FUZZY CONTROL OF VIBRATION OF A SMART CFRP LAMINATED BEAM

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SUMMARY: In the present study, fuzzy control of vibration of a hybrid smart composite beam actuated by electro-rheological fluids (ERF) and piezoceramics actuators is investigated. A carbon fiber reinforced plastics (CFRP) cantilevered beam containing ERF with bonded piezoceramics is prepared and vibrated forcibly with sinusoidal external excitation. Fuzzy model of controlled element containing two actuators is formed in consideration of intense nonlinearity in ERF actuator. Parameters of membership functions and linear equations of fuzzy inference system in Sugeno style are identified by using a hybrid neuro-fuzzy system. Fuzzy controller for vibration control of the composite beam is designed based on the fuzzy model by using the modern control theory. The effect of vibration control system with a fuzzy controller is verified by simulation and experiment.

KEYWORDS: vibration, composite laminates, piezo-ceramic actuators, ER fluids, fuzzy control, nonlinearity, fuzzy model, system identification.

INTRODUCTION

Smart fiber composite materials that incorporate embedded or integrated actuators and sensors during their manufacturing process have recently attracted significant attention for their potential applications in structural vibration control. To successfully apply this new technology, actuator materials such as piezoelectric ceramics, electro-rheological fluids (ERF) and shape memory alloys play an important role. Recently, there are several studies featuring these types of actuators simultaneously to satisfy a broad range of performance specifications [1],[2],[3].

In this study, a carbon fiber reinforced plastics (CFRP) composite beam containing ERF with bonded piezoceramics is prepared. The ERF and piezoceramics are used as actuators for vibration control of the composite beam. Fuzzy model of controlled element containing two actuators is formed in consideration of intense nonlinearity in ERF actuator. Parameters of membership functions and linear equations of fuzzy inference system in Sugeno style are identified by using Adaptive-Network-based Fuzzy Inference System (ANFIS) model which is one of the hybrid neuro-fuzzy systems for function approximation and which uses learning

function of neural network. Fuzzy controller for suppressing the deflection at the free end of the cantilevered composite beam is designed based on the fuzzy model. The effect of vibration control system with a fuzzy controller is verified by simulation and experiment.

SPECIMEN AND EXPERIMENTAL SETUP

The specimen consists of two CFRP laminated plates (Toray T300/#2500) and an ERF layer (Nippon Shokubai TX-ER2072) as shown in Fig. 1. The stacking sequence of the CFRP laminates used here is $[\ 45°\ ]_{2S}$. The specimen is 250 mm in length, 20 mm in width and 1.2 mm in thickness. The thickness of CFRP laminate is 0.5 mm. The thickness of ERF layer is chosen 0.2mm in order to intensify the electric field applied to ERF as much as possible considering the fabricating limitation. In the specimen, ERF are filled between two CFRP laminated plates and sealed by a silicon rubber in the same manner as proposed by Choi et al [4]. Two CFRP laminates are used as a pair of electrodes to apply an electric field to ERF. In addition, a pair of piezoceramics (PZT) is bonded at 0.5 mm from the fixed end of the cantilevered specimen, since the strain is larger near the fixed end of the cantilevered specimen. The dimension of the piezoceramics is 30 mm in length, 15 mm in width and 0.2 mm in thickness, where the piezoceramics is isolated from the CFRP laminated plate using a kapton film.

