Intelligent Controllers/Adaptive Controllers for Active Vibration Control in Different Structures/Systems-A Review

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***Abstract*-This article presents in a cohesive way the use of intelligent/adaptive controllers to mitigate vibrations within smart structures. This article discusses (i) The three different techniques for making controllers to design AVC (Active Vibration Control) (ii) how these controllers are formed to eliminate the vibration of a smart structure (iii) Applications of intelligent/adaptive controllers in various structures/systems. These controllers are able to adjust according to the unstructured/structured uncertainties and hence the stability of the system increases. This paper helps the practicing engineers/beginners in this field, able to know how to design intelligent/adaptive controllers for AVC.**

Keywords-Active Vibration Control, intelligent/adaptive controllers, fuzzy logic controller, neural network controller, adaptive neuro fuzzy inference controller.

I.INTRODUCTION

The controllers have grown up to a very large extent over a past few years. The controllers are used specifically to act upon a particular input and control the action of a system. They have got tremendous significance and application potential in a smart /intelligent system. The classical controllers have also been used by researchers to control noise and structural vibrations like proportional, proportional derivative, proportional integral derivative etc. But these are not as efficient as intelligent controllers. Active vibration control (AVC) is one of the applications of smart structure. Leug (1936), founder of AVC gives the concept for cancelation of sound in a duct. In AVC, an external source of energy is used to control structural vibrations. It consists of sensors to observe the structural dynamics, a controller to collect the sensor signals & gives a suitable signal to actuators, and the actuators to follow the order of the controller. Such a structure is known as a 'smart structure'. Fuzzy controller, neural network controller, ANFIS controller comes under the category of adaptive/intelligent controllers. These can be used as an identifier/estimator when it is calculating the whole system response even for that position where sensor is not placed. Gustavo Luiz C.M. de Abreu et. al. [1] 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. Qing Lu et. al. [2] designed fuzzy logic controller for active vibration control of the cantilever beam attach with PZT patch. The centre of gravity method is used for defuzzification. The six linguistic values are taken for displacement. The genetic algorithm is used to optimize fuzzy logic controller membership function which is inspired by organic evolution having encoding, selection, crossover and mutation processes. A new fitness function is derived for genetic algorithm to find out the performance of membership function. The new fitness function has better convergence and de-amplification speed and high robustness than previous one because the optimum results have overlapping relationship. Yong Xia and Ahmad Ghasempoor [3] introduce active and adaptive neural network controller which produce a control signal by detecting noisy sinusoidal vibration parameter of a cantilever plate to eliminate the vibration. The multilayer feed forward ANN is utilized where 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 band pass 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. Xiaoxuji, Wilson wang [4] 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. M.A Hossainet. al. [5] 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, but have the disadvantage of more computing process and reduced vibration at lower resonant modes. At higher resonant modes GA shows better results in eliminating the vibrations.Active vibration control (AVC) is a system in which vibration of any beam or plate etc. is controlled by using an actuator which produces same quantity of vibration for counter balancing the vibration produced by the system. The basic block diagram of AVC is shown in figure 1.

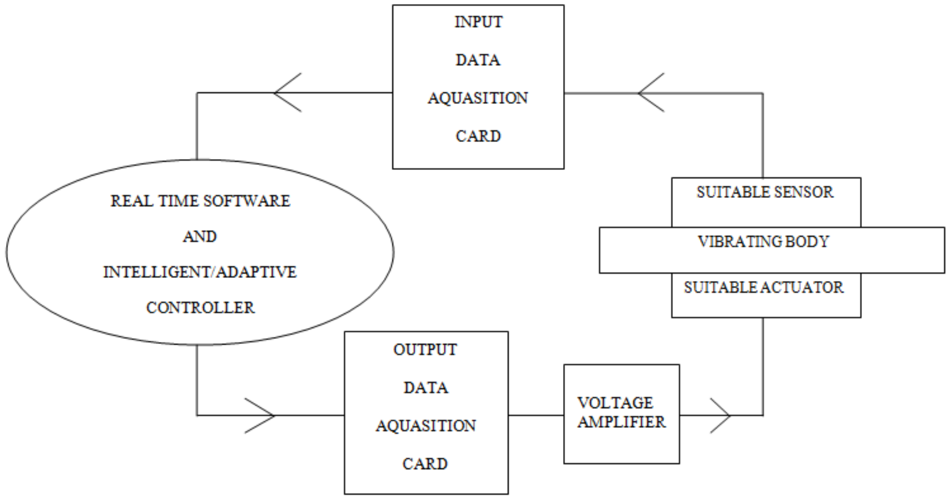

Fig.1Diagram of a general active vibration control

Vibration suppression is very necessary in aeronautics, astronautics, mechanical systems and various electronic systems like robotics and where high precision is required because of its low power consumption and less weight.

