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A hybrid artificial intelligence and IOT for investigation dynamic modeling of nano-system

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Abstract. In the present study, a hybrid model of artificial neural network (ANN) and internet of things (IoT) is proposed to overcome the difficulties in deriving governing equations and numerical solutions of the dynamical behavior of the nano-systems. Nano-structures manifest size-dependent behavior in response to static and dynamic loadings. Nonlocal and length-scale parameters alongside with other geometrical, loading and material parameters are taken as input parameters of an ANN to observe the natural frequency and damping behavior of micro sensors made from nanocomposite material with piezoelectric layers. The behavior of a micro-beam is simulated using famous numerical methods in literature under base vibrations. The ANN was further trained to correlate the output vibrations to the base vibration. Afterwards, using IoT, the electrical potential conducted in the sensors are collected and converted to numerical data in an embedded mini-computer and transferred to a server for further calculations and decision by ANN. The ANN calculates the base vibration behavior with is crucial in mechanical systems. The speed and accuracy of the ANN in determining base excitation behavior are the strengths of this network which could be further employed by engineers and scientists.
Keywords: artificial neural network; base vibration; internet of things; nano-systems; sensors

1. Introduction

Advancements in the technology of sensors are outdating operational works in industries. Nowadays, sensors take the duty of operators in inspection of the integrity and continuousness of a production line and devices. Systems similar to wind turbines, electro pumps and helicopter blades under extreme loads need to be checked unceasingly. On this matter, sensors have helped significantly (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, Kong *et al*. 2022). However, the sensors have their own physical dimensions and weight which sometimes pose some difficulties in design, specifically in moving systems. Micro sensors which are made from micro/nano-scale structure have overcome these problems. Use of this sensors is now overwhelming from mobile cell phones to quad-copters (Ebrahimi *et al*. 2019b, c, 2020b, Hashemi *et al*. 2019, Moayedi *et al*. 2019, 2020a, c, Mohammadgholiha *et al*. 2019, Mohammadi *et al*. 2019, Habibi *et al*. 2020, Oyarhossein *et al*. 2020, Shariati *et al*. 2020a, d, Shokrgozar *et al*. 2020b). Their satisfying performance and ease of use makes them an inevitable part of many devices. Smart systems use multiple micro-sensors which transferring collected data. The smart systems make the majority of the decisions without interference of human. The collecting data from sensors and decision making processes are delicate performances (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).

Using nano-systems in small-sized sensors have been attracted many industries in recent decade. Mechanical moving and rotating systems experiences dynamic loads and vibrations (Fan *et al*. 2022, Luo *et al*. 2022b, Michael *et al*. 2022, Wang *et al*. 2022b, c, Yang *et al*. 2022a, Zheng *et al*. 2022). Vibration of composite sandwich beams reinforced with nano structured materials is the focus of a study by Feng *et al*. (2017). They observed that with a small addition of graphene platelets (GPL) significant improvement in the bending responses of the nano-beam occur. Numerical solution was employed to obtain the static behavior of the structure. Pan *et al*. (2021) characterized vibrational energy absorption in nanocomposite beams using experimental and modified Biot's method. They observed that using 0.4% carbon nanotubes (CNTs) in the polymer matrix results in 0.41 improvement in the damping responses of the nanocomposite beams. It is also reported that extra using of CNT reinforcement cause deterioration of composite properties under dynamic loadings. Shi *et al*. (2018) reviewed the most recent articles on the polymer composites based on GPL. They provided valuable information on the preparation, properties and limitations in the polymer nanocomposites. The vibration and damping properties of nanocomposite rotating disks investigated by Ma *et al*. (2015) using general differential quadrature method. They concluded that layers configuration in laminated disk composite, rotation speed and geometrical

