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Research Paper

LQR TUNED ANFIS CONTROLLER FOR SISO ACTIVE VIBRATION CONTROL

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ABSTRACT

ANFIS controller for the active vibration control (AVC) of a flexible plate with single input and single output fashion is designed tuned with LQR controller. ANFIS controller is one of the best controllers to control a specific action. MATLAB simulation software is exercised to design it effectively and with highly accurate results. Finite element modeling of plate is done to perform all tests. The LQR controller is utilized to make ANFIS controller for active vibration control by changing parameters like length, breadth, thickness of plate, sensor location and initial displacement to the smart structure. The accuracy of the ANFIS controller results are demonstrated by applying various random inputs that shows the robustness of the proposed controller.

Keywords: Active Vibration Control, Finite Element Model, Linear Quadratic Regulator (LQR), Adaptive Neuro-Fuzzy Inference System (ANFIS).

1 Introduction

The flexible plate structures are utilized in several applications such as airplane wings and solar panels, aerospace structures, automobiles and civil structures like bridges, in antennas in satellites and in robotic designs. These engineering applications lead to high vibration whenexposetoenvironmental disturbances like winds, radiations and also due to presence of large mechanical parts which may cause structural fatigue, and reduce system effectiveness. Therefore, it is very important to reduce these undesirable vibrations to shape control, noise control, to prevent damage and to increase system efficiency otherwise accuracy and precision of the system may get affected. Besides piezoelectric substances have been widely used as sensors - actuators for active vibration control because piezoelectric materials provide economical, consistent, quick reaction, large operating bandwidth, low weight, low power consumption while actuating and sensing the vibrations in flexible structures. The combination of piezoelectric substances with the ANFIS controller makes a cheaper, reliable and high efficient controlling system. Xiaoxu ji, Wilson wang [1] designed an active vibration suppressor by using an adaptive neural fuzzy controller for a flexible structure. A recurrent identification network is formed to adaptively recognize system harmonics which is trained with the novel recurrent training technique to optimize the nonlinear input output mapping. Satishkumar. P. et al. [2] worked on the seat of a vehicle for reducing the axis acceleration and vertical displacement by using an air spring actuator and active force control. In this they made such a control loop that keep track on the developed force of the air spring actuator and feedback to the air spring actuator. Mumdani and Sugeno type fuzzy inference system is used by them to develop the desired

