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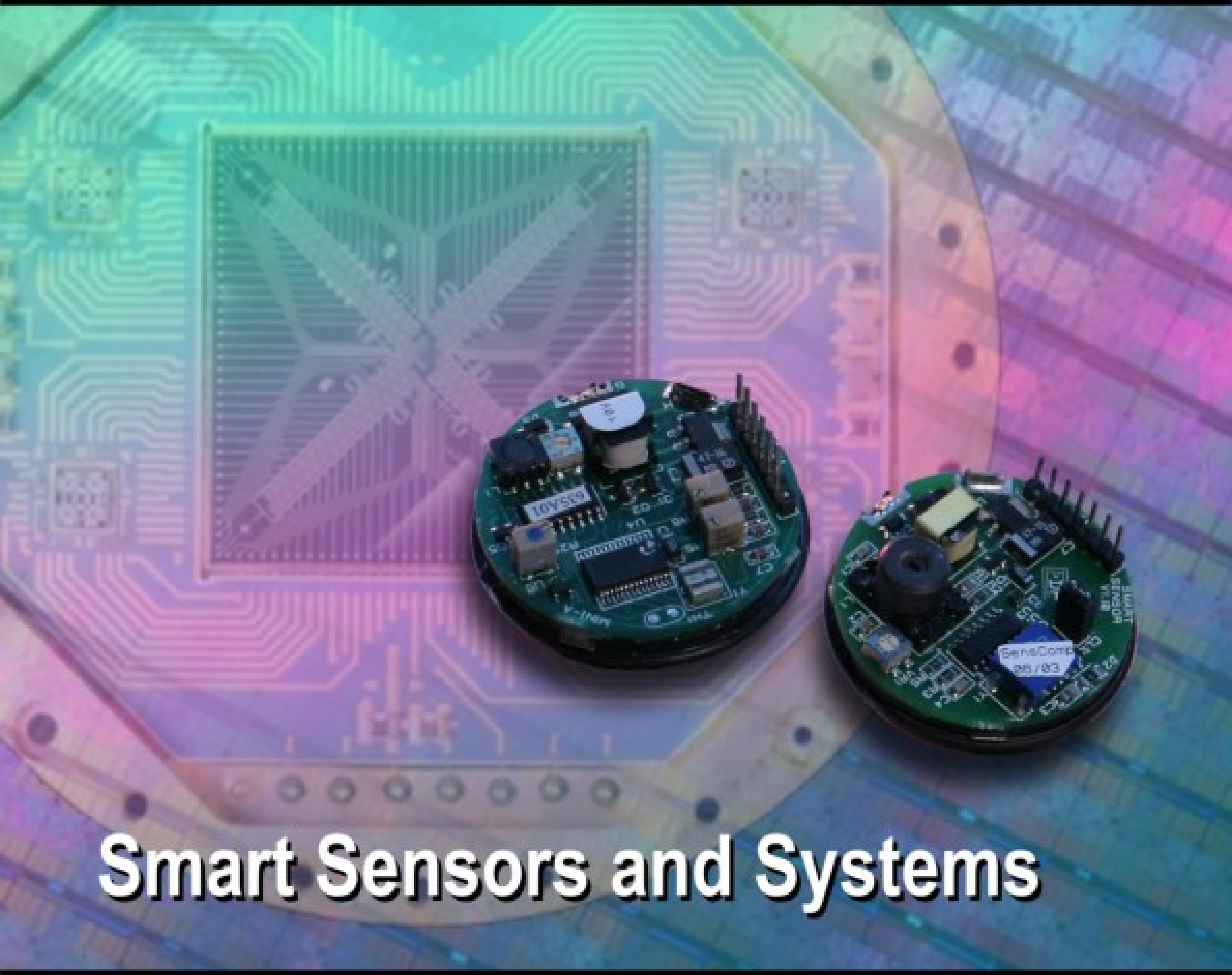

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Predicting the Deflections of Micromachined Electrostatic Actuators Using Artificial Neural Network (ANN)

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Abstract: In this study, a general purpose Artificial Neural Network (ANN) model based on the feed-forward back-propagation (FFBP) algorithm has been used to predict the deflections of a micromachined structures actuated electrostatically under different loadings and geometrical parameters. A limited range of simulation results obtained via CoventorWare™ numerical software will be used initially to train the neural network via back-propagation algorithm. The micromachined structures considered in the analyses are diaphragm, fixed-fixed beams and cantilevers. ANN simulation results are compared with results obtained via CoventorWare™ simulations and existing analytical work for validation purpose. The proposed ANN model accurately predicts the deflections of the micromachined structures with great reduction of simulation efforts, establishing the method superiority. This method can be extended for applications in other sensors particularly for modeling sensors applying electrostatic actuation which are difficult in nature due to the inherent non-linearity of the electro-mechanical coupling response. *Copyright © 2009 IFSA.*

