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A Self-Organizing Fuzzy Controller for the Active Vibration Control of a Smart Truss Structure

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1. Introduction

In the last two decades, the subject area of smart/intelligent materials and structures has experienced tremendous growth in terms of research and development. One reason for this activity is that it may be possible to create certain types of structures and systems capable of adapting to or correcting for changing operating conditions. The advantage of incorporating these special types of materials into the structure is that the sensing and actuating mechanism becomes part of the structure by sensing and actuating strains directly. Piezoelectric material is often suitable for this purpose. This type of material possesses direct and converse piezoelectric effects; when a mechanical force is applied to the piezoelectric material, an electric voltage or change is generated, and when an electric field is applied to the material, a mechanical force is induced. With the recent advances in piezoelectric technology, it has been shown that the piezoelectric actuators based on the converse piezoelectric effect can offer excellent potential for active vibration control techniques, especially for vibration suppression or isolation.

A truss structure is one of the most commonly used structures in aerospace and civil engineering (Yan & Yam, 2002). Because it is desirable to use the minimum amount of material for construction, trusses are becoming lighter and more flexible which means they are more susceptible to vibration. Passive damping is not a preferred vibration control solution because it adds weight to the system, so it is of interest to study the active control of such a structure. A convenient way of controlling a truss structure is to incorporate a piezoelectric stack actuator into one of the truss members (Anthony & Elliot, 2005).

An important feature of control system in the truss structure is the collocation between the actuator and the sensor. An actuator/sensor pair is collocated if it is physically located at the same place and energetically conjugated, such as force and displacement or velocity, or torque and angle. The properties of collocated systems are remarkable; in particular, the

stability of the control loop is guaranteed when certain simple, specific controllers are used (Preumont, 2002). It requires that the control architecture be decentralized, i.e. that the feedback path include only one actuator/sensor pair, and be thus independent of others sensors or actuators possibly placed on the structure.

The choice of the actuator/sensor location is another important issue in the design of actively controlled structures. The actuators/sensors should be placed at locations so that the desired modes are excited most effectively (Lammering et al., 1994). A wide variety of optimization algorithms have been proposed to this end in the literature. Two popular examples are Simulated Annealing (Chen et al., 1991) and Genetic Algorithms (Rao et al., 1991; Padula & Kincaid, 1999). Although these methods are effective, they fail to give a clear physical justification for the choice of the actuator/sensor placement. In this chapter, a more physical method used by Preumont et al. (1992) has been chosen. It involves placing the transducer in the truss structure at the location where there is the maximal fraction of modal strain energy. At this location, the actuator will couple most effectively into this mode of vibration, i.e., there will be maximum controllability of the specific mode by the actuator.

Research on the damping of truss structures began in the late 80's. Fanson et al. (1989), Chen et al. (1989) and Anderson et al. (1990) developed active members made of piezoelectric transducers. Preumont et al. (1992) used a local control strategy to suppress the low frequency vibrations of a truss structure using piezoelectric actuators. Their strategy involved the application of integrated force feedback using two force gauges each collocated with the piezoelectric actuators, which were fitted into different beam elements in the structure. Carvalhal et al. (2007) used an efficient modal control strategy for the active vibration control of a truss structure. In their approach, a feedback force is applied to each node to be controlled according to a weighting factor that is determined by assessing how much each mode is excited by the primary source. Abreu et al. (2010) used a standard H_∞ robust controller design framework to suppress the undesired structural vibrations in a truss structure containing piezoelectric actuators and collocated force sensors.

It is difficult to implement classical controllers to systems which are complex such as truss structures. Because of this active vibration control using fuzzy controllers has received attention because of their ability to deal with uncertainties in terms of vagueness, ignorance, and imprecision. Fuzzy controllers are most suitable for systems that cannot be precisely described by mathematical formulations (Zadeh, 1965). In this case, a control designer captures the operator's knowledge and converts it into a set of fuzzy control rules.

Fuzzy logic is useful for representing linguistic terms numerically and making reliable decisions with ambiguous and imprecise events or facts. The benefit of the simple design procedure of a fuzzy controller has led to the successful application of a variety of engineering systems (Lee, 1990). Zeinoun & Khorrami (1994) proposed a fuzzy logic algorithm for vibration suppression of a clamped-free beam with piezoelectric sensor/actuator. Ofri et al. (1996) also used a control strategy based on fuzzy logic theory for vibration damping of a large flexible space structure controlled by bonded piezoceramic actuators and Abreu & Ribeiro (2002) used an on-line self-organizing fuzzy logic controller to control vibrations in a steel cantilever test beam containing distributed piezoelectric actuator patches.

In general, fuzzy logic controllers use fuzzy inference with rules pre-constructed by an expert. Therefore, the most important task is to form the rule base which represents the experience and intuition of human experts. When this rule base is not available, efficient control can not be expected.

The self-organizing fuzzy controller is a rule-based type of controller which learns how to control on-line while being applied to a system, and it has been used successfully for a wide variety of processes (Shao, 1988). This controller combines system identification and control based on experience. Therefore, only a minimal amount of information about the environment needs to be provided.

The main purpose of this chapter is to demonstrate how active vibration control of a truss structure can be achieved with the minimal input of human experts in designing a fuzzy logic controller for such a purpose. For this, the self-organizing controller is used which uses the input and output history in its rules (Abreu & Ribeiro, 2002). This controller has no rules initially, but forms rules by defining membership functions using the plant input-output data as singletons and stores them in a rule base. The rule base is updated as experience is accumulated using a self-organizing procedure. A simple method for defuzzification is also presented by adding a predictive capability using a prediction model.

The self-organizing controller is numerically verified in a truss structure using a pair of piezoceramic stack actuators. The control system consists of independent SISO loops, i.e. decentralized active damping with local self-organizing fuzzy controllers connecting each actuator to its collocated force sensor. A finite element model of the structure is constructed using three-dimensional frame elements subjected to axial, bending and torsional loads considering electro-mechanical coupling between the host structure and piezoelectric stack actuators. To simulate the effects of disturbances on the truss, an impulsive force is applied to excite many modes of vibration of the system, and variations in the structural parameters are considered. Numerical simulations are carried out to evaluate the performance of the self-organizing fuzzy controller and to demonstrate the effectiveness of the active vibration control strategy.

2. The truss structure

The truss structure of interest in this chapter is depicted in Fig. 1. It consists of 20 bays, each 75 mm long, made of circular steel bars of 5 mm diameter connected with steel joints (80g mass blocks) and clamped at the base. It is equipped with active members as indicated in the Fig. 1. They consist of piezoelectric linear actuators, each collinear with a force transducer.

2.1 Governing equations

Consider the linear structure of Fig. 1 equipped with a discrete, massless piezoelectric stack actuator. The equation governing the motion of the structure excited by a force f and controlled by a piezoelectric actuator (f_a) is