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force and to calculate mass of the system. The velocity of the sprung mass and deflection of the suspension is taken as the input variables of the fuzzy controller. The output variable is air spring force. The membership functions used in the controller are triangular and trapezoidal function. The centre of gravity method is used as defuzzification technique. Arian Bahrami et. al. [3] developed PD like fuzzy logic based Active Vibration control of the piezoelectric stewart platform which are actually platform for a very large space telescope made up by combination of the small telescope. Each leg of the stewart platform is six leg parallel mechanism having six DOF consists of a linear piezo stack actuator, a collocated velocity sensor, a collocated displacement sensor and flexible tips for the connections with the two end plates. These can be affected by gravity loads, attitude control and thermal loads etc. which in turn affect the global resolution. This type of the controller has 294 control rules. Mamdani type (max-min) inference is employed to obtain the best possible results. The centre of gravity method is used for defuzzification. In this way a controller is made to control the piezo stack actuator to reduce the stewart platform vibration. Gustavo Luiz C.M. de Abreu et. al. [4] designed a self organizing fuzzy logic controller to control the vibration of the flexible steel cantilever beam having piezoelectric patches as actuator. Fuzzy rules are generated using input output pairs which are regularly updated real time. A new defuzzification technique is developed by adding a prediction model to the defuzzification process. A.Hossain Nezhad Shirazi et. al. [5] investigated about fuzzy logic controller performance for active vibration control of a rectangular plate made up of functionally graded material (which has resistance to ultra high temperature environment and tolerance of stress singularities) using piezoelectric patches as sensor and actuator to the Proportional Integral and Derivative controller. The first nine natural frequency of the plate and modes of the plate are calculated by double Fourier series. Triangular functions are used to represent the input output variables utilizing five membership functions. Mamdani type fuzzy inference system is used with maximum type of aggregation and center of gravity type is used for defuzzifiction. Banna Kasemi et. al. [6] studied semi active vibration fuzzy PID controller of the magneto-rheological damper. The fuzzy PID controller is found better in adaptive conditions based on the fuzzy rules than PID controller (good for step and impulse road disturbance inputs) and force response is considered over varying current and displacement for MR damper model. Jing-jun Wei et. al. [7] investigated on the experimental comparison on the active vibration control of the flexible manipulator with collocated piezoelectric sensor and actuator of the Fuzzy controller and a combine controller (combination of fuzzy and PI controller). Triangular, trapezoidal and Gaussian are used as membership function. Membership functions of fuzzy variables are grouped into six groups to compare the effects of control methods. Shiuh-Jer Huang et.al. [8] worked on self organizing fuzzy controller for active vibration control. The principle is that two fuzzy subsets are changing based on output response and error change which are observed for every sampling instance. Qing Lu et. al. designed fuzzy logic controller for active vibration control of the cantilever beam attach with PZT patch. A new fitness function is derived for genetic algorithm to find out the performance of membership function. Yuksel Hacioglu et al. [9] worked on the reduction of the vibrations in the vehicle suspension system using proportional derivative and proportional integral fuzzy controller with sliding surface. The controller is divided into two parts proportional derivative (PD) and proportional integral (PI) in which inputs are selected by sliding surface functions and their derivatives. Zhanli Jin et. al. [10] effort on fuzzy controlled genetic based optimization technique for reduction of vibration of cylindrical shell integrated with piezoelectric sensor and actuator. The principle is to dissipate vibrating energy. The fuzzy rule base system is integrated with GA to improve search process. The new method tested is more efficient and better than pure GA method. Mujde Turkkan et. al. [11] investigated active vibration control of bus suspension system model having seven degree of freedom that uses air spring with auxiliary chambers controlled by multi input single output fuzzy controller. H Gu et. al. [12] demonstrated the control of vibration of 11 feet I beam using fuzzy positive position controller which is utilized to control the vibration of smart structures. To control the vibrations a fuzzy gain tuner is used to control the gain of positive position feedback controller at initial stage and thereafter. Hongwei Si et.al. [13] proved that the adaptability of the conventional fuzzy controller is bounded. The Mamdani fuzzy controller is used and seven triangular membership functions are taken. The Min max rule of inference is used. The center of area method of defuzzification is used. Yong Xia and Ahmad Ghasempoor [14] introduce a neural network controller which generates a control signal by detecting noisy sinusoidal vibration parameter of a cantilever plate to stop the vibration. The multilayer feed forward ANN is utilized in which one hidden layer of log sigmoid neurons and one output layer of three log sigmoid neurons are used. Many uncertainties are introduced, firstly pushing the shaker against the beam and secondly bandpass filtering the analog input signal from sensor to provide a bias to the higher frequency harmonics. Such system helps in eliminating the time delay sensitivity. Scott D. Snyder [15] uses the feed-forward neural network control system to control sound and vibration by making a control signal which is the result consequent from a pure tone reference signal containing some level of harmonics. The algorithm is also having a filter based controller which is using gradient decent type algorithm. The limitation of the system is that only linear signal with respect to the reference signal can be surely evaluated and performed. There is a need of continuous updating of the FIR filter weights so that a robust system can be formed. Ratneshwar Jha and Jacob Rower [16] formed a neural network controller which is controlling harmonics of the inputs impulse, sine wave; band limited white noise provided the offline training. An error back propagation technique for multilayer perceptron neural network model is utilized by them. Neural Network Identifier is also used simultaneously with neural network controller to predict the system response to the input and depend on response neural network controller generating the control signal to suppress the vibrations. Subrata Bhowmik [17] worked on semi active control strategy for rotary type magneto rheological damper based on neural network on a base excited shear frame structure. Training data is taken from hysteresis loop and force displacement trajectory. Magnetorheological damper which is semi active device is utilized as a sensor and actuator damper changing the frictional force with respect to changing current and vice versa. Chao-Chee Ku et. al. [18] presented diagonal recurrent neural network which is actually recurrent neural network having a hidden layer and this hidden layer is made of self recurrent neurons. Two DRNN's (diagonal recurrent neuro-controller) are used one for identification purpose and other as a controller. Yali Zhao et. al. [19] investigated of active vibration control of an aluminum plate using a Filtered-Error Back Propagation Neural Network. The comparison between FEBPNN and FXBPNN is done in which FEBPNN is faster than FXBPNN in terms of speed. CP Smyser and K Chandrashekhra [20] worked on robust neural network controller on composite beam which have configuration of sensor and actuator layers in between the beam plates. The output of the Linear Quadratic Gaussian (LQG) controller is provided to the neural network controller for training sample data offline using back propagation algorithm. Rajiv Kumar, S.P Singh and H.N Chandrawat [21] examined Linear Vector Quantisation (LVQ) neural network for active vibration control of a smart structure for an inverted L shape body for first three natural frequencies. Yangmin li, Yugang liu, Xiaoping liu [22] worked on the elimination of the vibration of the modular robot having nine degree of freedom by genetic algorithm based back propagation neural network. Genetic algorithm with back propagation removes many shortcomings of the traditional methods also it optimizes the various parameters of the neural network. M.A. Hossain [23] investigated into the making of smart active vibration control system utilizing evolutionary genetic algorithm and adaptive neuro fuzzy inference system of a cantilever beam given transverse vibration using finite difference method. A set of experiments has been performed to establish the adaptability of the used algorithm. ANFIS is found better at lower natural frequency and GA is found to better at higher natural frequency. M.A Hossain et. al. [24] investigated contrasted performance of the intelligent estimators and controllers (evolutionary genetic algorithm (GA) and adaptive neuro fuzzy inference system algorithm (ANFIS)) for active vibration control systems for a flexible beam stimulated with transverse vibration using finite difference method. The Matlab tool is used for both the GA and ANFIS for designing and implementation. For identification purpose ANFIS (Sugeno type FIS) is found to be better in respect of error convergence and a disadvantage is that it is somewhat more computing process and reduce vibration at lower resonant modes. At higher resonant modes GA shows better results in eliminating vibration. A.A.M. Al-khafaji et. al. [25] investigated into the system identification/estimation of the two dimensional cantilever plate structures without having the previous knowledge about the mathematical model of structure using ANFIS technique. After it, the control strategy is designed for vibration elimination. NI instruments are used to get the data of the plate using piezo beam type accelerometer. After conditioning of data passed to analog to digital converter, then processes through Labview software. The preprocessing ability of the ANFIS makes it faster and better than other techniques. Akihiko Kumagai et. al. [26] worked on the controller for dynamic modeling of shape memory alloy actuators made up of ANFIS. With the help of SMA it is possible to make tiny mechanism used in variety of application like robots and small smart toys, valves, latches and locks etc. A PD control scheme is used to calculate the voltage which is added to the open loop input voltage which finally given to the current amplifier. In this way it reveals the capacity of this kind of controller to control the motion of SMA actuator. A. Aldair et.al. [27] made a ANFIS controller to suppress the vibration of a vehicle suspension system to increase the ease for passenger which has more nonlinearity handling capacity than conventional techniques. This is done by supplying control forces to vehicle suspension system during travelling. The vibration at each corner of the vehicle and inclination of the body get reduced due to it. First the fuzzy optimized PID controller is designed by using the evolutionary algorithm. The data from it is used to form NF controller then neural network is used to tune the parameters of fuzzy inference system's (FIS) membership function. The four types of the disturbances are included (i) amplitude of input sine wave of road profile (ii) amplitude of input square wave of road profile (iii) bending inertia torque with random road profile (iv) breaking inertia torque with random road profile. ANFIS controller is formed using data generated by LQR controller and it is verified by giving it various inputs which are not provided during training mechanism.

