Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

Fuzzy modeling of vibration of a smart CFRP composite beam and control effect by using the model

Susumu Oda & Takeshi Takawa

Version of record first published: 02 Apr 2012.

Adv. Composite Mater., Vol. 15, No. 4, pp. 357–370 (2006)

Fuzzy modeling of vibration of a smart CFRP composite beam and control effect by using the model

SUSUMU ODA [1], TAKESHI TAKAWA [2,*]

[1] *Graduate School of Engineering, Osaka Institute of Technology, 5-16-1 Ohmiya, Asahi-ku, Osaka, 535-8585 Japan*
[2] *Faculty of Engineering, Setsunan University, 17-8 Ikedanakamachi, Neyagawashi, 572-8508, Japan*

Received 1 September 2005; accepted 11 October 2005

Abstract—Vibration control for a smart carbon fiber reinforced plastics (CFRP) composite beam actuated by piezoceramics (PZT) and electro-rheological fluids (ERF) is investigated in this paper. Since the application of linear control theory to the vibration control is very difficult due to the intensive nonlinearity of the ERF actuator, a fuzzy model of the controlled element containing two actuators is constructed. In this study, the time delay of the response of the actuator is also taken into consideration. A controller for vibration suppression of the composite beam is designed based on the fuzzy model for guaranteeing stability of the vibration control system. The effect of the control system is verified by experiment and simulation.

Keywords: Fuzzy modeling; vibration control; composite beam; actuator; nonlinearity; time delay.

1. INTRODUCTION

Composite materials are presently of increasing interest to researchers because it is possible to design them for specific purposes by the combination of two or more base materials. In particular, fiber reinforced plastics (FRP) are well-known as light and strong fiber materials, and the idea of smartening to show more advanced functions by adding some functions in these composite materials has been explored and is under continuing investigation [1].

In this research, vibration control is investigated for a smart carbon fiber reinforced plastics (CFRP) composite beam actuated by piezoceramics (PZT) and electro-rheological fluids (ERF) actuators [2]. It is possible for the smart composite to satisfy good performance over a broad frequency range by using ERF, which is

*To whom correspondence should be addressed. E-mail: takawa@ise.setsunan.ac.jp effective in the low frequency range, and PZT, which is effective in the high frequency range [3].

In this study, the influence of time delay of input voltage as the response of the actuators is also taken into consideration.

Designing the controller based on conventional linear control theory is difficult because ERF has an intensive nonlinearity. Recently, there have been several reports of nonlinearity or uncertainty in the vibration control of structures using ERF and piezoelectric materials [4–8]. For example, the nonlinear control system is linearized by adding the square root of the voltage proportional to ER damper velocity to the damper in the case of vibration control of cars [4].

In addition, vibration control of a robot arm using ERF based on robust control theory [5], and control of smart structures embedded in piezoelectric fiber [6] are practiced. Moreover, the methods based on neural network theory [7] and genetic algorithms [8], which are kinds of intelligent controls, have been investigated for systems using piezoelectric materials.

However, we are not aware of any investigation that included the influence of the time delay of the input voltage to date.

We describe the function method to extract linear characteristics, and use the phase plane method [9] as a control method for nonlinearity. The robust control method [9], which deals with a linear system as the base and is not influenced very much by the uncertainty, is applied for the uncertain system. However, if controlled elements become diversified and nonlinear characteristics become significant, then the above-mentioned methods cannot manage these characteristics and they are not applicable.

On the other hand, fuzzy control, neural networks, genetic algorithms, and so on, known as intelligent controls, which are superior in ability to describe nonlinearity, have recently started to be studied.

In these intelligent controls, fuzzy control is convenient to describe the control system with uncertainty, since it can change the characteristics of the control system corresponding to the range of the parameter variation. Fuzzy control theory is easy for a control engineer to understand. Moreover, at present, it is applied to analyze the stability of the system necessary in designing a control system [10]. This time fuzzy control method is adopted considering the above-mentioned points.

In this study, the model of the controlled element containing actuators is formed by using fuzzy theory accepting the concept of uncertainty. After that, the controller for suppressing the vibration of the composite beam is designed based on the fuzzy model, taking the stability condition of the control system into consideration. Lastly the control effect is confirmed.

2. SPECIMEN AND EXPERIMENTAL SETUP

The specimen used in this study is shown in Fig. 1, and consists of two CFRP laminated plates, ERF and PZT [2]. In Fig. 1, 'A' shows the cross-sectional drawing

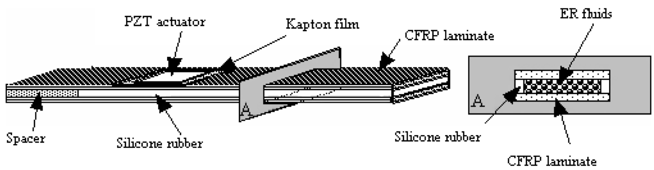

Figure 1. A schematic view of the specimen.

of the specimen. The spacer is inserted between two CFRP laminated plates in order to fill the ERF and adhere it by using epoxy adhesive. The ERF is filled between the gap by using capillary action and is sealed by silicon rubber. A pair of PZT actuators are bonded near the fixed end of the cantilevered specimen on the surface of the CFRP laminated plates, where the PZT is isolated from the CFRP laminated plates using a kapton film because the laminated plates are electrically conductive.