$$M\ddot{x} + C\dot{x} + Kx = bf + b_a f_a \tag{1}$$

where K and M are the stiffness and mass matrices of the structure, obtained by means of the finite element model using the three-dimensional frame elements (Kwon & Bang, 1997) (each node has six degrees-of-freedom), C is the damping matrix; b and b_a are, respectively, the influence vectors relating to the locations of the external forces (f) and the active member in the global coordinates of the truss (the non-zero components of b_a are the direction cosines of the active bar in the structure), and f_a is the force exerted by an active member.
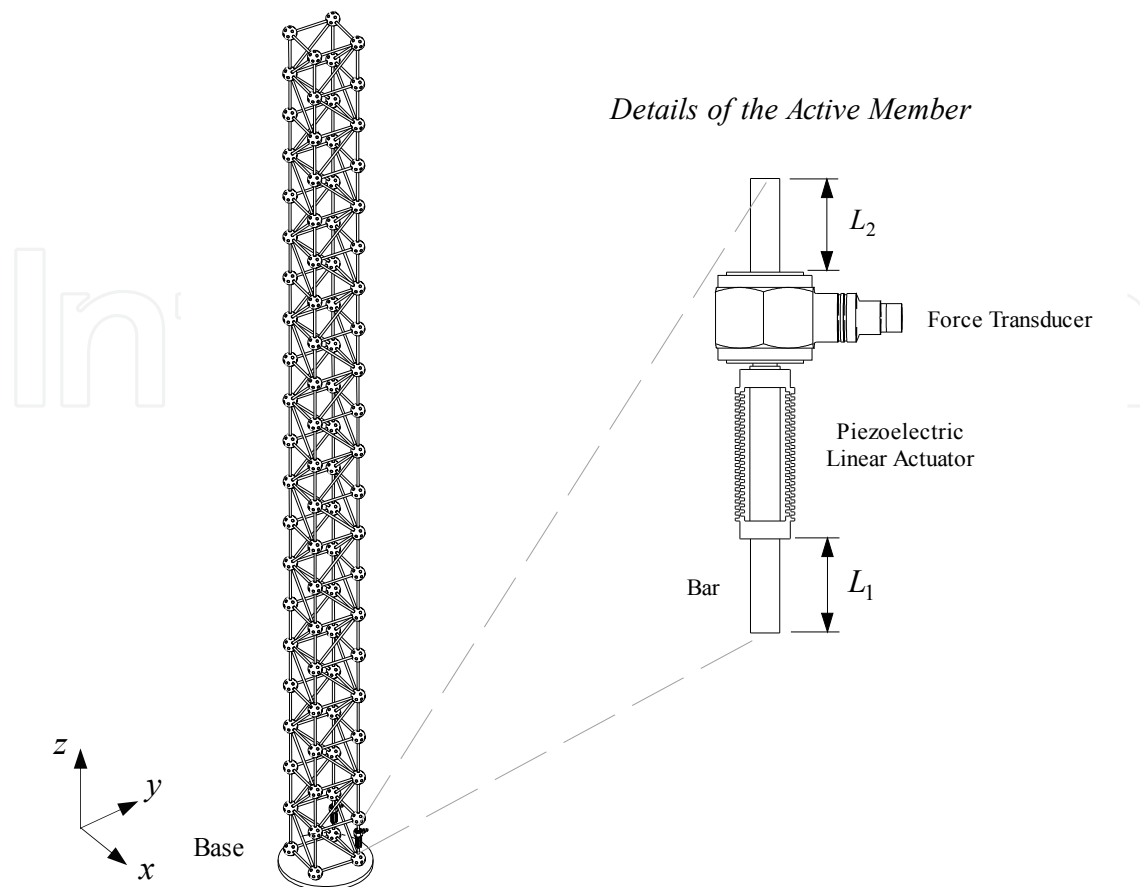
Fig. 1. Truss structure with a pair of active members.

Consider the piezoelectric linear tranducer of Fig. 1 is made of n_a identical slices of piezoceramic material stacked together. Since damping is considered to be negligible, the force exerted by an active member is defined by (Leo, 2007)

$$f_a = K_{eq}\left(\Delta - n_a d_{33} V\right) \tag{2}$$

where d_{33} is the piezoelectric coefficient, V is the voltage applied to the piezo actuator, Δ is the displacement at the end nodes of the active member i.e., Δ is the sum of the free displacement of the piezoelectric actuator ($n_a d_{33} V$) and the displacement due to the blocked force of the actuator (f_a / K_a), and K_{eq} is the equivalent stiffness of the actuator, such that

$$\frac{1}{K_{eq}} = \frac{L_1 + L_2}{EA_t} + \frac{1}{K_a} \tag{3}$$

where K_a is the combined stiffness of the actuator and force sensor, and E and A_t are respectively the Young's modulus and cross-sectional area of the bar shown in Fig. 1.

The elongation Δ of each actuator is linked to the vector of structural displacements by

$$\Delta = b_a^T x \tag{4}$$

The equation governing the structure containing the active member can be found by substituting Eqs. (2) and (4) with Eq. (1). The new equation is

$$M\ddot{x} + C\dot{x} + \left(K - K_{eq}b_ab_a^T\right)x = bf - b_aK_{eq}n_ad_{33}V \tag{5}$$

where K is the stiffness matrix of the structure excluding the axial stiffness of the actuator. The equation (5) can be transformed into modal coordinates according to

$$x = \Phi\eta \tag{6}$$

where Φ is the matrix of the mode shapes, which can be determined by solving the eigenvalue problem

$$M\ddot{x} + \left(K - K_{eq}b_ab_a^T\right)x = 0 \tag{7}$$

Assuming normal modes normalized such that $\Phi^T M\Phi = I$ and introducing the modal state vector $x_n = \begin{bmatrix} \eta & \dot{\eta} \end{bmatrix}^T$, the transformed equation of motion (5) becomes

$$\dot{q} = Aq + B_1 f + B_2 V \tag{8}$$

where

$$A = \begin{bmatrix} 0 & I \\ -\bar{K} & -\bar{C} \end{bmatrix}, \; B_1 = \begin{bmatrix} 0 \\ \Phi^T b \end{bmatrix} \text{ and } B_2 = \begin{bmatrix} 0 \\ -\Phi^T b_a K_{eq} n_a d_{33} \end{bmatrix} \tag{9}$$

and $\bar{K} = \text{diag}(\omega_i^2)$, $\bar{C} = \text{diag}(2\zeta_i\omega_i)$, ω_i is the i-th natural frequency of the truss and ζ_i is the associated modal damping.

Similarly to Eq. (2), the output signal of the force sensor, proportional to the elastic extension of the truss, is defined by

$$y = C_2 q + D_{22} V \tag{10}$$

Where

$$C_2 = \begin{bmatrix} K_{eq}b_a^T\Phi & 0 \end{bmatrix} \text{ and } D_{22} = -K_{eq}n_ad_{33} \tag{11}$$

3. Actuator placement

More than any specific control law, the location of the active member is the most important factor affecting the performance of the control system. Good control performance requires the proper location of the actuator to achieve good controllability. The active member should be placed where its authority in controlling the targeted modes is the greatest. It can be achieved if the transducer is located to maximize the mechanical energy stored in it. The ability of a vibration mode to concentrate the vibrational energy in the transducer is measured by the fraction of modal strain energy v_i defined by (Preumont, 2002)

$$v_i = \frac{\phi_i^T\left(K_{eq}b_ab_a^T\right)\phi_i}{\phi_i^T\left(K - K_{eq}b_ab_a^T\right)\phi_i} = \frac{K_{eq}\left(b_a^T\phi_i\right)^2}{\omega_i^2} \tag{12}$$

The Eq. (12) is the ratio between the strain energy in the actuator and the total strain energy when the structure vibrates in its *i*-th mode. Physically, v_i can be interpreted as a compound indicator of controllability and observability of mode *i* by the transducer. The best location for the transducer in the truss structure is the position which has the maximal fraction of modal strain energy of the mode to be controlled.

Here, the control objective is to add damping to the first two modes of the structure by using two active elements. The search for candidate locations where these active members can be placed is greatly assisted by the examination of the first two structural mode shapes which are shown in Fig. 2.