A. Fuzzy Controller

The fuzzy system modeling is first explored by Takagi and Sugeno. They found a lot of application of it in control, prediction and inference.
The fuzzy logic controller is based on simple human reasoning. The design of fuzzy logic controller is simply based on three steps.
1) Fuzzification.
2) Rule base generation.
3) Defuzzification.

1)Fuzzification:
First of all input and output variables for the fuzzy controller are selected. Then the designer has to give the input and output in a suitable range. The range for input variables may be selected by observing the data for input variables, for a considerable length of time. The range for output variables may be selected by looking at specifications which guarantee the safety of the actuator. Fuzzy sets are then constructed over all input variables and output variables. In the fuzzy controller for active vibration control, the input is generally the displacement and velocity of the plate taken. The range of the output depends on the suitable length of the value of "k" which depends on control force required.
2)Rule base generation:
The rules are designed based on human reasoning. A fuzzy inference step is invoked for each of the relevant rules to produce a conclusion based on their matching degree. The conclusion is produced on the base of two methods (1) the clipping method (2) the scaling method. Both methods generate an inferred conclusion by suppressing the membership function of the consequent. The extent to which they suppress the membership function depends on the degree to which the rule is matched. The lower the matching degree, the more the suppression of membership functions. After it all the fuzzy conclusions are combine through superimposing is based on applying the max fuzzy disjunction operator to multiple possibility distributions of the output variable.
3)Defuzzification:
In this step, depending upon the rules which get fired, a crisp value is obtained for the output variables which are the final output of the fuzzy system. There are two major techniques for defuzzification.
1)The Mean of Maxima (MOM) method:
The Mean of Maxima (MOM) defuzzification calculates the average of all variable values with maximum membership degrees. It is given by the following formula:

$$\text{MOM (A)} = (\textstyle\sum_{y*\varepsilon P} y*)/ |P| \quad (1)$$

Where P(A) is the set of output values y with the highest membership degree in A.

$$P=\{y*|\mu A(y*)\} \quad (2)$$

It will give the maximum value.

2) The centre of area or centroid method:

The centroid is given by the algebraic expression.

$$q_r = \frac{\int \mu(F_0) F_0 \, dF_0}{\int \mu(F_0) \, dF_0} \quad (3)$$

Where F_0 is the fuzzy variable and $\mu(F_0)$ is the membership value of the fuzzy variable

There are three types of fuzzy inference systems. The term control engineering refers to a discipline whose main concern is with problems of regulating and generally controlling the behavior of physical systems (an interconnected collection of physical objects or entities that together serve a specific purpose or function predictable in accordance with physical laws).The design process is generally a multistage process involving

1)Selection of control design technique or methodology: The design methodology is divided as time domain and frequency domain based. Frequency domain design range from loop shaping to H_∞ based design techniques while time domain design methods range from simple PID design to linear quadratic optimal control.

2)Determination of technical design objectives: This section requires interpreting, refining and quantifying the given external performance objectives into a set of technical design objectives compatible with the given design methodology.

3)Development of the plant model: This section tells that we should have a predictive model of the plant. In general such a model is a mathematical description of the behavior of thegiven physical system and is derived according to applicable physical laws.

4)Selection of controller structure and parameters: The simplification and linearization of the plant model equilibrium or an operating point is a vital step in control design process.

Fuzzy logic control attempts to come to terms with the informal nature of the control design process. There are many type of architecture used for fuzzy logic control.

1) Mamdani architecture for fuzzy control: This is proposed by E.H. Mamdani in 1974. This architecture is lacking of clear statement of control design objectives and informal knowledge of the operation of the given plant can be codified in terms of if then rules and make a strategy for a linguistic control. The rule base control strategy of it is of the form:

if OA_1 is -----and OA_2 is ----- and ----- then CA_1 is ----- and CA_2 is ------ and so on.

This maps observable attributes (OA_1 ,OA_2------)of the physical system into controllable attributes(CA_1, CA_2-----). and so on.

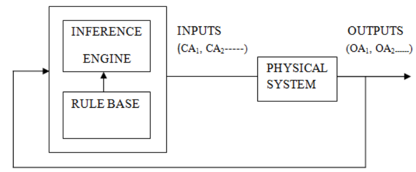

Fig.2 Diagram of a mamdani architecture for fuzzy control.

2)The Sugeno-Takagi architecture: The natural extension of the notion of fuzzy logic control is by means of this Sugeno-Takagi architecture (Takagi-Sugeno-Kang, TSK) architecture. The rule set defines regions of action of conventional differential algebraic control laws in this particular type of controller. In this paradigm the rule set is made up of r rules of the form.

Rule i: if x_1 (t) is M_{i1}, x_2 (t) is M_{i2}…….., and x_n(t) is M_{in} ,

then y = $a_{i0} + a_{i1} x_1(t) + a_{i2} x_2(t) + \ldots\ldots + a_{in} x_n(t)$.

where x_1, x_2, x_3.........$x_n$are the antecedent variables and y is the consequent variables. Moreover M_{i1},M_{i2},......... M_{in} are fuzzy sets defined over the respective domains of definitions of x_1,x_2,............$X_n$while a_{i0}, a_{i1}, $a_{in}$are constant coefficients that characterized the linear relationship defined by the ith rule in the rule set, i = 1,2,3………..r.