2 Methodology

To design the Anfis controller we first have to do the FEM modeling of the cantilever plate then we have to make the LQR controller to reduce the vibrations then we will design the Anfis controller to diminish the vibration.

2.1 Finite Element & State Space Formulation

The equations belonging to finite element modeling are:

$$[M]\{\ddot{\zeta}\} + [K_{qq}]\{\zeta\} + \sum_{k=1}^{n_{e_i}}[T_k]_i^T\,[K_{q\Phi}]_i\{\Phi\} - \{F\} = 0, \tag{1}$$

$$\sum_{k=1}^{n_{e_i}}([K_{\Phi_q}]_i\,[T_k]_i\{\zeta\} + [K_{\Phi\Phi}]_i\{\Phi\} + \mathrm{Q}_a) = 0 \tag{2}$$

Where $[T_k]_i$ is the distribution matrix which shows the position of the k-th element in the plate structure by using zero-one inputs, where the zero input means that no piezoelectric actuator/sensor is present, and one input means that there is an actuator/sensor in that particular element position, n_{e_i} is the number of finite elements of the i-th piezoelectric actuator/sensor, and $\{\zeta\}$ is the nodal displacement vector of the global structure. The figure 1 shows the diagram of the coordinated system of a laminated finite element with the integrated piezoelectric material on which the equations are based.

2.2 Modal LQR control

In the case of optimal control, the following Lyapunov quadratic functional, to be minimized, is defined:

$$J_m = \left(\frac{1}{2}\right)\int_0^\infty(\{X_m\}^T[Q_m]\{X_m\} + \{u^T\}[R_m]\{u\})dt: \tag{3}$$

Then, the following equations hold:

$$\{X_m\} = [\Phi]^{-1}\{X\}$$
$$\begin{Bmatrix}\{\eta\}\\\{\dot{\eta}\}\end{Bmatrix} = \begin{bmatrix}[\Phi]^{-1} & 0\\ 0 & [\Phi]^{-1}\end{bmatrix}\begin{Bmatrix}\{q\}\\\{\dot{q}\}\end{Bmatrix}, \tag{4}$$

Modal weighting matrices $[Q_m]$and$[R_m]$ are related to the well known traditional weighting matrices [Q] and [R], respectively, by

$$[Q_m] = [[\Phi]^{-T}[Q][\Phi]^{-1}] \text{ and } [R_m] = [[\Phi]^{-T}[\mathrm{R}]\,[\Phi]^{-1}] \tag{5}$$

The input forces are defined by the relation:

$$\{u\} = -[K_m]\{X_m\} = -[K_m]\begin{Bmatrix}\{\eta\}\\\{\dot{\eta}\}\end{Bmatrix}, \tag{6}$$

where $[K_m]$, the modal gain matrix, is given by $[K_m] = \left[[R_m]^{-1}[B_{u_m}]^T[S_m]\right]$; and obtained solving the following Ricatti equation in the modal state space:

$$[S_m][A_m] + [A_m]^T[S_m] - [S_m][B_{u_m}][R_m]^{-1}[B_{u_m}]^T[S_m] + [Q_m] = [0] \tag{7}$$

Figure 2 shows the finite element structure of the cantilever plate which we use in our experiments. It is divided into 64 rectangular similar elements which are formed by combining 81 nodes representing the finite points having three degree of freedom in the structure.

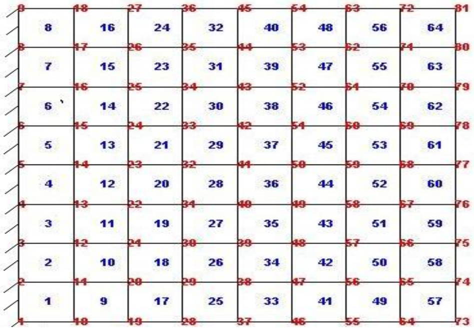

Fig. 2 - Finite element Smart Cantilever Plate with node numbering

2.3 ANFIS Controller

The term ANFIS represents Adaptive-Network-Based Fuzzy Inference System, proposed by Jang, 1993. The ANFIS approach is an alliance of neural networks and fuzzy inference systems. The ANFIS approach find outs the rules and membership functions from data. In ANFIS controller the special architecture based on Sugeno type of inference system enables the use of hybrid learning algorithms that are faster and more efficient as compared to the classical algorithms such as the error back propagation technique. There is a limitation structurally that it should be only feed forward network. Fuzzy inference systems are also known as fuzzy rule based systems, fuzzy models etc. These are having the five different blocks to give the output (i) a rule based containing a no. of fuzzy if then rules (ii) a database which defines the membership functions of fuzzy set used in the fuzzy rules (iii) a decision making unit which perform the inference operations on the rules (iv) a fuzzification interface which transforms the crisp sets into degree of match with linguistic values (v) a defuzzification interface which transform the fuzzy results of inference into a crisp output. The rule based and database is jointly known as knowledge base. The figure 3 is representing the flow chart to design ANFIS controller.