Keywords: MEMS, Electrostatic, Neural network, Micromachined structure

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1. Introduction

In recent years, electrostatic actuators have found applications for numerous sensors, particularly in pressure sensor [1], micropump [2] and microphone [3]. In these sensors development, it is essential to consider the electro-mechanical coupling effects during the design and modeling stages.

Researchers have proposed numerous analytical solutions to solve the electro-mechanical coupling effects associated to the electrostatically actuated structures [4-10]. However, the process of developing the analytical models is tedious as there is still no simple analytical solution to the classical law governing the actuator's behavior under electrostatic pressure [4]. This is one of the main reasons most researchers resolved to using finite element analysis (FEA) software for the design and analysis of actuators subjected to electrostatic loading. Nevertheless, it has been observed that simulations using FEA software takes considerable time and efforts in modeling especially when the behavior is non-linear, as in the case of electrostatic loading. Thus, there is a need to supplement the FEA so that parametric studies can be accomplished with less effort and time.

This paper serves the purpose where it will present the application of ANN for optimizing parametric studies simulations. ANN is chosen due to its capabilities in building up the quite complex and non-linear model through training by making use of available data obtained from FEA simulations. Once trained, the network can then be fed with any unknown input and are able to predict the output with high level of accuracy with less computational time.

2. Artificial Neural Network (ANN)

Artificial neural network (ANN) is based on the working process of human brain in decision making. It is categorized under artificial intelligence method and has been applied in many different fields such as control [11], finance, aerospace, industrial and manufacturing [12, 13].

Fig. 1 shows a typical neural network consisting of sets of input, hidden layer, output and weighting functions. The artificial neurons are organized in layers with one or more intermediate hidden layers placed between the input layer and output layer, and send their signals "forward". Each layer has a number of neurons connected with neurons in the adjacent layers through unidirectional connections. The information flow is only allowed in one direction during the training process; that is from the input layer to the output layer through the hidden layers. There can be any number of hidden layers in the architecture. The hidden layer has a synaptic weighting matrix, W_m associated with all the connections made from the input layer to the hidden layer. The synaptic weights are assumed to be fixed and training process must be carried out to adjust the weights to perform a desired mapping. One of the training algorithms that can be used is the back-propagation method.

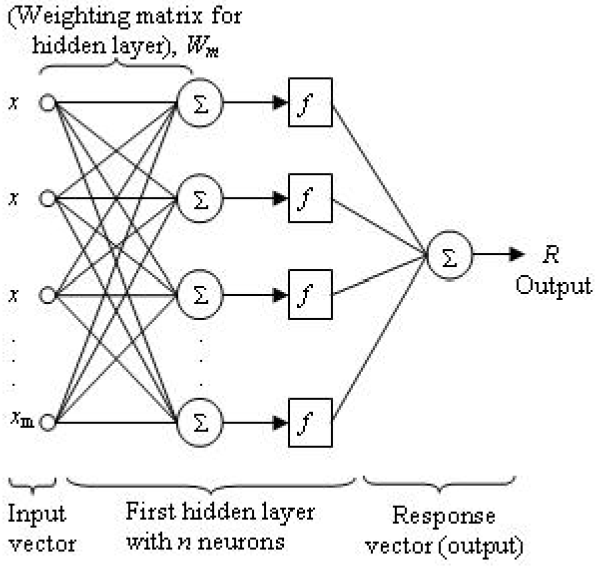

Fig. 1. Feed-forward multilayer perceptron ANN.

In this paper, the multi layer perceptron neural network has been trained using the back-propagation algorithm, hence the term “feed-forward back-propagation (FFBP)” algorithm. The back-propagation algorithm uses supervised learning where the algorithm is provided with examples of the inputs and outputs that the network is required to compute and then an error defined as the sum square error (SSE) is calculated. SSE is nothing but the difference between the actual and the predicted results. In other words, the network is defined to correlate between the inputs and the outputs by training the network with available data. Initially, the network obtains some information signals by neurons in the input layer and the output produced from the first layer is then fed subsequently into the second layer and so on. The errors are then propagated backwards. The idea of the back-propagation algorithm is to reduce this error until ANN learns the training data. The training begins with random weights and the goal is to adjust them so that the error will be minimal. Training continues until the errors converged to a specified value or after reaching the maximum epoch. Once the network is trained, it can then be fed with any unknown input and is expected to predict the output with a high degree of accuracy.

