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Article *in* Journal of Intelligent Material Systems and Structures · March 1996

DOI: 10.1177/1045389X9600700208

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An Adaptive Fuzzy Control Algorithm for Model-Independent Active Vibration Damping of Flexible Beam-Like Structures

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ABSTRACT: The present study deals with an AFCA (Adaptive Fuzzy Control Algorithm) for an Euler-Bernoulli approximation of a two-dimensional version of a cantilever beam-like orthogonal tetrahedral space truss. Transient disturbances, modeled as a unit impulse, excite all the modes of the beam. The resulting transverse displacement at the free end of the beam and its corresponding rate are observed by sensors placed there, and active control of the beam is provided by a collocated force actuator.

A design methodology, based on fuzzy logic which assumes no *a priori* knowledge of plant dynamics, for the closed-loop control algorithm results in relatively quick settling times, low overshoots and dying out of vibration within a few seconds. The control algorithm is enhanced and made much faster by eliminating the need of repeatedly solving the set of differential equations of motion of an emulated dynamic vibration absorber. When the control force is turned off after a mere 15 seconds, almost all the vibrational energy is dissipated as the beam returns to its undisturbed state throughout its length. In addition, the performance of the AFCA is insensitive to varying initial conditions. To examine the robustness of the control system to changes in the temporal dynamics of the cantilever beam, the transient disturbance response to a considerably perturbed plant is simulated. The Young's modulus of the beam was raised as well as lowered by 60%, substantially perturbing the natural frequencies of vibration compared to the nominal plant. The AFCA provided similar settling times and rates of vibrational energy dissipation, satisfying the aim of plant model independence.

BACKGROUND

FUTURE aerospace applications include concepts such as large space stations, high resolution radar and communication antennas, astronomical observatories, solar power stations, and very large span, high altitude, long endurance unmanned aircraft. Qualifying as a LFS (Large Flexible Structure), such facilities may generally comprise of repetitive latticed trusses, span large areas with a few intermediate supports, are light in weight and extremely flexible, and consequently are characterized by a large number of high density, low frequency structural modes.

A LFS may need to meet target tracking, slewing, stringent line-of-sight and jitter control, pointing accuracies, and microgravity acceleration requirements. However, when disturbed, the structure is likely to remain excited for some time because of its high structural modal density at low frequencies and possibly small damping. Therefore, it is vital to introduce means for passive energy dissipation, active control, or their combination to restrain the response of a given structure within an "in-mission displacement-time allowables envelope" by using vibration control methods.

This paper was originally presented at ICAST '95, November 13–15, 1995, Key West, Florida.

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INTRODUCTION

A typical LFS may be characterized by low inertia, light inherent damping, undamped rigid modes, low natural frequencies, high modal density, and some joint nonlinearity. The dynamic characteristics of the above are poorly known and therefore make the analytical modeling of the structural dynamic problem of a LFS cumbersome with substantial uncertainties. Hence, it would be advantageous to develop control design strategies that literally require no a priori knowledge on the plant temporal model.

Robustness of a LFS control in the presence of uncertainties has been an area of intense research. One such method, based on the positivity design assures that the closed loop system will be characterized by stability as well as an energy dissipation related to the input/output behavior. Hyland (1993) describes this energy dissipative law that combines collocated actuator and sensor pair as electromagnetically emulating passive structural damping. Hollkamp and Starchville (1994) present a piezoelectric actuator that emulates an inherently stable dynamic vibration absorber. This self-tuning piezoelectric absorber is made adaptive by tuning the electric resonance (i.e., by adjusting the shunt inductance and resistance).

The parameters of the above absorber may be adapted to provide minimum time-control for large deviations, of the measured state of the plant from the desired state, and a

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minor amount of control for small deviations. Thus, nonlinear control actions, corresponding to a lightly damped absorber with a large mass ratio, which fully utilize the range of actuator displacements, send the plant state hurtling toward the desired state. On the other hand, in the vicinity of this desired state, the absorber is heavily damped, having a small mass ratio. Heuristic rules, based on basic "common sense" engineering insight, coupled with fuzzy reasoning provide crisp values for lightly, large, heavily, and small.