The fixed end of the cantilevered beam is vibrated under forced sinusoidal excitation with the natural frequency of the first flexural mode using the vibration testing facility. The vibration responses of the composite beam are measured by the non-contacting laser displacement pick-up, and the personal computer calculates the magnitudes of the voltage applied to the PZT and ERF actuators. The feedback of the deflection of the cantilevered beam is adopted in this control method.

3. FUZZY MODELING

3.1. Characteristics of actuators

The outline of the actuators is as follows. In the case of PZT, it generates voltage when it is strained by applying force onto it and it generates strain or stress when it is subjected to an applied voltage. After we had obtained a Bode diagram of the system containing the composite beam with PZT experimentally, it was confirmed that the transfer function of PZT should be 1st phase lead element [11].

The phenomenon whereby the observed viscosity of a fluid increases significantly in an applied external electric field and the viscosity returns to its original magnitude when the electric field is removed is called ER efficiency, and a fluid that exhibits this phenomenon is called ERF. The characteristic of ERF is shown in Fig. 2. In this figure, y is the deflection of the composite beam, f_E is the control force applied to the composite beam by the ERF, v_2 is the input voltage to ERF and k_e is the coefficient:

$$f_E = k_e v_2^2 \operatorname{sgn}(\dot{y}) + n\dot{y}. \tag{1}$$

This control force can be considered to consist of the viscous damping force without an applied electric field and the coulomb friction damping force with the electric field [3] (on referring to equation (1)). In this case, the characteristics of the ERF cannot be expressed by using the input-output relation between the input v_2 and the output f_E, and the modeling, so the characteristics are considered to be difficult to assess.

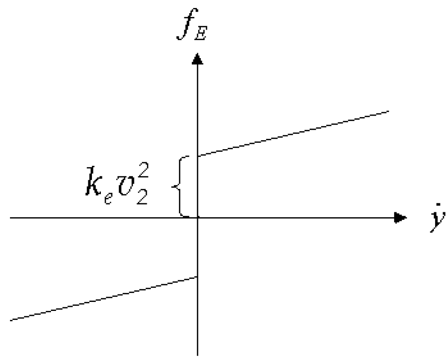

Figure 2. The characteristics of ERF.

In this study the viscous damping force $n\dot{y}$ of ERF is separated from the control force of ERF and is included in the viscous damping force of the composite beam, because the composite beam also has the characteristic of the viscous damping force [11]. As a result, it can be considered that only the coulomb friction can be considered as the characteristics of the ERF, as shown in equation (2), excluding the second term of the right side from equation (1):

$$f_E = k_e v_2^2 \operatorname{sgn}(\dot{y}). \tag{2}$$

However, the relation between the input v_2 of ERF and the output f_E is remarkably nonlinear as shown in equation (2) in this case, too, and it is difficult to linearize the relation simply.

3.2. Formation of fuzzy model

The block diagram of the vibration control system is shown in Fig. 3. It comprises the CFRP composite beam $G_b(s)$, PZT $G_p(s)$ and ERF $G_E(s)$ is regarded as the controlled element $P(s)$. Then the input voltage v_1 and v_2 applied to the two actuators and the disturbance signal f are the inputs of the controlled element $P(s)$

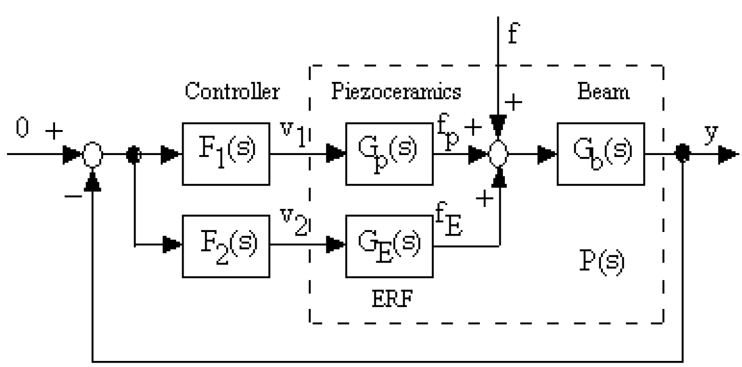

Figure 3. Block diagram of the vibration control system.

and the deflection y at the free end of the cantilevered composite beam is the output. As described previously, ERF shows intense nonlinearity, and the application of linear control theory is very difficult. Therefore we are obliged to use the fuzzy model of the controlled element and the control input for restraining vibration of the composite beam is obtained based on the fuzzy model. The advantage of the fuzzy model is that the process can be divided into several rules and can be expressed as the approximately linearized system in each rule in a remarkably complicated nonlinear system.

