

Investigation of Dynamic Behavior of Smart Piezoelectric Actuators Using Artificial Neural Networks

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ABSTRACT:

The purpose of this study is to investigate microelectromechanical behavior of smart piezoelectric actuators using Artificial Neural Networks due to simple, multi harmonic and dynamic pulse excitations. Regarding to complexity and time-consuming analyses of vibration of smart structures, existing classical models are often insufficient. Nowadays, artificial intelligence tools are used for modeling such complex phenomena. The theoretical model is a three-layer piezoelectric composite beam that behaves as an axial actuating mechanism. This actuator consists of an elastic core sandwiched between two piezoelectric active outer layers. The piezoelectric layers are polarized transversely, i.e., the polarization vector is parallel to the applied electric field intensity vector. For initializing the electromechanical effect, an electric field is applied to the piezoelectric layers. The finite element modeling is constructed using ANSYS. Then, harmonic and dynamic vibration analyses are performed and the responses of smart beam are calculated. The required data used for artificial intelligence were collected from vibration analyses. Obtained results demonstrate that artificial neural network is in good agreement with observed values.

KEYWORDS: Piezoelectric Actuators, Harmonic and Dynamic Vibration, Artificial Neural Networks.

1. INTRODUCTION

Smart or intelligent materials can adaptively change or respond to an external environmental stimulus and produce a useful physical or chemical effect such as volume, mechanical stress change, reversibility oxidization-deoxidization and so on. The stimuli may include mechanical stress, temperature, an electric or magnetic field, photon irradiation, or chemicals. Over the past 10 to 20 years, a number of materials have been given the term smart based on their interesting material properties. Other names for these types of materials are intelligent materials, adaptive materials, and even structronic materials. Applications of the smart materials have drawn attention in aerospace engineering, civil engineering, mechanical, electronic and even bio-engineering

From the discovery of the piezoelectric inverse effect (actuation effect), this active materials have found a wide range of applications for vibration and noise control of structures. The analysis of a coupled piezoelectric structure has recently been keenly researched because piezoelectric materials are more extensively used either as actuators or sensors. For any

piezoelectric material the charge developed due to strain in the material is known as *Direct Effect* and the deflection due to applied electric field is known as *Converse Effect*.

Examples include the analytical modelling and behavior of a beam with surface-bonded or embedded piezoelectric sensors and actuators [1–3], and the use of piezoelectric materials in composite laminates and for vibration control [4]. The use of finite element method in the analysis of piezoelectric coupled structures has been studied [5–8]. Crawley and de Luis [9] developed the analytical model for the static and dynamic response of a beam structure with segmented piezoelectric actuators either bonded or embedded in a laminated composite. Owing to their good characteristics of lightweight and electromechanical coupling effects, piezoelectric materials have been studied in other application fields, such as the shape control of structures, acoustic wave excitation, health monitoring of structures, etc. [10–13].

Researchers have so far designed vibration-based energy harvesters. Electrostatic, electromagnetic, and piezoelectric are the most commonly three methods of

conversion from mechanical vibration energy to electrical energy. The piezoelectric effect has been found to be the most effective of the three methods. In recent years, the development of energy harvesting from vibrating structures with piezoelectric sensors mounted on the surface has been a major focus of many research groups [14–18]. Piezoelectric materials have the ability to generate an electrical charge when an applied mechanical load such as pressure, force, and vibration.

Predicting vibration analysis of smart structures is an important factor in earthen energy harvesting or actuation mechanism. Corresponding vibration analysis problem is a complex phenomenon. Nowadays for modeling complex phenomenon, artificial intelligence methods such as artificial neural network are widely used. Hence, in this paper, studies are made on finite element and artificial neural network modeling of linear harmonic and dynamic vibration of cantilever piezo-laminated beam.

2. THEORETICAL FORMULATION

2.1. Mathematical assumptions

The orthotropic adaptive beam model considered here, as shown in Fig. 1, is based on the following electromechanical kinetic, kinematic, and constitutive law assumptions:

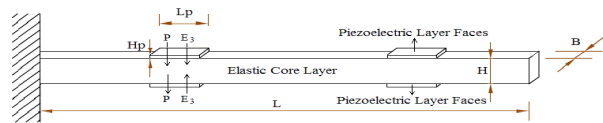


Fig. 1. The smart composite beam geometry with the piezoelectric outer layers and elastic core layer

- The mechanical and electrical variables are so small that the linearized elasticity and piezoelectricity theories are applicable.
- The elastic materials (the core layer) and piezoelectric materials (the outer layers) are orthotropic but homogeneous.
- Each piezoelectric outer layer is completely covered by one integrated electrode, so there is only one applied control voltage to the actuator layer and one measured voltage observed from sensor layer.
- The interlayer bonds among layers are such that one can apply no slip boundary conditions.
- The lateral displacements of all layers in each given cross section along the beam axis, in the beam thickness direction are the same.

