Application of Improved Fuzzy Controller for Smart Structure

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Abstract—**In order to reduce the vibration of smart structures, this paper gets the optimal location of piezoelectric patch by the D-optimal design principle, and then uses the fuzzy logic to control the smart structures vibration. The fuzzy IF-THEN rules are established on analysis of the motion traits of cantilever beam. The fuzzy logic controller (FLC) designs base on using the displacement and velocity of the cantilever beams tips as the inputs, the control force on cantilever beams as the output. This new method improves calculation efficiency and reduces calculation complexity. Besides that, the paper establishes parameter self-adjustment factor in fuzzy controller by s-function to make the fuzzy logic control more effective. The simulation results with Matlab illustrate that the proposed method has a better control performance than existing methods.**

Index Terms—**smart structures, optimal location, fuzzy IF-THEN rules, fuzzy logic controller, parameter self-adjustment, s-function**

I. Introduction

In 1985 Bailey and et al. [1] performed experimental research on active vibration control using surface-bonded piezoelectric polymer actuators on a cantilevered beam. Their experiment has greatly inspired the active vibration control related field. Recently, much research has been developed in the field of smart materials and structures. Piezoelectric is a kind of smart material, due to the following two characteristics: the first is direct and inverse piezoelectric effects and the second is the ability to be used as the sensor or the actuator in active vibration control systems. Vibration control of smart structures is very important because of the lightly damped of the materials which were used. The placement of piezoelectric patches plays an important role in the design procedure of the active structures. The researchers have focused on development of the optimal piezoelectric patch location. Guo and et al [2] presented a global optimization of sensor locations based on the damage detection method for structural health monitoring systems. Martin Kögl and et al [3] presented a novel approach to the design of piezoelectric plates and shell actuators using topology optimization. In this approach, the optimization problem consists of distributing the piezoelectric actuators in such a way as to achieve a maximum output displacement in a given direction at a given point of the structure. Cao and et al [4] use the element sensitivities of singular values to identify optimal locations for actuators.

There have been many performance criterion presented, such as controllability and observability of control system measures, dissipation energy measures and system stability measures. However, in order to make use of the above-mentioned measures, a flexible structure state space equation should be modeled by the given location of piezoelectric patches. The D-optimal design principle is an optimization method presented by Bayard and et al [5] which suggests that the maximum determinant of Fisher Information Matrix Criteria is chosen as the optimization function and then simplified to determine an optimal principle for the best location for piezoelectric elements.

In the regions of civil engineering and the spaceflight engineering, the structures always accompany with complicated kinetic characteristics and uncertain factors. On the other hand, a robot system is a highly nonlinear and heavily coupled mechanical system. The mathematical model of such system usually consists of a set of linear or nonlinear difference equations derived by using some form of approximation and simulation. In 1983, Brown and Yao [6] used the fuzzy theory to the engineering structures at first time. In 1986, Juang and Elton [7] adopted fuzzy logic to estimate the density of earthquake on the extent of damage for the constructions. Battaini [8] designed the fuzzy logic control about mass systems and experimented. Symans and Kelly [9] applied fuzzy logic control strategy to control the system of control. Based on the virtues of fuzzy logic control, H.Park [10] established the approximate model of the driver, the sensor and the fuzzy logic controller to solve the problems of vibrations for flexible structure. The result indicated that the fuzzy logic control had the stronger robust and self-adaptive for the linear and non-linear system. R.Y.Y.Lee [11] carried on the similar experiments of designing the ordinary fuzzy logic controller and self-buildup controller for the non-linear

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piezoelectric driver. The simulated result showed that the fuzzy logic control has excellent suppression effectiveness on the vibration of non-linear flexible. This paper presents an optimization method using the D-optimal design principle simplified to determine an optimal principle for the best location of piezoelectric elements, and then designs a fuzzy logic controller to control the beam's vibration. The simulation results show that this proposed method has more superiority than the others.