(a)   (b)   (c)
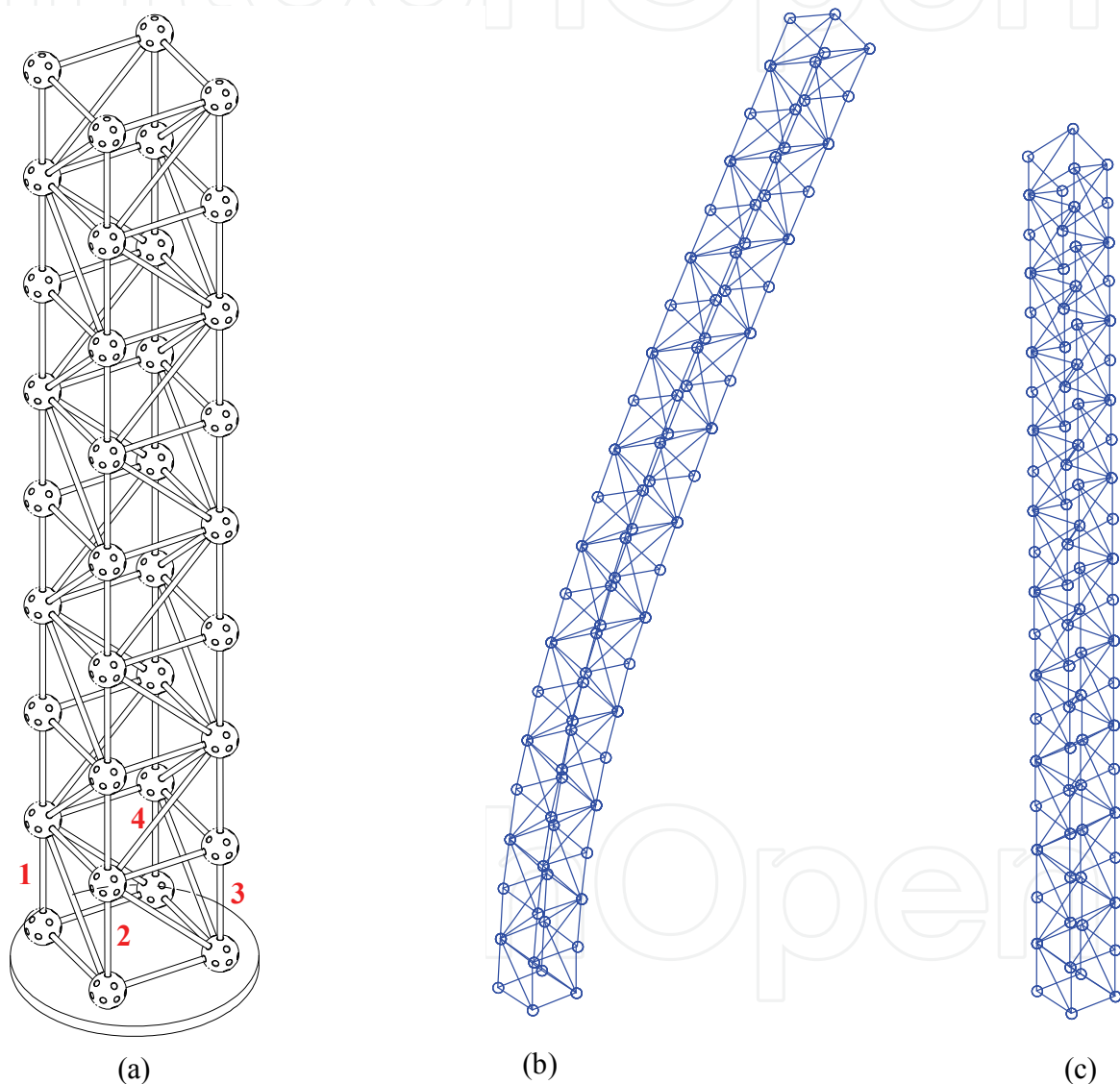
Fig. 2. a) disposition of the active elements; b) first mode shape (12.67 Hz) and c) second mode shape (12.69 Hz).

Assuming the main characteristics of both transducers as: K_{eq} = 28 N/μm and $n_a d_{33}$ = 1.12×10⁻⁷ m/Volts, the fractions of modal strain energy v_i, computed from Eq. (12), are shown in Table 1, which gives the six possible combinations of the two positions of the actuators from the four candidate positions shown Fig. 2a.

Positions	v_1 (%)	v_2 (%)
1 & 2	11.22	8.79
1 & 3	16.39	0.00
1 & 4	11.08	9.46
2 & 3	1.63	3.00
2 & 4	16.93	0.04
3 & 4	14.26	15.68

Table 1. Fraction of modal strain energy in the selected finite elements.

From Fig. 2 and the Tab. 1 it can be seen that when the active members are located at positions 3 and 4, the sum of the fractions of modal strain energies v_1 and v_2 are maximal. Thus these positions are chosen for the transducers in the actual truss as shown in Fig. 1.

4. Design of the self-organizing fuzzy controller

Consider the truss structure with the active members described in Section 3. Each active member consists of a piezoelectric linear actuator collocated with a force transducer. In this section, a decentralized active damping controller is considered with a local Self-Organizing Fuzzy Controller (SOFC) connecting each actuator to its collocated force sensor (y).
The control voltage (V) applied to each actuator is defined as

$$V(s) = \frac{u}{s + \varepsilon} \tag{13}$$

where s is the Laplace variable, u is the output of the SOFC and the constant ε is to avoid voltage saturation and it must be lower than the first natural frequency of the structure (Preumont et al., 1992). The integral term $1/s$ introduces a 90º phase shift in the feedback path and thus adds damping to the system (Chen et al, 1989). It also introduces a -20 dB/decade slope in the open-loop frequency response, and thus reduces the risks of spillover instability (Preumont, 2002).
Using the backward difference rule (Phillips & Nagle, 1990), Eq. (13) can be written in the time domain as

$$V_{k+1} = e^{-\varepsilon\, dt} V_k + u_k \varepsilon\, dt \tag{14}$$

where k is the sampling step and dt is the sampling time.
Based on the steps in designing a conventional Fuzzy Logic Controller (FLC), the SOFC design consists of six steps: 1) the definition of input/output variables; 2) definition of the control rules; 3) fuzzification procedure; 4) inference logic procedure, 5) defuzzification procedure, and 6) the self-organization of the rule base.

4.1 Definition of input/output variables
In general, the output of a system can be described with a function or a mapping of the plant input-output history. For a Single-Input Single-Output (SISO) discrete time systems, the mapping can be written in the form of a nonlinear function as follows

$$y_{k+1} = g\left(y_k, y_{k-1}, \ldots, u_k, u_{k-1}, \ldots\right) \tag{15}$$

where y_k and u_k are, respectively, the output and input variables at the k-th sampling step. The objective of the control problem is to find a control input sequence which will drive the system to an arbitrary reference point y_{ref}. Rearranging Eq. (15) for control purposes, the value of the input u at the k-th sampling step that is required to yield the reference output y_{ref} can be written as follows

$$u_k = h\left(y_{ref}, y_k, y_{k-1}, \ldots, u_{k-1}, u_{k-2}, \ldots\right) \tag{16}$$

which can be viewed as an inverse mapping of Eq. (15).

While a typical conventional FLC uses the error and the error rate as the inputs, the proposed controller uses the input and output history as the input terms: y_{ref}, y_k, y_{k-1}, y_{k-2}, …, y_k, u_{k-1}, u_{k-2}, …. This implies that u_k is the input to be applied when the desired output is y_{ref} as indicated explicitly in Eq. (16).

4.2 Definition of the control rules

In this work, the key idea behind the SOFC is not to use rules pre-constructed by experts, but forms rules with input and output history at every sampling step. Therefore, a new rule R, with the input and output history can be defined as follows

$$\begin{aligned} R^{(j)} : \text{IF } y_k \text{ is } A_{1j}, \; y_{k-1} \text{ is } A_{2j}, \ldots, \; y_{k-n+1} \text{ is } A_{nj}, \\ \text{AND } u_{k-1} \text{ is } B_{1j}, \ldots, \; u_{k-m} \text{ is } B_{mj}, \text{ THEN } u_k \text{ is } C_j \end{aligned} \tag{17}$$

where n and m are the number of output and input variables, A_{1j}, A_{2j}, …, A_{nj} and B_{1j}, B_{2j}, …, B_{mj} are the antecedent linguistic values for the j-th rule and C_j is the consequent linguistic values for the j-th rule.