3. FINITE ELEMENT MODELING

In this paper, the finite element modeling of smart piezoelectric beam is constructed using ANSYS® software. Then, the tip deflection of smart beam due to

variety single and multi harmonic and dynamic pulses is calculated by dynamic analysis with ANSYS®. The fixed- free supported smart piezoelectric beam is shown in Fig. 1. The corresponding geometric and material parameters are listed in Table 1 and Table 2, respectively. It's worth to be mentioned that the piezoelectric material are assumed as PZT5H. There are some assumptions for smart piezoelectric beam modeling as below:

- The SOLID 45 element is used for modeling of elastic core of beam.
- The SOLID5 element is used for the piezoelectric actuators modeling.
- Element meshes was fined so that the answer for two consecutive steps has not tangible difference.

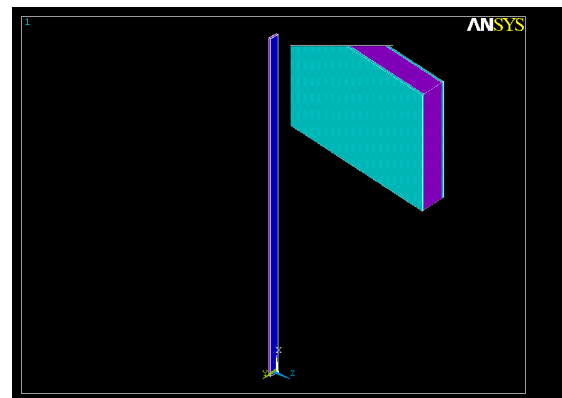


Fig. 2. Schematics of smart piezoelectric beam in ANSYS software with Cross-Section

Table 1. Geometrical parameters of piezoelectric beam

	Length of beam	Width of beam	Core Thickness	Piezoelectric Thickness
Abbreviation	L	w	t _b	t _p
Value in SI system	0.50	0.050	0.010	0.001

Table 2. Material and Piezoelectric parameters of piezoelectric beam

	Modulus of Elasticity of Core	Modulus of Elasticity of Piezoelectric	Piezoelectric Constants
Abbreviation	E _b	E _p	e ₃₁ , e ₃₃
Value in SI system	70.3×10 ⁹	128×10 ⁹	-6.5, 23.3

The vibration analyses are performed for: (i) half-Sin and half-Cos single harmonic; (ii) Multi harmonic based on first and second natural frequencies of smart piezoelectric beam; (iii) Rectangle, triangle, downward and upward ramp dynamic pulse applied to the tip of beam. The results are shown in Fig. 1 to Fig. 1, respectively.

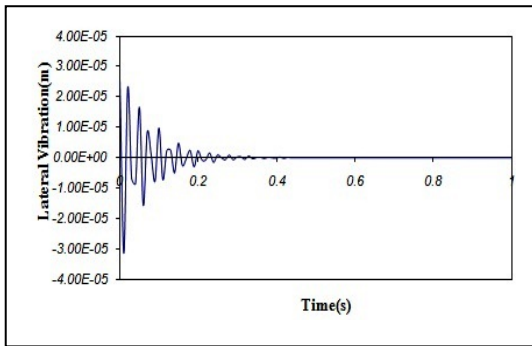


Fig. 3. Tip deflection of smart piezoelectric beam under single Half-Sin harmonic vibration

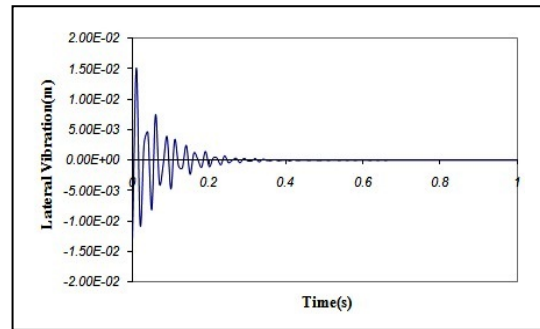


Fig. 7. Tip deflection of smart piezoelectric beam under rectangle pulse vibration