II. Modeling and Theory

In this section, we consider beam or plate type structures bonded with rectangular shaped piezoelectric sensors and actuators. The sensors and actuators are symmetrically collocated on both sides of the same position of the structure. The research of reference [12] is verified that the symmetrical collocation can avoid observation spillover and control spillover induced by modal truncation, and ensures the controlled system is minimum phase system. The finite element method can analyze the arbitrary geometry models and the anisotropic properties of the piezoelectric materials. Considering the piezoelectric effect, special finite elements with a degree of volts have been developed. These elements have become available in some commercial finite element software such as ANSYS. In this paper, the solid45 3-d solid elements are used to model the host structures and the solid5 3-d solid elements are used to model the piezoelectric elements for analysis the low modals of flexible structure are extracted using ANSYS software.

III. D-optimal design principle

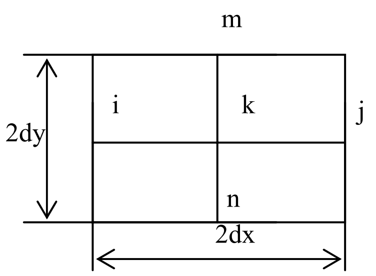

Figure 1. Piezoelectric patch finite element

Actually, sensors are used to estimate state parameter. Based on the theory of mathematical statistics, the determinant of Fisher Information Matrix det*(F)* has inverse ratio to low bound of variance of parameter unbiased estimation. Due to the symmetrical collocation of the piezoelectric patches, if the locations of sensors have been confirmed, the actuators will be at the same locations as the sensors. For a lightly damped structure, the D-optimal design principle can be simplified to decouple the problems of placement of actuators/sensors and input control. The principle can be written as:

$$\max(\det(F)) \tag{1}$$

Subject to $\beta \in B_m, B_m = \{\beta : \sum_{k=1}^{M} \beta_k = m\}$

where β is the location selection matrix; B_m is the set of possible locations. The objective function can also be written as:

$$S(m) = \max_{\beta} \sum_{i=1}^{N} \log\left(\sum_{k=1}^{M} \beta_k \frac{(\gamma_k^T \phi_i)^2}{\varphi_k^2}\right) \tag{2}$$

where N and M are the number of modals and the possible locations of sensors, m is the number of the sensors; β_k is composed of 0 and 1, if $\beta_k = 1$, this denotes that a sensor is located on the location, in contrast, if $\beta_k = 0$, this denotes that the location has no a sensor; γ_k is a vector coefficient related to kth location of sensor; ϕ_i is a ith normalized mode shape vector; φ_k is covariance of sensor signal noise, it can be defined as 1.

The physical sense of (2) can be regard as finding the location of maximum charges or volt output. Therefore, $\gamma_k^T \phi_i$ is equivalent to the output charges of sensors. If we suppose that the sensor area is enough small relative compared to the beam (plate), the sensor charge can be written as

$$q = D \times A = A \times (D_x + D_y) \tag{3}$$

$$D_x = d_{31} E_{pe} \varepsilon_x = d_{31} E_{pe} \frac{\partial^2 \omega}{\partial x^2} \frac{t_p}{2} \tag{4}$$

$$D_y = d_{31} E_{pe} \varepsilon_y = d_{31} E_{pe} \frac{\partial^2 \omega}{\partial y^2} \frac{t_p}{2} \tag{5}$$

Where Dx is the electric displacement generated by the x axis strain, Dy is the electric displacement generated by the y axis strain, and A is the area of sensor. For the beam structure, electric displacement is generated by unidirectional strain. d31 is the piezoelectric strain constant. Ep and t_p are the Young modulus and the thickness of the piezoelectric patch. ω is the deflection of structure. Dimensions of the piezoelectric patch and the finite element are shown in Fig. 1.

