAD's dynamics with the MCS model.

If we pay attention to Fig. 6, it is obvious that there is an indirect influence from Φ_0 on the frequency of the MEEAD and the mentioned effect is remarkable at the initial wave numbers.

The influences of applied external voltage, employing two kinds of size-dependent theory and radius ratio on the dynamics of the MEEAD are investigated in Fig. 6.

Provided diagrams in Fig. 7 present that, as the inserted external voltage and radius ratio increase, the frequency of

Table 3 Material properties of MEE structure

Material constants	Magnetidue
Elastic (GPa)	$c_{11} = 226, c_{12} = 125, c_{13} = 124, c_{33} = 216,$ $c_{44} = 44.2, c_{55} = 44.2, c_{66} = 50.5$
Piezoelectric ($C m^{-2}$)	$e_{31} = -2.2, e_{33} = 9.3, e_{15} = 5.8$
Dielectric ($10^{-6} C V m^{-1}$)	$s_{11} = 5.64, s_{22} = 5.64, s_{33} = 6.35$
Piezomagnetic ($N A m^{-1}$)	$q_{15} = 275, q_{31} = 290.1, q_{33} = 349.9$
Magnetoelastic ($10^{-6} N_s VC^{-1}$)	$d_{11} = 5.367, d_{33} = 2737.5$
Magnetic ($10^{-6} N_s^2 C^{-2}$)	$r_{11} = -297, r_{33} = 83.5$
Thermal moduli ($10^{-6} N Km^{-2}$)	$\beta_1 = 4.74, \beta_3 = 4.53$
Pyroelectric ($10^{-6} C N^{-1}$)	$P_3 = 25$
Pyromagnetic ($10^{-6} N Am K^{-1}$)	$\lambda_3 = 5.19$
Mass density ($10^3 kg m^{-3}$)	$\rho = 5.55$

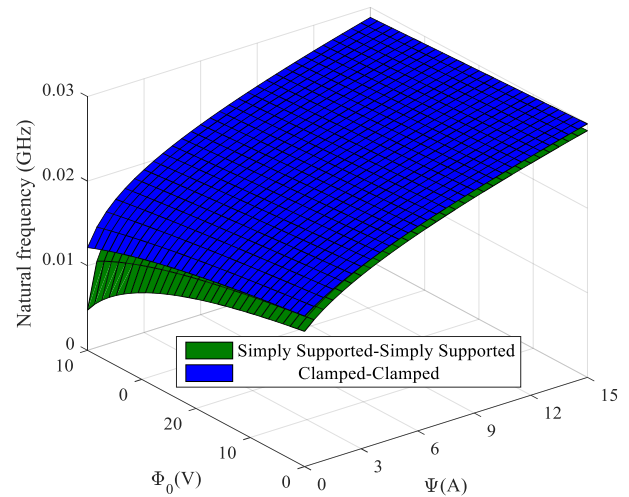


Fig. 4 A comparative study for investigating the influences of the applied ampere, applied voltage, and different boundary conditions on the system's dynamics

