Advances in Nano Research, *Vol. 14, No. 2 (2023) 141-154*
https://doi.org/10.12989/anr.2023.14.2.141

Hybrid adaptive neuro-fuzzy inference system method for energy absorption of nano-composite reinforced beam with piezoelectric face-sheets

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(*Received February 4, 2022, Revised June 14, 2022, Accepted June 15, 2022*)

Abstract. Effects of viscoelastic foundation on vibration of curved-beam structure with clamped and simply-supported boundary conditions is investigated in this study. In doing so, a micro-scale laminate composite beam with two piezoelectric face layer with a carbon nanotube reinforces composite core is considered. The whole beam structure is laid on a viscoelastic substrate which normally occurred in actual conditions. Due to small scale of the structure non-classical elasticity theory provided more accurate results. Therefore, nonlocal strain gradient theory is employed here to capture both nano-scale effects on carbon nanotubes and microscale effects because of overall scale of the structure. Equivalent homogenous properties of the composite core is obtained using Halpin-Tsai equation. The equations of motion is derived considering energy terms of the beam and variational principle in minimizing total energy. The boundary condition is assumed to be clamped at one end and simply supported at the other end. Due to nonlinear terms in the equations of motion, semi-analytical method of general differential quadrature method is engaged to solve the equations. In addition, due to complexity in developing and solving equations of motion of arches, an artificial neural network is design and implemented to capture effects of different parameters on the in-plane vibration of sandwich arches. At the end, effects of several parameters including nonlocal and gradient parameters, geometrical aspect ratios and substrate constants of the structure on the natural frequency and amplitude is derived. It is observed that increasing nonlocal and gradient parameters have contradictory effects of the amplitude and frequency of vibration of the laminate beam.

Keywords: composite curved beam; Hamilton's principle; nonlocal strain gradient theory; piezoelectric

1. Introduction

Motion sensors are widely used is dynamical systems to observe loading conditions and vibration of the systems (Zhang *et al*. 2016, Wang *et al*. 2018, Gao *et al*. 2022). The type of loading i.e., harmonic, impact, constant, etc. could be detected by pattern of vibration in the motion sensors (Peng *et al*. 2022, He *et al*. 2022, Lei *et al*. 2022). On the other hand, abnormal vibration patterns could be a sign of malfunctioning of the dynamic system. Motions sensors must both light weight enough to not disturb the mass properties of the system and also reliable to accurately send signals to the control center (Lu *et al*. 2021, Zhou *et al*. 2021, Shen *et al*. 2022). In this regard, piezoelectric equipped small-scale beams has been an appropriate candidate for motion sensors (Lai *et al*. 2020, Zhang *et al*. 2020, 2022d).

Many research studies have been devoted to the mechanical behavior analyses of piezoelectric equipped small-scale structures (Ke and Wang 2012, Abazid and Sobhy 2018, Habibi *et al*. 2019a, Mahinzare *et al*. 2019, Shokrgozar *et al*. 2019, Al-Furjan *et al*. 2020h, 2021, Chen *et al*. 2020, Lori *et al*. 2020, Lori Dehsaraji *et al*. 2021, Shamsaddini Lori *et al*. 2021, Yu *et al*. 2022). Abazid and Sobhy (2018) investigated the bending of functionally graded piezoelectric small-plates under thermo-electro-mechanical loading conditions. They utilized shear deformable shear theory to obtain the displacement field in the plate and further utilized modified couple stress theory to obtain the relationship between stress and strain tensor components in the small-plate. Using this method makes it possible to capture the micro-scale phenomenon in the structures. The results indicated the significant influence of the electrical and geometrical parameters on the bending behavior of these plates. Al-Furjan *et al*. (2021) investigated the dynamic stability of rotating cylinders with a piezoelectric layers to observe the critical rotational velocity. The cylinders contains flow of fluids and different shear deformation shell theories were employed to present the displacement field. In addition, a non-classical elasticity theory was applied in the constitutive equations. The behavior of the flowing fluids inside the cylinder also modeled using Navier-Stokes relations. The results of this study reveals that using PD controller it is possible to reduce vibrational effects in rotating cylindrical shell. Chen *et al*. (2020) presented the vibrational responses of a disk with a piezoelectric layer posed on a viscoelastic substrate. They utilized modified couple stress theory to consider small scale effects of the structure. The aim of using piezoelectric layer is to control the vibration of the disk which was claimed to be highly successful in the structure. Moreover, viscoelastic substrate is shown to be effective in alleviating instability problems.