The motion equation in this system is considered to be the second-order system fundamentally [11], and the control forces f_P and f_E of PZT and ERF actuators are the functions of the input voltage v_1 and v_2, respectively. Therefore the motion equation can be expressed by equation (3):

$$\begin{aligned} m\ddot{y} + c\dot{y} + ly &= f + f_P + f_E \\ &= f + g_1(v_1) + g_2(v_2) \\ &= f + pv_1 + qv_2 + r, \end{aligned} \tag{3}$$

where f_P and f_E are the control forces of the PZT and ERF actuators, respectively, to the composite beam; $g_1(v_1)$ and $g_2(v_2)$ are the functions of the voltage v_1 and v_2; p and q are the coefficients in the case of linearizing f_P and f_E by using v_1 and v_2; r is the constant in the case of linearizing f_P and f_E; m is the equivalent mass of the composite beam; c is the viscous damping coefficient and l is the equivalent spring coefficient. In the case of the equation (3), $g_2(v_2)$ is significantly nonlinear, and therefore the parameters q and r which arise in linearizing $g_2(v_2)$ change with every rule.

The differential value of the deflection y at the free end of the beam is approximated as shown in the next equation by using the central difference to discretize the equation (3):

$$\dot{y}(k) = \frac{y(k+1) - y(k-1)}{2h}, \tag{4}$$

$$\ddot{y}(k) = \frac{y(k+1) - 2y(k) + y(k-1)}{h^2}, \tag{5}$$

where h is the time interval. The next equation (6) is obtained by substituting equations (4) and (5) into equation (3):

$$\begin{aligned} y(k+1) = {} & \frac{4m - 2lh^2}{2m + ch} y(k) + \frac{-2m + ch}{2m + ch} y(k-1) \\ & + \frac{2ph^2}{2m + ch} v_1(k) + \frac{2qh^2}{2m + ch} v_2(k) \\ & + \frac{2h^2}{2m + ch} f(k) + \frac{2h^2 r}{2m + ch}. \end{aligned} \tag{6}$$

Therefore if this system is expressed by the second-order discrete model [2], then equation (7) is given.

$$y(k+1) = a_1 y(k) + a_2 y(k-1) + a_3 v_1(k) + a_4 v_2(k) + a_5 f(k) + a_6, \tag{7}$$

where $a_1, \ldots, a_6$ are coefficient parameters. But in the case of considering the change with time of the input voltage $v_1(k)$ and $v_2(k)$ as the response of the actuators, the time delays $v_1(k-1)$ and $v_2(k-1)$ of one sampling period are added into the right-hand side of equation (7) and the next equation is used:

$$y(k+1) = a_1 y(k) + a_2 y(k-1) + a_3 v_1(k) + a_4 v_1(k-1) + a_5 v_2(k) + a_6 v_2(k-1) + a_7 f(k) + a_8. \tag{8}$$

The relation between the input and the output of ERF has significant nonlinear characteristics as mentioned above, and the output characteristics of ERF vary from the case of $\dot{y} > 0$ to the case of $\dot{y} < 0$. So the coefficients of the equation (8) should be varied depending on the sign of $\dot{y}$ in fuzzy modeling. In this case Δy as shown in equation (9) is used in place of $\dot{y}$. Therefore the identification for fuzzy modeling is carried out by using equation (10) in place of equation (8):

$$\Delta y(k) = y(k) - y(k-1), \tag{9}$$

$$y(k+1) = a'_1 y(k) + a'_2 \Delta y(k) + a_3 v_1(k) + a_4 v_1(k-1) + a_5 v_2(k) + a_6 v_2(k-1) + a_7 f(k) + a_8, \tag{10}$$

where $a'_1 = a_1 + a_2$, $a'_2 = -a_2$.