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parameters as well as nonlocal effects could have considerable effects on the frequency and amplitude of the disk. Moreover, it was reported that even number of layers in the laminated composite leads to more stable vibrational responses. Buckling instability of cylindrical shellsmade form polymer composite reinforces with GPL in the subject of a study by Shokrgozar *et al*. (2020a). They concluded that using general differential quadrature method (GDQM) effects of different geometrical and material factors can be captured. The result of this study could be utilized in design of industrial sensors. Porosity is an intrinsic characteristic of GPL-reinforced nano-composite materials. Pourjabari *et al*. (2019) clarified the effects of three type of porosity distribution patterns on the frequency of nano-systems. They utilized strain gradient based models to govern the differential equations and showed that the porosity had undoubted effects on the dynamic responses of the system under different mechanical and thermal loading conditions. Control of vibration in dynamical nano-systems is an imperative subject in small scales. Piezoelectric patches are widely used in the nano-systems to control the vibration amplitude. Al-Furjan *et al*. (2020g) did an extensive analysis on the vibration control of nano-composite shell structure to observe influences of different factors on the frequency and amplitude. They utilized numerical methods to solve governing equation of the nano-system and applied external voltages to alter vibrations responses. They discussed the applications of such PD controllers in smart industrial systems. Dynamic and static stability of nano-systems under thermal loadings have been broadly investigated in literature. Nano-systems in industrial applications frequently experiences harsh thermal conditions and their behavior and structural integrity are of importance in such cases. Linear thermal bucking of cylindrical small-size panels were analyzed using two dimensional equations of motions and numerical DQM-based method by Moayedi *et al*. (2020b). The panel was made of nano-composites based on GPL-reinforcements. Nonlinear distributed thermal loading along thickness direction were imposed on the structure to observe critical loading condition causing static instability. The results showed substantial effects of GPL weight fraction and curvature on the critical loading conditions. Other applications of numerical methods similar to finite elements and finite difference method could be found in following references (Hashemi *et al*. 2019, Al-Furjan *et al*. 2020c, Al-d, e, f, Bai *et al*. 2020, Cheshmeh *et al*. 2020, Li *et al*. 2020b, Lori *et al*. 2020, Najaafi *et al*. 2020, Shariati *et al*. 2020e, Xiong *et al*. 2020, Guo *et al*. 2021b, Liu *et al*. 2021a).

Applications of internet of things (IoT) have been widespread since its emerge in 2009 (Ashton 2009). The underlying principle of IoT laid in the direct contact between smart devices through internet-based networks. These types of direct contacts include data and command transformations. The traditional industrial control systems have local calculations with specific commands. The drawbacks of such systems is the limitation in computational ability and decision making under unknown conditions which in some cases results in unexpected shutdown of the systems. On the other hand, the widespread usage of nano-system based sensors makes traditional control systems obsolete. On the other hand, data collection, analysis and transfer on such small system is a great challenge. Therefore, small-size sensors are customized to collects and transfer data through wireless systems, make their usage feasible in different applications such as in biomedical systems and moving industrial equipment. Wen *et al*. (2020) reviewed the applications of IoT in wearable sensors in health systems. Applications of IoT in transferring data from chemical sensors and also in drug delivery systems were discussed and therapeutic aspects of these sensors integrated with IoT were clarified. Medical application of IoT in asthma patients is explored by Singh *et al*. (2021). They proposed a cloud based system to monitor the air condition that a patient is exposed to using wearable sensors and further transferring data to smart phones using wireless systems. Aggarwal and Kumar (2019) utilized IoT in the automation of irrigation process as an instance of industrial utilization of IoT. They used several sensors to evaluate the moisture and temperature of the soil. The data from sensors were transferred to a computation center through wireless systems. The decision making system employed ANN to decide the perfect time and duration of irrigation process.

Using ANN in prediction of behavior of different system behavior in recent decade attracts engineers and scientific communities. Alam *et al.* (2019) utilized IoT data in health care systems to feed required data for training and a deep machine neural network. They successfully validated the results of neural network by comparing the results with benchmark data sets. Wang *et al*. (2021) utilized IoT and neural network to identify vibration duration and depth in concrete structure to assess the life and long term operation of such structures. The concluded results were verified by experimental works. Convolutional neural network based deep learning is utilized by Chung and Jung (2020) in data analysis of health care system and to further therapy recommendations. They claimed that using this approach in total 13% improvement were observed in the predictions compared to other methods. A thorough review on application of ANN in detection and therapy of different classes of structured and unstructured categories of healthcare data presented by Jiang *et al*. (2017). Raghupati and Raghupati (2017) explored the effects of food and exercise habits on the chronic conditions employing ANN. They found that smoking and alcohol consumption are detrimental to chronic conditions while consumption of vegetable and fruit as well as physical exercises alleviate the conditions. Waste production in European countries in both healthcare systems and chemical productions were investigated by Adamović *et al*. (2018). Usage of ANN and ANN-based models are widespread and interested readers are referred to the following references for more study (Yegnanarayana 2009, Tamasco *et al*. 2013, Kotkunde *et al*. 2014, Mohamed *et al*. 2016, Subramanian and Palaniappan 2021, Wang *et al*. 2021, Narayana *et al*. 2022)