3. Modeling and Simulations

For a typical micromachined electrostatic actuator, there exist two electrodes separated by an air gap where the working electrode (top electrode) will be supplied with a voltage while the counter-electrode (bottom electrode) will be grounded. Charges induced between the electrodes generate electrostatic attraction force acting on the working electrode which in turn resulted in deflection of the working electrode. Since the working electrode will be fixed on at least one of the sides, deflection and subsequently distribution of the charges and its corresponding electrostatic force on the working electrode changes accordingly; illustrating the coupling mechanism of the electro-mechanical effects as shown in Fig. 2. In this study, the micromachined structures analyzed are the diaphragm, fixed-fixed beams and cantilevers actuators. A basic schematic of these actuators are shown in Fig. 3.

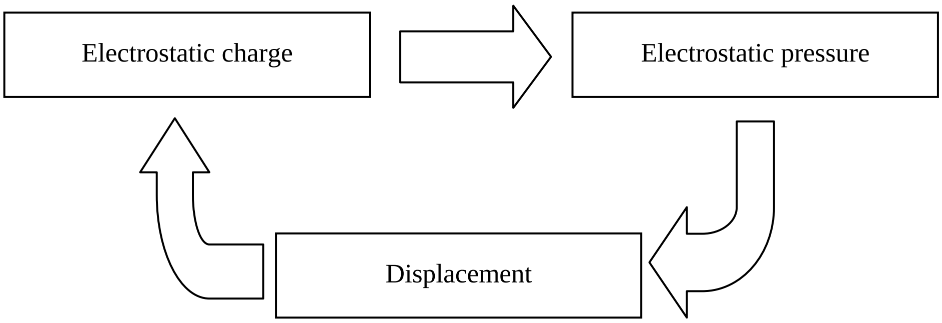

Fig. 2. Electro-Mechanical coupling interaction.

3.1. CoventorWare™ Simulation

Finite element analysis (FEA) using CoventorWare™ is carried out to evaluate the deflection of the diaphragm, fixed-fixed beam and cantilever for different types of electrical loading, residual stress and geometrical parameters. The electrodes are made up of polysilicon layer with material properties as summarized in Table 1. The addition of residual stress for the polysilicon working electrode will be defined in the material properties database of CoventorWare™.