Thus the ith rule in fuzzy model is expressed by equation (11) using "IF–THEN" rule [12] in order to introduce fuzzy inference process.

$$\begin{aligned}
&\mathit{IF} \quad y(k) \in A_{i1}, \Delta y(k) \in A_{i2}, v_1(k) \in A_{i3}, v_1(k-1) \in A_{i4},\\
&\qquad v_2(k) \in A_{i5}, v_2(k-1) \in A_{i6} \text{ and } f(k) \in A_{i7},\\
&\mathit{THEN} \quad y(k+1) = a'_{i1} y(k) + a'_{i2} \Delta y(k) + a_{i3} v_1(k) + a_{i4} v_1(k-1)\\
&\qquad\qquad + a_{i5} v_2(k) + a_{i6} v_2(k-1) + a_{i7} f(k) + a_{i8}\\
&\qquad\qquad = h_i(k),
\end{aligned} \tag{11}$$

where $A_{ij} (j = 1, 2, \ldots, 7)$ are fuzzy sets of $y(k)$, $\Delta y(k)$, $v_1(k)$, $v_1(k-1)$, $v_2(k)$, $v_2(k-1)$ and $f(k)$ in the antecedents in ith rule, respectively, and $h_i(k)$ shows a function of sampling number k, and a'_{ij} $(j = 1, 2)$ and a'_{ij} $(j = 3, 4, \ldots, 7)$ are parameters of linear equations in the consequents in the ith rule of all rules. The membership degree of $y(k)$ is given by Gaussian curves as shown in equation (12).

$$B\{y(k)\} = \exp\left[\frac{-\{y(k) - c\}^2}{2\sigma^2}\right], \tag{12}$$

where c is the average of the horizontal axis data in Gaussian curves, and σ is the standard deviation of the data.

The membership functions of other variables are in the same manner as the above-mentioned variable. Then the weight ω_i (adaptation degree) of the input variables in the ith rule is given by the product of membership degrees of the input variables as shown in the next equation.

$$\omega_i(k) = B_{i1}\{y(k)\} \cdot B_{i2}\{\Delta y(k)\} \cdot B_{i3}\{v_1(k)\} \cdot B_{i4}\{v_1(k-1)\} \cdot B_{i5}\{v_2(k)\} \cdot B_{i6}\{v_2(k-1)\} \cdot B_{i7}\{f(k)\}, \tag{13}$$

where B_{ij} $(j = 1, 2, \ldots, 7)$ are the fuzzy sets and show the values of the membership degrees of $y(k)$, $\Delta y(k)$, $v_1(k)$, $v_1(k-1)$, $v_2(k)$, $v_2(k-1)$ and $f(k)$. Then the inference value of the output variable can be obtained as follows [12] when the number of rules is r:

$$y(k+1) = \frac{\sum_{i=1}^{r} \omega_i(k) h_i(k)}{\sum_{i=1}^{r} \omega_i(k)}. \tag{14}$$

3.3. Identification of fuzzy model

A system identification test is conducted for the fuzzy modelling of the controlled element involving the two actuators. In this case, it is advisable to use the ideal white noise as input data $v_1(k)$ and $v_2(k)$, but the signal of the maximum-length linear shift register sequence (M-sequence) [13], which is a kind of pseudo-random binary signal, is adopted because it is difficult to realize the white noise. In case of the disturbance input $f(k)$, it is not the signal of the M-sequence but a sinusoidal signal having the natural frequency of the first flexural mode of the composite beam is used. The input data given to PZT and ERF in the system identification test are shown in Fig. 4. In the system identification test, voltages of −50 V and 50 V are

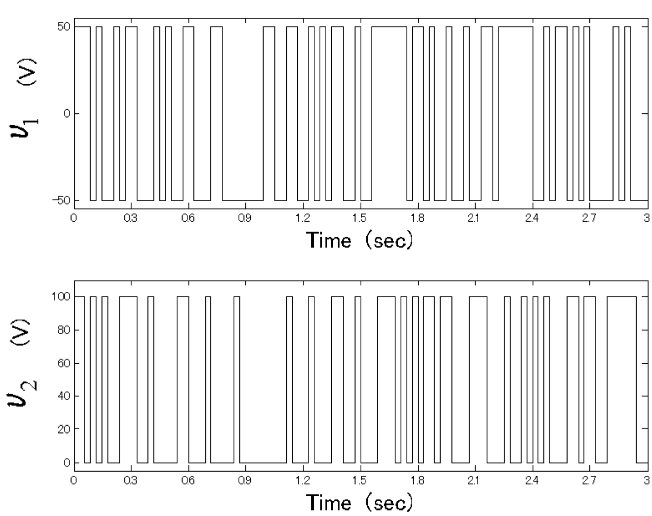

Figure 4. Input signal of the controlled element.

given to PZT and voltages of 0 V and 100 V are given to ERF in place of the signal of 0 and 1 generated by M-sequence.