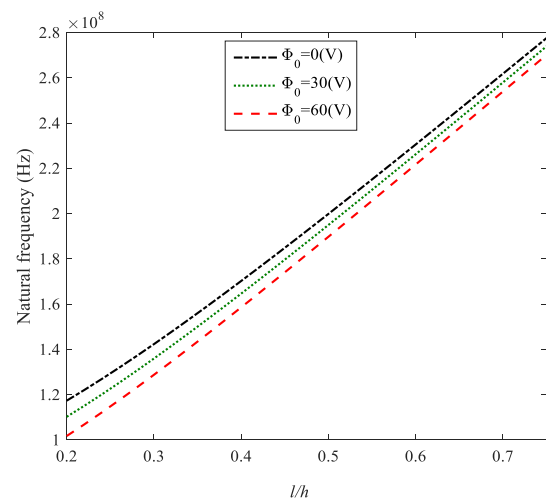


Fig. 5 Frequency of the MEEAD versus l/h for various Φ_0

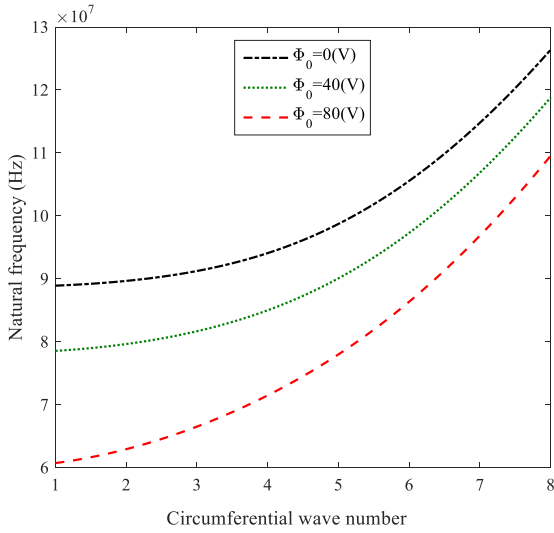


Fig. 6 Frequency of the MEEAD versus circumferential wave number for different Φ_0