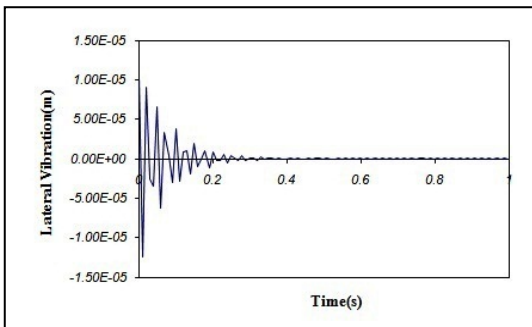


Fig. 4. Tip deflection of smart piezoelectric beam under single Half-Cos harmonic vibration

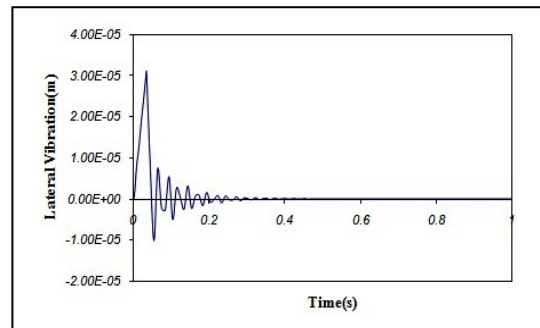


Fig. 8. Tip deflection of smart piezoelectric beam under triangle pulse vibration

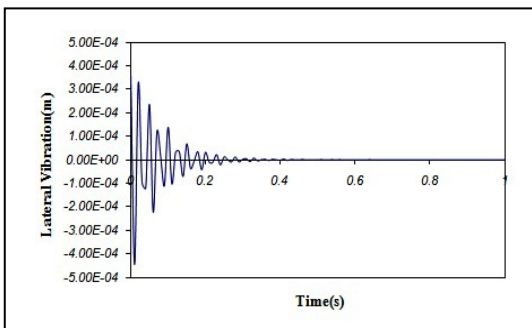


Fig. 5. Tip deflection of smart piezoelectric beam under multi-harmonic with first frequency vibration

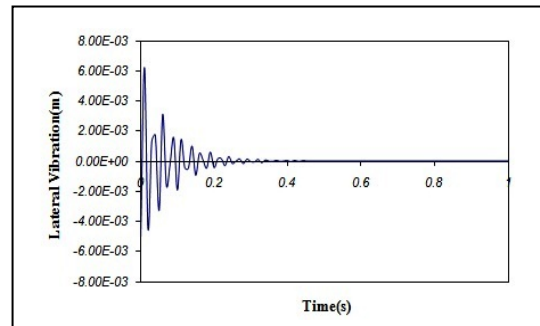


Fig. 9. Tip deflection of smart piezoelectric beam under Downward Ramp pulse vibration

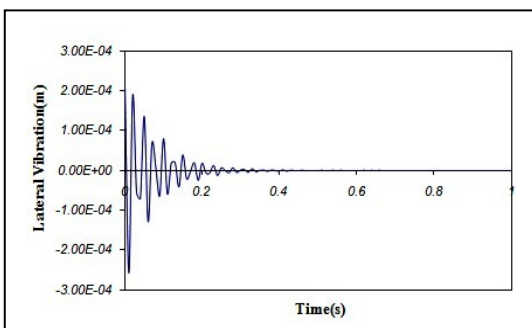


Fig. 6. Tip deflection of smart piezoelectric beam under multi-harmonic with second frequency vibration

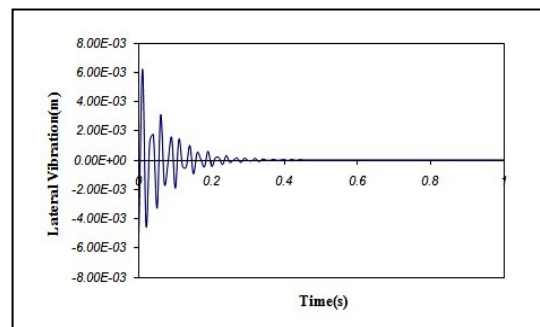


Fig. 10. Tip deflection of smart piezoelectric beam under Upward Ramp pulse vibration