From a control engineering standpoint the application of the TSK based scheme would be in constructing a nonlinear control law by augmenting piecewise linear relationships of the form that appears in the consequent of the above equation. Manu Sharma, SP Singh, BL Sachdeva [6] created fuzzy logic based independent modal space and fuzzy logic based modified independent model space controller. The inputs to the fuzzy logic based controller are modal displacements and the modal velocities of the modes which are to be controlled. A real kalman observer is used in which a given set of rules is to be executed in every sampling interval. Nine simple rules are engaged so that the control code completes within the allotted sampling time in fuzzy logic controller. Varun Kumar, Deepak Chhabra [7] worked on the fuzzy logic controller for active vibration control of cantilever plate. The tip displacement and tip velocity is taken as the input to the controller and control force is taken as the output. Rule base consists of nine rules. The controller found suitable for first three modes of vibration of the beam. A. HossainNezhadShiraziet. al. [8] 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 motion equation of plate is derived from classical plate theory and the first nine natural frequency of the plate and modes of the plate are calculated by double Fourier series. Fuzzy logic controller is found to be more capable to eliminate the plate vibration as comparison to PID controller. 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. BannaKasemiet. al. [9] studied semi active vibration fuzzy PID controller of the magneto-rheological damper which is having the characteristics of the active devices and reliability of the passive devices in a car. MR contains the 20 to 40 % of pure iron particle in the fluid of dimension of few microns. The force and displacement were observed for different velocities and different starting stroke in the experiment. The force applied is directly proportional to the current applied due to it attracts iron particles to form a chain. 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. [10] 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). Both can effectively reduce the vibration where PI is used for low measured errors and fuzzy is used for higher value than a set value. The optimal location of the sensor and actuator is found by genetic algorithm. 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. Max min product composition fuzzy inference is used to control the fuzzy control rules. The centre of average defuzzification method is used for defuzzification. Shiuh-Jer Huang et.al.[11] worked on self organizing fuzzy controller for active vibration control which has the learning ability with time varying instability of the system causing vibrations. Also the control rules are updated online. The principle is that two fuzzy subsets are changing based on output response and error change which are observed for every sampling instance. Based on this, only four rules in the table is modified and fired so it increases the learning capacity as the sampling frequency is increasing. YukselHacioglu et al. [12] worked on the reduction of the vibrations in the vehicle suspension system using proportional derivative and proportional integral fuzzy controller with sliding surface. In the controller inputs are changed according to some predefined rules and system states are generated and provided to sliding surface and forced to stay there. 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. The integrated output is provided to the vehicle suspension system in this way vibrations get reduced. Triangular membership function is used. The proposed controller is better efficiency than passive, PID and fuzzy controller. Zhanli Jin et. al. [13] effort on fuzzy controlled genetic algorithm based optimization technique for reduction of vibration of cylindrical shell integrated with piezoelectric sensor and actuator. The design, size and location of the piezoelectric patch on the shell are computed using fuzzy set theory. 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. Three examples of simply supported plate, a simply supported cylindrical shell and a clamped simply supported plate are also discussed to show the convergence of the method. The results represent that the piezo-patch should be placed within the area separated by nodal lines of vibrations. The centroid method is used for defuzzification. MujdeTurkkanet. al. [14] 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. It is providing both ride comfort and protection to road irregularities. The inputs to fuzzy controller are errors of suspension end velocities, their acceleration and suspension gap velocities and four control forces are considered. H Gu et. al.[15] 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 (PPF) controller at initial stage and thereafter. The fuzzy system is trained desired data with least square algorithm. The three type of PPF control methods are discussed (1) a standard PPF (2) PPF with fuzzy gain tuning (3) PPF with batch least square fuzzy gain tuning. The experiment shows that PPF with batch least square fuzzy gain tuning is best among the three in quick reduction. The centre of average is used for defuzzification. KanjuroMakiharaet. al. [16] gave a fuzzy based controller to reduce adaptive (consists of fuzzy inference and semi active switching approach) multimodal vibration of a CFRP plate. He also showed that a single piezoelectric actuator can reduce two modes of vibrations. The proposed fuzzy controller has better adaptability to change in input disturbances than traditional fuzzy controller. Hongwei Si et.al.[17] proved that the adaptability of the conventional fuzzy controller is bounded. In this they designed a self adjustable fuzzy controller for vibration control of large flexible space truss mounted with piezo sensor and actuator. In order to improve fuzzy logic controller the scaling of universes of discourse technique is used. The input and center of output membership function of fuzzy is taken as input universes of discourse and output universes of discourse. A type of lyapunov function is considered to be the adaptive rule of input universes of discourse and based on this the center value of output membership function was accepted. 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.