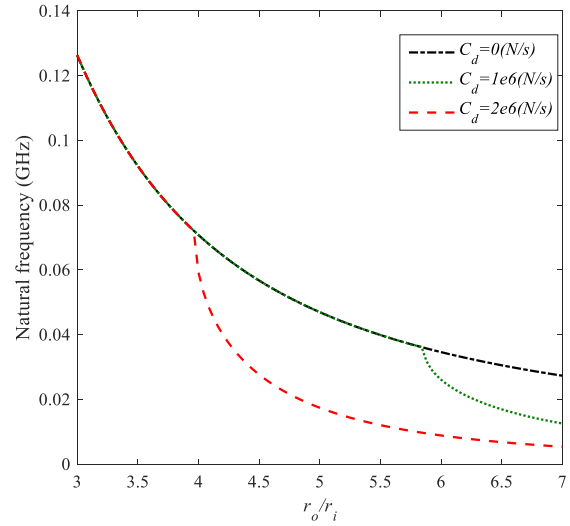


Fig. 8 The frequency of the MEEAD with respect to r_0/r_i for different C_d

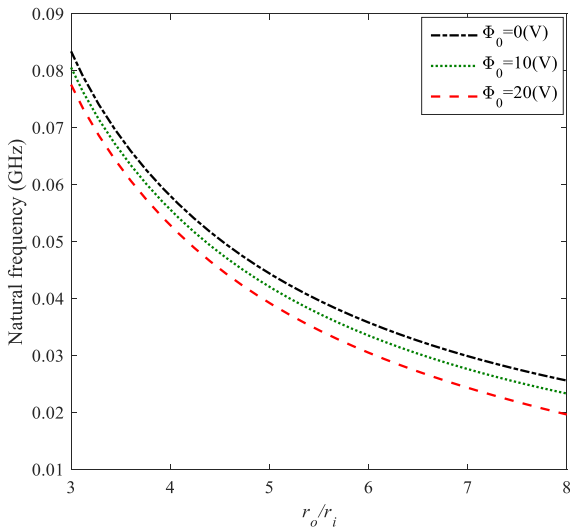


Fig. 7 Frequency of the MEEAD versus radius ratio for different Φ_0

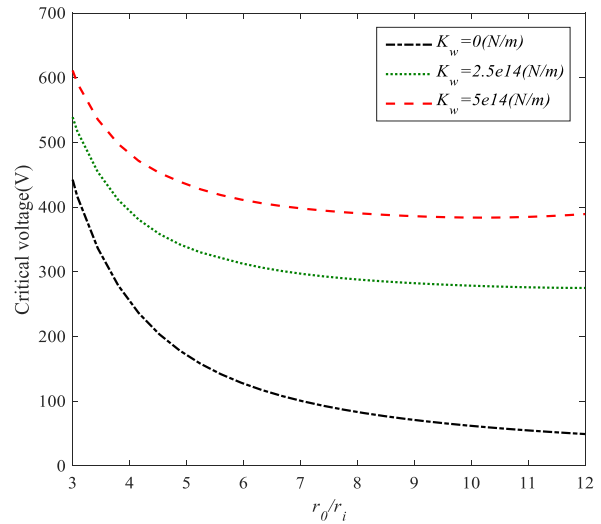


Fig. 9 MEEAD's crucial voltage with respect to r_0/r_i for various K_w

the MEEAD decreases but should have the attention that for both size-dependent theories the mentioned effects become remarkable in the grater radius ratio. Furthermore, for the higher value of applied voltage, there is a critical radius ratio, and this critical value will increase by increasing the length scale parameter and decreasing applied voltage.

On the dynamics of the MEEAD is shown in Fig. 8 for different C_d and Clamped-Free boundary conditions.

The overall outcome which are be able to be observed from the provided diagrams in Figure 8 would be that when the viscoelastic substrate has been inserted, as the C_d raise, the frequency would be able to be boosted; however, we have to attend the mentioned enhancement happening for the MEEAD with a greater radius ratio. In other words, the MEEAD's frequency would not be impressed by C_d parameter in the less amount of r_0/r_i . Moreover, as we would be able to observe through Figures 6 there would be ranges of r_0/r_i in which we would not be able to find any

influences from C_d parameter on the system's dynamics, and the ineffective range becomes close due to improving the damping parameter of the substrate. The most interesting outcome would be that, when the material length scale parameter raises the influence of C_d parameter on the system's dynamics declines.

Given diagrams in Fig. 9 inform that, as the K_w increase, the critical voltage of the MEEAD improves; however, paying attention to the mentioned enhancement becomes remarkable in the greater radius ratio. In addition, the impacts of elastic factor and radius ratio on the critical voltage of the system become weak and strengthened, respectively. Furthermore, When the substrate would be supposed, the influence of the radius ratio on the crucial MEEAD's voltage would be reduced. It means that the impact of the radius ratio on the crucial voltage of the smart disk decreases by increasing the elastic parameter of the substrate.