Parameters of the membership functions of the fuzzy sets in the antecedents and linear equation in the consequents of the fuzzy model are determined based on the result of the system identification test by using Adaptive-Network-based Fuzzy Inference System (ANFIS) model [14], which adjusts the parameter of the fuzzy inference system by using a learning function of the neural network. Examples of membership functions are shown in Fig. 5. The value of the fundamental membership functions of the input variables $y(k)$, $\Delta y(k)$, $v_1(k)$, $v_1(k-1)$, $v_2(k)$, $v_2(k-1)$ and $f(k)$ are decided as 1, 2, 2, 1, 2, 1, 1, respectively, as the result of simulation, and in this case the total number of rules is $1 \times 2 \times 2 \times 1 \times 2 \times 1 \times 1 = 8$. Figure 6

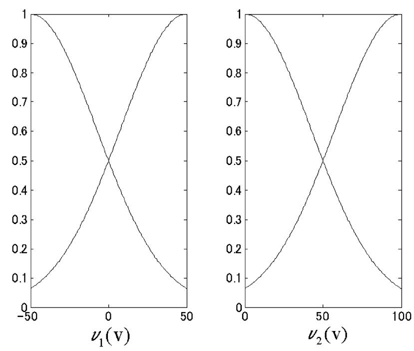

Figure 5. Examples of membership functions.

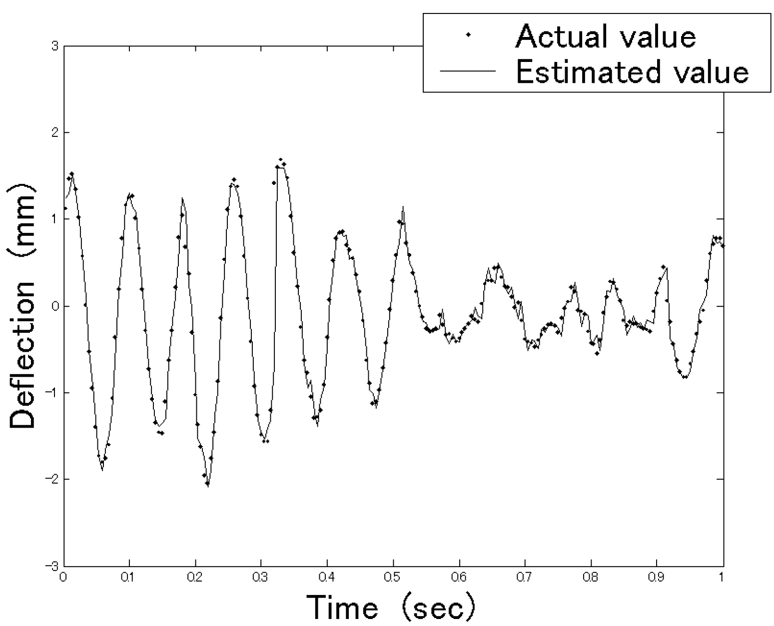

Figure 6. Accuracy of the fuzzy model of the controlled element.

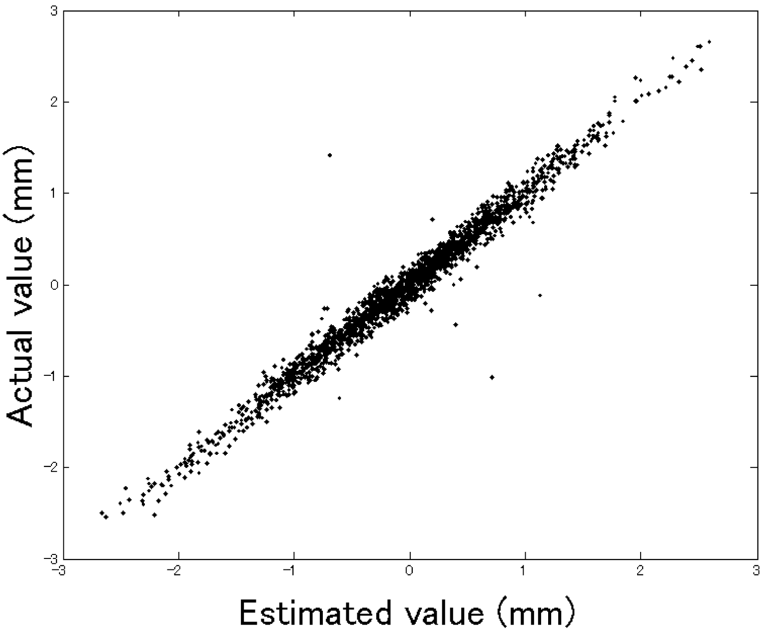

Figure 7. The correlation between the actual value and the estimated value.

shows the accuracy of the estimated value of the deflection obtained by the parameter identification using application software MATLAB [15] for control system design. It can be confirmed that the estimated value by fuzzy model is a fairly good approximation of the actual value. Figure 7 shows the figure of correlation of the estimated value with the actual value.