Beam structures are the simplest structure to be used in the sensing movement in the dynamic systems (Khorshidi *et*

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ISSN: 2287-237X (Print), 2287-2388 (Online)

al. 2022, Zhang *et al*. 2022c, Zhu and Zhao 2022). Formulation of piezoelectric mechanical behavior using Hamilton's principle is presented by Nadal and Pigache (2009). Piezoelectric beam vibration response of was also presented and compared to finite element method. Ke *et al*. (2012) investigated nonlinear vibration of composite beam structure using nonlocal elasticity theory and Hamilton's principle. Size-dependency and effects of external voltage loads variations were applied to observe the frequency responses of the beam structure. Naderi *et al*. (2021) utilized static and dynamic instability of nano-scale beams using both classical and nonlocal theories in piezoelectric equipped beams. Moreover, they consider energy harvesting capability of beam structures. Ebrahimi and Barati (2017) investigated effects of elastic substrate and external applied voltage on the buckling instability in nano-size beams employing nonlocal elasticity of Eringen theory. Differential form of Eringen's nonlocal elasticity theory is employed to capture the electromechanical responses of beam structure under various boundary and loading conditions (Eltaher Mohamed *et al*. 2020). Controlling of vibration beam structure is also a subject of interest in many articles. Bruant and Proslier (2016) considered a sub-sized piezoelectric patch on a functionally graded beam to find the best location of the patch for controlling vibration of the beam. They utilized numerical method in different boundary conditions and found that based on the geometry and boundary condition the optimum location of the piezoelectric patch varied.

Curved beam structures are different from straight beams in both formulation and dynamic responses. Several articles presented various formulation of the curved beams. Instability of the curved beam was presented by Babaei and Eslami (2019). Piezoelectric patches served as vibration actuator in their analysis and the beam was assumed to be functionally graded. The results of the study indicated that thermal and small-scale effects considerably alters the snap-through instability of the beam structure. Hajianmaleki and Qatu (2013) reviewed articles on the vibration straight and curved beam structures.

Solving equation od motions in solid mechanics in most cases requires numerical methods (Nejad *et al*. 2016, Amelirad and Assempour 2019, Habibi *et al*. 2019a, Mohammadi *et al*. 2019, Al-Furjan *et al*. 2020g, Bai *et al*. 2020b, Shokrgozar *et al*. 2020a, Amelirad and Assempour 2021, Guo *et al*. 2021b, Safarpour *et al*. 2021). Numerical methods beside their complicity in preparing equations and also computational costs are not versatile in terms of adding new parameters to investigate. In such cases, the whole formulation and process of solving should be repeated. In this regard, researches in this field have utilized artificial intelligence methods to reduce the time of obtaining results having the same level of accuracy as the numerical methods (Abbod *et al*. 2007, Singh *et al*. 2020, Zhang *et al*. 2022f).

Effects of viscoelastic foundation on vibration of curved-beam structure with clamped and simply-supported boundary conditions is investigated in this study. In doing so, a micro-scale laminate composite beam with two piezoelectric face layer with a carbon nanotube reinforces composite core is considered. The whole beam structure is laid on a viscoelastic substrate which normally occurred in actual conditions. Due to small scale of the structure non-classical elasticity theory provided more accurate results. Therefore, nonlocal strain gradient theory is employed here to capture both nano-scale effects on carbon nanotubes and microscale effects because of overall scale of the structure. Equivalent homogenous properties of the composite core is obtained using Halpin-Tsai equation. The equations of motion is derived considering energy terms of the beam and variational principle in minimizing total energy. The boundary condition is assumed to be clamped at one end and simply supported at the other end. Due to nonlinear terms in the equations of motion, semi-analytical method of general differential quadrature method is engaged to solve the equations. In addition, due to complexity in developing and solving equations of motion of arches, an artificial neural network is design and implemented to capture effects of different parameters on the in-plane vibration of sandwich arches. At the end, effects of several parameters including nonlocal and gradient parameters, geometrical aspect ratios and substrate constants of the structure on the natural frequency and amplitude is derived.

2. Related research

2.1 Geometry of the micro-scale sandwich curved-beam

The structure and geometry of the curved beam sandwich structure on a viscoelastic substrate is depicted schematically in Fig. 1. The sandwich beam in made of 3 layers, two piezoelectric facesheets with thickness h_p and one nan-composite core layer with h_c thickness. The total thickness of these layers is denoted as h. Initial curvature radius of the structure is R and the whole beam structure is posed on a viscoelastic substrate with C_p as viscous coefficient, K_p as Pasternak coefficient and K_w as Winkler coefficient. Moreover, one end of the beam structure is completely tied and restricted from motion in any direction. The other end is restricted only in the radial direction and is free to move in conferential direction.

2.2 Displacement field based on first-order shear defamation theory

In this study, we assume small deformation theories in elastic range for all materials. The displacement field for curved beam in polar curvilinear coordinate system for first order shear deformation theory (FSDT) (Xiao *et al*. 2022, Zhang *et al*. 2022e, Bai *et al*. 2023) is as follows (Habibi *et al*. 2016, 2018a, b, 2019b, d, e, Ebrahimi *et al*. 2019a, Esmailpoor Hajilak *et al*. 2019, Pourjabari *et al*. 2019, Safarpour *et al*. 2019a):

$$\begin{aligned} u_\theta(z,\theta,t) &= -(R+z)\frac{\partial u_{r0}(\theta,t)}{\partial s} \\ &+u_{\theta 0}(\theta,t)\left(1+\frac{z}{R}\right)+f(z)\phi(\theta,t) \\ u_r(z,\theta,t) &= u_{r0}(\theta,t) \\ u_{op}(z,\theta,t) &= 0 \end{aligned} \tag{1}$$