4.3 Fuzzification procedure

In a conventional FLC, an expert usually determines the linguistic values A_{1j}, A_{2j}, …, A_{nj} and B_{1j}, B_{2j}, …, B_{mj}, and C_i by partitioning each universe of discourse. In this paper, however, this linguistic values are determined from the crisp values of the input and output history at every sampling step and a fuzzification procedure for fuzzy values is developed to determine $A_{1j}, A_{2j}, ..., A_{(n+1)j}$, $B_{1j}, B_{2j}, ..., B_{mj}$, and C_i from the crisp y_k, y_{k-1}, y_{k-2}, …, $y_{k-n+1}, u_{k-1}, u_{k-2}, \ldots, u_{k-m}$ and u_k, respectively. The fuzzification is done with its base on assumed input or output ranges. When the assumed input or output range is $[a, b]$, the membership function for crisp y_i is determined in a triangular shape

$$\mu_{A_i} = \begin{cases} 1 + (y - y_i)/(b - a) & \text{if } a \le y < y_i \\ 1 - (y - y_i)/(b - a) & \text{if } y_i \le y < b \\ 0 \end{cases}, \text{ for } i = 1, 2, \ldots, n \tag{18}$$

Note that all linguistic values overlap on the entire range $[a, b]$, and furthermore, every crisp value uniquely defines the membership function with the unity center or vertex value and identical slopes: $-1/(b-a)$ and $1/(b-a)$ for the right and left lines, respectively (see Fig. 3).

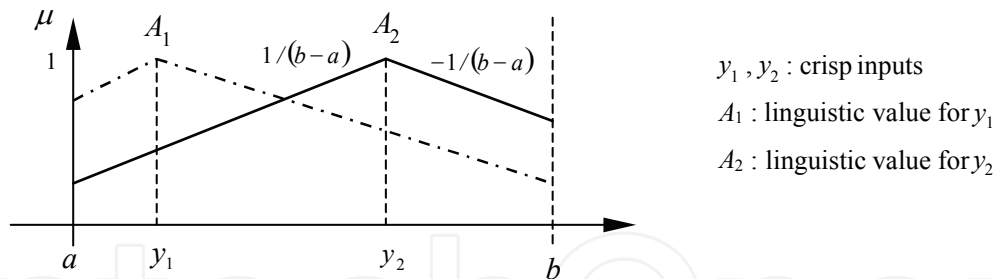Fig. 3. Fuzzification procedure for A_{1j}, A_{2j}, ..., A_{nj}, B_{1j}, B_{2j}, ..., B_{mj} or C_j.

The Fig. 3 shows the fuzzification procedure for crisp variables y_1 and y_2, where A_1 and A_2 are the corresponding linguistic values (fuzzy sets) with membership functions defined in the range $[a,b]$. Thus, this fuzzification procedure requires only the minimal information in forming the membership functions.

4.4 Inference logic procedure

To attain the output fuzzy set, it is necessary to determine the membership degree (w_i) of the input fuzzy set with respect to each rule. If input fuzzy variables are considered as fuzzy singletons, the membership degree of the input fuzzy variables for each rule may be calculated by using a specific operator (*AND*). As with the conventional FLC, the operator used here is the *min* operator described for the *i*-th rule

$$w_i = \min[(A_{1i} \wedge y_1),...,(A_{(n+1)i} \wedge y_{n+1}),(B_{1i} \wedge u_1),...,(B_{mi} \wedge u_m)] \tag{19}$$

where $\wedge$ is the *AND* operation.

This mechanism considers the minimum intersection degree between input fuzzy variables and the antecedent linguistic values for the example: *i*-th and *j*-th rules, as shown in Fig. 4.
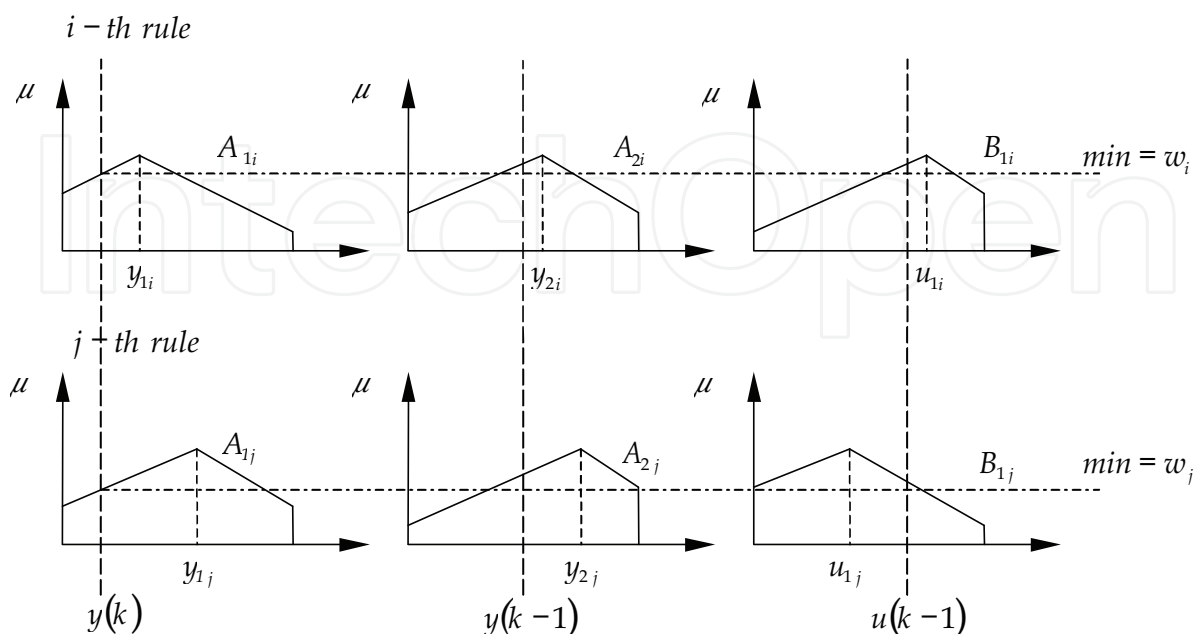
Fig. 4. Inference mechanism.

The membership degrees w_i and w_j thus defined reflect the contribution of all input variables in the i-th and j-th rules. The evaluation of the membership degree value w with three fuzzy input variables, y_k, y_{k-1} and u_{k-1}, is shown in Fig. 4, where the i-th rule is closer to the input variables than the j-th rule and thus $w_i > w_j$.

The consequent linguistic value or the net linguistic control action, C_n is calculated for taking the α-cut of C_n, where $\alpha = \max\left[\mu(C_n)\right]$. To find the control range for the example shown in Fig. 4, each operation forms the consequent fuzzy set, and the range with its membership degree is deduced as a control range for each rule, i.e., $\left[a,b\right]$ for the i-th rule, and $\left[c,d\right]$ for the j-th rule as the respective ranges. As a result of this inference, the net control range (NCR), which is the intersection of all control ranges, is determined, i.e., $\left[c,b\right]$ as shown in Fig. 5, where C_i and C_j are the consequent fuzzy sets for the i-th and j-th rules, respectively.
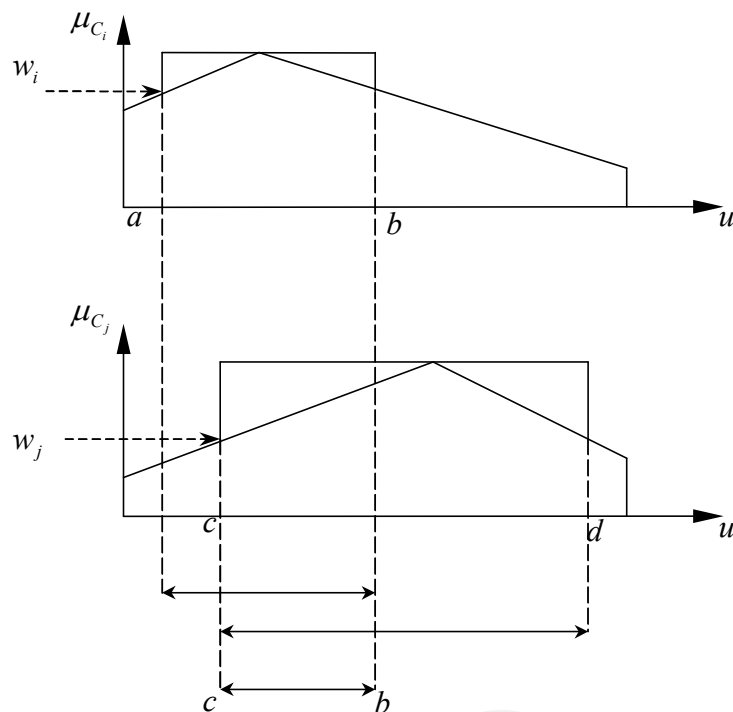
Fig. 5. The Net Control Range (NCR) with two rules.