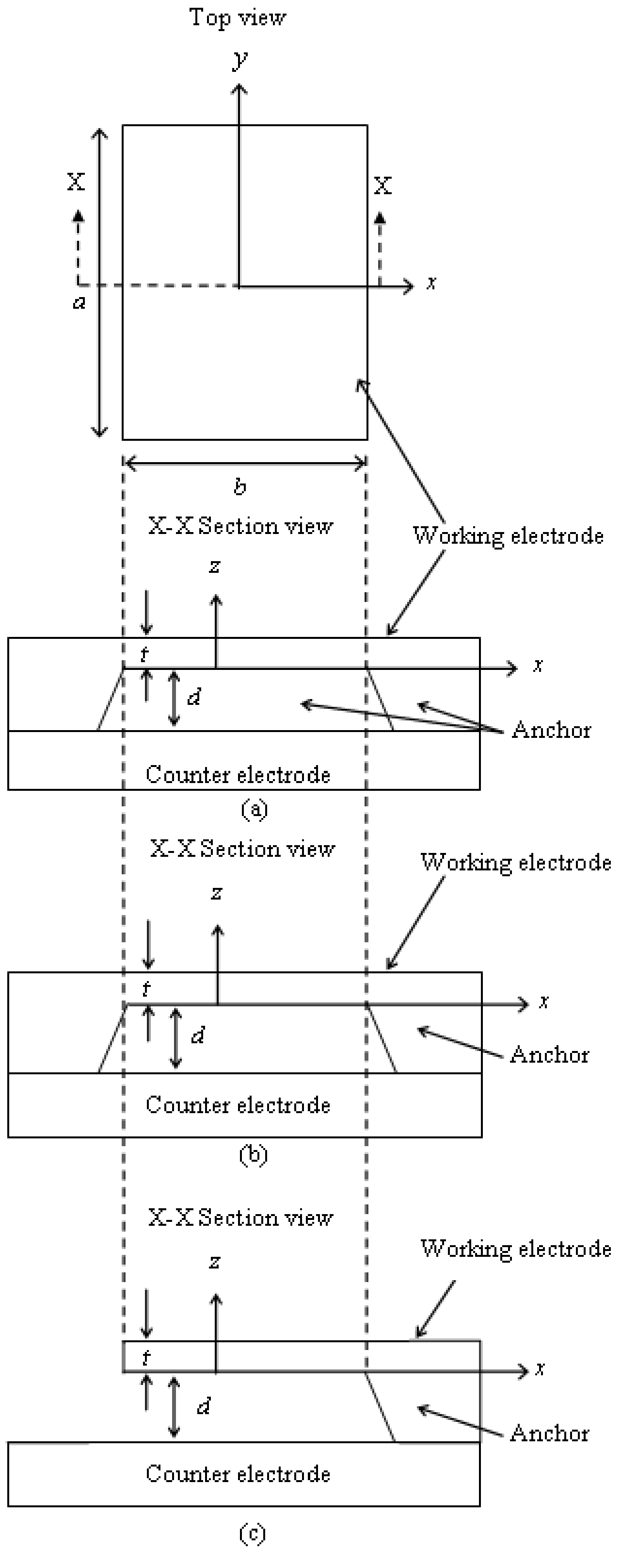

Fig. 3. Basic schematic of an electrostatically actuated (a) diaphragm, (b) fixed-fixed beam actuator and (c) cantilever.

Table 1. Material properties for polysilicon electrodes.

Material properties	Value
Young's modulus	160 GPa
Poisson ratio	0.22
Density	2.23^{-15} (kg/µm^3)

Simulations to find the deflection of the electrostatic actuators are carried out using the coupled-field electro-mechanical solver, CoSolveEM™ available in CoventorWare™. The sides (periphery) of the working electrode will be defined with the 'fixall' boundary condition whenever the sides are fixed and this is applied in accordance to the types of micromachined structures analyzed. The 'fixall' boundary condition applied will restrict movement of the working electrode on that particular side in all direction. For the diaphragm structure, all the four sides of the working electrode model will be applied with the 'fixall' boundary conditions. Likewise for the fixed-fixed beam, two edges of the working electrode model will be defined while only a single side of the cantilever model is fixed. Other boundary condition to be defined includes application of voltage on the model where the working electrode will be applied with an actuation voltage while the counter-electrode will be grounded (Voltage=0). Meanwhile, meshing of the actuators have been achieved using Manhattan bricks meshing. A typical meshed model of the electrostatic diaphragm actuator with all the applied boundary conditions is shown in Fig. 4.

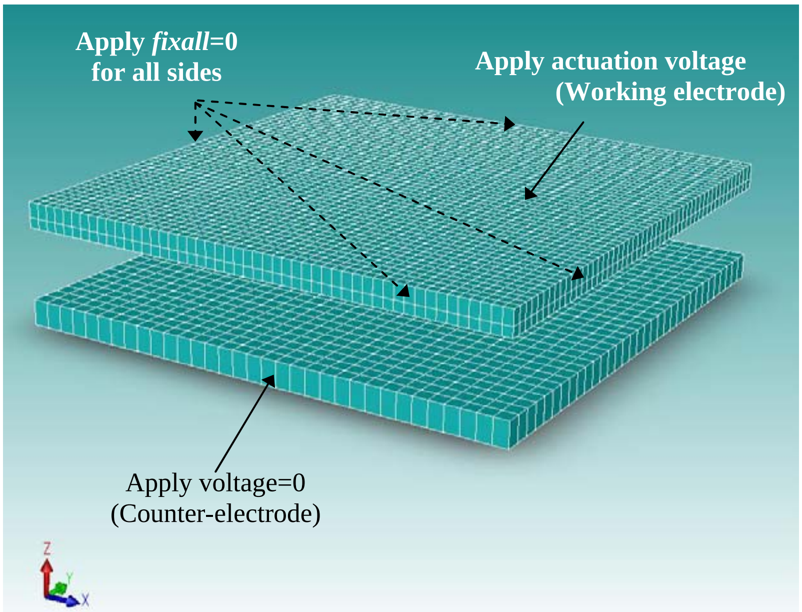

Fig. 4. Meshed model of the electrostatic diaphragm actuator with relevant boundary conditions.