Based on second-order difference scheme, $\frac{\partial^2 \omega}{\partial x^2}\Big|_k$ and $\frac{\partial^2 \omega}{\partial y^2}\Big|_k$ can be expressed as:

$$\frac{\partial^2 \omega}{\partial x^2}\Big|_k \approx d_x^2 \omega = \frac{\omega(i) + \omega(j) - 2\omega(k)}{(dx)^2} \tag{6}$$

$$\frac{\partial^2 \omega}{\partial y^2}\Big|_k \approx d_y^2 \omega = \frac{\omega(m)+\omega(n)-2\omega(k)}{(dy)^2}$$

(7)

Substitute (4) (5) (6) (7) into (3) to yield

$$q = d_{31} E_{pe} A \lambda_k$$

(8)

where

$$\lambda_k = \frac{t_p}{2}\left(\frac{\omega(i)+\omega(k)-2\omega(j)}{(dx)^2} + \frac{\omega(m)+\omega(n)-2\omega(j)}{(dy)^2}\right)$$

;

The deflection of structure ω can be expressed by mode shape ϕ_i

$$\omega = \sum_{i=1}^{N} \eta_i \phi_i \qquad (9)$$

where η_i is ith modal generalized coordinate, substitute (9) into (8), assuming $\sum_{i=1}^{N} \gamma_k^T \phi_i = q$, γ_k^T can be written as

$$\gamma_k^T = \frac{1}{2} \eta_i A d_{31} E_{pe} \lambda_k^i \qquad (10)$$

where

$$\lambda_k^i = \phi_i \frac{t_p}{2}\left(\frac{1}{(dx)^2}[0 \ldots 1_i \quad -2_k \quad 1_j \ldots 0] + \frac{1}{(dy)^2}[0 \ldots 1_m \quad -2_k \quad 1_n \ldots 0]\right);$$

ϕ_i is a ith normalized mode shape vector. Substitute (10) into (2), objective function can be simplified as:

$$S(m) = \max_{\beta} \sum_{i=1}^{N} \left(\sum_{k=1}^{M} \eta_i \beta_k \lambda_k^i\right) \qquad (11)$$

Note (11), we conclude that the objective function is composed of all step of mode shapes with the coefficient η_i .

With the vibration generating force, the equation of motion in modal coordinates can be written as:

$$\ddot{\eta}_i(t) + 2\xi_i \omega_i \dot{\eta}_i(t) + \omega_i^2 \eta_i(t) = \frac{1}{M_i} f(t)$$

(12)

where $\ddot{\eta}_i$, $\dot{\eta}_i$ and η_i represent modal acceleration, velocity and displacement, respectively, ω_i and ξ_i are the natural frequency and damping ratio of the ith mode, due to flexible structure and absence of interior damping, $\xi_i = 0$.

For a different force, every mode shape has a different proportion in the vibration of a structure. Assuming that the vibration generating force is taken as a unit impulse, structure vibrates according to the lower mode shape and the other mode shapes can be ignored. Assuming that the vibration generating force is taken as sine force with a frequency of θ, the vibration of structure has relation to the frequency of the force rather than uniquely according to one mode shape. For the above-mentioned, in order to develop the performance of the vibration, the adhered patches must control every mode shapes. So, the piezoelectric patches should be placed on the maximum of all the mode stains. Unitary mode stain can be written as:

$$\overline{\lambda_k^i} = \lambda_k^i / \max(\phi_i)$$

(13)

Integrating equation (13) and (11), a new objective function can be written as

$$S^*(m) = \max_{\beta} \sum_{i=1}^{N} \left(\sum_{k=1}^{M} \beta_k \overline{\lambda_k^i}\right)$$

(14)

Accordingly, the performance criterion of the sensor locations can be obtained using mode shapes of structures.

IV. FUZZY LOGIC CONTROLLER

A. Modeling the piezoelectric structure with the finite element

The piezoelectric material is PVDF of β . It lays on the above and below surfaces that acting as the piezoelectric sensors and actuators respectively. The sensor and actuator are symmetrically collocated on the structure in the same position. Considering the coupling effect, the equations which use the limit element could be written as:

$$M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = F + U \qquad (15)$$

Where M,K and C is the whole mass, the whole stiffness, the whole damping respective, while $u(t)$ 、 $\dot{u}(t)$ 、 $\ddot{u}(t)$ is the displacement, velocity and acceleration, F is the external force ; U is the force produced by the piezoelectricity. In the process of modeling, the influence of the force which produces by on account of the piezoelectric material is neglected. So the model is approximate. The figure of the active vibration control of intelligent structure is shown in Fig.2.