4. ARTIFICIAL NEURAL NETWORKS (ANN)

An artificial neural network is an information-processing system that has certain performance characteristics in common with biological neural networks. It is one of the artificial intelligence techniques where the intelligence results from communication between different neurons. It is also a useful tool for solving different engineering problems because it can approximate a desired behavior without the need to specify a particular function. This is a big advantage of artificial neural networks compared to multivariate statistics. A neural network is characterized by (1) its pattern of connections between the neurons (called its architecture), (2) its method of determining the weights on connections (learning algorithm), and (3) its activation function. See Fig. 1

There are two important issues concerning the implementation of artificial neural networks. The first issue involves a specification of the network size (the number of layers in the network and the number of neurons in each layer). This task involves decision on the number of neurons required in the hidden layer. Generally, the more complex mapping the larger the number of hidden neurons required. The second issue involves finding the optimal values for the connection weights. Starting with a small number of neurons and gradually increasing the network size until the desired accuracy is achieved address the first problem. However, this approach heavily depends on the ability to find the optimal weights. The objective function (typically mean square error) used to train the ANN has many local optima and extensive regions of poor sensitivity to variations in weights. Back propagation is a learning algorithm for a multilayered neural network in which the weights are modified via propagation of an error gradient backward from the output to the input. The model of the peak discharge prediction presented in this research, using artificial neural networks, uses back-propagation algorithm to solve a feed-forward artificial neural network

Among the applied neural networks, the feed forward neural networks (FFNN) with back-propagation (BP) algorithm are the most common used methods in solving various engineering problems. FFNN technique consists of layer being fully connected to the preceding layer by weights. Fig. 1 illustrates the common three-layer feed forward type of an artificial neural network.

Learning of these ANNs is generally accomplished by BP algorithm. The back-propagation algorithm involves two steps. The first step is a forward pass, in which the effect of the input is passed forward through the network to reach the output layer. After the error is computed, a second step starts backward through the network. The errors at the output layer are propagated back toward the input layer with the weights being

modified as follows (ASCE Task Committee [19-20]):

$$\Delta w_{ij}(n) = -\varepsilon \frac{\partial E}{\partial w_{ij}} + \alpha \Delta w_{ij}(n-1) \quad (1)$$

where $w_{ij}(n)$ is weight between node i and j , and $\Delta w_{ij}(n)$ and $\Delta w_{ij}(n-1)$ are weight increments between node i and j during the n th and $(n-1)$ th pass, or epoch. ε and α are called learning rate and momentum factor, respectively. They are positive and have a value between 0 and 1.

The optimal weights are found by minimizing a predetermined error function (E) of the following form:

$$\sum_P \sum_p (y_i - t_i)^2 \quad (2)$$

Here, y_i is the component of an ANN output vector Y , t_i is the component of a target output vector T , p is the number of output neurons and P is the number of training patterns.

Several forms of activation functions have been used in ANNs, such as linear, binary sigmoid, bipolar sigmoid, hyperbolic tangent, etc. the hyperbolic tangent function, which is used in this paper, is given as:

$$f(x) = \frac{\exp(x) - \exp(-x)}{\exp(x) + \exp(-x)} \quad (3)$$

More details on the ANN can be found in Fausett [17].

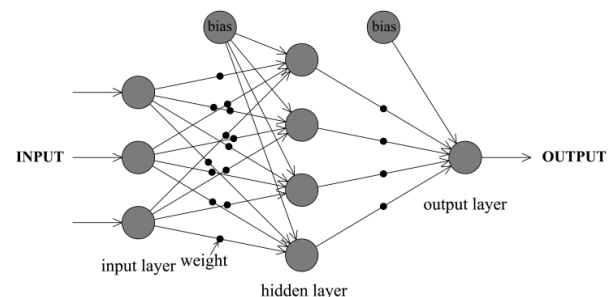


Fig. 11. Schematic representation of three-layer feed forward artificial neural network

4.1. Data Set

The data sets used in this paper are the single and multi harmonic and pulse dynamic simulations presented in previous section.

For modeling, the data set is divided into three parts: training, checking and testing set. The training and testing data set are used for learning and evaluating the developed models, respectively. The checking data set is a part of the training data set used to decrease over-training. In order to predict the harmonic and dynamic behavior of microelectromechanical piezoelectric actuators, 120 data points of total 160 data were selected of which 100 data points were used as the

training set, 20 data points as the checking set and the remaining as the testing set.