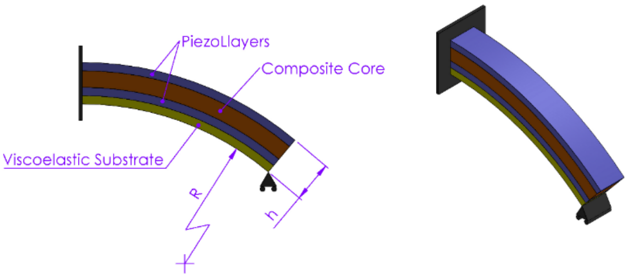

Fig. 1 Curved-beam made of laminate composite with clamped and simply supported ends

in which, z is the radial distance from the central axis of the curved beam, θ is the counterclockwise circumferential coordinate. Displacement components in radial, circumferential and out-of-plane direction are denoted by u_r, u_θ and u_{op}, respectively. The 0 subscript shows the quantity on the central axis of the curved beam with initial radius of R. It should be noted that variable s is the directional length of the central axis of the curved beam and equals to $s = R\theta$ and $\frac{ds}{d\theta} = R$

2.3 Strains in curved beams

Having the displacement field and assuming small-deformation theory of elasticity the strain components could be easily calculated using the definition of strain tensor in polar coordinate system (Habibi *et al*. 2017, 2019a, c, Safarpour *et al*. 2018, 2019b, 2020, Alipour *et al*. 2020, Ebrahimi *et al*. 2020a, Ghazanfari *et al*. 2020, Chen *et al*. 2022):

$$\boldsymbol{\epsilon} = \frac{1}{2}(\nabla \boldsymbol{u} + \nabla \boldsymbol{u}^T) \tag{2}$$

which results in:

$$\begin{aligned}
\epsilon_\theta &= \frac{1}{r}\frac{\partial u_\theta}{\partial \theta} + \frac{u_r}{r} \\
&= -\frac{zR}{z+R}\frac{\partial^2 u_{r0}}{\partial s^2} + \frac{u_{r0}}{z+R} + \frac{\partial u_\theta}{\partial \theta} + \frac{f(z)}{R}\frac{\partial \phi}{\partial s} \\
\epsilon_r &= \frac{\partial u_r}{\partial r} = \frac{\partial u_{r0}}{\partial z} = 0 \\
\epsilon_{op} &= 0
\end{aligned} \tag{3}$$

having in mind that $r = R + z$.

2.4 Consistency relationship between layers

The condition between layers are considered to be fully bonded in which normal and tangential relative movement is restricted. Therefore, the following relations must be held in interface of the layers (Ebrahimi *et al*. 2019b, c, 2020b, Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, b, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, 0b, Shokrgozar *et al*. 2020b):

$$\begin{aligned}
u_{rpl}\left(-\frac{h_c}{2}, \theta, t\right) &= u_{rc}\left(-\frac{h_c}{2}, \theta, t\right) \\
u_{rpu}\left(\frac{h_c}{2}, \theta, t\right) &= u_{rc}\left(\frac{h_c}{2}, \theta, t\right) \\
u_{\theta pl}\left(-\frac{h_c}{2}, \theta, t\right) &= u_{\theta c}\left(-\frac{h_c}{2}, \theta, t\right) \\
u_{\theta pu}\left(\frac{h_c}{2}, \theta, t\right) &= u_{\theta c}\left(\frac{h_c}{2}, \theta, t\right)
\end{aligned} \tag{4}$$

It must be noted that these relations does not guarantee the continuousness of the strain field as passing through interfaces. They only maintain the continuity of the displacement field (Zhang *et al*. 2022a, b, Li *et al*. 2023).

2.5 Constitutive equations based on nonlocal strain gradient theory

Here we employed nonlocal strain gradient theory to observe vibrations response and energy absorption of the arches structure. Moreover, using this theory it is possible to capture the micro- and nan-effects of the small structures. The relationship between stress tensor $\boldsymbol{\sigma}$ and strain tensor $\boldsymbol{\epsilon}$ in small deformation space and linear material behavior is as follows (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020c, d, e, f, Bai *et al*. 2020a, Cheshmeh *et al*. 2020, Li *et al*. 2020a, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020c, Xiong *et al*. 2020, Guo *et al*. 2021c, Liu *et al*. 2021a):

$$[1 - (e_0 a)^2\, \nabla^2]\mathbb{C}^{-1}\boldsymbol{\sigma} = (1 - l_m^2 \nabla^2)\boldsymbol{\epsilon} \tag{5}$$