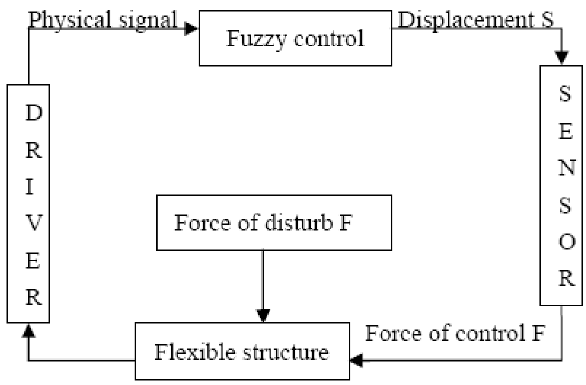

Figure 2. Active of vibration piezoelectric structure

B. Modeling the relation of fuzzy logic control

The field of fuzzy system and control has been making a big progress motivated by the practical success in industrial process control. Fuzzy systems can be used in as closed-loop controllers. In this case the fuzzy system measures the outputs of the process and takes control actions on the process continuously. The fuzzy logic controller uses a form of quantification of imprecise information (input fuzzy sets) to generate by an inference scheme, which is based on a knowledge base of control force to be applied on the system.

The advantage of this quantification is that the fuzzy sets can be represented by a unique linguistic expression such as small, medium, and large etc. The linguistic representation of a fuzzy set is known as a term, and a collection of such terms defines a term-set, or library of fuzzy sets. Fuzzy control converts a linguistic control strategy usually based on expert knowledge into an automation control strategy. There are three functions required to be performed by fuzzy logic controller before the controller can generate the desired output signals. The first step is to fuzzify each input. This can be realized by associating each input with a set of fuzzy variables. In order to give semantics of a fuzzy variable a numerical sense, a membership function is assigned with each variable. The logical controller is made of four main components: (1) Fuzzifier; (2) Knowledge base containing fuzzy IF-THEN rules and membership functions; (3) Fuzzy reasoning; and (4) Defuzzifer interface [13, 14].

In this paper, fuzzy logic controller is designed as the double-input, single-out (DISO) system: The inputs are the displacement and the velocity of the tip of cantilever beams, and the output is the control force on cantilever beams. In this fuzzifier, the displacement is defined from -5 to 5(-5,-4,-3,-2,-1,0, 1,2,3,4,5),the velocity is defined from -2 to 2(-2,-1,0, 1,2),the control force is defined from -7 to 7 (-7,-6,-5,-4,-3,-2,-1,0,1,2,3,4,5,6,7). Two types of membership functions commonly adopted in fuzzy logic control are triangle and trapezoidal shape. We use these two type membership functions. In this paper, compared with other methods, the method of Mom was more effective. Accordingly, in this paper, a way of establish fuzzy system is proposed as following:

(1) At first, the scope of the displacement and the velocity are the maximal response of when received step response.

(2) Plot the scopes of displacement's and the force of control's out NB,NM,NS,ZO,PS,PM,PB; Then plot the scopes of velocity 's out N and P.

(3) According to the fuzzy rule of L.A.Zadeh's[15], we get the process of fuzzy illation.

At last, we use the way of Mom method to calculate in order to obtain the result.

C. The rule of fuzzy control and the fuzzy controller

The fuzzy rule shows the fuzzy relation between the input and output. The inputs and output are connected with this relationship. In this paper, the displacement of the tip of cantilever beam is chosen for the one input, the velocity is the other. In tradition method, the inputs usually are the velocity and the rate of the velocity. In this way, the time of calculation has been improved.

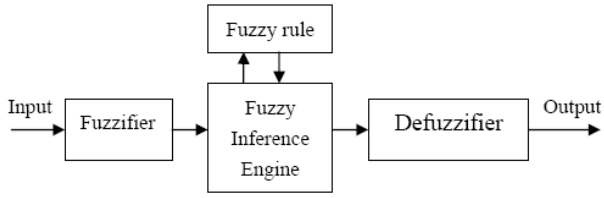

Figure 3. The basic configuration of the fuzzy system

Basing on the control rules, the signal is translated to the driver. The function of fuzzy logic controller is making the inputs fuzz up. In other words, it is the fuzzy control that executes the process of fuzzed. The fuzzy control's basis was the rule database which was composed of several rules. The final purpose of the fuzzy logic controller was to make the fuzzy rule come true, Fig. 3. The method of control vibration is minimized the response of displacement of cantilever beam.