In the present study, a hybrid model of artificial neural network (ANN) and internet of things (IoT) is proposed to overcome the difficulties in deriving governing equations

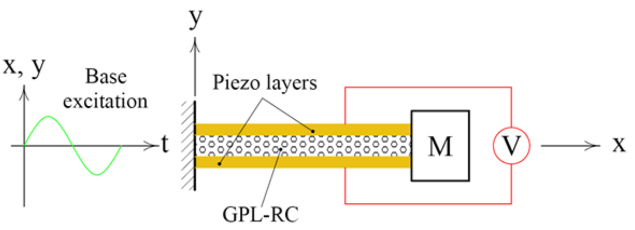

Fig. 1 Femur bone, porous GPLRC wedge and nanocomposite graft as assembled in SolidWorks and mesh generated in Ansys workbench

and numerical solutions of the dynamical behavior of the nano-systems. Nonlocal and length-scale parameters alongside with other geometrical, loading and material parameters are taken as input parameters of an ANN to observe the natural frequency and damping behavior of micro sensors made from nanocomposite material with piezoelectric layers. The behavior of a micro-beam is simulated using famous numerical methods in literature under base vibrations. The ANN was further trained to correlate the output vibrations to the base vibration. Afterwards, using IoT, the electrical potential conducted in the sensors are collected and converted to numerical data in an embedded mini-computer and transferred to a server for further calculations and decision by ANN.

2. Mathematical simulation of microstructures

2.1 Cantilever nano-beam as vibrational sensor detector

A nano-system utilized as vibration detection are schematically illustrated in Fig. 1. This nano-system is a sandwich beam with GPL-reinforced composite (GPL-RC) core and two upper and lower piezoelectric patch layers. The system is aimed to capture base excitation in both x and y directions. Pure x excitation only conduct axial movements but when combined to the y direction movement it cause more bending. To enhance the vibration of the nano-beam a small mass is attached to its free end. The bending vibration of the nano-beam cause accumulation of electricity voltages in the piezoelectric layers which can be directly measured by voltmeter circuit. This simple illustrations is the motivation of base vibration detection by measuring the voltage induced in the piezoelectric layers. Therefore, this mechanisms can be regarded as a nano-system sensors. The size and weight of the system due to use of GPL-RC is not a limitation in design. So that it can be sized from micro scale to macro scale. However, the micro scale sensors are of interest in the present study since this sensors are aimed to measure vibrations on moving systems.

As other sensors this type of sensors has to be calibrated for better application. However, the vibration responses of such systems are significantly dependent on the various materials and geometrical parameters as well as size effects. Thus, although the measured voltage is a determining parameters for each individual sensor, for a combination of sensors all of these parameters have to be taken into consideration.

2.2 Governing equations of GPL-RC nano-beam

In the current study, we focus on the applications of such sensors and detailed mathematical modeling and simulations are avoided since they are presented in many studied (Shariati *et al*. 2020b, c). In this section, a brief description of the mathematical foundations and solution method are provided. The basic governing equations are obtained using elasticity formulations of isotropic materials for both piezoelectric layers and GPL-RC core in small deformation space. Moreover, to capture size effects nonlocal strain gradient model is utilized. The equations of motion is generally obtained using Hamilton's principle (Adamian *et al*. 2020, Al-Furjan *et al*. 2020a, b, Li *et al*. 2020c, 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):

$$\int_0^t (\delta U - \delta K - \delta W)dt \tag{1}$$

where U is the variation of energy induced by elastic deformation of the material (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), K represents the variation of kinematic energy and W is the variation of all external works. Nonlocal strain gradient formulation is given below:

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

In the above equation, $\boldsymbol{\sigma}$ is the stress tensor and $\boldsymbol{\epsilon}$ is the strain tensor. The fourth-order elasticity tensor is represented by $\mathbb{C}$. The $e_0 a$ in nonlocal parameter and l_m is the length scale parameter. The internal characteristic length is represented by a. Laplacian operator is defined as:

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{3}$$

The third-order tensor $\mathbb{D}$ is called the piezoelectric tensor and $\boldsymbol{E}$ is the electric field strength. This concludes the basic equations of the nonlocal strain gradient nano-beam. The equations are further solved by general differential quadrature method (GDQM) for clamped boundary conditions (Ma *et al*. 2022, Zhao *et al*. 2022, Hou *et al*. 2021, Huang *et al*. 2021b, c, Jiao *et al*. 2021, Liu *et al*. 2021d, Moradi *et al*. 2021, Xu *et al*. 2021, Dong *et al*. 2022, Luo *et al*. 2022a, Yang *et al*. 2022b, Yu *et al*. 2022).

3. IoT circuit

The described base vibration sensor is embedded in a circuit which is schematically depicted in Fig. 2. Acquisition of the data is by voltmeters attached to piezoelectric layers on each sensor. This voltage data is further analyzed on an Arduino board to calculate amplitude and frequency of the voltage. This collected data is then transferred to a high power processing center on a server to

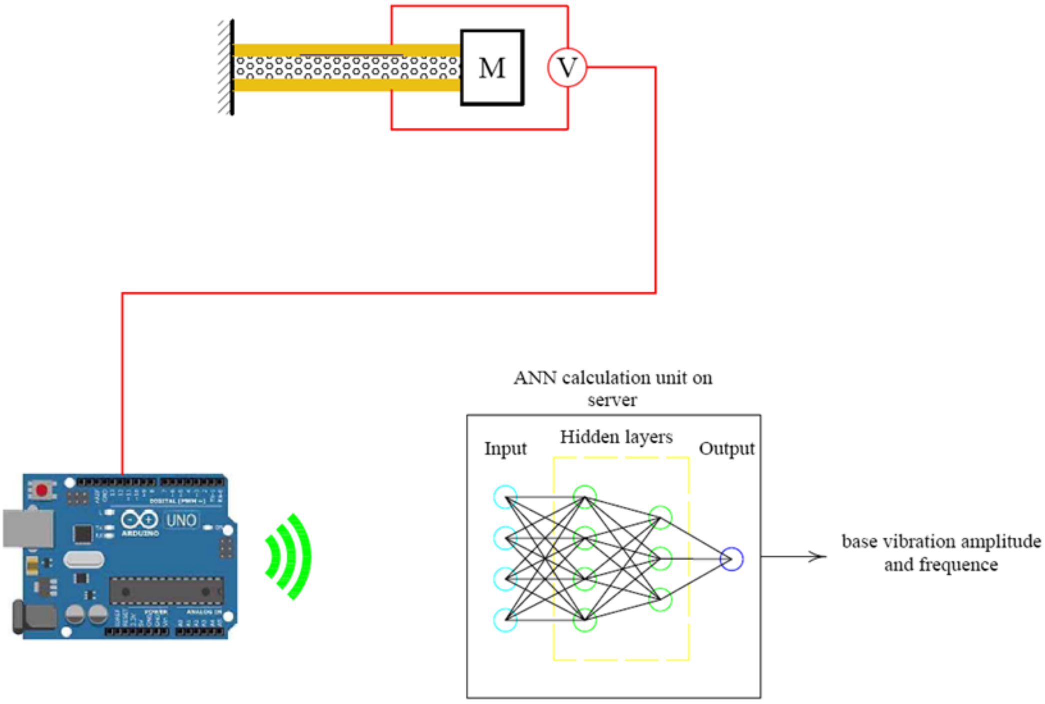

Fig. 2 Designed IoT circuit to collect induced voltage in piezoelectric layer and transferring it to server through wireless network