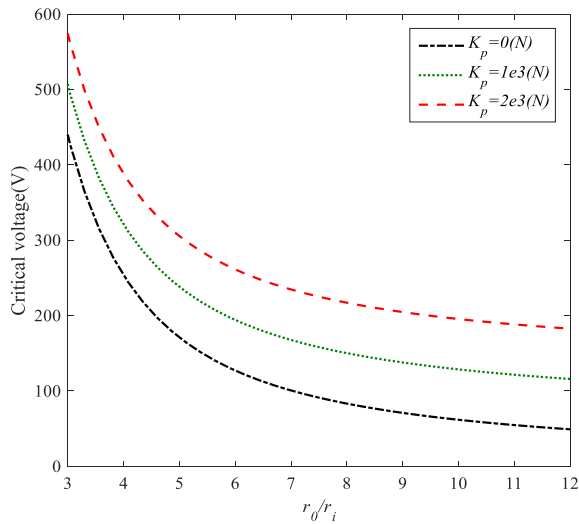


Fig. 10 Critical voltage of a MEEAD versus r_o/r_i for different K_p

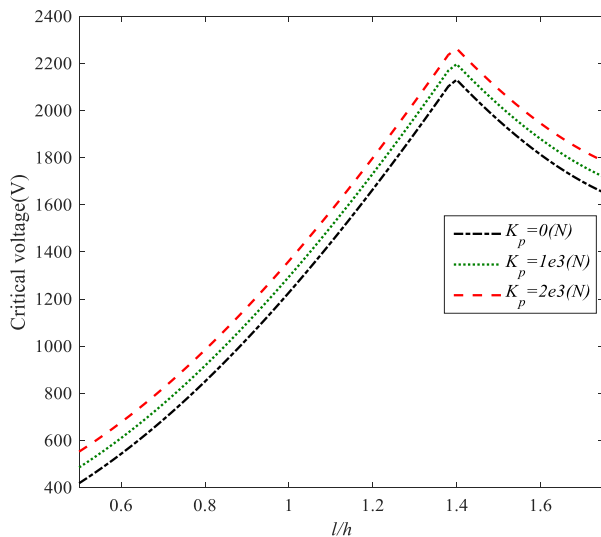


Fig. 11 Critical voltage of a MEEAD versus l/h for different K_p

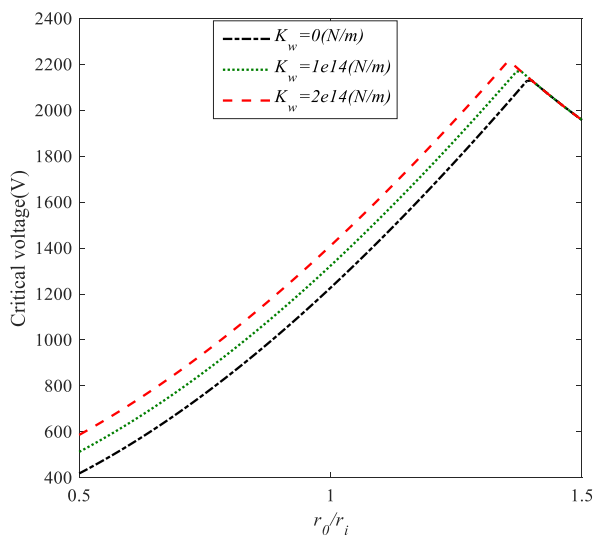


Fig. 12 Critical voltage of a MEEAD versus r_o/r_i for different K_w

The MEEAD’s vibration has been illustrated in Fig. 10 by assuming MCS model for multifarious Pasternak parameters of the substrate (K_p) and C-F boundary conditions. Disclosed data in Fig. 10 provides that when the substrate would be inserted, as the K_p raise, the crucial voltage of the MEEAD would be boosted; however, should have the attention that the mentioned enhancement would become highlighted in the higher radius ratio.

Dynamic information of the MEEAD versus to length scale parameter (l/h) is shown in Fig. 11 for different Pasternak factor of the foundation (K_p) and Clamped-Free boundary conditions.

The presented information in Fig. 11 shows that for each K_p , as the length scale parameter increases the critical applied voltage of the MEEAD increases as long as a maximum value for the critical factor is appeared, after the maximum point there is an exponential decline

In the critical applied voltage of the MEEAD due to increasing the length scale parameter. As conclusion, there is a critical length scale parameter in which the relation between l/h and critical applied voltage changes from direct to indirect. In addition, as can be seen in Fig. 11 there is a direct effect from Pasternak factor on the critical applied voltage of the MEEAD. Furthermore, if the Pasternak foundation is reinforced the critical length scale parameter doesn’t have any changes so it means that the critical value of l/h parameter doesn’t affect by the Pasternak parameter.

The given diagrams in Fig. 12 inform that, as the K_w increase, the critical voltage of the MEEAD improves but should have the attention that mentioned enhancement becomes remarkable in the grater radius ratio. Furthermore, When the substrate would be supposed, the influence of the radius ratio on the crucial voltage of a MEEAD is reduced. It means that the influence of the radius ratio on the crucial voltage of the smart disk decreases by increasing the elastic parameter of the substrate.