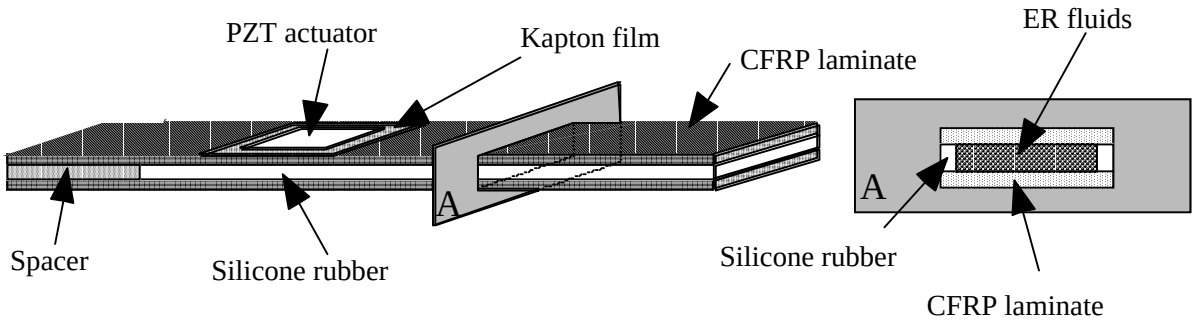

Fig. 1: A schematic view of specimen

The experimental setup consists of a non-contacting laser displacement pick-up, a personal computer and two types of actuators as shown in Fig. 2. In the experiment, the specimen is supported on a shaker. The fixed end of the cantilevered beam was vibrated forcibly with the sinusoidal excitation having the natural frequency, 9.4 Hz of the first flexural mode using the vibration testing facility. The amounts of the control input signals to two actuators are calculated by a fuzzy controller.

FORMATION OF FUZZY MODEL

The block diagram of vibration control system using both ERF and piezoceramics actuators is shown in Fig. 3. It can be considered that input voltages v_1 and v_2 applied to the two actuators and the disturbance signal f are the input of the controlled element and the deflection y at the free end of the cantilevered composite beam is the output of the controlled element as shown in Fig. 4 when the composite beam containing the actuators is regarded as the controlled element of the vibration control system.