A philosophy similar to the above was applied by Heckenthaler and Engell (1994) to develop a fuzzy, nonlinear control law which achieves robust, near minimum-time, control for the level controls in a laboratory two-tank system. An overview of the key points in applying fuzzy control to various industrial applications is provided by Sugeno (1985). Schwartz et al. (1994) survey recent applications of fuzzy sets and approximate reasoning. Meyer, Burke, and Hubbard (1993) use velocity feedback with positive-definite feedback gain and collocated piezoelectric transducers in a control methodology integrating sliding mode control, distributed parameter systems theory, and fuzzy logic to develop vibration damping of a cantilever beam. A frequency-shaped LQR adaptive control scheme, based on a priori knowledge of the intervals of system-parameter variations and fuzzy-logic, is applied to vibration suppression of a cantilever beam using collocated piezoceramic transducers (Zeinoun and Khorrami, 1994).

OBJECTIVE OF THIS STUDY

The present research involves the application of a fuzzy logic based adaptive control strategy to actively control structural vibrations of a typical LFS in light of transient disturbances. No a priori information on the plant model is required for controller development. Since real time implementation is of importance, computational efficiency of the algorithm is a priority. The highlights of the model-independent algorithms developed within the framework of this research, are presented in the following sections. Closed-loop performance and robustness, with respect to changes in the temporal dynamics, is examined.

PROBLEM DESCRIPTION

The LFS studied is a two-dimensional version of a cantilever beam-like orthogonal tetrahedral space truss, modeled by using an Euler-Bernoulli approximation. Such trusses are typical of large space structures (Necib and Sun, 1989). The discrete, collocated transducers applied to actively control the above structure emulate the behavior of a dynamic vibration absorber. Figure 1 describes the 2-D beam-like lattice with a virtual absorber attached. The first five modes of the structure are considered in the MATLAB (Math Works, 1992) simulation. The respective natural frequencies, given in [rad/sec] and corresponding to the beam model, are displayed in Table 1 (Cohen and Weller, 1994).

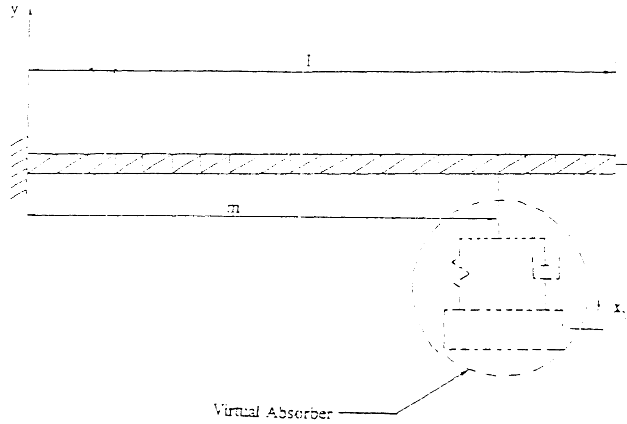

***Figure 1.** A 2-D version of a beam-like lattice with an absorber attached.*

The structure, subjected to an initial condition unit impulse, provides similar transient disturbance to each of the first five bending modes, thereby exciting all of them. The closed-loop controller is applied at the lapse of a second, at which time the beam is in the vicinity of the maximum open-loop amplitude (see Figure 2). The control law is fed with sensor readings of displacement and velocity, placed at a distance 1 (m = 1) from the fixed end. An additional sensor, positioned midway between the fixed and the free ends, at 1/2, observes the transverse displacement-time history.