4.5 Defuzzification procedure

Deffuzification is the procedure to determine a crisp value from a consequent fuzzy set. Methods often used to do this are the center of area and the mean of maxima (Driankov et al., 1996). Here, the purpose of defuzzification is to determine a crisp value from the NCR resulting from the inference. Any value within the NCR has the potential to be a control value, but some control values may cause overshoot while others may be too slow. This problem can be avoided by adding a predictive capability in the defuzzification. A method is presented which modifies the NCR to compute a crisp value by using the prediction of the output response. The series of the last outputs is extrapolated in the time domain to estimate y_{k+1} by the Newton backward-difference formula (Burden and Faires, 1989). If the extrapolation order is n, using the binomial-coefficient notation, the estimate $\hat{y}_{k+1}$ is calculated as follows

$$\hat{y}_{k+1} = \sum_{i=0}^{n} (-1)^i \binom{-1}{i} \nabla^i y_k \qquad (20)$$

where

$$\nabla^i y_k \overset{\Delta}{=} \nabla \left(\nabla^{i-1} y_k \right), \text{ where } \nabla y_k \overset{\Delta}{=} y_k - y_{k-1} \text{ for } i \geq 2 \qquad (21)$$

Defuzzification is performed by comparing the two values, the estimate $\hat{y}_{k+1}$ and the reference output y_{ref} or the temporary target y_{k+1}^t, generated by

$$y_{k+1}^t = y_k + \alpha \left(y_{ref} - y_k \right) \qquad (22)$$

where y_{k+1}^t is the reference output or the temporary target and α is the target ratio ($0 < \alpha \leq 1$). The value α describes the rate with which the present output y_k approaches the reference output value. The value α is chosen by the user to obtain a desirable response. When the estimate exceeds the reference output, the control has to slow down. On the other hand, when the estimate has not reached the reference, the control should speed up. Two possible cases will therefore be considered: Case 1) $\hat{y}_{k+1} < y_{k+1}^t$ and Case 2) $\hat{y}_{k+1} > y_{k+1}^t$.

To modify the control range, the sign of $u_k - u_{k-1}$ is assumed to be the same as the sign of $y_{k+1}^t - \hat{y}_{k+1}$. Thus, for Case 1 the sign of $y_{k+1}^t - \hat{y}_{k+1}$, hence the sign of $u_k - u_{k-1}$, is positive, implying that u_k has to be increased from the previous input u_{k-1}.
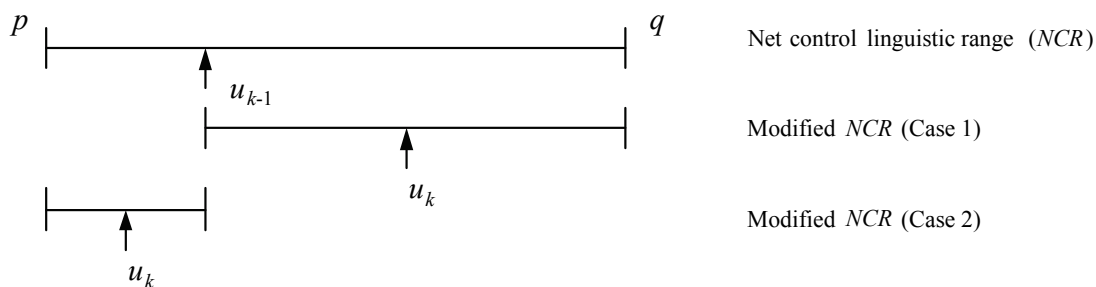
Fig. 6. The defuzzification procedure.

The final crisp control value u_k is then selected as one of the midpoints of the modified NCR as shown in Fig. 6.

$$u_k = \begin{cases} \left(u_{k-1} + q \right) / 2 & \text{for Case 1} \\ \left(p + u_{k-1} \right) / 2 & \text{for Case 2} \end{cases} \qquad (23)$$

where p and q are the respective lower and upper limits of the NCR resulting from the inference mechanism (Section 4.4).

4.6 Self-organization of the rule base

The rules of the SOFC are generated at every sampling time. If every rule is stored in the rule base, two problems will occur: 1) the memory will be exhausted, and 2) the rules which are performed improperly during the initial stages also affect the later inference.

For this reason, the fuzzy *rule space* is partitioned into a finite number of domains of different sizes and only one rule, is stored in each domain. Figure 7 shows an example of the division of a rule space for two output variables y_k and y_{k-1}.
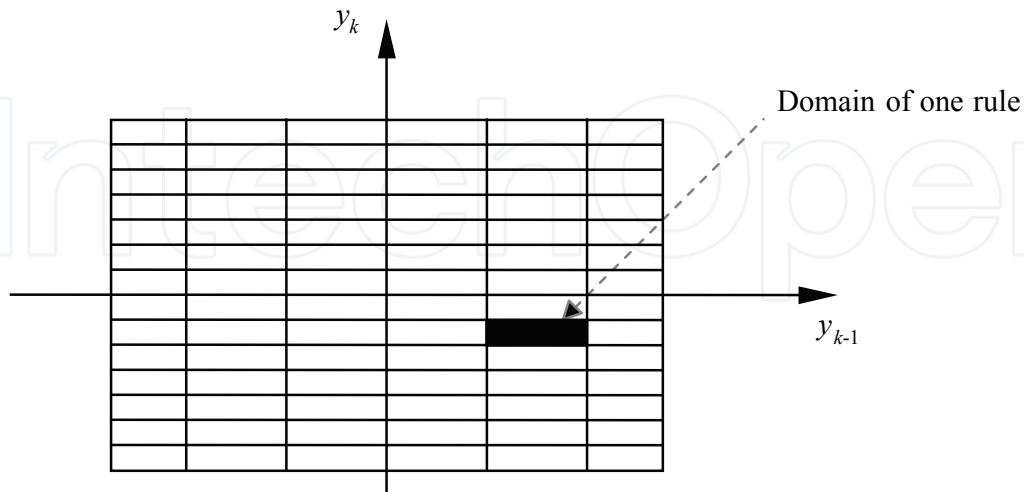

Fig. 7. Division of a two-dimensional rule space.

Figure 8 shows the rule base updating procedure. If there are two rules in the same domain, the selection of a rule is based on comparison of y_k in both rules. That is, if there is a new
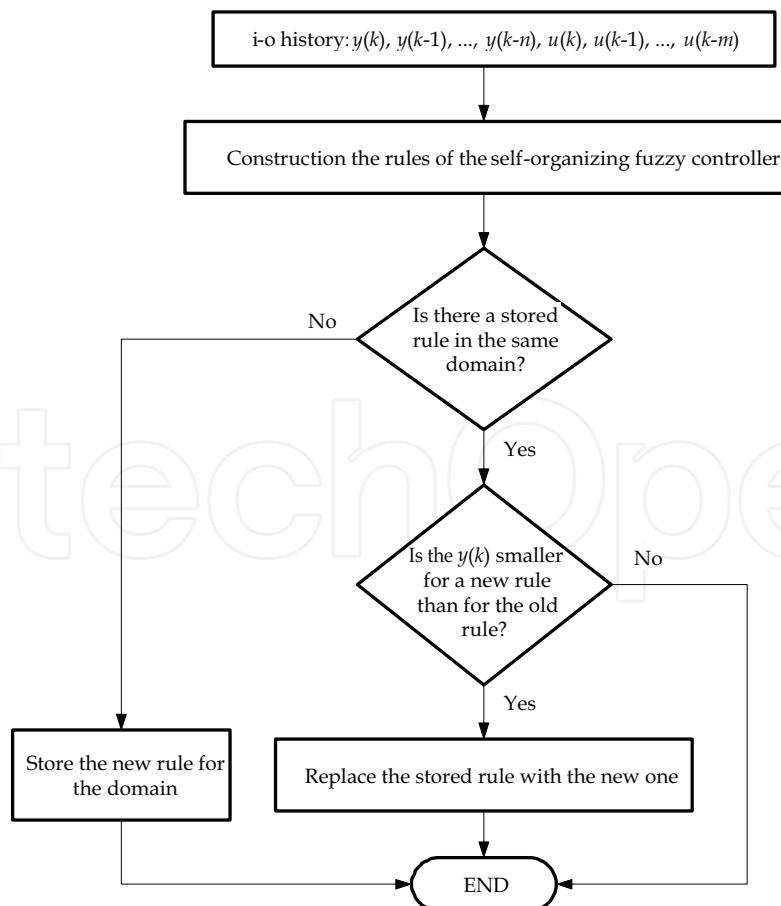