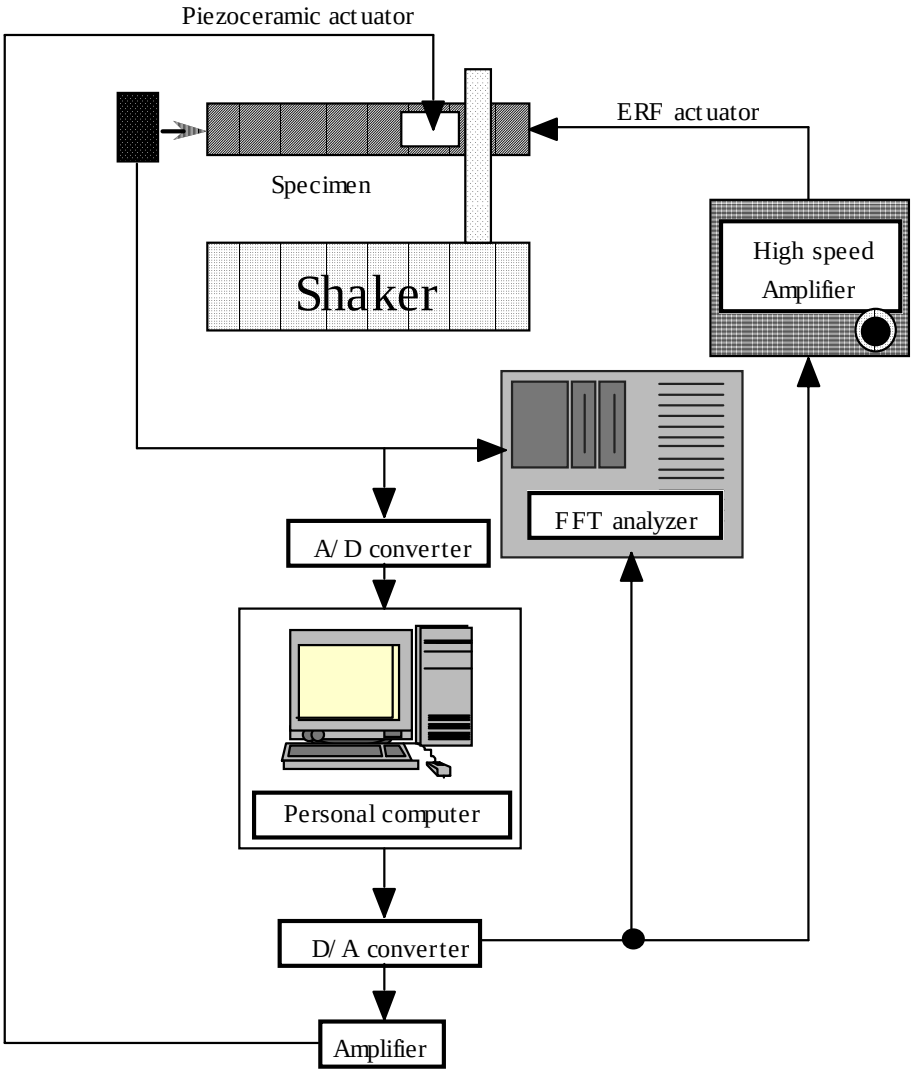

Fig. 2: Experimental setup

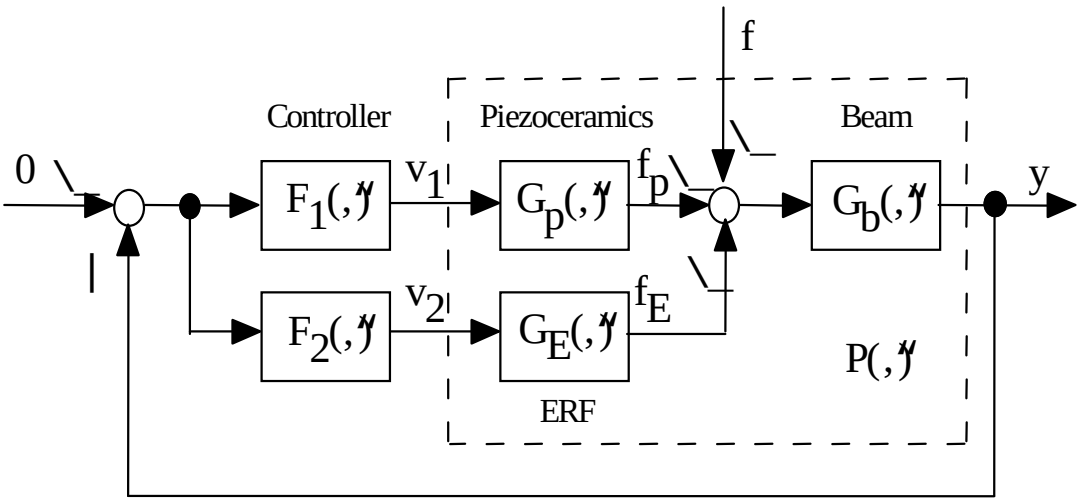

Fig. 3: Block diagram of vibration control system

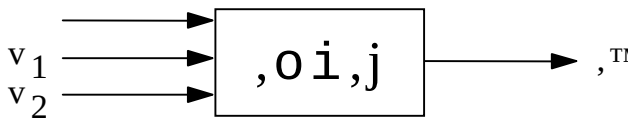

Fig. 4: Input and output of controlled element

In ERF containing numerous dielectric particles, damping force consists of viscous damping force without electric field and coulomb friction damping force with electric field. As it can be considered that the viscous damping force is inherently included in damping force of the composite beam, only coulomb friction is considered. The coulomb friction damping force f_E is considered to be in proportion to the square of voltage applied to ERF as sown in Eqn.1.

$$f_E = k_e v_2^{\,2} \mathrm{sgn}(\dot{y}) \tag{1}$$

where v_2 is the voltage applied to ERF, k_e is a coefficient. This transfer characteristics indicating the relation between input v_2 and output f_E is intensively nonlinear and so designing the controller based on the linear control theory is very difficult. Accordingly, a fuzzy model of controlled element is formed and a fuzzy controller for vibration control of the composite beam is designed based on the fuzzy model.

Discrete linear equation of vibration of the composite beam is given by Eqn.2 assuming that the vibration system of the composite beam can be expressed by the second order motion equation.

$$y(k+1) = a_1 y(k) + a_2 y(k-1) + a_3 v_1(k) + a_4 v_2(k) + a_5 f(k) + a_6 \tag{2}$$

The linear equation as stated above is used in the consequents in fuzzy model of controlled element in Sugeno style. System identification test is conducted for fuzzy modeling of the controlled element involving the ERF and piezoceramics actuators. Parameters of membership functions of the antecedents and linear equations in the consequents of fuzzy inference system in Sugeno style are determined by using ANFIS model [5] which is one of the hybrid neuro-fuzzy systems of function approximation and which uses learning function of neural network. In this case as the sign of the output f_E of ERF changes depending on that of $\dot{y}$ as shown in Eqn.1, y(k) is used in place of y(k-1), where

$$f\phi y(k) = y(k) - y(k-1) \tag{3}$$

Therefore the identification is carried out by using Eqn.4 in place of Eqn.2 in the consequents in fuzzy model.