B. Artificial Neural Network

The Artificial Neural Network (ANN) is a computational tool based on the interconnection of the neuron/nerve cells in the nervous systems of the human brain which is called Biological

Neural Network (BNN). Both having the basic processing units are called neurons/nodes. Each node performs a simple operation to compute its output from its inputs which is transmitted through links connected to other nodes. Many concepts and properties of BNN are realistically imitated by the ANN. ANN are a type of non-linear processing system ideally suited for a wide range of tasks, especially where there is no algorithm is present for completion of task.ANN can be trained to solve convinced problems using a learning method and sample data. In this way, ANN can be used to perform different tasks depending on the training be given. With proper training, ANN is capable of simplification, the ability to recognize similarities among different input patterns, especially patterns that have been corrupted by noise/disturbances and environmental uncertainties. By looking at the tremendous advantages of ANN in the situation handling capacity, many researchers use this in varieties of problems. The diagram of basic processing element called neuron in ANN is shown in figure 3.

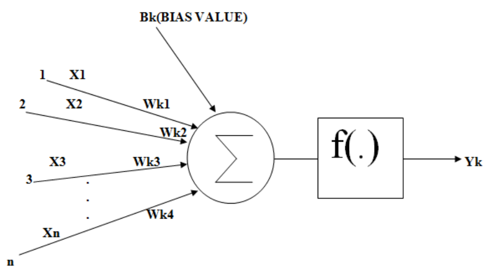

Fig.3 Diagram of a single artificial neuron

Where X_1, X_2, X_3 and so on X_n are the inputs to the neuron, Wk_1, Wk_2, Wk_3. . . .Wk_n are corresponding weights and bk is bias. Y_k is output of the neuron and f(.) is any function on which a neuron will response or will give the output. These are connected to each other to form a network. The response is obtained on the randomly selected input termed as training data. The general model of interconnected processing units consists of summing part followed by an output part. The summing part receives N input values and weights each value and compute a weighted sum. The weighted sum is called the activation value. The output part produces a signal from activation value. The sign of the weight for each input determines whether the input is excitatory (positive weight) or inhibitory (negative weight).The input could be discrete or continuous data values and likewise the outputs also could be discrete or continuous. The output of the neuron is given by

$$yk = f(\sum(xi * wi) + bk) \tag{4}$$

Where i varies from 1 to k. This is called as McCulloch Pitts model of ANN. The one of the major feature of the ANN is its learning capability. The various learning algorithms of ANN adjust the parameters such that the neural network learns to improve its performance for a given task. There are three types of neural network learning algorithms. The first one supervised learning which uses a set of training data such that input output mapping of neural network becomes more and more consistent with training data eg. back propagation. The second one is reinforcement learning algorithm which uses positive and negative reinforcement signals about the NN's performance to adjust its parameters. The feedback signal is less informative in it than supervised learning but it does not require training data. The third one is the unsupervised learning which is similar to clustering techniques need not require training data.For a given set of inputs to the network, outputs are computed for each neuron in the first layer and forwarded to the next layer. The signals propagate on a layer-by-layer basis until the output layer is reached. The weights and biases remain unchanged during the 'forward pass'. The output of the network is compared with the desired value (t_j) and difference gives the error.

$$e_j = t_j - y_j \tag{5}$$

The total error is defined by following equation, where *c* is the number of neurons in the output layer.

$$\mathrm{E} = \frac{1}{2}\sum_{\mathrm{j}=1}^{\mathrm{c}} \mathrm{e}_{\mathrm{j}}^{2} \tag{6}$$

The error *E* represents the cost function, and the weights and biases are updated to minimize it.The computed partial derivatives (sensitivity) $\partial E/\partial w_{ji}$ determine the search direction for updating the weights w_{ji} as

$$w_{ji}(k+1) = w_{ji}(k) - \eta \frac{\partial E(k)}{\partial w_{ji}(k)} \tag{7}$$

*k*is the current time and (k + 1) is the next time step. The above update formula is refined using a 'momentum term' that has a stabilizing effect on the back-propagation algorithm. The training of the NN is complete when the error (or change in the error) reduces to a predetermined small value.

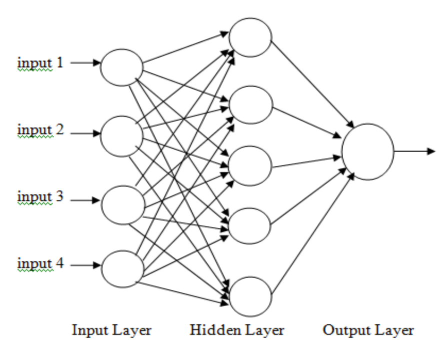

Fig. 4 Diagram of an artificial neural network.