4. CONTROL BASED ON FUZZY MODEL

4.1. Calculation of control input

The discrete linear equation (8) is expressed by equation (15) in terms of a state equation:

$$\mathbf{y}(k+1) = \mathbf{A}\mathbf{y}(k) + \mathbf{B}\mathbf{v}_1(k) + \mathbf{C}\mathbf{v}_2(k) + \mathbf{d}f(k) + \mathbf{e}, \tag{15}$$

where

$$\mathbf{y}(k) = \begin{pmatrix} y(k) \\ y(k-1) \end{pmatrix}, \quad \mathbf{v}_1(k) = \begin{pmatrix} v_1(k) \\ v_1(k-1) \end{pmatrix}, \quad \mathbf{v}_2(k) = \begin{pmatrix} v_2(k) \\ v_2(k-1) \end{pmatrix}$$

$$\mathbf{A} = \begin{pmatrix} a_1 & a_2 \\ 1 & 0 \end{pmatrix}, \quad \mathbf{B} = \begin{pmatrix} a_3 & a_4 \\ 0 & 0 \end{pmatrix},$$

$$\mathbf{C} = \begin{pmatrix} a_5 & a_6 \\ 0 & 0 \end{pmatrix}, \quad \mathbf{d} = \begin{pmatrix} a_7 \\ 0 \end{pmatrix}, \quad \mathbf{e} = \begin{pmatrix} a_8 \\ 0 \end{pmatrix}.$$

Now the following equations (16) and (17) are considered:

$$\mathbf{G} = (\mathbf{B} \quad \mathbf{C}), \tag{16}$$

$$\mathbf{v}(k) = \begin{pmatrix} \mathbf{v}_1(k) \\ \mathbf{v}_2(k) \end{pmatrix}. \tag{17}$$

The equation (15) is replaced by equation (18) in the case of the ith rule:

$$\mathbf{y}(k+1) = \mathbf{A}_i\mathbf{y}(k) + \mathbf{G}_i\mathbf{v}(k) + \mathbf{d}_i f(k) + \mathbf{e}_i, \tag{18}$$

where $\mathbf{A}_i$, $\mathbf{G}_i$, $\mathbf{d}_i$ and $\mathbf{e}_i$ are the coefficient parameters in the ith rule's consequent. The control input $\mathbf{v}(k)$ for stabilizing the deflection $\mathbf{y}(k+1)$ in equation (18) can be expressed by feedback of the state variable $\mathbf{y}(k)$ in ith rule as follows:

$$\mathbf{v}(k) = -\mathbf{F}_i\mathbf{y}(k), \tag{19}$$

where $\mathbf{F}_j$ is the feedback coefficient in ith rule. The control input can be formed by integrating the control input in each rule as shown in equation (20).

$$\mathbf{v}(k) = \frac{\sum_{i=1}^{r}\omega_i(k)\{-\mathbf{F}_i\mathbf{y}(k)\}}{\sum_{i=1}^{r}\omega_i(k)}. \tag{20}$$

In this case, the result of inference is obtained by integrating the linear equations resulting from the fuzzy model as follows:

$$\begin{aligned}\mathbf{y}(k+1) &= \frac{\sum_{i=1}^{r}\omega_i(k)\{\mathbf{A}_i\mathbf{y}(k) + \mathbf{G}_i\mathbf{v}(k) + \mathbf{d}_i f(k) + \mathbf{e}_i\}}{\sum_{i=1}^{r}\omega_i(k)} \\ &= \frac{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)[\{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}_j\}\mathbf{y}(k) + \mathbf{d}_i f(k) + \mathbf{e}_i]}{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)}. \end{aligned} \tag{21}$$

The above-stated equation can be expressed by equation (22):

$$\mathbf{y}(k+1) = \mathbf{H}(k)\mathbf{y}(k) + \mathbf{d}(k)f(k) + \mathbf{e}(k), \tag{22}$$

where the coefficients in this equation are expressed as follows:

$$\mathbf{H}(k) = \frac{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)[\{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}_j\}]}{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)},$$

$$\mathbf{d}(k) = \frac{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)\mathbf{d}_i}{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)},$$

$$\mathbf{e}(k) = \frac{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)\mathbf{e}_i}{\sum_{i=1}^{r}\sum_{j=1}^{r}\omega_i(k)\omega_j(k)}.$$

The linear discrete-time system expressed by equation (23) is globally asymptotically stable if there is any positive symmetric matrix $\mathbf{P}$ that satisfies equation (24) based on Lyapunov's stability theory [10]:

$$\mathbf{y}(k+1) = \mathbf{H}(k)\mathbf{y}(k), \tag{23}$$

$$\mathbf{H}^T(k)\mathbf{P}\mathbf{H}(k) - \mathbf{P} < 0. \tag{24}$$

This inequality is satisfied when equation (25) holds.

$$\forall i, j \in \{1, 2, \ldots, r\}, \quad \{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}_j\}^{\mathrm{T}}\mathbf{P}\{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}_j\} - \mathbf{P} < 0. \tag{25}$$

In this case, $\mathbf{y}(k)$ corresponding to equation (22) is bounded if the input $f(k)$ is bounded [16].