5. RESULTS AND DISCUSSION

An artificial neural network was developed, separately for each vibration analysis type, using training and checking data to predict the dynamic behavior and tip displacement of piezoelectric actuator. Before learning the ANNs, the training input and output values are normalized in the range of -1 to 1, using the following equation:

$$x' = 2 \frac{x - x_{\min}}{x_{\max} - x_{\min}} - 1 \quad (4)$$

where x_{\min} and x_{\max} denote the minimum and maximum of data set.

After examining different topologies with tangent hyperbolic activation function, the best topology for all models was found to be $2 \times 7 \times 1$ (neurons in the input \times hidden \times output layers). Two inputs are time and harmonic or dynamic excitation magnitude. The output layer refers to the tip deflection of smart piezoelectric beam.

After learning, the developed ANNs are evaluated using the testing data. The comparison between observed and predicted tip deflection of smart piezoelectric beam using the testing data are shown in Figure 12 to Figure 20, respectively.

A statistical comparison between the observed and predicted parameters of tip deflection was applied to evaluate the developed soft computing models using bias, root mean square error (RMSE), scatter index (SI) and correlation coefficient (CC) are defined as follows:

$$bias = \frac{1}{N} \sum_{i=1}^N (y_i - t_i) \quad (5)$$

$$RSME = \sqrt{\frac{1}{N} \sum_{i=1}^N (y_i - t_i)^2} \quad (6)$$

$$SI = \frac{RSME}{Average\ Observed\ Value} \times 100 \quad (7)$$

$$CC = \frac{\sum_{i=1}^N (t_i - \bar{t}_m)(y_i - \bar{y}_m)}{\sqrt{\left(\sum_{i=1}^N (t_i - \bar{t}_m)^2\right) \left(\sum_{i=1}^N (y_i - \bar{y}_m)^2\right)}} \times 100 \quad (8)$$

where N is the number of observations; t_i is an observed value; y_i is a predicted value; \bar{t}_m is the observed mean value; and \bar{y}_m is the predicted mean value. Table 3 and Table 4 show the error statistics of the proposed ANN models in predicting the tip

deflection of smart piezoelectric beam due to harmonic and dynamic vibrations, respectively.

Table 3. Statistics of the predicted tip deflection due to harmonic vibrations using the testing data

	Half-Cos pulse	Half-Sin Pulse	W1	W2
RMSE	1.55e-4	2.75e-5	1.56e-4	5.62e-5
MAE	1.31e-4	2.05e-5	4.49e-5	3.58e-5
bias	1.98e-5	-4.72e-7	-1.52e-5	-7.24e-6
R ²	0.9999	0.9998	0.9639	0.9428

Table 4. Statistics of the predicted tip deflection due to dynamic vibrations using the testing data

	Triangle Pulse	Downward Ramp	Upward Ramp
RMSE	9.41e-6	1.20e-4	8.06e-7
MAE	7.84e-6	7.52e-5	5.79e-7
bias	4.49e-7	1.37e-5	-5.56e-7
R ²	0.9999	0.9995	0.974

6. CONCLUSION

In this study, using ANNs soft computing tools some models were developed to predict vibration analysis of smart composite laminated cantilevered beam. First, the finite element numerical models of a smart composite beam were constructed in ANSYS. The poling direction and electric field intensity in the active materials were in the beam thickness direction. Then, harmonic and dynamic vibration analyses are performed and the responses of smart beam are calculated. Finally, the database compiled by the authors contains tip deflection of smart beam under various harmonic and dynamic pulses and was used to analyze. Obtained results demonstrate that ANN is in good agreement with numerical values.

7. ACKNOWLEDGMENT

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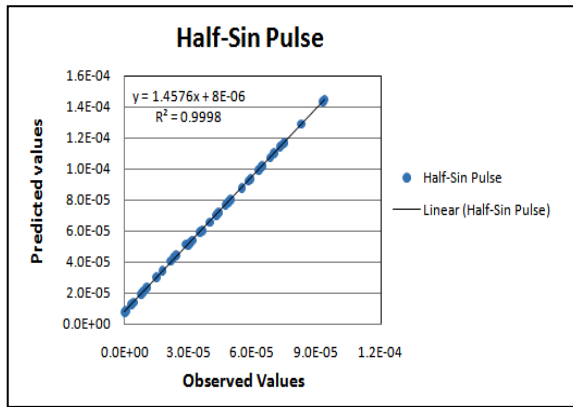