PROPOSED APPROACH

A two phase approach is developed, as follows:

- *Phase One*—The fuzzy adaptation strategy developed selects the most appropriate damping factor for the virtual absorber. The mass ratio of this absorber is a function of the damping factor as described by Cohen et al. (1995), whereby a lightly damped absorber corresponds to a large mass ratio and vice-versa. Based on this mass ratio, the absorber is then tuned to the fundamental frequency of the beam, obtained from the open-loop transverse displacement sensor output (see Figure 2). After each sensor reading, the damping and the mass ratios of the absorber adapt themselves using a fuzzy decision-making process. The above act of adaptation is followed by the calculation of the actuation force by solving the second order differential equations concerning the equa-

***Table 1.** Natural frequencies of the structure in Figure 1 [rad/sec].*

Mode	First	Second	Third	Fourth	Fifth
Frequency	1.59	9.98	27.95	54.77	90.53

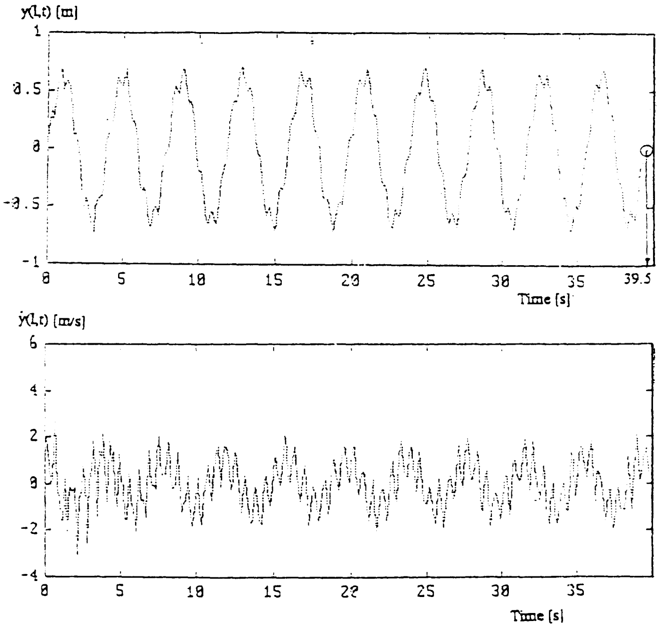

Figure 2. Response of the reference open-loop system.

tions of motion of the emulated absorber. This approach not only assures inherent stability associated with passive absorbers, but also circumvents the phenomenon of modal spillover.

- *Phase Two*—In the next phase, the control algorithm is made much faster, without any loss in performance. Data clusters mapping the sensor outputs and the input control force, for varying initial conditions, are examined to obtain linguistic fuzzy rules. This "data in, rules out" method maps the input-output relation of the "expert" (emulation of the adaptive dynamic vibration absorber) used in the previous phase. After enough data is used to fine-tune the rules, the "expert" is dropped and the control algorithm is now comprised of fuzzy rules alone. Now, only the basic mathematical operators (+, −, *, /) are used, thus substantially reducing the computational effort to determine the control force.

PHASE ONE: FUZZY ADAPTATION STRATEGY

Fuzzy logic, on which the fuzzy control is based, is a convenient way to map an input space into an output space. The major mechanisms of FLC (Fuzzy Logic Control) are: a set of if-then statements called linguistic control rules; and a fuzzy inference system that interprets the values in the input vector and, based on the linguistic rules, assigns values to the output vector. The experience of the past decade, with the successful marketing of a wide variety of products based on the FLC (Kosko, 1994), has shown that for certain applications, FLC provides superior results to those obtained by other conventional means.

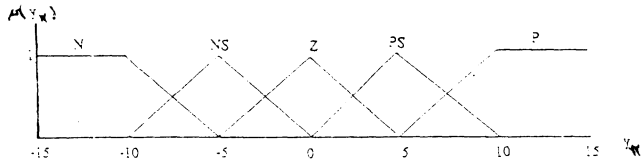

Figure 3. Membership functions for the fuzzy sets characterizing y_N.

Fuzzy Membership Functions

The first step in building the fuzzy part of the controller involves the Fuzzification of the input/output parameters. Here, the transverse displacement $y(m,t)$ and the transverse velocity $\dot{y}(m,t)$ of the beam are normalized to yield the dimensionless variables y_N and $\dot{y}_N$, respectively, using the following relations:

$$y_N = N_y \cdot y(m,t)$$

$$\dot{y}_N = N_{\dot{y}} \cdot \dot{y}(m,t) \qquad (1)$$

where N_y and $N_{\dot{y}}$ function as tuning parameters for the arbitrarily chosen membership functions illustrated in Figures 3 and 4, respectively. The use of these "tuning knobs" substantially cuts the degrees of freedom involved in reaching the required membership functions. In addition, once N_y and $N_{\dot{y}}$ are found, the sensitivity of individual fuzzy sets to the closed-loop performance is examined. Since no improvement is obtained, no additional changes are made to the arbitrarily selected membership functions of y_N and $\dot{y}_N$.