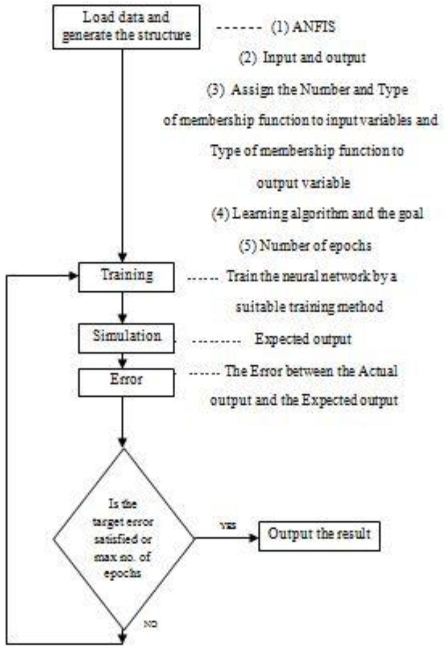

Fig. 3 - Flow Chart of ANFIS Controller

The figure 4 is showing the training criteria/mechanism of ANFIS controller for active vibration control of the metallic plate integrated with piezo sensor and actuator at the top and bottom surface of the plate. In this various inputs related to plate is feed to the LQR controller and gain of the LQR controller is given to the training mechanism of ANFIS controller.

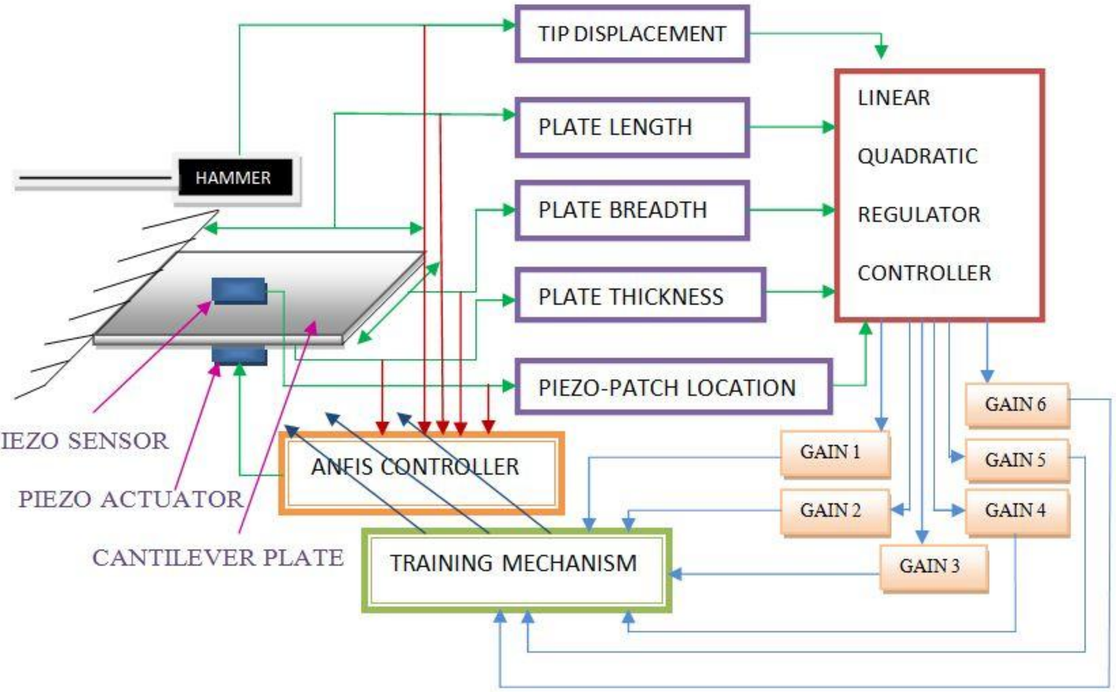

Fig. 4 - Training Mechanism of the ANFIS controller

3 Results

To design the ANFIS controller first we have to design the LQR controller. We will train the ANFIS controller with the inputs and output of the LQR controller in the Matlab tool. The input of the LQR controller is shown in the Table 1.