In the above equation $e_0 a$ is represents the nonlocal parameter which includes nonlocality e_0 and internal characteristic length a and l_m denotes the length scale parameter of the gradient theory. The operator ∇^2 is the Laplacian operator in which is defined in two dimensional polar coordinate system as below (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020b, Liu *et al*. 2020b, Zare *et al*. 2020, Dai *et al*. 2021b, Habibi *et al*. 2021, He *et al*. 2021, Huang *et al*. 2021a, Liu *et al*. 2021b, Zhang *et al*. 2021):

$$\nabla^2 = \frac{1}{r^2}\frac{\partial^2}{\partial \theta^2} + \frac{1}{r}\frac{\partial}{\partial r} + \frac{\partial^2}{\partial r^2} \tag{6}$$

Therefore, Eq. (5) could be expanded in the following form:

$$\begin{aligned}
\mathbb{C}^{-1}\left[\boldsymbol{\sigma} - (e_0 a)^2 \left(\frac{1}{r^2}\frac{\partial^2 \boldsymbol{\sigma}}{\partial \theta^2} + \frac{1}{r}\frac{\partial \boldsymbol{\sigma}}{\partial r} + \frac{\partial^2 \boldsymbol{\sigma}}{\partial r^2}\right)\right] \\
= \boldsymbol{\epsilon} - l_m^2 \left(\frac{1}{r^2}\frac{\partial^2 \boldsymbol{\epsilon}}{\partial \theta^2} + \frac{1}{r}\frac{\partial \boldsymbol{\epsilon}}{\partial r} + \frac{\partial^2 \boldsymbol{\epsilon}}{\partial r^2}\right)
\end{aligned} \tag{7}$$

Assuming that the elasticity tensor $\mathbb{C}$ is constant for the materials in this study. On the other hand, for the case of piezoelectric layers another term affects the state of strain coming from applied external voltage. The constitutive equation for the piezoelectric layers is as given below (Liu *et al*. 2020a, Wang *et al*. 2020, Zhou *et al*. 2020, Dai *et al*. 2021a, Guo *et al*. 2021a, Shao *et al*. 2021, Wu and Habibi 2021):

$$[1 - (e_0 a)^2\, \nabla^2]\mathbb{C}^{-1}\boldsymbol{\sigma} + \mathbb{D}^{-1}\mathbf{E} = (1 - l_m^2 \nabla^2)\boldsymbol{\epsilon} \tag{8}$$

In which $\mathbb{D}$ is the direct piezoelectric effect and $\mathbf{E}$ is the strength of the electric field. It is worth mentioning that piezoelectric layer could be utilized to produce electrical field when a strain field is applied to the material and this application is of interest in the current study to absorb vibrational energy.

2.6 Minimizing total energy of structure to obtain equations of motion

Minimizing the total energy of the structure is called Hamilton's principle which presented the equations of motion of a structure. In the following equation, neglecting thermal effects, variations of all the energies in the structure is presented (Ma *et al*. 2022, Zhao *et al*. 2022, Hou *et al*. 2021, Huang *et al*. 2021b, c, Jiao *et al*. 2021, Liu *et al*. 2021c, Moradi *et al*. 2021, Xu *et al*. 2021, Dong *et al*. 2022, Luo *et al*. 2022b, Michael *et al*. 2022, Wang *et al*. 2022b, Yang *et al*. 2022, Yu *et al*. 2022).

$$\delta\int_0^t \left(U-K-W_{piezo}-W_{ext}\right)dt=0 \tag{9}$$

The term U includes internal energy of the structure which in absent of thermal energies reduces to elastic energy of the material (Fan *et al*. 2022, Wang *et al*. 2022a, Xia *et al*. 2022):

$$U=\int_V \boldsymbol{\sigma}:\boldsymbol{\epsilon}\,\mathrm{d}V \tag{10}$$

The second term represent the kinetic energy of the structure which is expressed as:

$$U=\frac{1}{2}\int_V \boldsymbol{\rho}\mathbf{v}.\mathbf{v}\mathbf{d}\boldsymbol{V} \tag{11}$$

where ρ is the density of the material and $\mathbf{v}$ is the velocity vector of material point (Yan *et al*. 2018, Luo *et al*. 2022a, Peng *et al*. 2022). In addition to these conventional energies, the work done by external forces is denoted by W_{ext}:

$$W_{ext}=\int_S \mathbf{F}_{ext}.\mathbf{u}\,\mathrm{d}S \tag{12}$$

Finally, the expression of the energy added by piezoelectric effects could be given by (Tiersten 1967):

$$W_{piezo}=\int_V \mathbf{D}:\mathbf{E}\,\mathrm{d}V \tag{13}$$

where $\mathbf{D}$ is the electric flux density within the piezoelectric material and it is equal to $\mathbf{D}=\mathbb{D}^{-1}\mathbf{E}$. Therefore, substituting Eqs. (10)-(13) into Eq. (9) results in:

$$\delta\int_0^t \left(\frac{1}{2}\boldsymbol{\sigma}:\boldsymbol{\epsilon}-\frac{1}{2}\boldsymbol{\rho}\mathbf{v}.\mathbf{v}-\mathbf{F}_{ext}.\mathbf{u}-\mathbf{D}:\mathbf{E}\right)dt \tag{14}$$