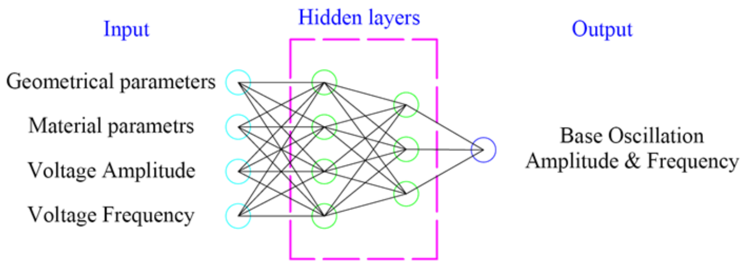

Fig. 3 Designed ANN model for prediction of vibrational behavior of base oscillation.

act as part of input of ANN. The sensor depicted in this figure is a representative of several other nano-sensors which collects data from different sections of a moving system. The decision making process is all on the computing server which used smart decisions based on previous training which is more flexible than traditional 0 and 1 programs.

4. Artificial Neural Network (ANN) design

Neural networks in general consists of three kinds of layers: input, hidden and output layers. The input layer provided parameters required by network to make calculations. In the current study, properties of the sensor made from nano-beam are parts of inputs. In the output layer we desire to the amplitude and frequency of the base which is unknown to us in practical problems. To achieve this goal, the frequency and amplitude of the piezoelectric voltage is needed. Thus, voltage vibration characteristics are also one of the ANN (Chen *et al*. 2021, Liu *et al*. 2021c, 2022, Gao *et al*. 2022, Meng *et al*. 2022). However, relationship between inputs and output is unknown the network. This relationship must be defined in the third kind of layers, i.e., hidden layers, which includes simple mathematical relations with some constants called weights and biases which have to be adjusted in the training process (Yu *et al*. 2019, Kong *et al*. 2020, Li *et al*. 2020a, Feng *et al*. 2021, Wang *et al*. 2022a). The training process is a procedure in which known and reliable inputs and outputs are fed into the network to adjust its weights and biases. Furthermore, the trained network must be tested by another independent set known and reliable data. If the prediction of the network in testing process is acceptable and close to the actual provided data, the network is considered to be trained and is ready for further predictions in unknown condition of the base vibrations (Zhu *et al*. 2022).

A schematic of the designed ANN for the current IoT problem is shown in Fig. 3. As observed inputs include material properties, geometry of the nano-beam and voltage measured during the process. The training of the network is performed using numerical results of the aforementioned problem. On this basis, the nano-system could be utilized to acquire vibrations of base of the sensor in different application, for example in detection of infrequent vibration of turbine shafts.

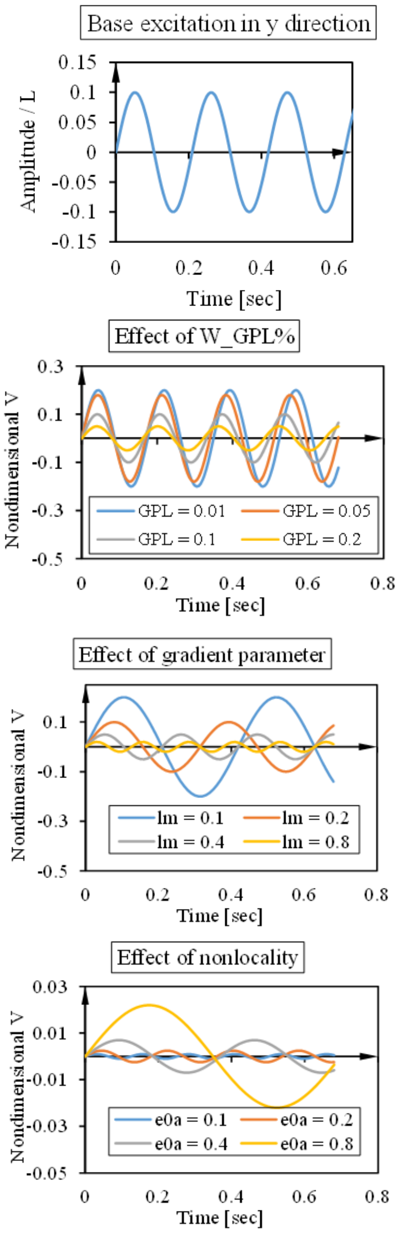

Fig. 4 An example of piezoelectric voltage responses in different material characteristic conditions as a result of base harmonic oscillation