Therefore the control system as expressed by equation (22) is bounded input–bounded output (BIBO) stable if there is any positive symmetric matrix $\mathbf{P}$ which satisfies equation (25). The same value of $\mathbf{P}$ cannot necessarily be obtained for all $\mathbf{F}_j$ when $\mathbf{P}$ is obtained from equation (25) after obtaining $\mathbf{F}_j$ in each rule by solving an optimal regulation theory. Therefore it is better to obtain both $\mathbf{P}$ and $\mathbf{F}_j$ simultaneously by solving equation (25).

In this case the feedback gain values $\mathbf{F}_j$ are obtained as the same values regardless of the values of j. As a result, $\mathbf{F}_j$ should be replaced by $\mathbf{F}$ as shown in equation (26):

$$\forall i, j \in \{1, 2, \ldots, r\}, \quad \{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}\}^{\mathrm{T}}\mathbf{P}\{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}\} - \mathbf{P} < 0. \tag{26}$$

However, this equation is not linear with respect to $\mathbf{P}$ and $\mathbf{F}$, and cannot easily be solved. By applying the Schur Complement [17] to equation (26) after the replacement of equation (27) and (28), the linear matrix inequality (LMI) as expressed by equation (29) can be obtained:

$$\mathbf{X} = \mathbf{P}^{-1}, \tag{27}$$

$$\mathbf{Y} = \mathbf{F}\mathbf{X}, \tag{28}$$

$$\begin{pmatrix} \mathbf{X} & (\mathbf{A}_i\mathbf{X} - \mathbf{G}_i\mathbf{Y})^{\mathrm{T}} \\ \mathbf{A}_i\mathbf{X} - \mathbf{G}_i\mathbf{Y} & \mathbf{X} \end{pmatrix} > 0. \tag{29}$$

This inequality is linear regarding the unknown variables $\mathbf{X}$ and $\mathbf{Y}$, and can be should numerically for $\mathbf{X}$ and $\mathbf{Y}$.

The feedback gain $\mathbf{F}$ can be obtained by using equation (28). The control input $\mathbf{v}(k)$ can be expressed by equation (30) in place of equation (19), since $\mathbf{F}$ is obtained as the same value regardless of the rules:

$$\mathbf{v}(k) = -\mathbf{F}\mathbf{y}(k). \tag{30}$$

Then the deflection of the composite beam which is the output of the controlled element can be calculated by equation (31).

$$\mathbf{y}(k+1) = \frac{\sum_{i=1}^{r} \omega_i(k)[\{\mathbf{A}_i - \mathbf{G}_i\mathbf{F}\}\mathbf{y}(k) + \mathbf{d}_i f(k) + \mathbf{e}_i]}{\sum_{i=1}^{r} \omega_i(k)}. \tag{31}$$

4.2. Control effect

The responses of a vibration control system with controllers are shown in Figs 8, 9 and 10. The fuzzy controller started to function at about 0.5 seconds after the initial time in all cases. Figure 8 shows the simulation result if we do not consider the time delay of the input voltage v_1 and v_2 as the response of actuators (that is to say, the case of using equation (7) in place of equation (8)).

Figure 9 shows the experimental result in the case of giving the control inputs v_1 and v_2 that are calculated without considering the time delay to the actuators. Figure 10 shows the simulation result if the time delay of the input voltage is taken into consideration.

The following results are found from these figures.

(1) When the time delay of the input voltage is not considered as the response of actuators, both the simulation result and the experiment result provide high accuracy, and it is confirmed that the fuzzy model is effective (see Figs 8 and 9).

(2) When the time delay of the input voltage is taken into consideration, it is confirmed by simulation that the control accuracy becomes still higher (see Figs 8 and 10).

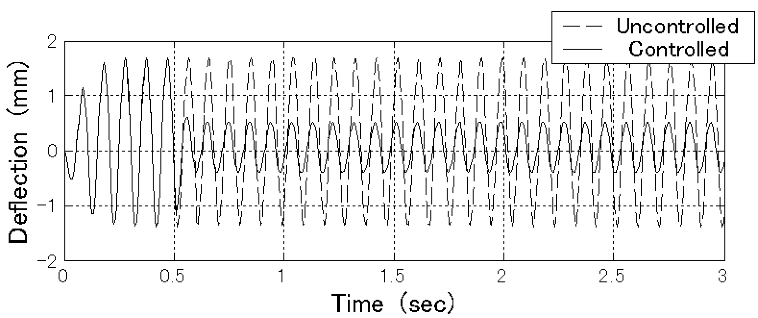

Figure 8. Deflection response of the beam without taking the time delay into consideration (simulation result).