Fuzzy sets for the normalized transverse displacement, y_N, are characterized by membership functions μ_N, μ_{NS}, μ_Z, μ_{PS} and μ_P that map elements of the universe of discourse, y_N, into the closed interval [0,1] as follows:

$$\mu_L = y_N \rightarrow [0,1] \qquad \text{for } L = N, NS, Z, PS, P \qquad (2)$$

where L stands for one of the linguistic terms used in this effort to categorize y_N, i.e., N (negative), NS (negative small), Z (zero), PS (positive small), and P (positive). The membership functions given in Equation (2) express the degree to which y_N belongs to some category L. These fuzzy sets may be viewed by plotting y_N versus μ_L as shown in Figure 3. For example, for the normalized displacement, y_N, a crisp value of 1.0 corresponds to 25 percent positive small and 75 percent zero.

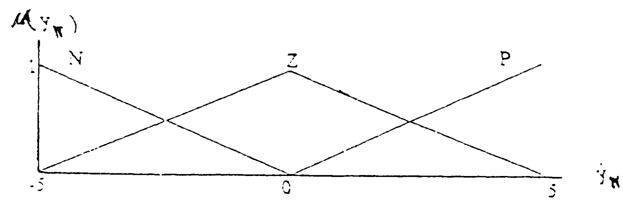

Figure 4. Membership functions for the fuzzy sets characterizing $\dot{y}_N$.

Similarly, fuzzy sets for the normalized transverse velocity, $\dot{y}_N$, are characterized by the membership functions μ_Q, for $Q = N, Z,$ and P [where N (negative), Z (zero), and P (positive)]. In Figure 4, $\dot{y}_N$ is mapped out onto the characteristic fuzzy sets. In this case, it was sufficient to describe the mapping by using only three membership functions. The fuzzy sets for the damping factor, δ, presented in Figure 5, are characterized by four membership functions μ_S, μ_M, μ_L and μ_{EL} [where S (small), M (medium), L (large), and EL (extra large)]. This mapping was initially based on insight and previous work (Cohen and Weller, 1994). However, some fine-tuning, of the medium and large fuzzy sets, was required to further reduce settling times.

Fuzzy Rule-Base and Interface

The fuzzy adaptation strategy, presented in this effort, is based on rules inspired by "common sense" engineering reasoning whereby large values of the inputs require a lightly damped absorber, which would provide quick rise times. However, when the plant state is in the vicinity of the desired state, the damping factor is large to reduce the overshoot and steady state error. The resulting rule-base that converts fuzzified inputs into a fuzzy output is presented in Table 2. For example, the rule described by the first row, first column, in Table 2, reads "if y_N is negative AND $\dot{y}_N$ is positive, then the damping factor, δ, is small".

As observed in Table 2, and as is common practice in fuzzy logic control, the rule-base contains quite a few rules relating to the same output variable. Therefore, to obtain an overall output in the fuzzy state, an inference method is applied. First, the degree of fulfillment of each and every rule is found by applying the fuzzy "AND" operation. Let us represent the individual elements of the rule-base "matrix", presented in Table 2, as $\delta_{ij} (i = 1,3; j = 1,5)$, where:

$$\delta_{ij} = \text{Minimum}\,(\mu_Q, \mu_L) \tag{3}$$

for

Q = positive, zero and negative
L = negative, negative small, zero, positive small, and positive.