Mesh sensitivity analyses have been conducted on each model to ensure that the ensuing simulation results obtained are independent of mesh densities. Parametric studies are then accomplished by simulating the model using different range of values for each parameter as given in Table 2 with the set of reference value for the remaining parameters kept constant where applicable. Results obtained from the FEA simulations will then be used for training the ANN model.

Table 2. Range of parameters analyzed in CoventorWare™ for parametric studies.

Parameters	Range	Increment	Reference value
Voltage, *V* (V)	0-10	0.5	3
Length, *a* (μm)	100-1000	100	500
Width, *b* (μm)	100-1000	100	500
Thickness, *t* (μm)	0.2-1.0	0.1	0.5
Air gap, *d* (μm)	1-5	0.5	2
Residual stress, σ (MPa)	0-100	10	20

3.2. Artificial Neural Network (ANN)

For prediction on the deflection of the electrostatically actuated micromachined structures using artificial neural network (ANN), a general purpose feed-forward back-propagation (GPFFBP) has been constructed as shown in Fig. 5. This ANN model includes an additional neuron; in the form of numerical representation (Num); to represent the types of micromachined structures to be analyzed as shown in Table 3. Introduction of the additional neuron will help to improve functionality of the ANN model where different types of electrostatically actuated micromachined structures can also be analyzed using the same modeling.

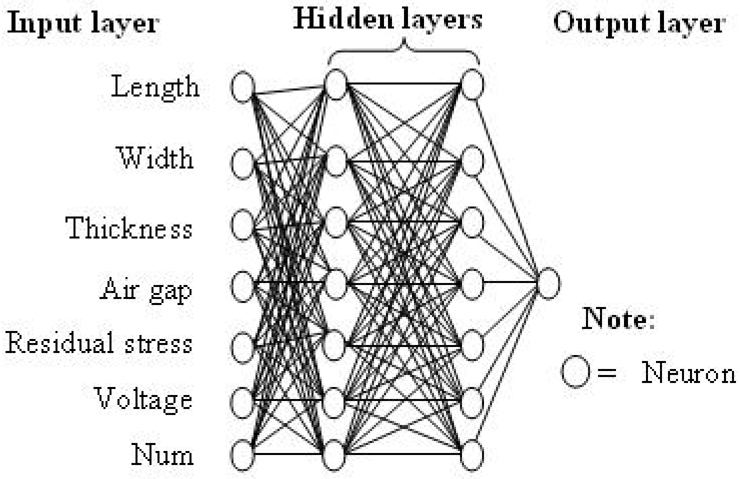

Fig. 5. Proposed general purpose feed-forward back-propagation (GPFFBP) ANN model.

Table 3. Numerical representation for the types of micromachined structures to be analyzed in the GPFFBP ANN model.

Numerical representation (Num)	Types of micromachined structures
1	Diaphragm
2	Fixed-fixed beam
3	Cantilever

For the present analysis, the ANN toolbox available in MATLAB version 2006a is utilized. Analyses are done to predict the deflection of the working electrodes for different input parameters and types of micromachined structures. The ANN architecture used in this work is the FFBP with 2 hidden layers. Table 4 shows the details of the ANN architecture used while Table 5 shows the three values of deflection results for each sets of parameters from CoventorWare™ simulations, including the reference value, which will not be used as training inputs into the ANN model. Simulation data that were not trained will be used instead to verify the accuracy of the ANN results by comparing the predicted ANN results to the FEA simulation results.

Table 4. Architecture of the GPFFBP ANN model.

Parameters	Type /Value
Transfer function	All logsig
Hidden layer	2 hidden layer
Maximum epoch	1000
Learning rate	0.000001
Sum Square Error (SSE)	1e-7

Table 5. Three sets of parameters not trained in ANN.

Parameters	Value
Voltage, V (V)	1, 3, 6.5
Length, a (μm)	300, 500, 700
Width, b (μm)	200, 500, 900
Thickness, t (μm)	0.5, 0.8, 0.9
Air gap, d (μm)	2, 3, 4.5
Residual stress, σ (MPa)	20, 40, 60

4. Results and Discussion

Once a trained ANN is obtained, it can be used for predictions of the center deflection for any input parameters within the simulation ranges. However, the trained ANN model needs to be first validated with existing published results and FEA simulation results in order for the methodology to be used with confidence.