5.1 Comparing DNN outcomes with those provided in Figure 5 for $\Phi_0 = 60$ (V)

For comparing the ADADELTA performance with another optimizer, Zeiler (2012) investigated their errors in classifying the handwriting MNIST dataset digits for 50 epochs. As the aforementioned figure demonstrated, ADADELTA performance exceeds other optimization techniques and reaches the final amount of the error during the least number. Then, ADADELTA would be classified as one of the extremely fast optimizers which would be able to reach less amounts of the least error amongst well-known optimization techniques. As it is previously mentioned, ADADELTA approach has been applied to tune the factors of DNN to create a regression-based estimator of vibrations of a disk. The hidden layers’ activation function acts due to the Rectified linear unit (ReLU). The procedure of training has been conducted by employing 70% of the dataset. The results’ accuracy has been evaluated by investigating the MSE of the validation and testing part of the dataset. The training procedure’s outcomes have been shown in Fig. 13. According to this figure, the nuance between the predicted

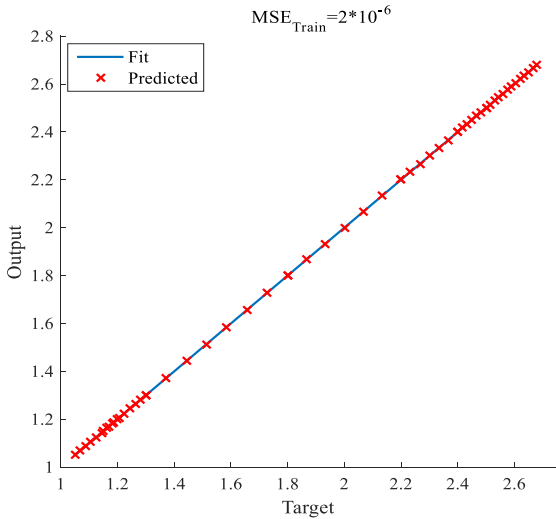


Fig. 13 DNN model estimation performance with respect to training data

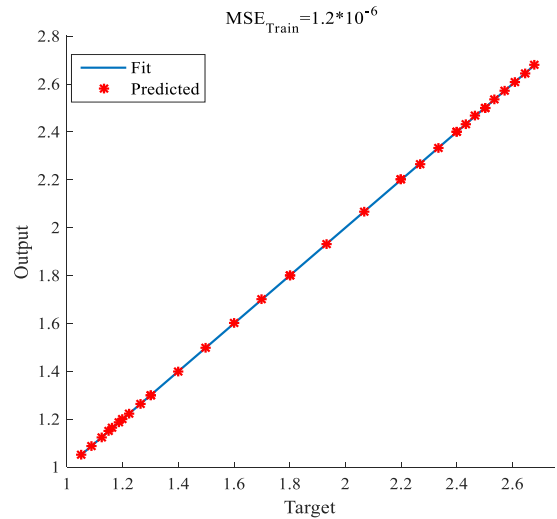


Fig.15 DNN model's estimation performance with respect to the training data

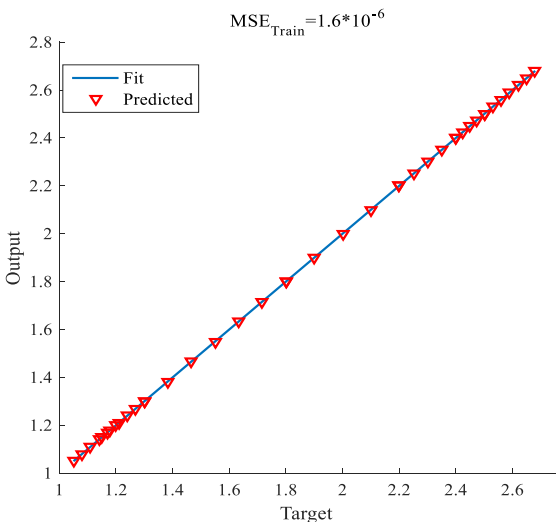


Fig. 14 DNN model's estimation performance with respect to test data

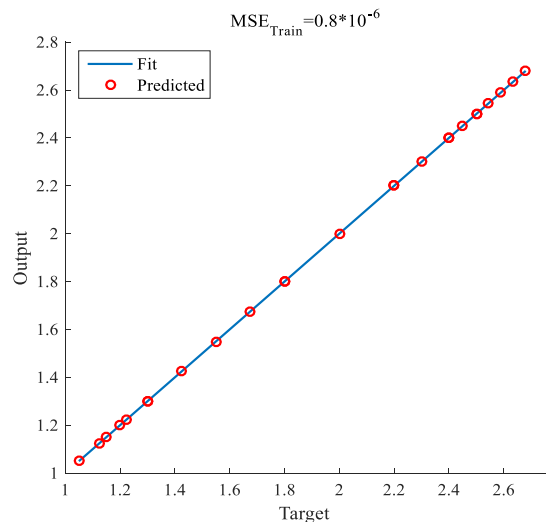


Fig. 16 DNN model's estimation performance with respect to the test data

frequencies and the expected ones would be totally desirable. It would be due to the fact that there are very small distances between the predicted points from the fitting line. The training procedure's small MSE ($MSE_{Train} = 2 * 10^{-6}$) implies the superb ability of ADADELTA for finding the suitable factors to tune the DNN. To make the mentioned performance of the mentioned fully connected DNN reliable, it would be needed to analyze the approach's accuracy toward verified and test sets.

Fig. 14 analyzes the accuracy of estimations conducted by DNN for the test dataset. According to this figure, the existing nuance between the estimated frequencies and the expected ones would be totally desirable. It would be due to the fact that there are very small distances in estimated points from the fitting line. The small MSE of the test procedure ($MSE_{Test} = 1.6 * 10^{-6}$) implies to the strength of the mentioned technique to estimate the vibration of the nano-scaled system.

The results of the training procedure are illustrated in