Then, from Table 2, the union of the fuzzy sets for the same output variable is taken to reach the membership functions of the output, described in Figure 5, as follows:

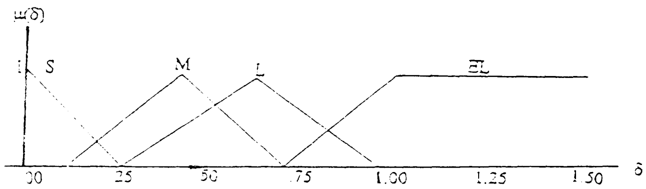

Figure 5. Membership functions for the fuzzy sets characterizing δ.

$$\begin{aligned}
\mu_S &= \delta_{11} + \delta_{15} + \delta_{31} + \delta_{35};\\
\mu_M &= \delta_{12} + \delta_{14} + \delta_{21} + \delta_{25} + \delta_{32} + \delta_{34};\\
\mu_L &= \delta_{13} + \delta_{22} + \delta_{24} + \delta_{33};\\
\mu_{EL} &= \delta_{23};
\end{aligned} \tag{4}$$

The rule-base, which was not made to be part of the tuning process, underwent only a single closed iteration to rid inactive rules. However, the sensitivity of closed-loop performance to changes in the rule-base was examined to verify the continued use of these heuristic rules.

Defuzzification

Finally, in order to reach a practical controller, a control action comprising of a single numerical value is required. Therefore, the space of the fuzzy damping factor, obtained using the method described in the previous section, is mapped into a nonfuzzy space (crisp) by defuzzification.

There are various strategies aimed at producing a crisp value. Some of the commonly used strategies are the center of area (COA), the mean of maximum, and the max criterion (Lee, 1990). Since there is no accepted systematic methodology for selecting a defuzzification strategy, herein, the COA scheme is adapted. This strategy was found to yield better steady-state performance when compared to the other above mentioned strategies (Lee, 1990). The COA method projects the centroid of the output membership function μ_R (for $R = S,M,L$ and EL), defined in Equation (4) as the crisp value of the output viscous damping factor, δ:

$$\delta = \frac{\sum_R \mu_R \cdot A_R \cdot c_R}{\sum_R \mu_R \cdot A_R} \tag{5}$$

Table 2. Rule-base for computing the viscous damping factor (δ).

	y_N Negative	y_N Negative Small	y_N Zero	y_N Positive Small	y_N Positive
$\dot{y}_N$ Positive	Small	Medium	Large	Medium	Small
$\dot{y}_N$ Zero	Medium	Large	Extra Large	Large	Medium
$\dot{y}_N$ Negative	Small	Medium	Large	Medium	Small

where

A_R = Area under the "R"th fuzzy set defined in Figure 5.
c_R = Centroid of the area A_R.
R = Small, Medium, Large and Extra Large (see Figure 5).

PHASE ONE: RESULTS

The closed-loop fuzzy-based adaptive controller, developed in Phase One, is now applied to the nominal plant. After some tuning, to a variety of initial conditions, the values of the tuning parameters, N_y and $N_{\dot{y}}$ are frozen:

$$N_y = 15 \text{ [1/m]}$$

$$N_{\dot{y}} = 0.5 \text{ [sec/m]} \quad (6)$$

The closed-loop displacement impulse response is presented in Figure 6. The application of the fuzzy-based control law results in relatively quick settling times, low overshoots, and dying out of vibration within a few seconds. When the control force is turned off after 16 seconds (about 10 seconds after settling time), almost all the vibrational energy is dissipated as the beam returns to its undisturbed state throughout its length. In addition, the performance of the control algorithm is insensitive to varying initial conditions.

To demonstrate the robustness of the control system to changes in the temporal dynamics of the cantilever beam, the transient disturbance response to a considerably perturbed plant is simulated. The Young's modulus of the beam was raised as well as lowered by 60%, substantially perturbing the natural frequencies of vibration. Results of this robustness test, described in Cohen et al. (1995), illustrate similar settling times and rates of vibrational energy dissipation, satisfying the aim of plant model independence.