5. Results

Effects of different parameters on the nondimensional voltage induced in the piezoelectric layers is depicted in Fig. 4. This representative graphs is an example of the abundant numerical simulations for the base vibration as input as depicted in Fig. 4, and voltage responses as function of strain gradient, nonlocality and weight fraction of GPL in the core composite. As seen, increasing strain gradient parameter results in decrease in nondimensional voltage of the piezoelectric layers as base oscillates. At the meantime, increase in nonlocal parameter reduces the amplitude of the voltage. Increasing weight fraction of the GPL in the core stiffen the whole structure resulting reduction in the displacement amplitude and consequently

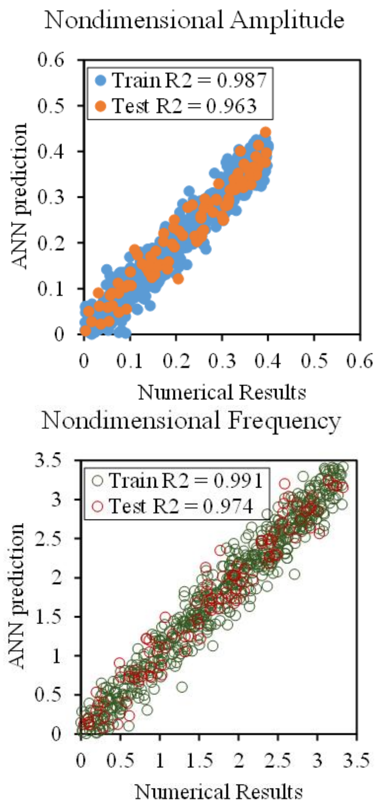

Fig. 5 Nondimensional amplitude and frequency of the base oscillation as calculated in numerical method in comparison with ANN prediction

decrease in voltage amplitude. On the other hand, gradient parameter rise leads to decrease in the frequency of the nano-system, while increase in the nonlocality increases frequency of the nondimensional voltage. An obvious result of increasing GPL fraction is the increase in the frequency.

Overall, 1230 sets of data from numerical simulations have been acquired to train and test the ANN. This network takes different material constants, geometrical parameters and voltage amplitude and frequency as inputs and predicts base oscillation as output. The training process of ANN takes 8300 epoch to reach error under 0.2%. The correlation between predicted amplitude of base vibration and numerical results is $R^2 = 0.987$ and for test data is $R^2 = 0.963$ which is highly satisfying. Figure 5 demonstrated the correlation of the amplitude and frequency of the base oscillation.

The results of this study indicate that ANN and IoT techniques could be joint together in industrial and health care systems to reduce human errors and have real-time observation and investigation of the system. Moreover, this hybrid model could be further linked to decision making network to make changes in the system to alleviate the fallacies.

6. Conclusions

In the present study, a hybrid model of artificial neural network (ANN) and internet of things (IoT) was proposed to overcome the difficulties in deriving governing equations and numerical solutions of the dynamical behavior of the nano-systems. Nonlocal and length-scale parameters alongside with other geometrical, loading and material parameters were taken as input parameters of an ANN to observe the natural frequency and damping behavior of micro sensors made from nanocomposite material with piezoelectric layers. The behavior of a micro-beam was simulated using famous numerical methods in literature under base vibrations. The ANN was further trained to correlate the output vibrations to the base vibration. Afterwards, using IoT, the electrical potential conducted in the sensors are collected and converted to numerical data in an embedded mini-computer and transferred to a server for further calculations and decision by ANN. The bold conclusions are as below:

• Increasing strain gradient parameter results in decrease in nondimensional voltage of the piezoelectric layers as base oscillates.

• ANN and IoT techniques could be joint together in industrial and health care systems to reduce human errors and have real-time inspection.

• The correlation between predicted amplitude of base vibration and numerical results is R^2 = 0.987 and for test data is R^2 = 0.963 which is highly satisfying.

• The proposed hybrid model could be further linked to decision making network to make changes in the system to alleviate the fallacies.

• Gradient parameter rise leads to decrease in the frequency of the nano-system.

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