Table 1 - Input Data to LQR Controller

Sno.	Length of element in meter	Breadth of element in meter	Thickness of element in meter	Piezo-patch location	Tip Displacement in meter
1	0.001	0.001	0.0006	1	0.002
2	0.0012	0.0012	0.00062	2	0.002
3	0.0015	0.0015	0.00065	3	0.002
4	0.0017	0.0017	0.00067	4	0.002
5	0.002	0.002	0.0007	5	0.002
6	0.0022	0.0022	0.00072	6	0.004
7	0.0025	0.0025	0.00075	7	0.004
8	0.0027	0.0027	0.00077	8	0.004
9	0.003	0.003	0.0008	9	0.004

10	0.0032	0.0032	0.00082	10	0.004
11	0.0035	0.0035	0.00085	11	0.006
12	0.0037	0.0037	0.00087	12	0.006
13	0.004	0.004	0.0009	13	0.006
14	0.0042	0.0042	0.00092	14	0.006
15	0.0045	0.0045	0.00095	15	0.006
16	0.0047	0.0047	0.00097	16	0.008
17	0.005	0.005	0.001	17	0.008
18	0.0052	0.0052	0.0012	18	0.008
19	0.0055	0.0055	0.0015	19	0.008
20	0.0057	0.0057	0.0017	20	0.008
21	0.006	0.006	0.002	21	0.01
22	0.0062	0.0062	0.0022	22	0.01
23	0.0065	0.0065	0.0025	23	0.01
24	0.0067	0.0067	0.0027	24	0.01
25	0.007	0.007	0.003	25	0.01

By getting these various inputs LQR produces the various gains to control the action. The output of the controller is shown in Table 2.

Table 2 - Gain Provide by LQR controller

Sno.	Gain1	Gain2	Gain3	Gain4	Gain5	Gain6
1	4.677411	-31.9282	-108.739	-20.9563	53.5054	-129.319
2	-14.3787	-72.3443	255.3083	37.54601	73.42814	201.8917
3	-20.1374	50.74599	239.5964	59.8494	-65.6089	247.929
4	-16.1161	-11.9382	-150.017	74.45356	25.87259	-258.178
5	21.23798	15.41322	197.4515	-90.3163	-31.4374	305.84
6	38.88137	-92.1546	-452.454	-94.6092	103.3633	-364.85
7	52.34708	-233.091	-860.594	-91.0115	174.5549	-422.443
8	-27.8543	172.1796	602.7134	68.99965	-174.068	376.3763
9	-0.56822	-1.94131	4.25802	35.27798	-48.7521	33.02254

10	-1.31921	-4.3663	-12.9597	52.24414	-61.6024	-62.0288
11	0.948321	-4.43118	-11.8407	-63.2522	-47.3237	-70.8145
12	-0.35991	1.962256	9.099279	70.37662	17.80585	73.71017
13	0.443301	-2.38416	-11.168	-78.2336	-19.8377	-82.6544
14	-1.52543	-6.96962	-19.1928	81.02836	-60.9201	-92.6776
15	-3.19868	10.05523	-32.3648	82.97872	98.79305	-103.399
16	1.845398	-5.875	15.1514	-65.2003	-91.2375	68.32207
17	1.396452	3.634601	12.6613	-52.1511	-29.075	240.5593
18	-3.91851	7.38078	-41.8305	82.17076	-43.0109	-296.554
19	5.832745	5.356281	68.34046	-103.641	-37.8834	311.1781
20	6.409538	1.441434	-79.4223	-115.279	-14.848	-313.531
21	-8.31803	1.462527	106.3576	126.0616	-16.6351	330.1982
22	-11.2011	-7.32294	139.8122	128.5659	49.90227	352.4775
23	-15.5229	-20.9292	-187.377	128.0266	76.30241	-384.188
24	12.27798	-25.8762	139.9761	-107.176	72.59495	373.3252
25	-21.7102	41.3752	84.66619	79.25896	-23.9612	567.7953

The graphs show the LQR controller controlled response with the uncontrolled response of the vibrating plate with respect to change in the value of length, breadth, thickness, piezo-location and tip displacement at the edge of plate. The blue is showing uncontrolled response and green one is showing the controlled response after apply LQR controller.

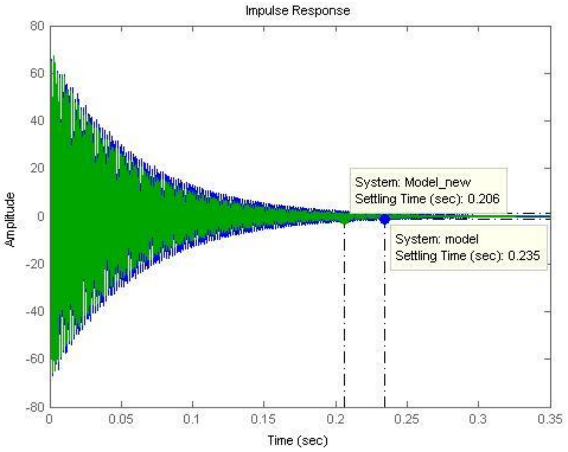

Fig. 5 - Controlled and uncontrolled response of the LQR controller at Length=0.002m, Breadth=0.002 m, Thickness=0.0007 m, piezo-patch location=5, tip displacement=0.002m.

Figure 5 shows the LQR controller controlled responses with the uncontrolled response of the vibrating plate when Length is 0.01m, Breadth is 0.01m, Thickness is 0.0006 m, piezo-patch location is 1 and tip displacement is 0.002 m.

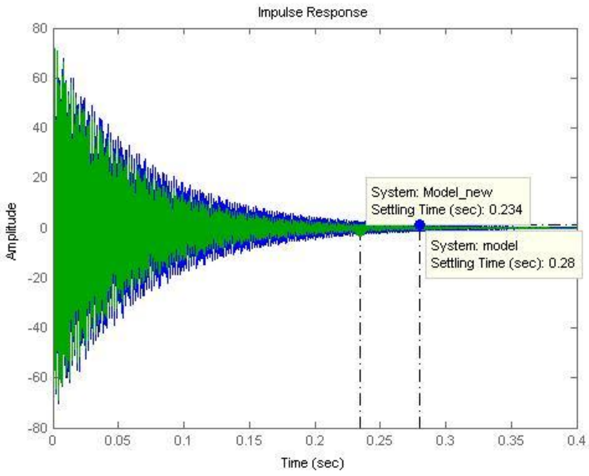

Fig. 6 - Controlled and uncontrolled response of the LQR controller at Length=0.0022 m, Breadth=0.0022 m, Thickness=0.00072 m, piezo-patch location=6, tip displacement=0.004m.