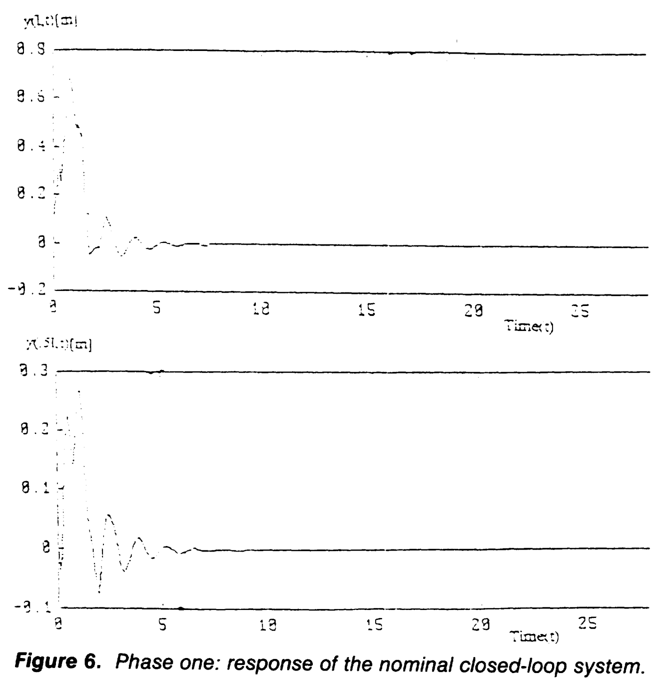

Figure 6. Phase one: response of the nominal closed-loop system.

PHASE TWO: DEVELOPMENT OF AFCA

A serious concern of the approach developed in Phase One, involves the solution of a 2-DOF differential equation at each measurement interval to calculate the control force. This problematic issue causes a time-lag that may rule out the possibility of any real-time implementation of the algorithm. Subsequently, the computational efficiency of the algorithm requires to be increased. One possibility is using fuzzy logic controllers, which are universal approximators [i.e., they are capable of approximating any real continuous function to arbitrary accuracy (Castro, 1995)], to directly map the sensor inputs onto the suitable control force. The major difficulty in realizing such a controller lies in finding the appropriate membership functions and rule base. However, this is certainly not the starting point here, since the controller developed in Phase one provides good performance, though not in real time. Let us relate to this controller as the "expert" which provides the necessary data to enable a learning process. A process, utilizing the mapping of the sensor outputs and the input control force for varying initial conditions, results in the linguistic fuzzy rules and the corresponding membership functions.

The above mentioned process, for finding the fuzzy rules and membership functions, is described by the flowchart in Figure 7 and is comprised of the eight following steps:

Step 1—For the proposed approach to be feasible, it is mandatory that the number and placement of sensors/actuators remains as they were in Phase One. Fuzzy sets, selected for the inputs/outputs, are characterized by membership functions as follows:

$$\mu_L = y(l,t) \rightarrow [0,1] \qquad \text{for } L = 1,2,\ldots,n$$

$$\mu_Q = y(l,t) \rightarrow [0,1] \qquad \text{for } Q = 1,2,\ldots,m \quad (7)$$

$$\mu_F = F(t) \rightarrow [0,1] \qquad \text{for } F = 1,2,\ldots,p$$

In addition to the number of membership functions per fuzzy set, the shape of each membership function must also be selected. In the present research, only triangular and trapezoidal shapes are considered and the maximum number of membership functions per fuzzy set are arbitrarily limited to five.

Step 2—The mapping of the transverse displacement versus the transverse velocity, measured at the free end of the beam, is divided into n*m cells. As shown in Figures 8–10, the fuzzy sets of the inputs and the output are each described by five linguistic terms, namely, *N* (Negative), *NS* (Negative Small), *Z* (Zero), *PS* (Positive Small), and *P* (Positive).