Performing the variation operation, using integration by part, definition of the small strains and divergence theorem the following equations of motions could be extracted (Nadal and Pigache 2009):

$$\begin{aligned}\operatorname{div}\boldsymbol{\sigma}&=\rho\ddot{\mathbf{u}}\\ \operatorname{div}\mathbf{D}&=\mathbf{0}\end{aligned} \tag{15}$$

Moreover, the boundary conditions are determined to be:

$$\begin{gathered}\mathbf{D}.\mathbf{n}=0,\ \frac{\partial u_r}{\partial s}=0\ and\ u_r=0\ at\ s=0,\\ EI\frac{\partial^2u_r}{\partial s^2}=0,\qquad \frac{\partial}{\partial s}\left(EI\frac{\partial^2u_r}{\partial s^2}\right)=0\ at\ s=L\end{gathered} \tag{1}$$

3. Material characteristics and equivalent composite properties

The elastic constants of different components of the structure as well as electrical properties of the piezoelectric layers are provided in Table 1.

Since in the present study we are interested in the overall vibration responses of the curved beam structure, the details of interaction between CNT and matrix in the composite core are not desired for our purpose. Instead, an equivalent of the elastic properties is employed for frequency and energy absorption analysis. There are several approaches to obtain the elastic constants of a composite material. Here, we utilized rule of mixture to convert heterogeneous properties to homogeneous one:

$$\begin{aligned}E_{RC}&=V_{CNT}E_{CNT}+V_mE_m\\ \nu_{RC}&=V_{CNT}\nu_{CNT}+V_m\nu_m\end{aligned} \tag{17}$$

where RC represent the reinforced composite and m denoted the matric properties. Parameters V are the volume fraction of the components. Solution procedure

4. Generalized differential quadrature method (GDQM)

The idea of the differential quadrature method is very simple although it is very effective. In this method, the derivative of a function in a domain is approximated by weighted values of the function value at certain points inside the domain called seeds (Safa *et al*. 2019, Shariati *et al*. 2019a, 2020d, f, Suhatril *et al*. 2019, Jahandari *et al*. 2021). Hence, at each point of the domain, here on the directional length of the curved beam, the derivative of the function is replaced by the following expression:

$$f'(x_i)=\sum_{j=1}^{N} w_{ij}f(x_j) \tag{18}$$

here, the weight coefficients are w_{ij} and N denoted number of seeds in the domain. There are several method for calculating weight coefficient for better performance and accuracy improvement of the method. In the present study, the shifted Legendre polynomial $P_n(x_i)$ is utilized as follows:

$$w_{ij}=\frac{1}{x_i-x_j}\frac{P_n(x_i)}{P_n(x_j)} \tag{19}$$

Table 1 The material properties of the beams in the current study

Piezo-magneto		Core	
$E_p(GPa)$	226	$E_m(GPa)$	2.5
$\kappa_{11}(C(mV)^{-1})$	5.64×10^{-9}	$E_{CNT}(GPa)$	600
$e_{31}(Cm^{-2})$	2.2	ν_m	0.34
$e_{15}(Cm^{-2})$	5.8	ν_{CNT}	0.19
$\kappa_{11}(C(mV)^{-1})$	6.35×10^{-9}	$\rho_m\left(\frac{Kg}{m^3}\right)$	1.72
$\rho\left(\frac{Kg}{m^3}\right)$	5.55	$\rho_{CNT}\left(\frac{Kg}{m^3}\right)$	1.19

Table 2 Comparison of non-dimensional natural frequency calculated by the present method with Ref.(Karkon 2018) for curved beam structure

		Mode of vibration			
h/L		1st	2nd	3rd	4th
0.01	Present	3.1409	6.2808	9.4182	12.5487
	Ref.	3.1413	6.2811	9.4176	12.5494
0.1	present	3.1149	6.091	8.8409	11.3429
	Ref	3.1157	6.0907	8.8405	11.3432
0.2	present	3.0448	5.6715	7.8388	9.6603
	Ref.	3.0453	5.6716	7.8396	9.6572

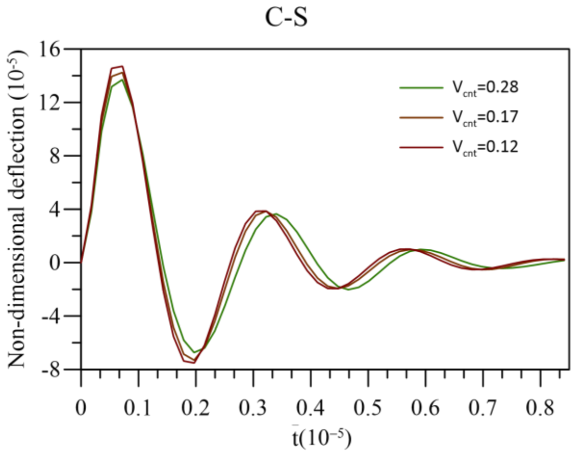

Fig. 2 Reliance of the vibration of small-scale sandwich curved beam on the CNT volume fraction

Moreover, roots of the Legendre polynomial are used as the seeds of the DQM method. Based on the accuracy required, polynomial degree is selected. In this study, Legendre polynomial of degree 7 is utilized for analysis.