$$y(k+1) = a_1' y(k) + a_2' f\phi y(k) + a_3 v_1(k) + a_4 v_2(k) + a_5 f(k) + a_6 \tag{4}$$

Thus i-th rule is expressed by Eqn.5.

$$\begin{aligned} &\text{IF} \quad y(k) \text{ is } A_i \text{ and } f\phi y(k) \text{ is } B_i \text{ and } v_1(k) \text{ is } C_i \text{ and } v_2(k) \text{ is } D_i \text{ and } f(k) \text{ is } E_i\,, \\ &\text{THEN} \quad y(k+1) = a_{1i}' y(k) + a_{2i}' f\phi y(k) + a_{3i} v_1(k) + a_{4i} v_2(k) + a_{5i} f(k) + a_{6i} \\ &\qquad\qquad = f_i\left(y(k), f\phi y(k), v_1(k), v_2(k), f(k)\right) \end{aligned} \tag{5}$$

where A_i, B_i ,C_i, D_i and E_i are fuzzy sets of the input variables in the antecedents, and

subscript i shows each parameter in i-th rule of all rules. The inference value of the output variable is given by Eqn.6.

$$y(k+1) = \frac{\sum_{i=1}^{r} f\ddot{Q}_i f_i}{\sum_{i=1}^{r} f\ddot{Q}_i} \tag{6}$$

where $_i$ is the degree of applicability of the antecedent for i-th rule, and is given by the product of membership degrees of the input variables, and r is the number of rules. Fig.5 shows accuracy of estimated value of the deflection y obtained based on the fuzzy model which is derived by using control design application soft MATLAB [6]. Parameters of Eqn.2 are decided based on parameters of Eqn.4.

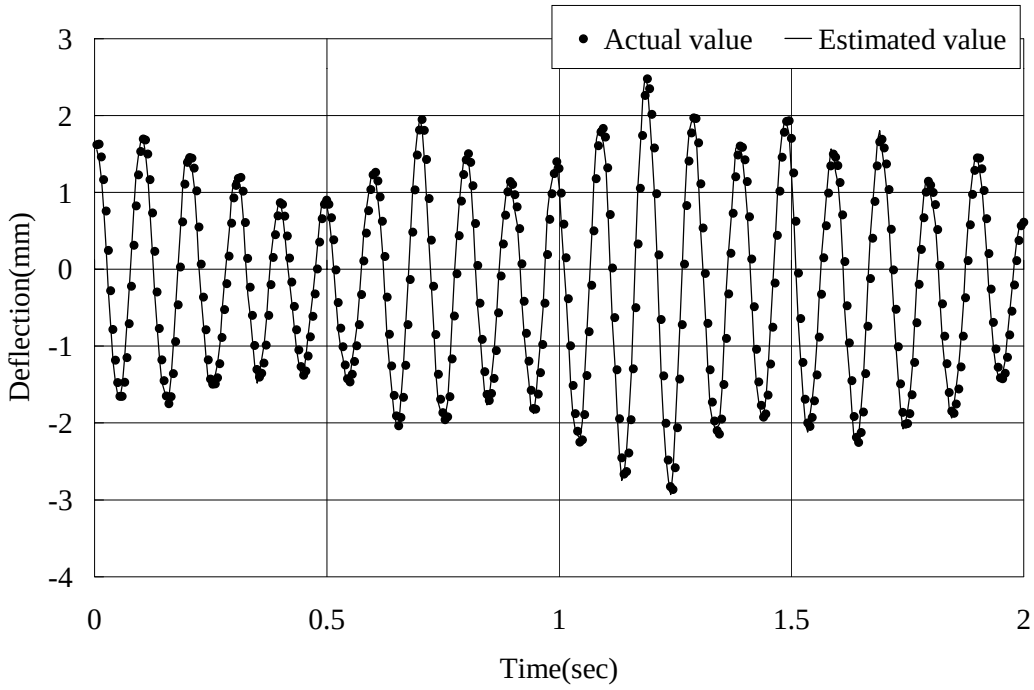

Fig. 5: Accuracy of fuzzy model of controlled element

DESIGN OF CONTROLLER

The discrete linear equation (Eqn.2) can be expressed by Eqn.7 in terms of state equations.