*Techniques used by researchers in ANN:*There are various types or techniques of the neural network which are often used by researchers to implement in different applications of AVC. These are basically different in no. of layers and neurons and how these neurons are connected to each other. Some of them which are frequently used by researchers in active vibration control are listed as

1)Feed forward neural network

2)Back propagation
3)Radial basis function (RBF) network
4)Recurrent neural network

1) Feed forward neural network: This is simple type of ANN in which information moves only in forward direction from input neurons to the output neurons passing through the hidden neurons if present. There is no feedback in the network

*2)Back propagation:*It is a contraction for "backward propagation of errors", is a common supervised technique for training artificial neural networks. From a desired output, the network learns from many inputs. Back propagation requires that the activation function used by theneurons be differentiable.

3)Radial basis function (RBF) network: RBF is based on the distance criteria from the centre of any function generally it is Gaussian. It shows great response in the multidimensional problems. In regression problems the output layer is then a linear combination of hidden layer values representing mean predicted output. RBF networks have the advantage of not suffering from local minima as in the other. This is because the only parameters that are adjusted in the learning process are the linear mapping from hidden layer to output layer. RBF networks have the disadvantage of requiring good coverage of the input space by radial basis functions.RBF network istypicallytrained with maximum likelihood framework by maximizing the probability of the data.

4)Recurrent Neural Network: It is opposite in functions with feed forward ANN. In this type of neural network data flows in two directions and it moves data from later stages to earlier stages

Scott D. Snyder [18] 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 can be surely evaluated and performed. The continuously updating of the FIR filter weights gives stability to the whole system and a robust system is formed. RatneshwarJha and Jacob Rower [19] 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. Samuel Da Silva, Vicente Lopes Junior and M.B. [20] worked on the active vibration control of a cantilever plate for the first two modes at the cost of changing frequency at 15% rate by using Linear Matrix Inequalities (LMI). The various parameters of the AVC like location of sensors and actuators and feedback controller all achieved through the use of LMI. Plant model is identified by Eigen system realization algorithm. ZhichengQiu, Biao Ma and Xiangton Zhang [21] made a vision feedback based active vibration control system for flexible manipulator by using radial basis function neural networks. The end side image processing methods are given by them. PD control algorithm output is used to train the radial basis neural network. E.Bianchi, G.L Ghiringhelli, D. Martini and P. Masarati [22] exertion on active noise and vibration neural network controller for a rectangle flat aluminum plate based on diagonal recurrent neural networks to reduce electromechanical harmonics with the help of software platform of RT-LINUX. A diagonal recurrent neural network is implemented characterized by one input layer, one output layer and one recursive hidden layer. The least mean square algorithm is utilized to train both the estimator and director. SubrataBhowmik [23] 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. S.H.Yaun, J.H.Han, I Lee [24] found the results and variations of sudden delamination of the composite beam with the help of neuro adaptive controller. Jimoh O. Pedro et. al. [25] presented an adaptive neural network-based feedback linearization slip control scheme for antilock braking system (ABS) to reduce vehicle braking distance. The multilayer perceptron neural network model is used to represent ABS. Levenberg-Marquardt algorithm is used to train the neural network with genetic algorithm optimized controlled gain signal. The difference between the wheel speed while braking is sensed and the braking pressure is controlled by the neural network controller. In this way braking distance is reduced. The designing of the system is having a lot of the problems though it is having a no. of challenges like nonlinearities in the suspension system and uncertainties like road conditions and road surface etc. The neural network based feedback linearization controller demonstrated robustness to both model and parametric uncertainties related to control of suspension. Chao-Chee Ku et. al. [26] 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 are used one for identification purpose and other as a controller. Based on the working of these, are named as diagonal recurrent neuro-identification (DRNI) and as diagonal recurrent neuro-controller (DRNC). The system is identified by DRNI and provide signal to the DRNC. DRNC is used to derive an unknown dynamics to minimize error between desired and the plant output. A generalized back propagation method is used to train both DRNI and DRNC. Lyapunov function is used to find the adaptive learning rates for the DRNN. Different cases were studied like bound input bound output nonlinear plant control, the non-BIBO nonlinear plant, tolerance to disturbances and the interpolation ability of DRNN based control system. It is better than fully connected recurrent neural network in terms of fewer weight required for training in it and mapping characteristics. It is tested for online adaptive ability, recovering ability from disturbance and interpolation ability. SelcukErkaya [27] investigated the effect of joint clearance on bearing vibrations of the mechanism. An experimental test rig is set up and a planar slider-crank mechanism with two imperfect joint with radial clearance is used by him as a model mechanism. The experiments with different cases of clearance size, running speeds and material type are performed to evaluate the effect of each characteristic. Three accelerometers are used by him to measure the vibration produced by bearings during the mechanism motion. For different speeds and clearance sizes he utilized the neural network to predict and estimate the vibration characteristics of the mechanism. Generalized regression neural network (GRNN) and RBF network both are used by him. He found the RBF network superior than the others for this purpose of identifying and analyzing of a mechanical system. When the steady state comes for running speed then data set for training neural network is obtained by the measurement of vibrations. Result of the experiment shows that the clearance size is directly proportional to the bearing amplitude. Feed-forward RBF with only one hidden layer, one input layer with five linear neurons, 1 output layer with 3 linear neuron, 1 hidden layer with 10 nonlinear neurons are used. Yali Zhao et. al. [28] investigated of active vibration control of an aluminum plate using a Filtered-Error Back Propagation Neural Network. A digital signal processor is used to implement back propagation neural network and filtered-x least mean square based controller. The proposed controller is proved to be efficient for nonlinear control problem to eliminate the vibration of the system. On comparing both FEBPNN and FXBPNN in terms of speed, FEBPNN is faster than FXBPNN. RatneshwarJha, Chengli He [29] do a comparative study of neural and conventional predictive adaptive controller for active vibration control of nonlinear and time varying smart structure. The neural network makes use of non linear neural network autoregressive external input plant model whereas other neural network uses linear autoregressive external input plant model. The neural adaptive predictive controller observed to be more efficient than adaptive generalized predictive controller. The controllers shows a great adaptability to change in plant dynamics and external disturbance applied to cantilever plate.