5. Artificial intelligence network

Using artificial intelligence method (Peng *et al.* 2020, Yan *et al.* 2020, Fu *et al.* 2022, Dong *et al.* 2023) has shown to be promising in delivering results with acceptable accuracy and without need to deal with numerical solution issues like convergency and stability of the procedure (Mohammadhassani *et al.* 2013, 2014, Shah *et al.* 2015, 2016a, b, Khanouki *et al.* 2016, Heydari and Shariati 2018, Shariat *et al.* 2018, 2020e, Chen *et al.* 2019, Luo *et al.* 2019, Xie *et al.* 2019, Naghipour *et al.* 2020, Razavian *et al.* 2020). Therefore, it this section we aimed to present an artificial neural network (ANN) to directly obtain the vibration response of the curved beam structure from affecting factors like geometrical and materials parameters. In this regard, an ANN according to Fig. 2 is designed with one input layer and one output layer. Moreover, the network was seen to have best performance with 2 hidden layers (Shariati 2008, 2011, 2018, 2019b, 2020e, Hamidian *et al.* 2011, Shah *et al.* 2015, 2016a, b, Khanouki *et al.* 2016, Toghroli *et al.* 2017, 2018, 2020, Chen *et al.* 2019, Li *et al.* 2019, Naghipour *et al.* 2020, Razavian *et al.* 2020, Hosseini and Toghroli 2021, Mehrabi *et al.* 2021).

The artificial networks generally require a set of validate and reliable data from experiment or simulation to the purpose of training. The required data in the present study is collected from the validated numerical simulations of the curved beam vibration. Moreover, a portion of the same dataset (20% of the collected data) is randomly separated to test the performance of the network. The neural networks during the training course needs to be checked continuously to avoid over-fitting. Therefore, 10% of the dataset is reserved for validation of the process. Among many parameters influencing vibration of the neural network, effects of CNT volume fraction, external voltage, substrate coefficient, length scale parameter and geometrical aspect ratios are selected to observe the reaction of the vibrating sandwich curved beam structure.

6. Results

6.1 Validation of the methodology

The presented methodology in the previous sections are now verified by solving similar geometry and loading condition presented in literature. In doing so, the results dimensionless natural frequency $\bar{\omega}=\omega L^2\left(\frac{I_0}{A_3}\right)^{\frac{1}{2}}$ for a simply-supported curved beam structure is presented in Table 2 for different geometrical ratio h/L. The viscoelastic foundation is eliminated in harmony with the reference study and the ratio of length of the beam to its curvature is $\frac{\pi}{360}$. As could be observed, the presented method performs very well in comparison to other methodologies and hence it will be further utilized to analyzing parametric study on the vibration behavior of the curved beam structure.

6.2 Numerical parametric study

Effects of different parameters on the natural frequency and amplitude of the sandwich curved beam structure on viscoelastic substrate (Moradi *et al.* 2022, Zhu *et al.* 2022, Fang *et al.* 2023, Zhao *et al.* 2023, Zheng *et al.* 2023). Fig. 2 presents the effect of the volume fraction of the CNT in the composite core layer on the vibration behavior of the curved beam. Other parameters of the study are set to be $K_p=K_w=0$, $\frac{L}{R}=\frac{\pi}{360}$, $\frac{L}{h}=10$ and nonlocal and length

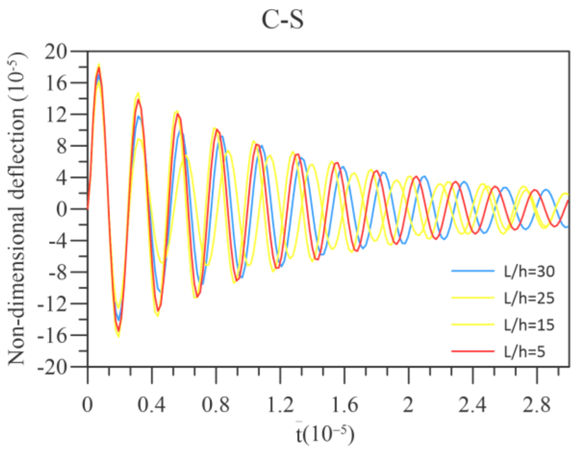

Fig. 3 Reliance of the vibration of small-scale sandwich curved beam on the ratio of length to height

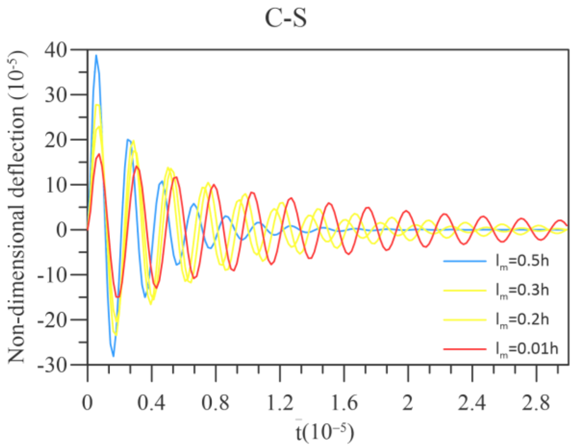

Fig. 4 Reliance of the vibration of small-scale sandwich curved beam on the length scale parameter