Fig. 8. The self-organization of the rule base.

rule which has an output smaller to the existing output in a given domain (*old rule*), the old rule is replaced by the new one. This updating procedure of the rule base makes the proposed fuzzy logic controller capable of learning the object plant and self-organizing the rule base. The number of rules increases as new input-output data is generated. It converges to a finite number in the steady state, however, and never exceeds the maximum number of domains partitioned in the rule space.

Figure 9 shows the architecture of the proposed FLC system. Initially, since there is no control rule in the rule base, the control input u_k for the first step is the median value of the entire input range. As time increases, the defuzzification procedure begins to determine whether the input has to be increased or decreased depending on the trend of the output. The sign of ∇u_k and the magnitude of u_k are determined in the defuzzification procedure. The self-organization of the rule base, in other words the *learning* of the system, is performed at each sampling time *k*.
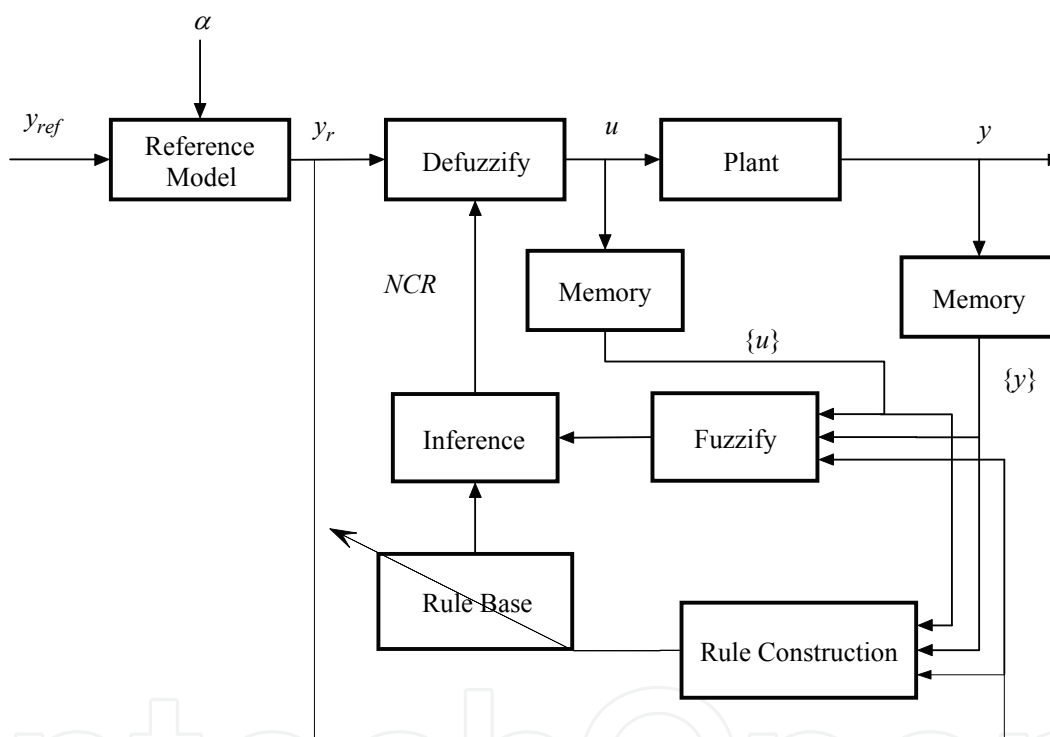
Fig. 9. The self-organizing fuzzy logic control system architecture.

5. Simulations and numerical results

Numerical simulations are presented to demonstrate the efficacy of the SOFC applied to the truss structure. The structure considered is the 20-bay truss with bays each of 75 mm. It has 244 members and 84 spherical nodes, and the nodes at the bottom are clamped (see Fig. 1). The passive members are made of steel with a diameter of 5 mm, and the damping matrix is assumed to be proportional to the stiffness and mass matrices so that $C = 10^{-1}M + 10^{-7}K$. At each node there is a centralized mass block of 80g which has six degrees of freedom (dof), translations and rotations in all directions, so the truss structure has 480 active dofs, and the state-space model consequently has an order of 960. The strategy is to control the first two modes (12.67 Hz and 12.69 Hz) by using two active members positioned in the elements

shown in Fig. 2a, and two decentralized SOFC (Eq. 14, where $\varepsilon = \omega_1 / 2$) connecting each actuator (considering K_{eq} = 28 N/μm and $n_a d_{33}$ = 1.12×10⁻⁷ m/Volts) to its collocated force sensor.

5.1 Parameters of the self-organizing fuzzy controller

In the numerical simulations, y_k, y_{k-1}, and u_{k-1}, u_{k-2} were used as input variables to the SOFC and the variables y_k and y_{k-1} were divided into five segments to partition the rule space. The second-order extrapolation (Eq. 20) was performed to estimate y_{k+1} as follows

$$\hat{y}_{k+1} = 2y_k - y_{k-1} \tag{24}$$

In both controllers, the output range (y) is –0.01 to 0.01 N, input range (u) is –0.5 to 0.5 V, the target ratio α was 0.5 (determined by trial and error), y_{ref} is zero and the sampling time is set to 0.001 seconds.

5.2 Simulation results

To verify the controller performance numerically, open loop and closed loop simulations were conducted and the results are presented and discussed. Firstly, an impulsive force is applied in y direction on the node at the top of the structure (see Fig. 1). White noise excitation with a force level of 0.01 N on each force transducer was also considered. The uncontrolled and controlled responses of the force transducers 1 and 2 in the time domain for impulsive excitation are shown in Figs. 10 and 11.