Fig. 15. According to this figure, the existing nuance between the estimated frequencies and the expected ones is totally desirable. It would be due to the fact that there are very small distances in estimated points from the fitting line. The small MSE of the training procedure ($MSE_{Train} = 1.2 * 10^{-6}$) implies to the superb abilities of ADADELTA for finding the proper factors to tune the DNN. To make the mentioned performance of the mentioned fully-connected DNN reliable, it would be needed to analyze the approach's accuracy toward verified and test sets.

Fig. 16 analyzes the accuracy of the predictions conducted by DNN for the test dataset. According to this figure, the existing nuance between the estimated frequencies and the expected ones is totally desirable. It would be due to the fact that there are very small distances in estimated points from the fitting line. The small MSE of the test procedure ($MSE_{Test} = 0.8 * 10^{-6}$) illustrates the strength of the mentioned technique to estimate the frequencies of the nano-sized system.

6. Conclusions

Based on the presented research, the mathematical formulations of small-scaled MEEAD due to the MCS mode have been extracted for the first time. Due to the FSDT and the variational approach, small-sized mathematical modeling, including related BCs and final governing equations, have been achieved. There were five coupling equations which were in terms of resultant forces along with displacement elements in its middle surface. Ultimately, the non-classical governing equations have been solved employing GDQ technique for multifarious BCs. The computational outcomes disclosed that:

- for the radius ratios more than critical one, changing the K_W parameter cannot make any effect on the critical applied voltage of the MEEAD
- there is a critical length scale parameter in which the relation between l/h and critical applied voltage changes from direct to indirect
- as the K_p increases, the critical voltage of the MEEAD can improve but should have attention that for both size-dependent theories, the mentioned improvement become remarkable for the grater radius ratio.
- when the size-dependent theory changes from classical to MCS theory, the impacts of Pasternak factor and radius ratio on the critical voltage of the system becomes weak and strengthened, respectively.
- the effect of the radius ratio on the critical voltage of the MEEAD decreases by increasing the elastic factor of the foundation
- there would be an indirect influence from Φ_0 on the MEEAD's frequency and the mentioned influence would be highlighted at the primary wave numbers
- there would be ranges of radius ratio in which we would not be able to find any impacts from C_d parameter on the system's dynamics, and this ineffective range would become close due to improvement in the damping parameter of the substrate.

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