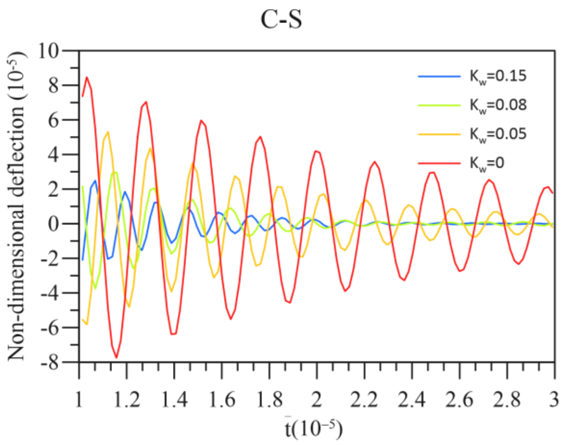

Fig. 5 Reliance of the vibration of small-scale sandwich curved beam on the K_w parameter

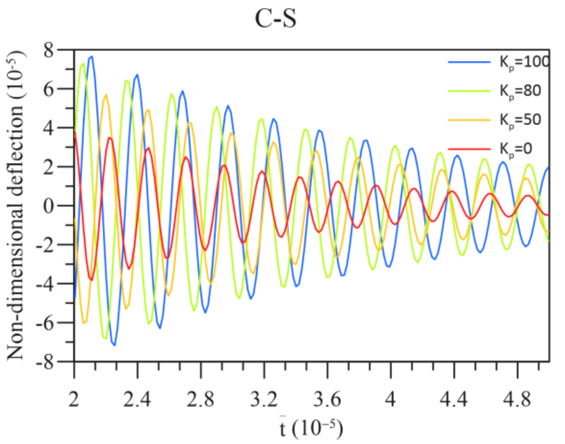

Fig. 6 Reliance of the vibration of small-scale sandwich curved beam on the K_p parameter

scale parameters are zero. As observed, volume fraction of the CNT in the core of the sandwich beam has a minor effect on the overall vibration response of the structure. Although, with increase in the V_{CNT} the frequency of the structure decreases by little amount. The damping of the vibration is a direct result of the energy absorption of the piezoelectric face sheets.

In Fig. 3, effect of slenderness of the beam is shown on the vibration responses of the curved beam. The slenderness is defined as ratio of length to the height of the beam. Increasing ratio of length to the height of the structure in general results in decrease in the natural frequency of the structure as is also seen in the case of sandwich curved beam. Moreover, the damping characteristics of the structure does not show an observable dependency on the slenderness of the curved beam.

Effect of the length scale parameter on the amplitude response and energy absorption of the curved beam in depicted in Fig. 4. It is seen that high values of the length scale, i.e., smaller beams, shows more stable vibration responses as the structure damps sooner for l_m=0.5h than other smaller values. On the other hand, the frequency of the structure also increase in smaller beam sizes.

Elastic substrate which is inevitable in small scale structures has significant influence on the vibration of curved beams. As seen in Fig. 5, increasing K_w parameter is in favor of the vibration of the curved beam structure as it results in decrease in amplitude and increase in the natural frequency.

Contrary to the K_w parameter, increase in the K_p parameter have a deleterious effect on the vibration and stability of the curved beam structure. In Fig. 6, it is shown that increase in this parameter both increase the amplitude and decrease the frequency of the structure which are not desirable. In addition, damping of the structure is considerable affected by this parameter. In high values of K_p, damping is much smaller than low values.

The parameter C_d also affected the damping of vibration in the curved beam structure as illustrated in Fig. 7. As expected, increase in this parameter significantly decrease the amplitude of the vibrating structure during time. Moreover, it decrease the frequency of the structure but this reverse effect is not comparable with the favorable effect decreasing amplitude.

6.3 ANN performance and accuracy in predicting results

Generally, trained neural networks presents the final

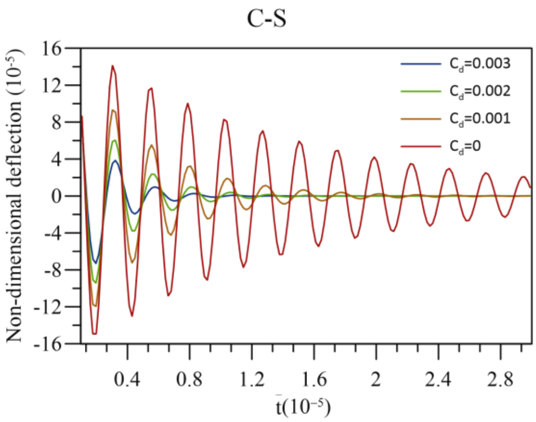

Fig. 7 Reliance of the vibration of small-scale sandwich curved beam on the C_d parameter