C. ANFIS Controller

The term ANFIS represents Adaptive-Network-Based Fuzzy Inference System, proposed by Jang, 1993. The ANFIS approach is a grouping 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 steps of fuzzy reasoning performed by fuzzy inference systems are:

1) Compare the premise part to obtain the membership values of each linguistic label (called as fuzzification).
2) Combine the membership values on the premise part to get the firing strength of each rule.
3) Generate the consequent of each rule depending on firing strength.
4) Aggregate the qualified consequents to produce a crisp output.

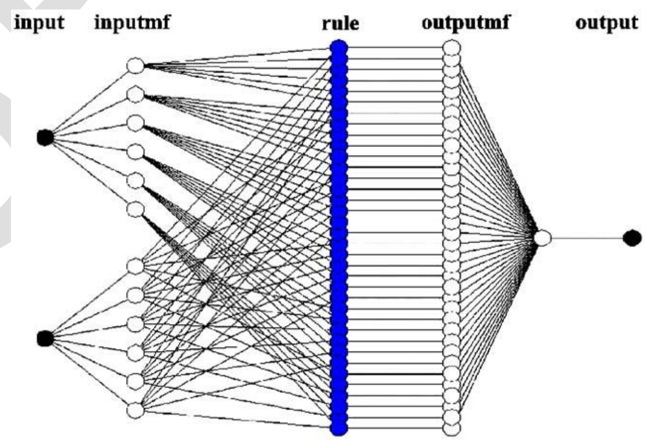

Fig. 5Diagram of ANFIS network structure.

Many researchers had done a lot of work in this ANFIS controller. A. Aldair et.al. [30] madean 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. A.A.M. Al-khafajiet. al. [31] 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 Kumagaiet. al. [32] 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 reveal the capacity of this kind of controller to control the motion of SMA actuator. S. Mallikarjunaiah and S. Narayana Reddy [33] performed adaptive neuro-fuzzy interface controller for balancing single flexible link of robot moving in a horizontal plane. Although PID and LQR controller is also used yet they both show some drawbacks due to the presence of a large no. of modes in the basic experimental body. The final adaptive controller used by them is a combination of PID and ANFIS (Adaptive Neuro Fuzzy Inference System) controllers tuned with back propagation algorithm. IntanZ.MatDarus, M.O.Tokhi, S.Z.MohdHashim [34] proposed an ANFIS based adaptive controller for suppression of vibration at the centre of the flexible plate. The table shows the different intelligent/adaptive controllers used by the scholars for AVC.

Sr.no.	Author Name	Year	Experimental body	Inputs	Outputs	Intelligent Controller
1	Abu S Islam et al.	1994	Composite beam	6 neurons in input layer, 4 neurons in hidden layer	2 output neurons	Back propagation NN
2	Scott D Snyder	1995	Cantilever beam	4 neurons in input layer, six in first hidden layer,4 in second hidden layer	Single output neuron	Feed forward NN
3	CP Smyser et al.	1996	Composite beam with sensor and actuator layer	Network one has 14 neurons in input and Network two has 12 input neurons.	12 output neuron in first NN and 2 in second NN	Cascaded Feed forward NN
4	Jae-Eung Oh et. al.	1997	Cantilever plate	1 input	1 output	Controller Based on Filtered-X Least Mean Square Algorithm
5	S.H.Youn et al.	2000	Composite beam with delamination	10 input neurons, 10 neurons in hidden layer for NNI,10 input neurons, 20 neurons in hidden layer for NNC	1output neurons forNNI,1output neurons forNNC	Error back propagation NN
6	RatneshwarJha et al.	2001	Cantilever plate	4 input neurons in NNI and 5 neurons in NNC	1 neuron in NNI and 1 neuron in NNC	Error back propagation NN
7	Gustavo Luiz C.M. de Abreu et. al.	2002	Cantilever beam	2 input	1 output	Fuzzy controller with prediction model
8	Qing Lu et. al.	2003	Cantilever beam	6 linguistic input Values	6 linguistic output values	Fuzzy controller optimized with GA
9	IntanZ.MatDarus et al.	2004	Flexible plate structure	2 input parameter for fuzzy layer	1 output neuron	Feed forward NN
10	H Gu et. al.	2004	11 feet I beam	1 input	1 output	Positive position controller with