The function of the fuzzy logic controller is to provide a force to prevent the vibration of the beam. On analysis of the motion traits of cantilever beam, the rules were obtained as fellows:

(1) If the displacement is PS and the velocity is PB, the tip of beam is up far from of equilibrium position. So it needs to add the downward force of NB and makes the tip of beam close to the reference values.

(2) If the displacement is PB and the velocity is PS, the tip of beam is upward to the maximum displacement. So it needs to add the downward force of NS and make the tip of beam close to the reference values.

(3) If the displacement is PB and the velocity is NS, the tip of beam is downward close to the equilibrium position. Adding the downward force of NS is required and makes the tip of beam close to the reference values.

(4) If the displacement is PS and the velocity is NB, the tip of beam is downward close to the equilibrium position. Adding the downward force of NB is required and makes the tip of beam close to the reference values.

(5) If the displacement is NS and the velocity was NB. The tip of beam is down far from of equilibrium position. The upward force of PB should be added and makes the end of beam close to the reference values.

(6) If the displacement is NB and the velocity was NS. The tip of beam is downward to the maximum displacement. The upward force of PS should be added and makes the end of beam close to the reference values.

(7) If the displacement is NB and the velocity is PS, the tip of beam is upward close to the equilibrium position. Making the tip of beam close to the reference values could be obtained by adding the P upward force.

(8) If the displacement is NS and the velocity is PB, the tip of beam is upward to the maximum displacement. Making the tip of beam close to the reference values could be obtained by adding the PB upward force.

Fuzzy IF-THEN rule base is obtained by the analysis, the author of this study, with many trial-and-errors. (Table I). Fuzzy IF-THEN rule is the center of control system. The fuzzy rule base is not invariable, it could be modify in practice. The system of fuzzy logic control is in Fig. 4.

TABLE I.
FUZZY IF-THEN RULE BASE

	NB	NM	NS	NO	PS	PM	PB
NB	ZO	PM	PB	ZO	NB	NM	ZO
NS	PS	PM	ZO	ZO	ZO	NM	NS
ZO	ZO	ZO	ZO	ZO	ZO	ZO	ZO
PS	PS	PM	ZO	ZO	ZO	NM	NS
PB	ZO	PM	PB	ZO	NB	NM	ZO

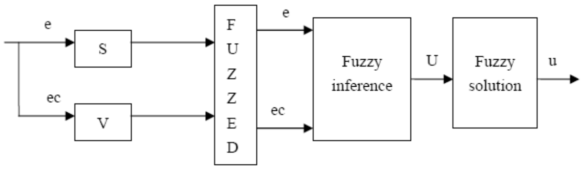

Figure 4. The system of fuzzy logic control

V. PARAMETER SELF-ADJUSTMENT

Base on the fuzzy logic control system, with big weighting coefficient to be used against bad errors, and small weighting coefficient of change rate to be used for slight errors. The principle of establish the parameter self-adjustment is using the different parameter self-adjustment factor to implement the fuzzy control rules. In this paper, the effective means of designing fuzzy logic controller with fuzzy logic toolbox of Matlab is introduced. Self-parameter is realized by compiling s-function. The organic combination of Matlab and Simulink makes the design and simulation of parameter self-adjustment fuzzy logic control system be easily and effectively. These show the means is easy and elastic. It can promote working efficiency of designers. The s-function is used to adjust the parameter because the blocks in Matlab are not enough. The source programmer of s-function is:

```
function[sys,x0,str,ts]=fpids(t,x,u,flag,m,AH,AL,Escope,
                              ECscope,Uscope)
   ke=m/Escope;
   kc=m/ECscope;
   ku=Uscope/m;
   switch flag,
   case 0,
   [sys,x0,str,ts]=mdlInitializeSizes(ke,kc,ku,m,AH,AL,
                   Escope,ECscope,Uscope);
  case 3,
   sys=mdlOutputs(t,x,u,ke,kc,ku,m,AH,AL,Escope,
        ECscope,Uscope);
  case {1,2,4,9}
    sys=[];
  otherwise
    error({'Unhandled flag=',num2str(flag)});
    end

function[sys,x0,str,ts]=mdlInitializeSizes(ke,kc,ku,m,AH,
                        AL,Escope,ECscope,Uscope)
 sys=[0,0,1,2,0,0,0];
function[sys]=mdlOutputs(t,x,u,ke,kc,ku,m,AH,AL,
              Escope,ECscope,Uscope)
  if  u(1)>=Escope
     u(1)=Escope;
    end
  if u(1)<-Escope
    u(1)=-Escope;
    end
  if  u(2)>=Escope
       u(2)=Escope;
       end
    if u(2)<-Escope
      u(2)=-Escope;
      end
    E=round(ke*u(1));
    EC=round(kc*u(2));
 add=(AH-AL)/m*abs(E)+AL;
  result=-(add*E+(1-add)*EC);
  if result>Uscope
    result=Uscope;
     end
  if  result<-Uscope;
     result=-Uscope;
     end
      sys=-result*ku;
```