Fig. 12. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under single Half-Sin harmonic vibration

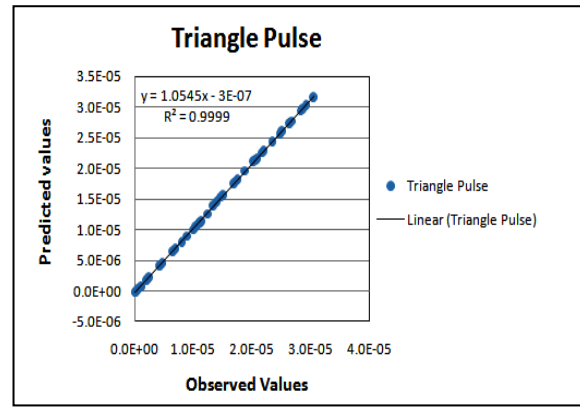


Fig. 15. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under triangle pulse vibration

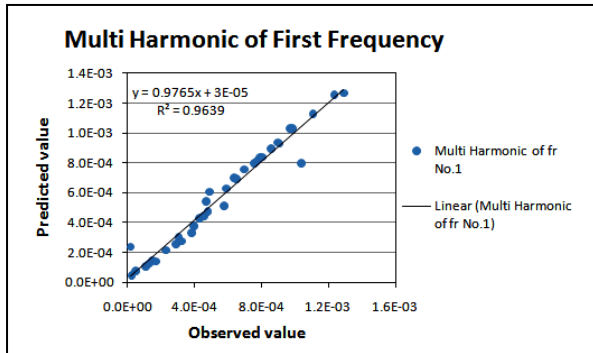


Fig. 13. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under multi-harmonic with first frequency vibration

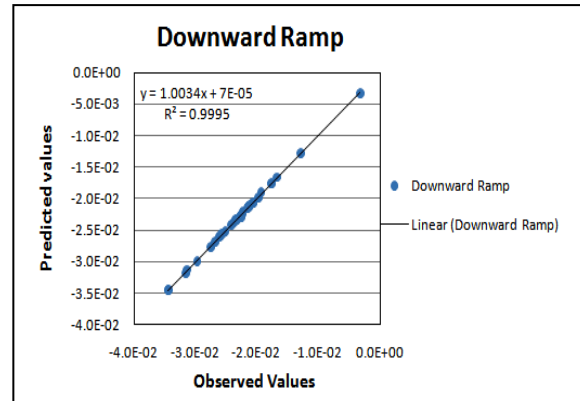


Fig. 16. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under downward pulse vibration

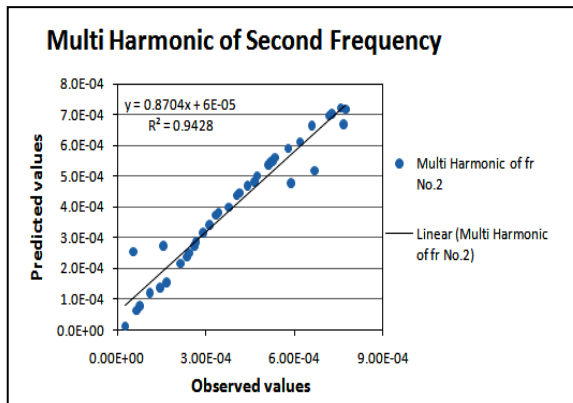


Fig. 14. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under multi-harmonic with second frequency vibration

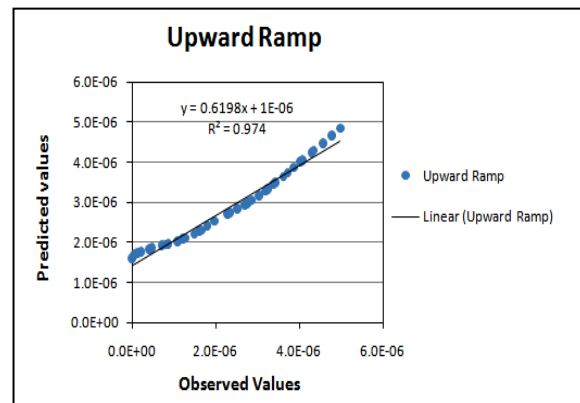


Fig. 17. Comparison between observed and predicted values obtained from ANN model for prediction of tip deflection under upward pulse vibration

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