4.1. Validation

As a proof of concept, some deflection results utilizing available input parameters of published literatures for diaphragm [3], fixed-fixed beam [9] and cantilever [10] actuated electrostatically have been obtained by re-simulating using CoventorWare™. Fig. 6 through 8 shows comparison of results for the center deflection of the working electrode between the published and the trained GPFFBP ANN model for different micromachined structures. Additionally, results for the diaphragm center deflection obtained using ANN have also been validated with the current CoventorWare™ simulations as shown in Table 6. The validations process successfully demonstrates the robustness and accuracy of the ANN model. The errors generated between predicted and existing results are generally less than 2% when a minimum four sets of training data are used.

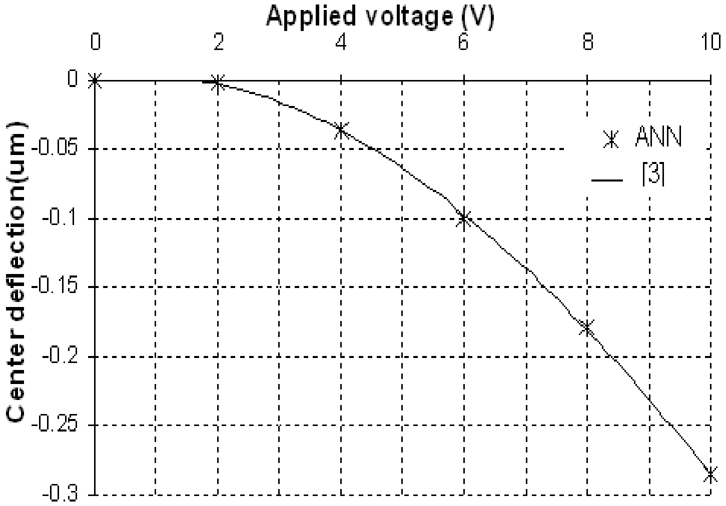

Fig. 6. Comparison of center deflection between ANN and [3] for diaphragm actuated electrostatically.

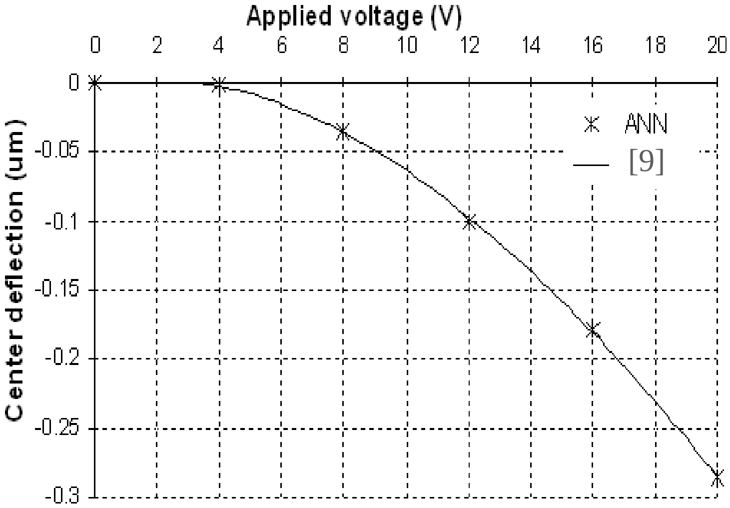

Fig. 7. Comparison of center deflection between ANN and [9] for fixed-fixed beam actuated electrostatically.

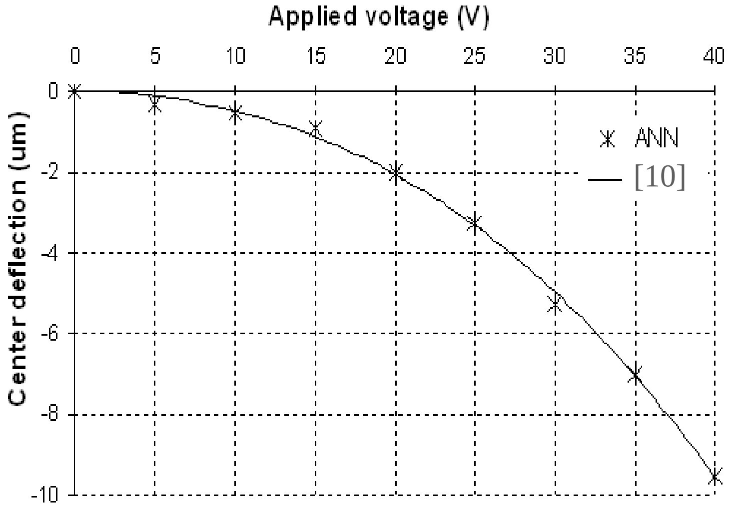

Fig. 8. Comparison of center deflection between ANN and [10] for cantilever actuated electrostatically.