Where m is the grade of the subset; AH is the upper limit of the adjustment; AL is the lower limit of the adjustment; Escope is the range of the error; ECscope is the range of the error rate; Uscope is the range of the controlled quantity.

VI. SIMULATION REMARKS

The Parameter of the beam and PVDF of β are given in Table II and Table III. The mass of cantilever beam is $0.108kg$, the rigidity of the beam is $73.8N \cdot m^2$, the damp is $0.05kg \cdot m^3 / s$ .The vibration of source is a step response in one period the time is $0.001s$. The surface of the cantilevered composite plate is partitioned into 40 basic numerical sub-areas, the configurations of the cantilevered plate are shown in Fig. 5. The number of the controlled modes N is set to 4. The modes were extracted by Ansys. The calculated data were showed in Fig 6.

The simulation system was performed by Matlab/Simulink block shown in Fig. 7. According to the fuzzy-rule of input and output, the rule viewer and control surface is described. The rule viewer is shown in Fig. 8, the control surface in Fig. 9.

The digital simulations and graphics are realized by MATLAB/Simulink software programmer. Tip position response of the beam is shown in Fig.10, while tip position response of the smart structure system with fuzzy logic control is shown in Fig.11. Fuzzy Logic Controllers is designed to control nonlinear vibration of a smart structure and the effects of the controllers over the system are examined. Fuzzy logic controller using in such system which has nonlinear vibrations gives a good result as tip position control of a smart structure. Settling time of system is approximately 9s, and the displacement of the tip beam is decreased from3.5mm to 2mm, so this method has practical value in preventing vibration of displacement. According to these results, suitable performance of fuzzy logic controller is determined for tip position control of a smart structure system. The fuzzy logic controller designed is established properly and this new controller can be used for such kind of system.

TABLE II.
AMETER OF THE BEAM

Length (mm)	Width (mm)	Thickness (mm)	Density Kg/m3	Flexibility modulusH(Pa)
350	25	4	2900	6.8e+10

TABLE III.
THE PARAMETER OF THE PIEZOELECTIC PATCHES

Length (mm)	Width (mm)	Thickness (mm)	Density Kg/m3	Flexibility modulusH(Pa)
35	25	1	8300	3.8e+9