						batch least square fuzzy gain tuning.
11	RatneshwarJha et. al.	2004	Cantilever plate	1 input	1 output	Neural adaptive controller
12	Yangmin Li et al.	2005	Module of robot	4 input neurons in input layer, 10 neurons in hidden layer	4 output neurons	Back propagation NN with genetic algorithm
13	Yugang Liu	2005	Modular manipulator	2 input neurons	1output neurons	Back propagation NN
14	Akihiko Kumagai et. al	2005	Shape memory alloy	4 input	2 output	ANFIS based feedback controller NN
15	Rajiv kumar et. al.	2006	Inverted L shape structure	3 input	2 output	Linear Vector Quantization NN.
16	Samuel Da Silva et al.	2006	Cantilever plate	2 input	1 output	Controller Based on Linear Matrix Inequalities
17	Rajiv kumar et. al.	2006	Inverted L shape structure	1 input	1 output	Adaptive hybrid controller
18	Yong Xia et al.	2009	Cantilever beam	3 inputs	3 outputs	Multilayer feed forward NN
19	SahinYildirim et al.	2009	Car suspension system	1 input neuron,10 neurons in hidden layer, momentum, learning rate	8 output Neurons	Back Propagation and radial basis NN
20	Jing-jun Wei et. al.	2009	Flexible manipulator	1 input	1 output	Fuzzy controller with PI controller
21	Karimsalahshoor et al.	2010	Steam turbine	2 input neurons	1output neuron	Back Propagation NN
22	A. Aldair et.al.	2010	Flexible beam	1 input	1 output	ANFIS controller tune with PID
23	Shi-Jie-Zheng et al.	2011	Composite beam with delamination	6 input neurons,18 neurons in fuzzification layer	2 output neuron	Radial basis NN
24	SubrataBhomik	2011	Shear frame structure	2 input(velocity and force)	1 output(current)	Neural network
25	XiaoxuJi et al.	2011	Flexible beam	2 inputs	1 outputs	Recurrent NN
26	A.HossainNezhadShirazi et. al.	2011	Rectangular plate with functionally graded material	5 inputs	5 outputs	Fuzzy logic controller and PID
27	BannaKasemi et. al.	2012	Magneto-Rheological Damper	2 input	1 output	Fuzzy logic controller with PID
28	ZhichengQiu et al.	2012	Flexible manipulator	3 input neurons, 14 neurons in hidden layer	1 output neuron	Radial basis NN

29	Chuen-Jyh-Chen	2012	Building rectangular Structure	1 input	1 output	Feed forward for NN classifier train with genetic Algorithm
30	NurhanafifiAbd. jalil	2012	Flexible cantilever beam	4 input neuron,10 neurons for hidden layer	1 output neuron	Back propagation NN
31	SelcukErkaya	2012	Slider crank mechanism	5 linear neurons for 1 input layer,10 nonlinear neurons for 1 hidden layer	3 linear neurons for 1 output layer	Feed forward NN
32	Jinxin Liu et al.	2013	Flexible plate	1000 no. of input neurons, 67 no. of hidden neurons for NNC n no. of neuron for input for NNI	2 no. of output neuron for NNC i no. of neuron in output for NNI	Back propagation NN
33	S.Mallikarjunaiah et al.	2013	Flexible link manipulator of a robot	2 input	1 output	Back propagation NN
34	Satishkumar. P. et al	2013	Seat of a vehicle	2 input	1 output	Fuzzy logic controller
35	YukselHacioglu et. al.	2013	Vehicle suspension system	1 input	1 output	Fuzzy logic controller tune with PD+PI
36	KanjuroMakihara et. al.	2013	CFRP plate	1 input	1 output	Adaptive fuzzy based controller
37	Arian Bahrami et al	2014	Stewart platform	1 input	1 output	Fuzzy logic controller

Table 1:Various Techniquesand Structures used by Authorsfor adaptive controller

II. INTELLIGENT/ADAPTIVE CONTROLLERS FOR DIFFERENT TYPE OF STRUCTURES

The intelligent/adaptive controllers can be used as controllers and identifier in variety of problems. Some researchers convinced to use it as controller for active vibration control, whether some use as estimator for various randomly changing structural and environment situations. In both the situation it serves with a very high precision and shows a great performance. Some of very interesting implementations of intelligent/adaptive controllers performed by the researchers are listed as follows:

1)The intelligent/adaptive controllers are used as an active vibration suppressor for various shapes like cantilever beam[35-36], cantilever plate[37-42], inverted L shape structure etc. In all these cases robust characteristics of the intelligent/adaptive controllers is experienced significantly. CPSmyser and K Chandrashekhra [43] 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. With the changing initial parameters like forces, inputs and neural network controller is more efficient than Linear Quadratic Gaussian (LQG).Arian Bahramiet. al. [44] 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. To simulate the PD fuzzy controller structural dynamic equation, sensor equation, fuzzy control laws are utilized in the Matlab to obtain the controller system. 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.