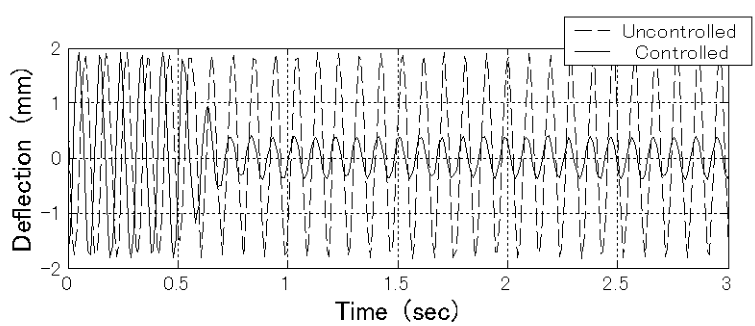

Figure 9. Deflection response of the beam without taking the time delay into consideration (experimental result).

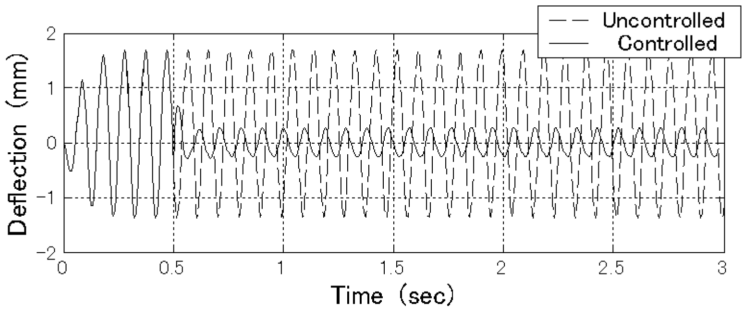

Figure 10. Deflection response of the beam obtained by taking the time delay into consideration (simulation result).

5. CONCLUSIONS

A fuzzy model of the controlled element is formed by using a hybrid neuro-fuzzy method considering the intensive nonlinearity of ERF, when control in giving forced vibration to a CFRP composite beam containing ERF with bonded PZT is investigated. The control input guaranteeing stability of the vibration system is obtained based on the fuzzy model. As a result of the investigation, an accurate fuzzy model is obtained, and it is confirmed by simulation that the control accuracy becomes still higher if the time delay of the input voltage as the response of actuators is taken into consideration.

REFERENCES

1. M. V. Gandhi and B. S. Thompson, *Smart Materials and Structure*, Chapman and Hall, London (1992).
2. T. Takawa, T. Fukuda and K. Nakashima, Fuzzy control of vibration of a smart CFRP laminated beam, *Journal of SMS* **9**, 215–219 (2000).
3. T. Fukuda, Smart Composite. Actuator materials and technology for smartening (3) ER fluids, *Journal of JSCM* **23**, 50–53 (1997).
4. M. Nakano, Controllable damper using ER fluids and new aspect of vibration control, *Journal of SICE* **34**, 707–711 (1995).
5. J. Furusho, Control of mechatronic systems using ER fluids, *Journal of SICE* **34**, 687–691 (1995).
6. K. Takagi, H. Satoh and M. Saigou, Vibration control of the metal core assisted piezoelectric fiber embedded in CFRP composite, in: *8th Symposium Control of Motion and Vibration*, Japan Society for Mechanical Engineering, Osaka, pp. 101–104 (2003).
7. J. H. Han, J. Tani, S. H. Youn and I. Lee, Application of artificial neural networks for adaptive vibration control of smart beam structures, *76th JSME Fall Annual Meeting*, Tohoku, pp. 341–342 (1988).
8. S. M. Silva, R. Ribeiro, J. D. Rodrigues and M. Vaz, Shape control of structures with PZT actuators using genetic algorithms, *13th ICCM*, Beijing, p. 556 (2001).
9. S. Hosoe, *Systems and Control*, Ohmsha, Tokyo (1997).
10. K. Tanaka, *Intelligent Control System*, Kyoritsu Publishing Co, Tokyo (1996).
11. T. Fukuda, T. Takada and T. Takawa, A study on smart composite beam-optimal vibration control of 1st flexural model by used of piezoelectric ceramics, *J. Soc. Mater. Sci.* **44**, 1255–1260 (1995).

12. K. Tanaka, *Advanced Fuzzy Control*, Kyoritsu Publishing Co, Tokyo (1994).
13. S. Adachi, *System Identification Theory for Users*, Society of Instrument and Control Engineers, Tokyo (1993).
14. J. S. R. Jang, Adaptive-network-based fuzzy inference systems, *IEEE Transactions on System, Man and Cybernetics* **23**, 665–685 (1993).
15. J. S. R, Jang and M. Gulley, Fuzzy Logic Toolbox User's Guide, The Math Works, Inc., Massachusetts (1995).
16. N. Hamada, N. Matsumoto and T. Takahashi, *Introduction to Modern Control Theory*, Corona Co, Tokyo (1997).
17. T. Sugie, *Analysis and Design of Robust Control System by LMI*, The Institute of Systems, Control and Information Engineers, Kyoto (1997).