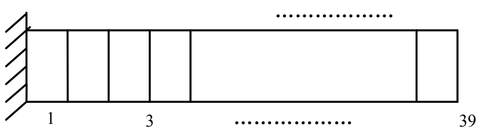

Figure 5. Configurations of the cantilevered plate

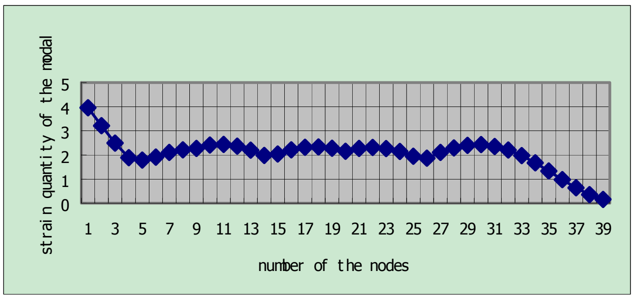

Figure 6. The strain quantity of the node

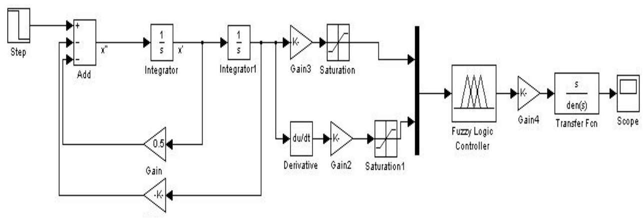

Figure 7. The fuzzy logic control system

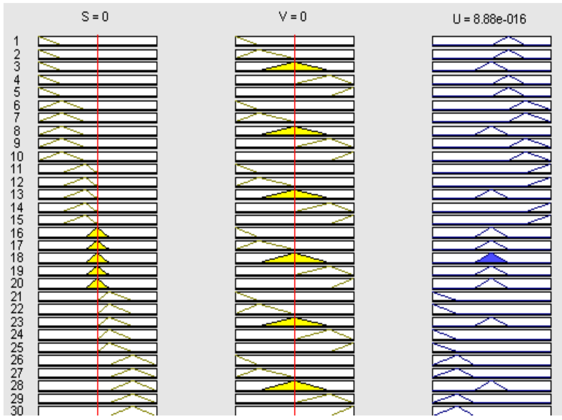

Figure 8. Rule viewer

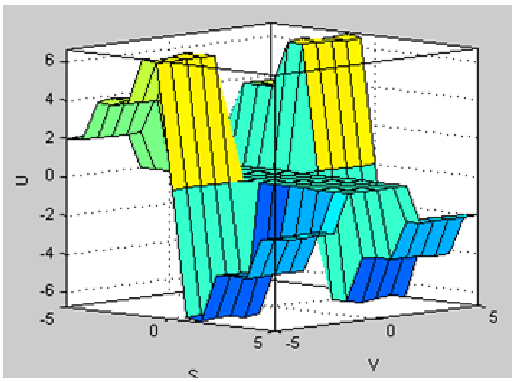

Figure 9. Control surface of Mom

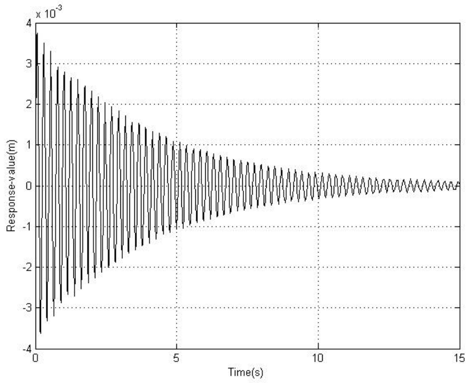

Figure 10. Tip position response of the beam

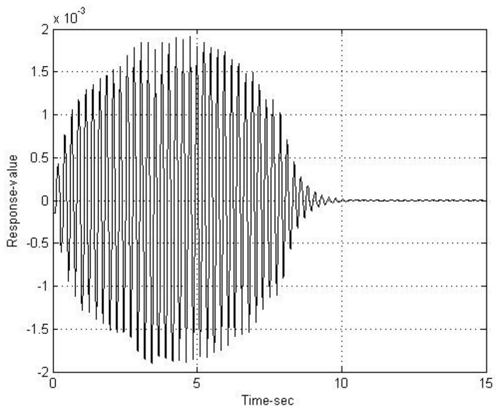

Figure 11. Tip position response of the beam with fuzzy logic controller

According to the result in Fig. 10, the system has an obvious oscillation phenomenon at the time of 4s. In order to avoid this phenomenon, we use parameter self-adjustment which is compiled by s-function to improve the control effect. Where m is 6, AH is 0.8, AL is 0.2, Escope is 0.005, ECscope is 0.1, Uscope is 0.008. The result was shown in Fig. 12. Settling time of system is approximately 8s; the displacement of the tip beam is decreased from 0.2mm to 0.043mm. In addition, this parameter self-adjustment method eliminates the oscillation phenomenon basically.