Table 6. Comparison of Diaphragm's Center Deflection Between ANN and CoventorWare™ Simulations.

Parameters	**Value**	**Center deflection (µm)**		**% Error**
		CoventorWare™	**ANN**	
Length, *a* (µm)	300	-0.001730	-0.001761	-1.76
	700	-0.061400	-0.061916	-0.83
Air gap, *d* (µm)	3	-0.014220	-0.014311	-0.64
	4.5	-0.004735	-0.004794	-1.23
Thickness, *t* (µm)	0.8	-0.023123	-0.023141	-0.08
	0.9	-0.020612	-0.020992	-1.81
Residual stress,σ (MPa)	40	-0.018619	-0.018802	-0.97
	60	-0.012641	-0.012800	-1.24

4.2. Parametric Studies

The trained GPFFBP ANN model has been used in the parametric studies for predictions of the center deflections of the micromachined structures. The trained GPFFBP ANN model can be used to accurately predict the center deflection for any input parameters within the investigated range. Fig. 9 through Fig. 11 show the center deflections of the micromachined structures for different thickness obtained via CoventorWare™ simulations along with the ANN results predicted using the untrained parameters given earlier in Table 5.

From the results, the accuracy for the predictions of the ANN model will improve further when more training data (FEA simulation results) are included. Generally it has been ascertained that in this study, the ANN model can yield predictions that is sufficient when a minimum four sets of data for each parameters are included for training as shown in Table 7. The low number of training data required is due to the non-scattered data exhibited from the FEA simulation results.

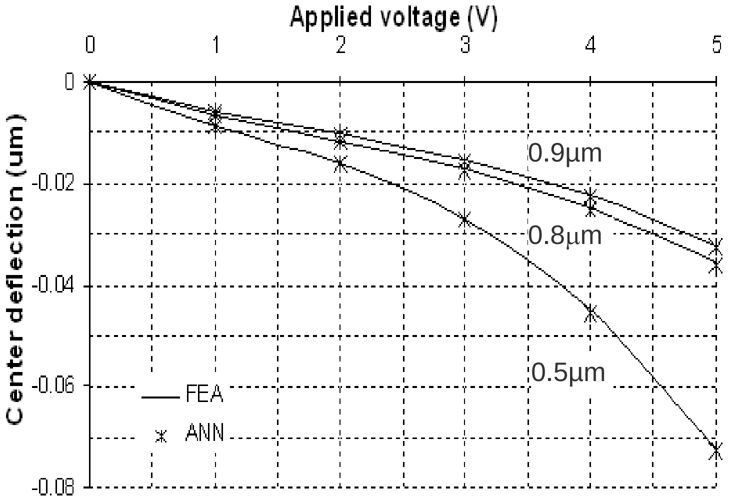

Fig. 9. Comparison of center deflection between ANN and FEA for different diaphragm thickness.

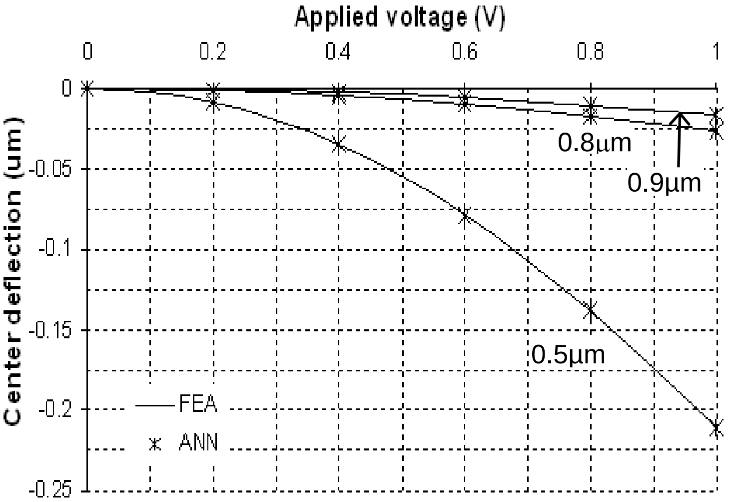

Fig. 10. Comparison of center deflection between ANN and FEA for different fixed-fixed beam thickness.