$$\mathbf{y}(k+1) = \mathbf{A}\mathbf{y}(k) + \mathbf{B}\mathbf{v}(k) + \mathbf{c}f(k) + \mathbf{d} \tag{7}$$

where

$$\mathbf{y}(k)=\begin{pmatrix} y(k) \\ y(k-1) \end{pmatrix}, \mathbf{v}(k)=\begin{pmatrix} v_1(k) \\ v_2(k) \end{pmatrix},$$

$$\mathbf{A}=\begin{pmatrix} a_1 & a_2 \\ 1 & 0 \end{pmatrix}, \mathbf{B}=\begin{pmatrix} a_3 & a_4 \\ 0 & 0 \end{pmatrix}, \mathbf{c}=\begin{pmatrix} a_5 \\ 0 \end{pmatrix}, \mathbf{d}=\begin{pmatrix} a_6 \\ 0 \end{pmatrix}$$

Control law as shown in Eqn.9 corresponding to the state equation (Eqn.8) in the i-th rule of fuzzy model is obtained by solving a regulator problem in the modern control theory as shown in Fig. 6.

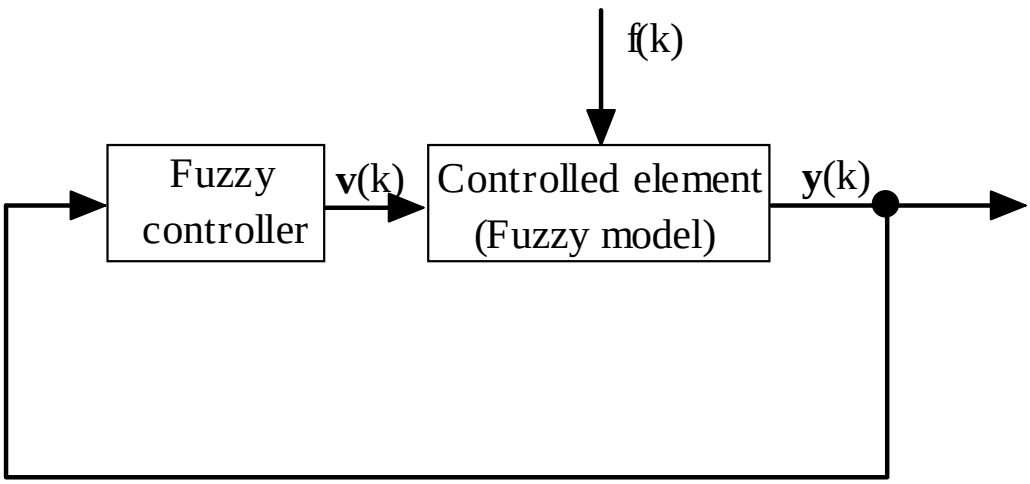

Fig. 6: Fuzzy control system

$$\mathbf{y}(k+1)=\mathbf{A_i}\mathbf{y}(k)+\mathbf{B_i}\mathbf{v}(k)+\mathbf{c_i}f(k)+\mathbf{d_i} \tag{8}$$

$$\mathbf{v_i}(k)=-\mathbf{F_i}\mathbf{y}(k) \tag{9}$$

where $\mathbf{A}_i$, $\mathbf{B}_i$, $\mathbf{c}_i$, and $\mathbf{d}_i$ are parameters in the i-th rule's consequent, and $\mathbf{F}_i$ is feedback coefficient of i-th rule's control law.

The controller **v**(k) can be formed by integrating all control laws based on the idea of parallel and dispersive compensation as shown in Fig. 7.

$$\mathbf{v}(k)=\frac{\sum_{i=1}^{r} f\ddot{Q}_i(k)\{-\mathbf{F_i}\mathbf{y}(k)\}}{\sum_{i=1}^{r} f\ddot{Q}_i(k)} \tag{10}$$