Figure 6 shows the LQR controller controlled responses with the uncontrolled response of the vibrating plate when Length is 0.0022m, Breadth is 0.0022m, Thickness is 0.00072 m, piezo-patch location is 6 and tip displacement is 0.004 m.

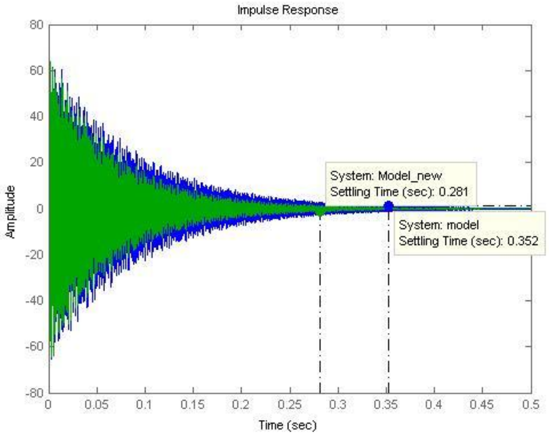

Fig. 7 - Controlled and uncontrolled response of the LQR controller at Length=0.0025 m, Breadth=0.0025 m, Thickness=0.00075 m, piezo-patch location=6, tip displacement=0.004m.

Figure 7 shows the LQR controller controlled responses with the uncontrolled response of the vibrating plate when Length is 0.0025m, Breadth is 0.0025 m, Thickness is 0.00075 m, piezo-patch location is 6 and tip displacement is 0.004 m.

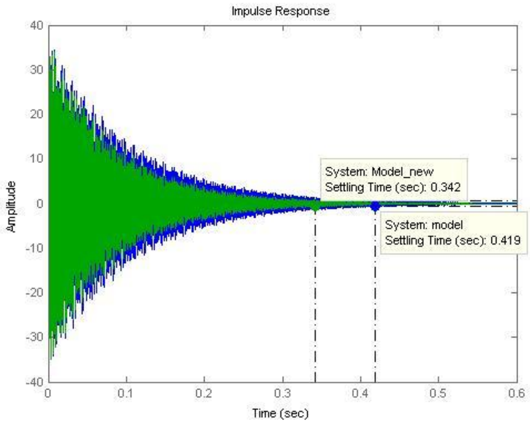

Fig. 8 - Controlled and uncontrolled response of the LQR controller at Length=0.0027m, Breadth=.0027m, Thickness=0.00077 m, piezo-patch location=8, tip displacement=0.004m.

Figure 8 shows the LQR controller controlled responses with the uncontrolled response of the vibrating plate when Length is 0.0027m, Breadth is 0.0027m, Thickness is 0.00077 m, piezo-patch location is 8 and tip displacement is 0.004 m.

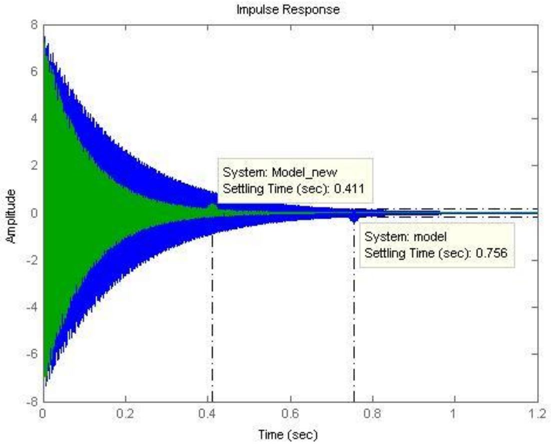

Fig. 9 - Controlled and uncontrolled response of the LQR controller at Length=0.007 m, Breadth=0.007 m, Thickness=0.003 m, piezo-patch location=25, tip displacement=0.01m.

Figure 9 shows the LQR controller controlled responses with the uncontrolled response of the vibrating plate when Length is 0.007m, Breadth is 0.007m, Thickness is 0.003 m, piezo-patch location is 25 and tip displacement is 0.01 m. Now the input and output data is used to train the Anfis controller. We will utilize the Matlab tool to make Anfis controller. For this we take a matrix of 25*6 in which we have 5 columns of various inputs (length, breadth, and thickness of plate, piezo location and Tip displacement) and a column of gain provided by LQR controller. Based on this the different Anfis controller networks produces different training error during training mechanism with input conditions and different gain provide by the LQR controller. For each input there is 3 membership functions are assigned and the output membership functions is of linear type. The membership function used is gauss membership function and hybrid training method is used to train the Anfis controller. The number of epochs taken is 3 and error is also calculated for this only. Figure 10 shows the graph of the error during training of an ANFIS network in Matlab tool.