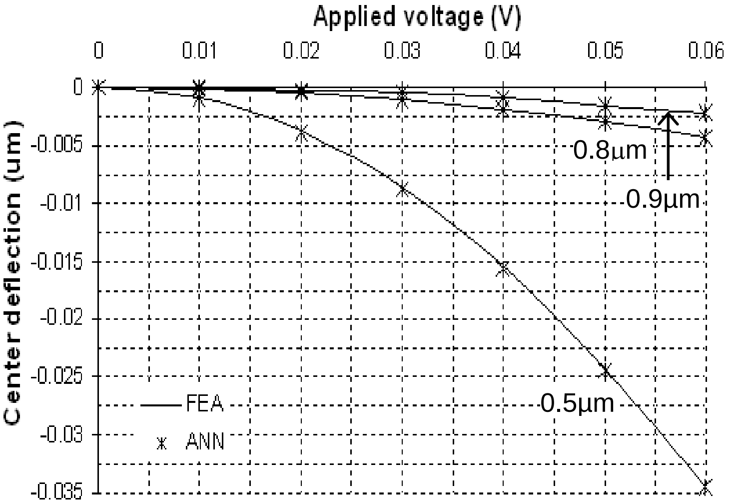

Fig. 11. Comparison of center deflection between ANN and FEA for different cantilever thickness.

Table 7. ANN Predictions for different number of training data.

Number of training data for each parameter	**Diaphragm center deflection using reference value for each parameter (µm)**		**% Difference**
	CoventorWare™	**ANN**	
2	-0.036000	-0.039344	9.289
3		-0.036722	2.006
4		-0.036544	1.511
5		-0.036544	1.511
6		-0.036544	1.511

5. Conclusions

A general purpose Artificial Neural Network (ANN) model based on the feed-forward back-propagation (FFBP) algorithm has been successfully developed to predict the deflections of micromachined structures actuated electrostatically under different loadings and geometrical parameters with errors of less than 2 %. The proposed ANN model will ultimately improve parametric studies with great reduction in simulations efforts. It has been observed that a minimum four sets of training data for each parameter would be sufficient to yield an accurate prediction of the deflections through the ANN simulations.

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Guide for Contributors

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Contributions are invited on all aspects of research, development and application of the science and technology of sensors, transducers and sensor instrumentations. Topics include, but are not restricted to:

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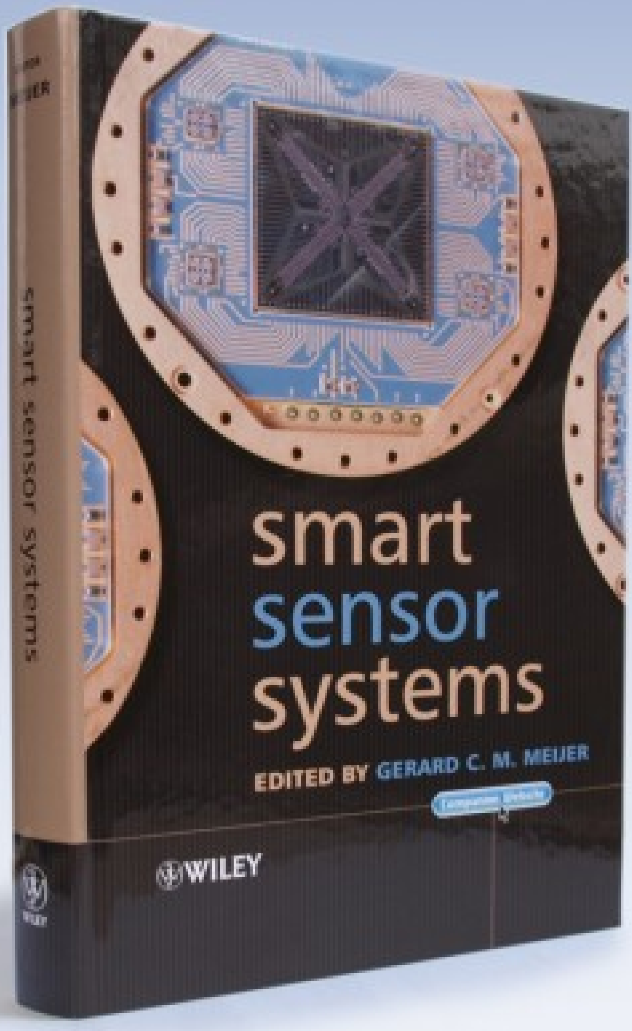
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