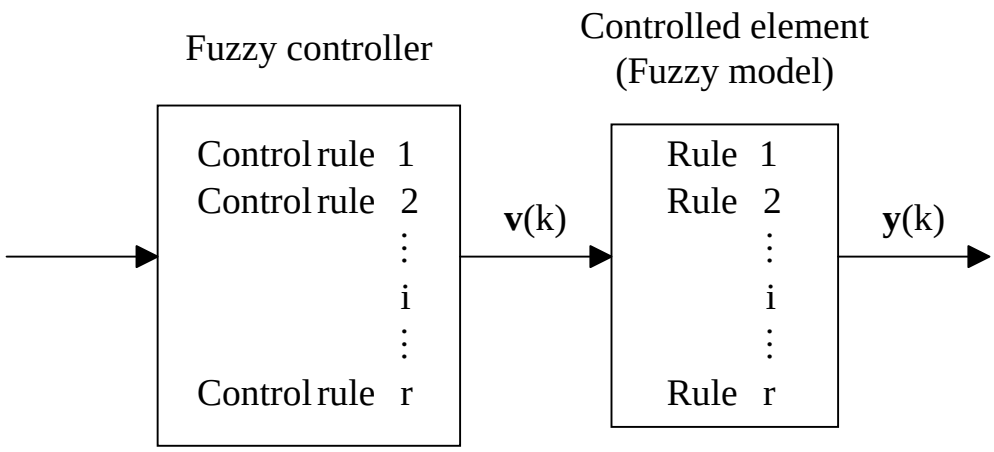

Fig. 7: Parallel and dispersive compensation

where $_i$(k) is the degree of applicability of the antecedent for i-th rule. In this case the output of controlled element is expressed by Eqn.11 based on Eqn.8 and Eqn.10.

$$\mathbf{y}(k+1)=\frac{\sum_{i=1}^{r} f\ddot{Q}_i(k)\{\mathbf{A_i y}(k)+\mathbf{B_i v}(k)+\mathbf{c_i} f(k)+\mathbf{d_i}\}}{\sum_{i=1}^{r} f\ddot{Q}_i(k)}$$

$$=\frac{\sum_{i=1}^{r}\sum_{j=1}^{r} f\ddot{Q}_i(k) f\ddot{Q}_j(k)\left[\{\mathbf{A_i}-\mathbf{B_i F_j}\}\mathbf{y}(k)+\mathbf{c_i} f(k)+\mathbf{d_i}\right]}{\sum_{i=1}^{r}\sum_{j=1}^{r} f\ddot{Q}_i(k) f\ddot{Q}_j(k)} \qquad (11)$$

The fuzzy control system is stable if there is any positive symmetric matrix **P** which satisfies both Eqn.12 and Eqn.13 based on Lyapunov's method [7].

$$\forall\, i, j \in \{1, 2, \cdots\cdots, r\}$$

$$\{\mathbf{A_i}-\mathbf{B_i F_i}\}^{\mathbf{T}}\mathbf{P}\{\mathbf{A_i}-\mathbf{B_i F_i}\}-\mathbf{P}<\mathbf{0} \qquad (12)$$

$$\mathbf{G_{ij}}^{\mathbf{T}}\mathbf{P}\mathbf{G_{ij}}-\mathbf{P}<\mathbf{0} \quad , \quad i<j \qquad (13)$$

where

$$\mathbf{G_{ij}}=\frac{\{\mathbf{A_i}-\mathbf{B_i F_j}\}+\{\mathbf{A_j}-\mathbf{B_j F_i}\}}{2}$$

In the controllers formed by Eqn.10, one which satisfies the stability conditions described above is adopted as a practical fuzzy controller. The simulation result of vibration control system with a fuzzy controller is shown in Fig. 8, and the experimental result is shown in Fig. 9. In both cases the fuzzy controller functioned at the initial time. These figures show the control effect obviously.