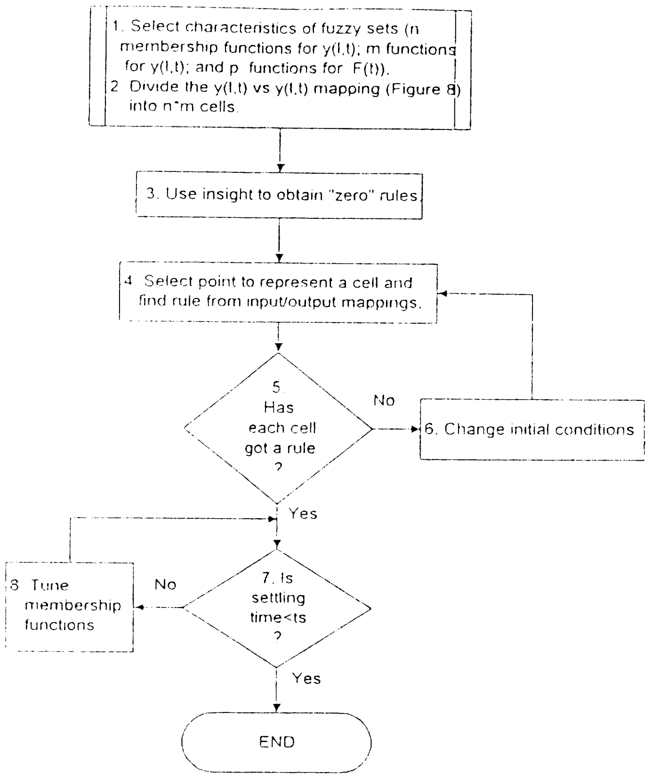

Figure 7. Phase two: obtaining fuzzy rules and membership functions.

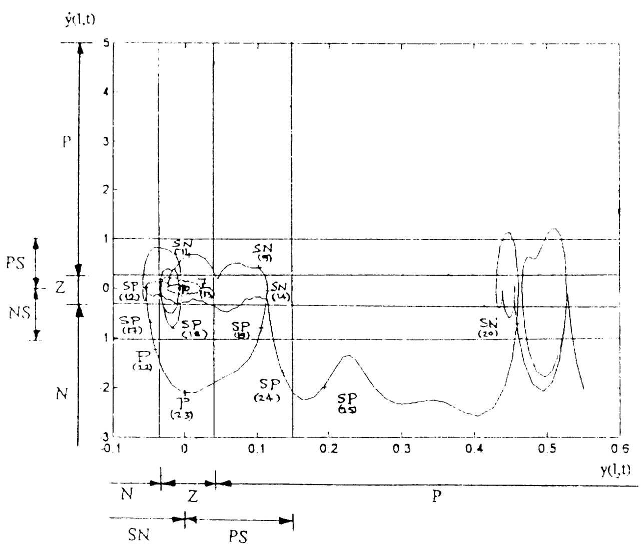

Figure 8. Phase one results: displacement, y(l,t) vs. rate, ẏ(l,t).

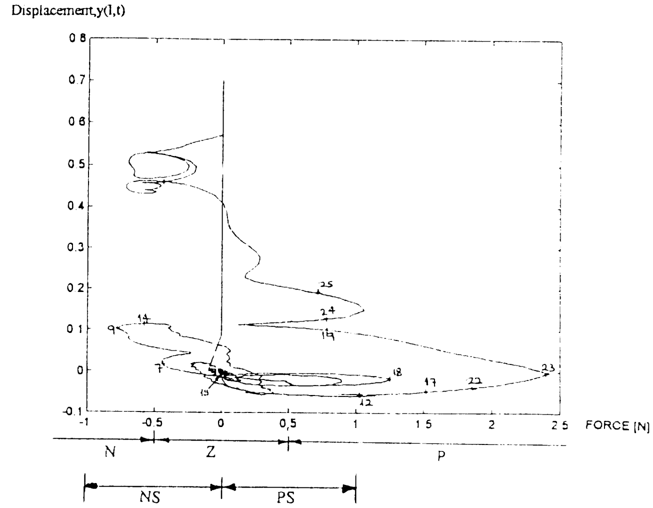

Figure 9. Phase one results: displacement, y(l,t) vs. control force, F(t).

Hence, for $n = m = 5$, there are in all twenty-five rules that form the rule base of the fuzzy controller. Furthermore, the pretuned descriptions (iteration zero) of each of the membership functions are obtained as shown in Figures 8–10. In Steps 3–6, the rules concerning each of the cells are formed.

Step 3—Simple structural insight is used to obtain the following ten "zero" rules.