This type of force is used as it will excite many modes of vibration and hence is a difficult test for the control system. From the results it can be observed that the sensor responses are reduced greatly. Figure 12 presents the corresponding control voltages.
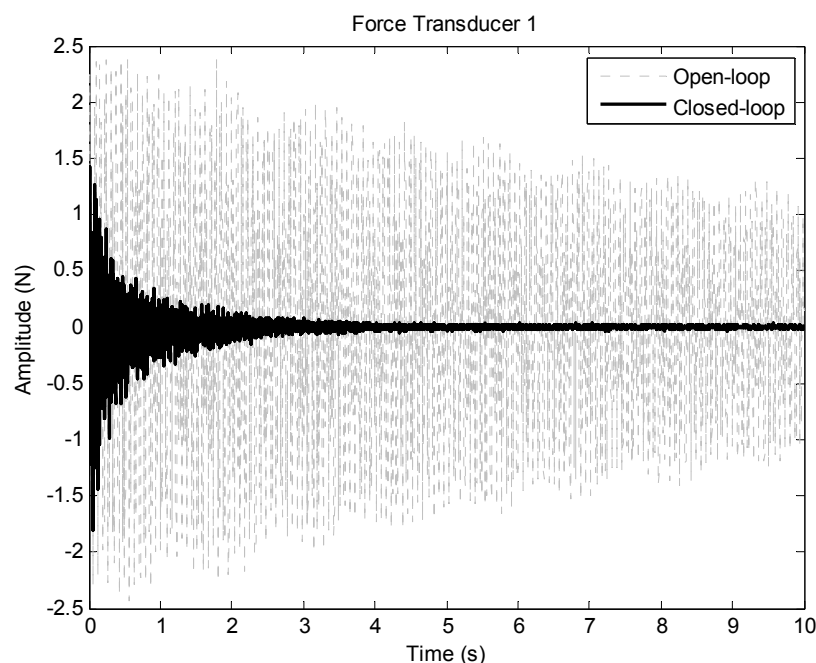

Fig. 10. Uncontrolled and controlled responses at the force transducer 1 with impulsive disturbance force.
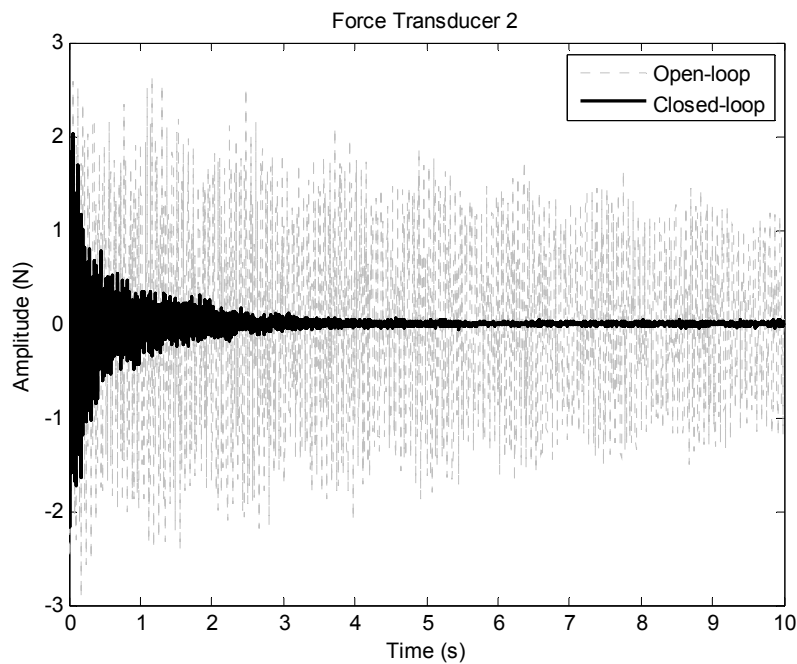
Fig. 11. Uncontrolled and controlled responses at the force transducer 2 with impulsive disturbance force.
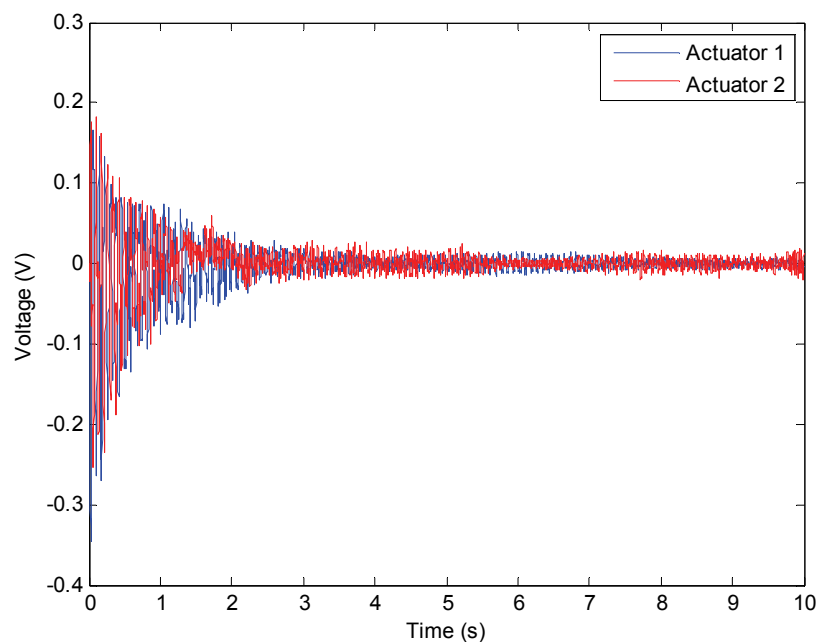

Fig. 12. Feedback control voltages applied by the piezoelectric actuators with impulsive disturbance force.

In Fig. 13, the proposed control algorithm starts with no initial rule and the number of generated rules is increased monotonically to 26 rules (each rule can be represented by Eq. 17).
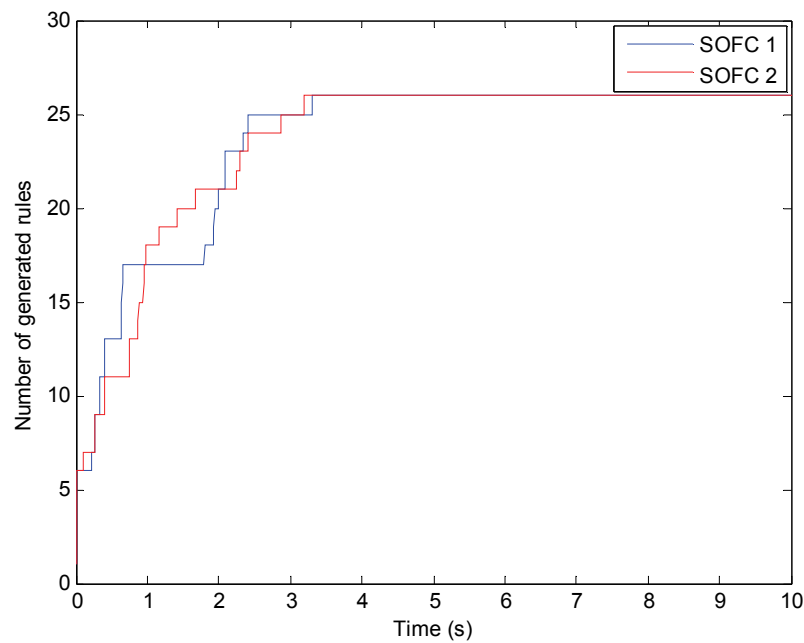
Fig. 13. Number of generated rules of SOFCs 1 and 2.