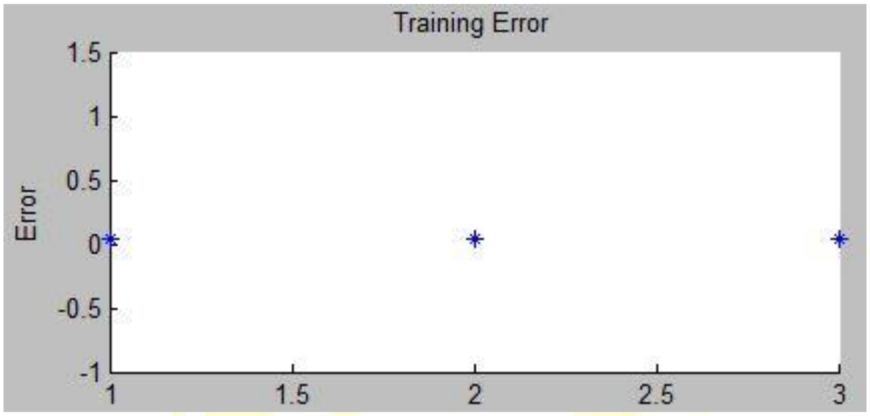

Fig. 10 - Error during Training of an ANFIS Network

Figure 11 shows the graph between output verse training data of network and the error in the training is less than 1%.

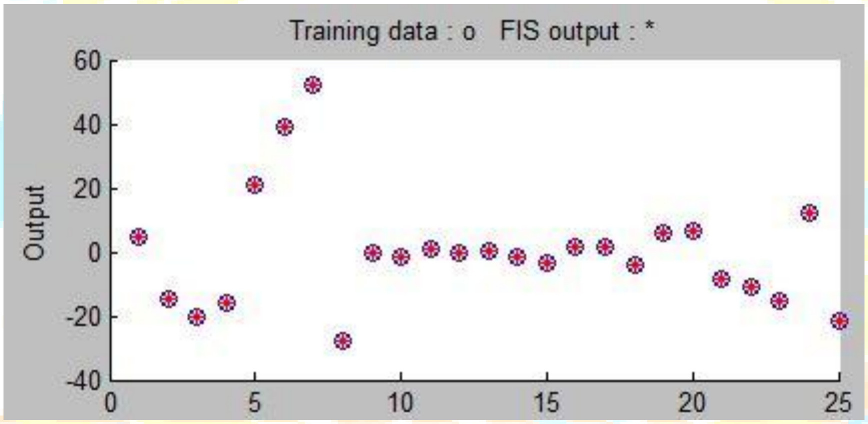

Fig. 11 - Output verses Training Data

After training of the Anfis structure looks like as shown in the figure 12. There are 5 inputs and a single output in it.

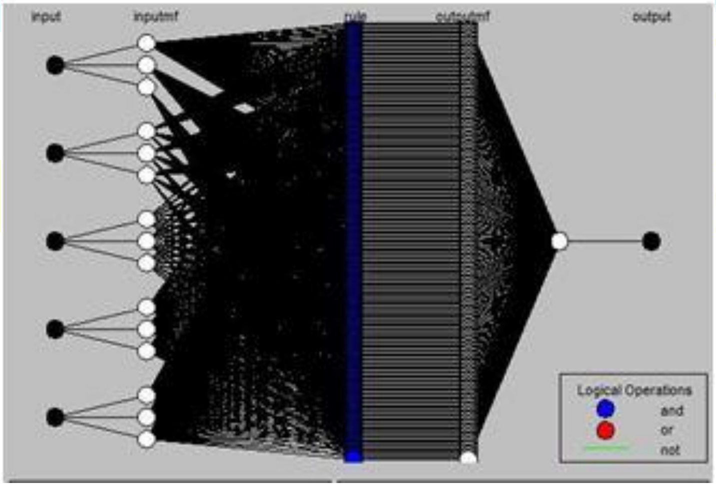

Fig. 12 - Anfis Structure after Training

Similarly we have made 5 more ANFIS structure for different gains provided by the LQR controller. The table is showing the different training error for different ANFIS structure.

Table 3 - Error after Training Data

ANFIS NETWORK 1 TRAINING ERROR	0.04094
ANFIS NETWORK 2 TRAINING ERROR	0.39472
ANFIS NETWORK 3 TRAINING ERROR	0.58061
ANFIS NETWORK 4 TRAINING ERROR	0.18838
ANFIS NETWORK 5 TRAINING ERROR	0.23101
ANFIS NETWORK 6 TRAINING ERROR	0.68637

The Anfis controller output response graphs are shown below in which random inputs are given and the controller is giving proper outputs. There is no effect of these changing conditions and Anfis controller producing the appropriate response to these inputs. The settling time of the vibrations when controller is applied is always less than the settling time when controller is not applied.

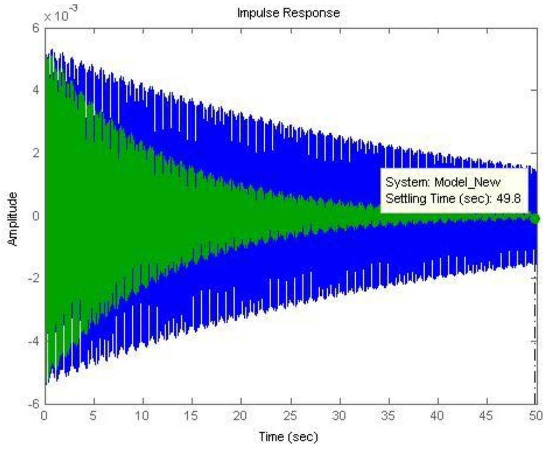

Fig. 13 - Uncontrolled and Controlled Responses (ANFIS) at the Edge of Plate when Length is 0.0012m, Breadth is 0.0012m, Thickness is 0.00062m, Piezo Location 3 and Tip Displacement .002m.