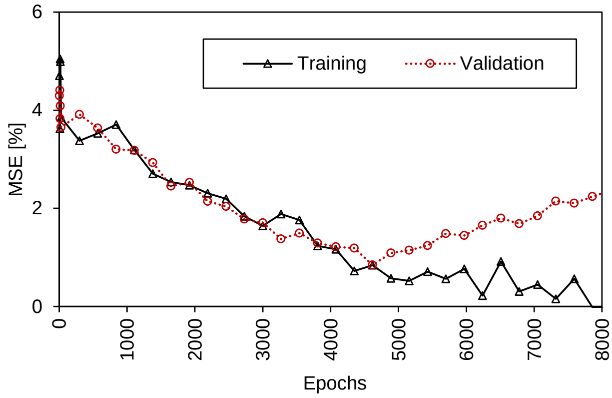

Fig. 8 Validation of the training process to avoiding over-fitting data

results of desired output. Therefore, the final results will be compared to the outcomes of the numerical simulation to check the performance of the ANN. ANNs could reach extremely small error margin when in the training process given sufficient time and epochs. However, caution must be exercised to avoid over-fitting by comparison of the mean square error (or other loss functions) of training and validation during the process. In Fig. 8, it is seen that after ~4500 epochs the difference errors between training and validations increases indicating that the best performance of the ANN before over-fitting. Thus, the weights and biases of the network at this point is saved for further processing.
Testing the trained network is a crucial part of the ANN design. Fig. 9 presents the performance of the ANN predictions with comparison of the numerical results. For deflection predictions the correlation between training results is R^2=0.893 while for testing it is R^2=0.887 which is satisfactory. In the case of the frequency prediction ANN performs much better than for deflections with correlation factor R^2=0.965 and R^2=0.952 for training and testing processes. Therefore, with high correlation factors, the ANN network performs acceptably in comparison to numerical results while requires extremely lower computational cost and ability to be extended for more factors incorporation in the prediction of the deflection and frequency.

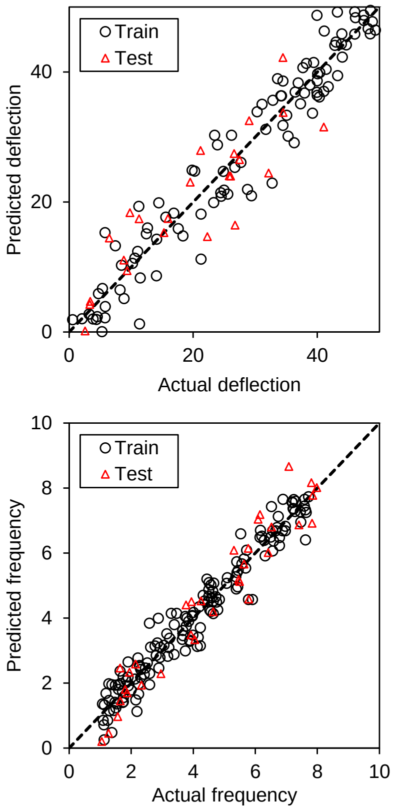

Fig. 9 Performance of ANN in the training and testing processes

7. Conclusions

Effects of viscoelastic foundation on vibration of curved-beam structure with clamped and simply-supported boundary conditions is investigated in this study. In doing so, a micro-scale laminate composite beam with two piezoelectric face layer with a carbon nanotube reinforces composite core is considered. The whole beam structure is laid on a viscoelastic substrate which normally occurred in actual conditions. Due to small scale of the structure non-classical elasticity theory provided more accurate results. Therefore, nonlocal strain gradient theory is employed here to capture both nano-scale effects on carbon nanotubes and microscale effects because of overall scale of the structure. Equivalent homogenous properties of the composite core is obtained using Halpin-Tsai equation. The equations of motion is derived considering energy terms of the beam and variational principle in minimizing total energy. The boundary condition is assumed to be clamped at one end and simply supported at the other end. Due to nonlinear terms in the equations of motion, semi-analytical method of general differential quadrature method is engaged to solve the equations. In addition, due to complexity in developing and solving equations of motion of arches, an artificial neural network is design and implemented to capture effects of different parameters on the in-plane vibration of sandwich arches. At the end, effects of several parameters including nonlocal and gradient parameters, geometrical aspect ratios and substrate constants of the structure on the natural frequency and amplitude is derived and the main results are:

- High values of the length scale, i.e. smaller beams, shows more stable vibration responses.
- Increasing ratio of length to the height of the structure in general results in decrease in the natural frequency of the structure
- Volume fraction of the CNT in the core of the sandwich beam has a minor effect on the overall vibration response of the structure.
- Increasing K_w parameter is in favor of the vibration of the curved beam structure.
- The designed ANN network performed acceptably in comparison to numerical results while requires extremely lower computational cost and ability to be extended for more factors incorporation in the prediction of the deflection and frequency.

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