To numerically verify the robustness of the designed SOFCs in presence of modelling errors, a set of numerical tests are conducted. In the present analysis, the natural frequencies and modal damping are the uncertain parameters. To attain the presented objective, the natural frequencies and the modal damping are reduced in 20% and 60%, respectively. In this situation, the uncontrolled and controlled responses of the force transducers 1 and 2 in time domain are shown in Figs. 14 and 15. Figure 16 presents the corresponding control voltages.
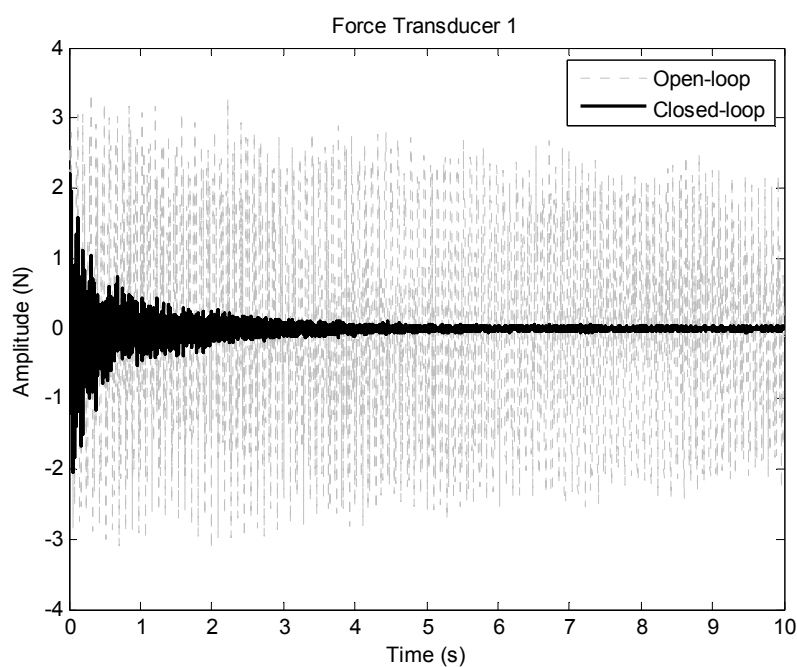
Fig. 14. Uncontrolled and controlled responses at the force transducer 1 with impulsive disturbance force in presence of modelling errors.
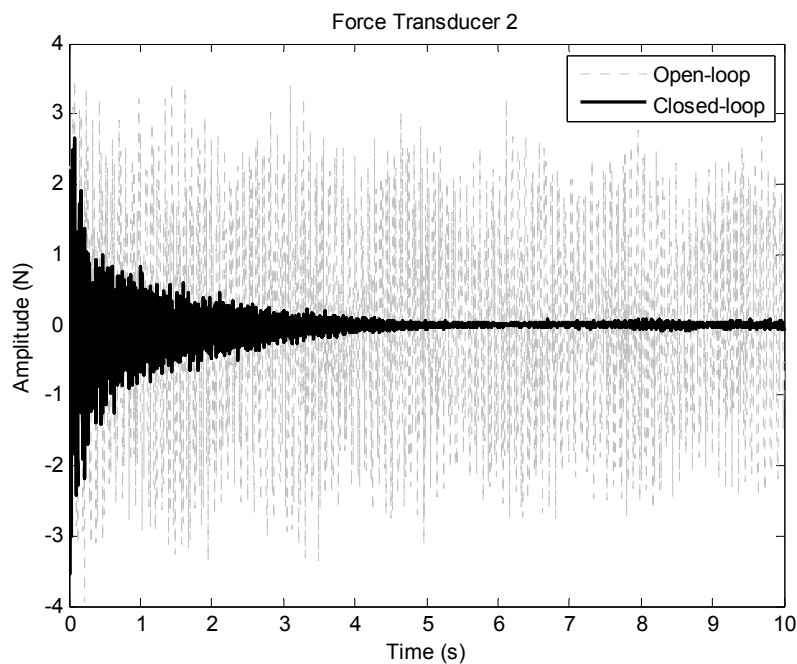
Fig. 15. Uncontrolled and controlled responses at the force transducer 2 with impulsive disturbance force in presence of modelling errors.
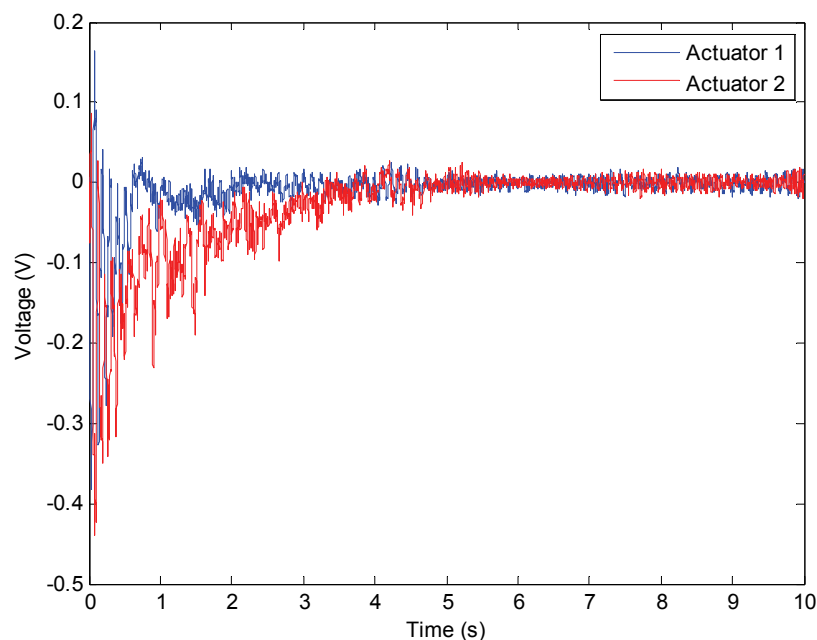

Fig. 16. Feedback control voltages applied by the piezoelectric actuators with impulsive disturbance force in presence of modelling errors.

In this case, the proposed control algorithm starts with no initial rule and the number of generated rules is increased to 26 rules (see Fig. 17).

The number of newly-generated rules is the same than the last case. This is because the system conditions for the controller are basically the same, i.e., no more rules need to be stored for a change of natural frequencies and modal damping.
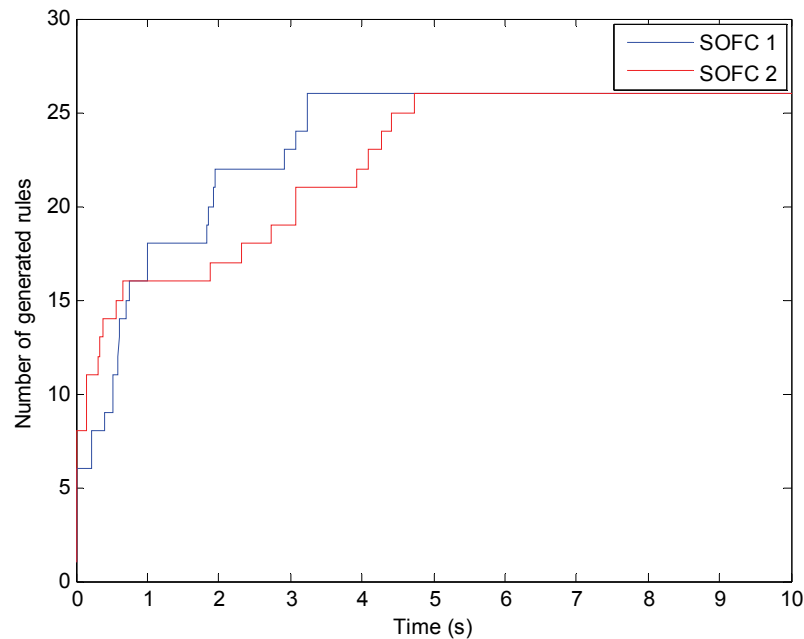
Fig. 17. Number of generated rules of SOFCs 1 and 2 in presence of modelling errors.

6. Conclusions

A self-organizing fuzzy controller has been developed to control the vibrations of the truss structure containing a pair of piezoelectric linear actuators collinear with force transducers. The procedure used for placing actuators in the structure, which has a strong intuitive appeal, has proven to be effective. The control system consists of a decentralized active damping with local self-organizing fuzzy controllers connecting each actuator to its collocated force sensor. The control strategy mimics the human learning process, requiring only minimal information on the environment. A simple defuzzification method was developed and an updating procedure of the rule was developed which makes the proposed fuzzy logic controller capable of learning the system and self-organizing the controller. A set of numerical simulations was performed, which demonstrated the effectiveness of the controller in reducing the vibrations of a truss structure. The numerical results have shown that piezoceramic stack actuators control efficiently the vibrations of the truss structure. It was also demonstrated that the fuzzy control strategy can effectively reduce truss vibration in the presence of modelling errors and under a several operating conditions.

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Vibrations are a part of our environment and daily life. Many of them are useful and are needed for many purposes, one of the best example being the hearing system. Nevertheless, vibrations are often undesirable and have to be suppressed or reduced, as they may be harmful to structures by generating damages or compromise the comfort of users through noise generation of mechanical wave transmission to the body. the purpose of this book is to present basic and advanced methods for efficiently controlling the vibrations and limiting their effects. Open-access publishing is an extraordinary opportunity for a wide dissemination of high quality research. This book is not an exception to this, and I am proud to introduce the works performed by experts from all over the world.

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