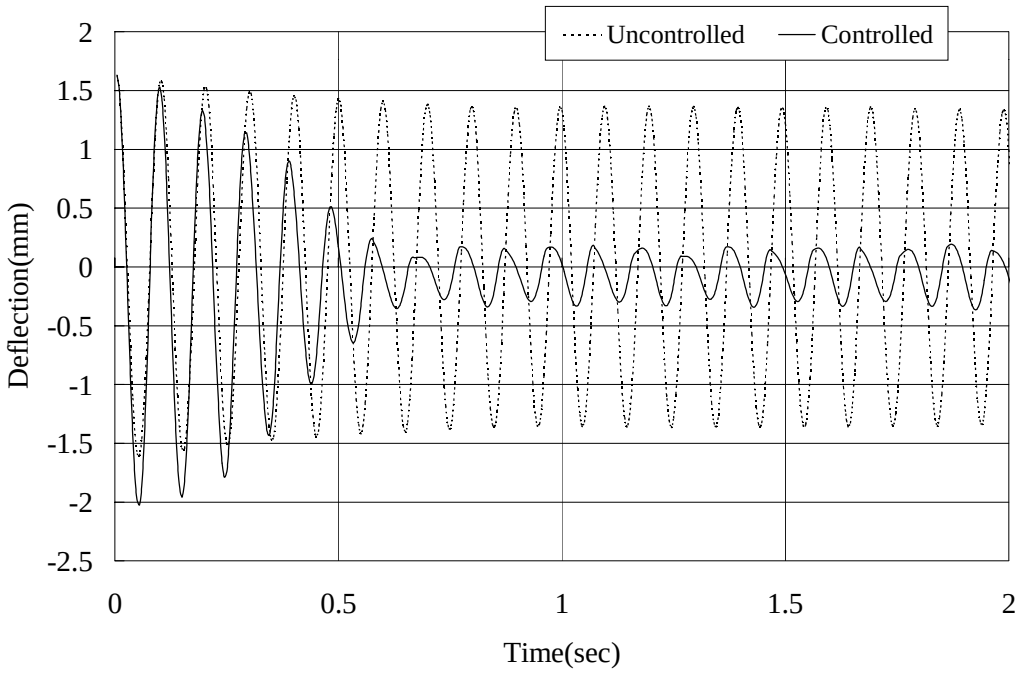

Fig. 8: Deflection response of the beam for exhibiting the effect of fuzzy controller (*simulation result*)

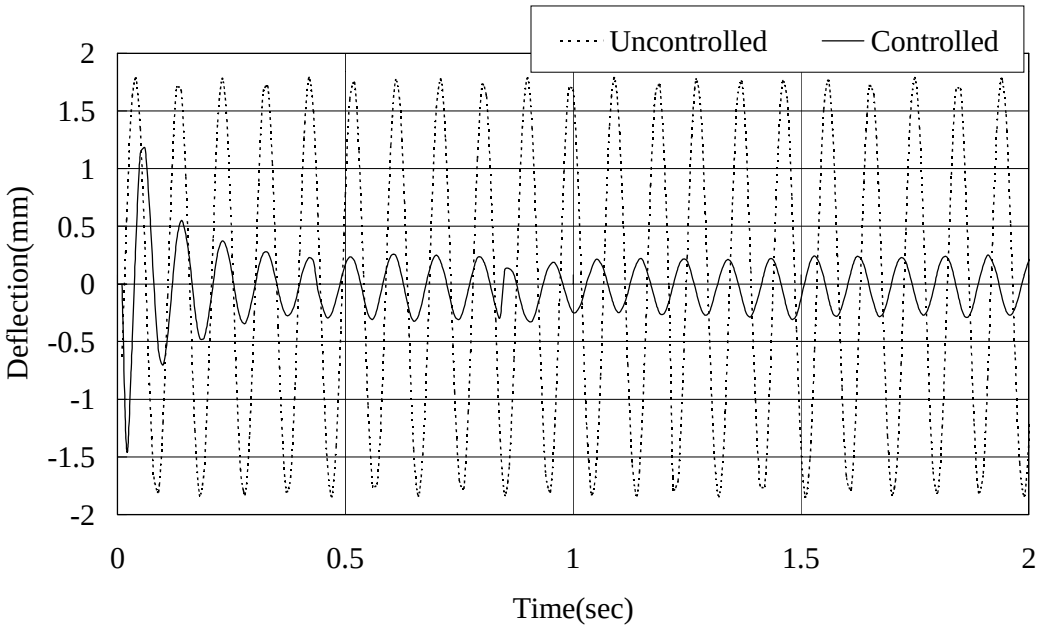

Fig. 9: Deflection response of the beam for exhibiting the effect of fuzzy controller (experimental result)

CONCLUSIONS

In order to examine the effect of vibration control of the composite beam based on fuzzy model, a CFRP composite beam containing ERF with bonded piezoceramics is prepared and vibrated forcibly with sinusoidal excitation. Fuzzy model of controlled element containing two actuators is formed by using a hybrid neuro-fuzzy system in consideration of intense nonlinearity in ERF actuator, and fuzzy controller is designed based on the fuzzy model by using the modern control theory. As the result of experiment and simulation, the effect of fuzzy controller is confirmed.

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