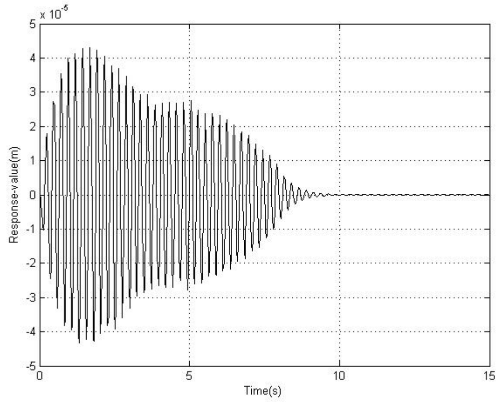

Figure 12. Tip position response of the beam with fuzzy logic controller

VII. Conclusion

This new fuzzy logic controller which designs in this paper improves calculation efficiency and reduces calculation complexity. More importantly, it has the obvious effect to reduce the displacement of the beams tips. Besides that, this paper uses a new method to design a fuzzy logic controller and compiles parameter self-adjustment factor with s-function. The simulation results show that this new fuzzy logic control has more superiority than the ordinary's, the performance is satisfactory.

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References

[1] Bailey, T. and Hubbard, J. E., 1985, Distributed piezoelectric polymer active vibration control of a cantilever beam, AIAA J. Guidance, Control Dynam, 8: 605-11.

[2] Guo, H. Y. Zhang, L. L. and Zhou, J. X., 2004, Optimal placement of sensors for structural health monitoring using improved genetic algorithms, Smart Materials and Structure, 13:528-534.

[3] Martin Kögl and Emílio, C. N., Silva, 2004, Topology optimization of smart structures: design of piezoelectric plate and shell actuators, Smart Materials and Structure, 14:387-399.

[4] Zongjie Cao, Bangchun Wen and Guangwei Meng, 2000, Topological optimization of placements of piezoelectric actuator of intelligent structure, Journal of Northeastern University (Natural Science), 21(4): 383-385.

[5] Bayard D. S., Hadaegh, F. Y. and Meldrum, D. R., 1988, Optimal experiment design for identification of large space structures, Automatica, 24(3): 357-364.
[6] Brown C.B., Yao J.T.P. (1983). “Fuzzy sets and Structural Engineering”. Journal of Structural Engineering, ASCE, No. 109, pp.1211-1225.
[7] Juang C., Elton D.J. (1986). “Fuzzy Logic for Estimation of Earthquake”. Intensity Based on Building Damage Record Civil Engineering System. No.3, pp.187-197.
[8] Battaini M., Casciati F., Faravelli L. (1998) “Fuzzy Control of Structural Vibration. An Active Mass System Driven by a Fuzzy controller”. Earthquake Engineering and Structural Dynamics, No.27, pp.1267-1276.
[9] Symans M.D. and Kelly A.S. (1999). “Fuzzy Logic Control of Bridge Structures Using Intelligent Semi Active Seismic Isolation Systems”. Earthquake Engng.Struct.Dyn,vol.28, pp.37-60.
[10] Park H., R.Agarwal, K.Nho (2000). “Fuzzy Logic Control of Structure Vibration of Beams”. Aerospace Aerospace Sciences Meeting and Exhibit, A IAA-0172.
[11] Lee R.Y.Y., Abdel-Motagaly K., Mei C. (1998). “Fuzzy Logic Control for Nonlinear Free Vibration of Composite Plates with Piezoactuators”. CAIAA, pp. 20-23.
[12] Ding Wenjing, 1994, Current main topics on active vibration control, Advances in mechanics 24(2): 173-180.
[13] L. Faravelli, T. Yao, Use of Adaptive Networks in Fuzzy of Civil Structures, Micricimput, Cilvil ENG. 11:67-76,1996.
[14] J.Yen, R. Langari. Fuzzy Logic-Intelligence Control and Information. Prentice Hall, Englewood Cliffs, NJ, 1998.
[15] Zadeh L.A. (1965). “Fuzzy set”. Informat. Control, vol. 8, pp. 338-353.

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