2)In some experiments they are utilized as a fascinating device to control jerks to a building type structure which shows that it can be used in the prevention from earthquake and volcano like natural disaster. Chuen-Jyh-Chen [46] developed a neural classifier controller with genetic algorithm to stop building structure shaking under free vibration and forced vibration execution. In this way it is an active mass damper system neural classifier controller is trained by genetic algorithm which is three layers feed forward neural network excited with sigmoid nonlinearities. Based on the classification of from system input output measurements, a response signal is generated proportional to this to stop disturbances.Jianjun Liuet. al.[47] proposed a back propagation algorithm to reduce vibration of the structures under earthquake having semiactive control devices (e.g. magnetorheological fluid damper)

3)In aviation industries where there is need for light weight of the device to reduce power consumption for noise and vibration mitigationof flexible spacecraft [48]. It can be served as a power efficient and less weight device. Jinxin Liu et al. [49] controls the low frequency noise radiation by combining neural network based neural network identifier and neural network controller.Albert Bosseet. al. [50] worked on reducing the vibration of the space trussstructure with the help of neural network.Zheng Kaiet. al. [51] made an adaptive truss structure with self learning active vibration control using fuzzy neural network.

4)In automotive industries where efficiency of vehicle suspension [52] system can be dramatically changed by use of the intelligent/adaptive controllers provide customer a luxurious experience. Satishkumar. P. et al. [53] 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 force and to calculate mass of the system. The system performance is analyzed in both the time domain and frequency domain. 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. Mumdani's minimum function is taken implication function. The centre of gravity method is used as defuzzification technique.SahinYildrin and IkbalEski [54] did their work to suppress the vibration of a car suspension system which is actually a 200 kg. Metal plate. The very frequently used back propagation neural network and radial basis neural network controller are utilized by them. Radial basis neural network is found to better to analyze automotive vehicle suspension system after comparison in between.

5)It can be used to find the natural frequency of the any moving or vibrating body. Rajiv Kumar, S.P Singh and H.N Chandrawat [55] 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. It overcome the drawback of LQR controller as it can't bear up with system parameters changing very rapidly like pay loads and position. The intelligent/adaptive controllers can also be used as an identifier and estimator of evaluating output of the portion of the body where sensor is not placed. Hence the solution converges to be fully satisfied with the material coordinates. Abu S Islam and Kevin C Craig [56] made a damage detection system for composite structure. A back propagation neural network has been trained with the frequencies of first five modes in both the damage condition and the healthy condition of the composite beam. The stiffness parameter of the beam is continuously observed because it directly affects the dynamic response of the structure. After a sufficient training to the neural network estimator, the location and intensity of damage can be evaluated easily. NurhanafifiAbd.Jalil [57] presented the comparison of ANN and ANFIS as an identifier and found ANN better than other with least square mean value.

6)A very new application is that they can also be used as damage detector of the body. It can predict exactly the strength of damage and the location on which damage to a body occurs. Shi-Jie-Zheng [58] performed the radial basis function neural network for structural health monitoring of composite beams optimized with the combination of genetic algorithm and fuzzy logic. Karimsalahshoor, MojtabaKordetani, Majid S. Khoshro [59] give a new technique of fault detection and diagnosis by the combination of spot vector machine and ANFIS classifier to find detections in steam turbine engine.

7)In emerging electronic industry developing robots and its manipulators[60, 61]very high intelligent devices where precision requirement is very important to the robot body having a lot of revolving motors [62] and high no. of degree of freedom shows dramatical results for controlling movement of a manipulator link. Yangminli, Yugangliu, Xiaoping liu [63] 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.

In this way we become aware of many applications and advantages of ANN over the traditional controllers.

CONCLUSION

There are many Intelligent/adaptive controllers can be used for mitigating vibration effectively, adaptively for various structures like cantilever beam, cantilever plate, modules of robot/manipulators, flexible structures, engine turbines, cable bridges, wind turbines, stewart platform etc. The scholars generally work with fuzzy, ANN and ANFIS based controllers which not only control vibrations but can also be apply as a high-quality identifier/estimator for the various structures. There are different techniques and arrangements to design different type of controller for smart structure to implement different applications.

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