As the settling time for controlled response of ANFIS controller is very less than the settling time of the uncontrolled response in the figure 13 so the result for applying random changing inputs to ANFIS controller are suitable.

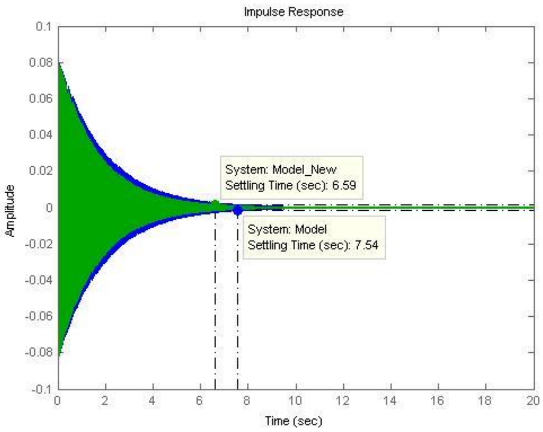

Fig. 14 - Uncontrolled and Controlled Responses (ANFIS) at the Edge of Plate when Length is 0.0010m, Breadth is 0.0010m, Thickness is 0.0006m, Piezo Location 24 and Tip Displacement 0.002m

It is clearly visible from the figure 14 by comparing settling time that it is showing the good controlling action to reduce vibrations.

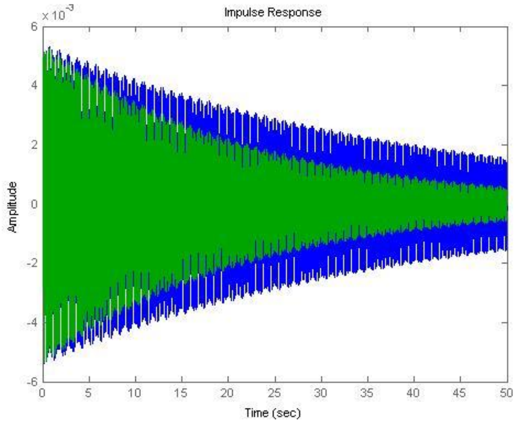

Fig. 15 - Uncontrolled and Controlled Responses (ANFIS) at the Edge of Plate when Length is 0.0017m, Breadth is 0.0017m, Thickness is 0.00067m, Piezo Location 4 and Tip Displacement .002m.

By observing the figure 15 it is clear that the controller is doing a very good job in reducing the vibrations of the plate.

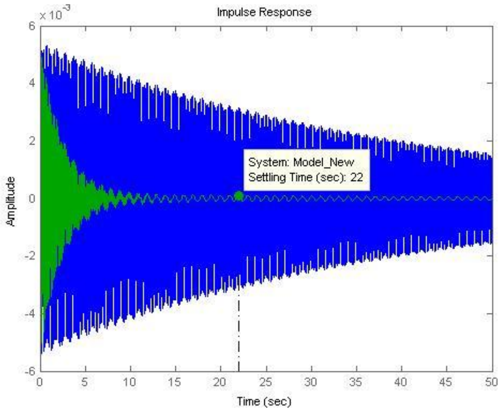

Fig. 16 - Uncontrolled and Controlled Responses (ANFIS) at the Edge of Plate when Length is 0.001m, Breadth is 0.001m, Thickness is 0.0006m, Piezo Location 1 and Tip Displacement is 0.002m.

In the figure 16 the settling time for controlled response of ANFIS controller is very less than the settling time of the uncontrolled response hence it is showing the highest degree of elimination of the vibrations of the plate.

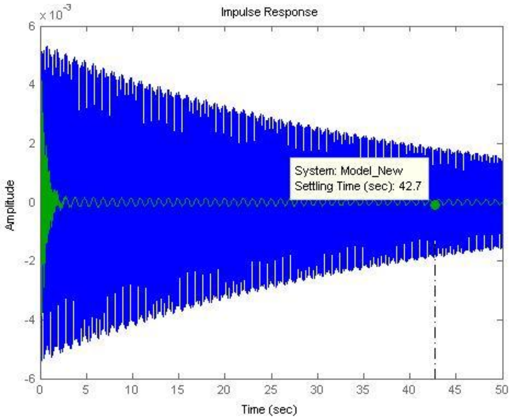

Fig. 17 - Uncontrolled and Controlled Responses (ANFIS) at the Edge of Plate when Length is 0.001m, Breadth is 0.001m, Thickness is 0.0006m, Piezo Location 24 and Tip Displacement is 0.002m.

By observing the figure 17 it is clear that settling time for controlled response of ANFIS controller is very less than the settling time of the uncontrolled response. In this way it is clear that the designed controller is the appropriate to reduce the vibrations of the plate.

4 Conclusion

The adaptive neuro fuzzy inference system network has been designed for active vibration control of a cantilever plate having finite length, breadth and thickness for single input and single output approach with the help of output gain generated by LQR controller. The five different Anfis structures are formed (each having a training error less than 1%) and combination of these structures make a robust Anfis controller. The trained Anfis network is tested for many values and it is performing well in different values which are not even provided in the training data. The designed Anfis network is able to reduce the vibrations effectively of any system which is subjected to impulsive force and a disturbance of white noise.

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