- If the transverse displacement $y(l,t)$ is Z
  and $\dot{y}(l,t)$ is P, then $F(t)$ is N;
  and $\dot{y}(l,t)$ is PS, then $F(t)$ is NS;
  and $\dot{y}(l,t)$ is Z, then $F(t)$ is Z;
  and $\dot{y}(l,t)$ is NS, then $F(t)$ is PS;
  and $\dot{y}(l,t)$ is N, then $F(t)$ is P.
- If the transverse velocity $\dot{y}(l,t)$ is Z
  and $y(l,t)$ is P, then $F(t)$ is N;
  and $y(l,t)$ is PS, then $F(t)$ is NS;
  and $y(l,t)$ is Z, then $F(t)$ is Z;
  and $y(l,t)$ is NS, then $F(t)$ is PS;
  and $y(l,t)$ is N, then $F(t)$ is P.

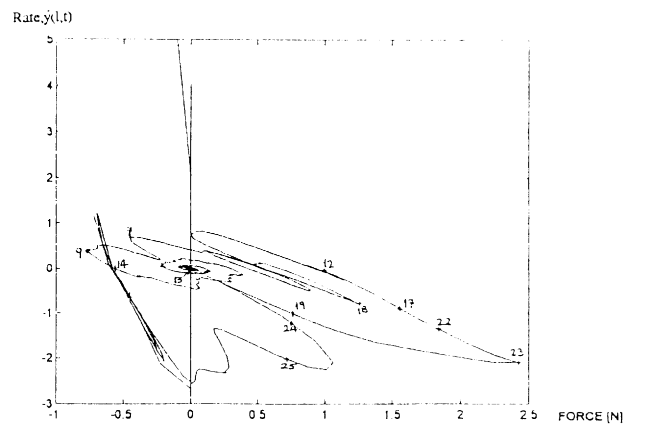

Figure 10. Phase one results: rate, ẏ(l,t) vs. control force, F(t).

Table 3. Rule-base for control force (Phase Two).

	y_N Negative	y_N Negative Small	y_N Zero	y_N Positive Small	y_N Positive
$\dot{y}_N$ Positive	Small negative	Small negative	Negative	Negative	Negative
$\dot{y}_N$ Positive small	Small positive	Small negative	Small negative	Small negative	Negative
$\dot{y}_N$ Zero	Positive	Small positive	Zero	Small negative	Negative
$\dot{y}_N$ Negative small	Positive	Small positive	Small positive	Small positive	Small negative
$\dot{y}_N$ Negative	Positive	Positive	Positive	Small positive	Small positive

Step 4—Each cell is represented by a point (as near to its center as possible) as shown in Figure 8. The resulting rule of each cell is obtained by tracing the control force applied by the virtual absorber (see Figures 9–10). Note that there is no contradiction among the rules obtained from Steps 3 and 4. However, if such a contradiction results, then the advised corrective action would be to redo cell division.

Steps 5 and 6—After Steps 3 and 4, there may be certain cells for whom no rule has been reached, due to the simple reason that no data was collected for these cells. Even though rules for all cells may not be required, it is advised to make an attempt to "complete" the rule base using the following principles:

- The rule base of a symmetric structure (the one considered here, shown in Figure 1 is symmetric with respect to its longitudinal axis) is symmetric by nature (see Table 3).
- Different initial conditions will cause the controlled beam to "move" through different cells on its spiral way towards settling down.

The resulting rule base is described in Table 3.

Steps 7 and 8—The final two steps mainly involve the fine tuning of the membership functions for improvement in performance. In the particular case studied, a minimum settling time was the only objective. The rule base, obtained from mimicking the absorber, is frozen during the fine-tuning process. The membership functions that best served the above objective are presented in Figure 11.

PHASE TWO: RESULTS

The Phase Two fuzzy controller has the same inference and the defuzzification methods as described in Phase One. This controller is applied to suppress the transient vibration problem, concerning the structure in Figure 1, described earlier. The resulting closed loop response is presented in Figure 12. A comparison of the response in Phase One (Figure 6) and that of Phase Two (Figure 12) yields the following observations:

- After the control force is turned off, in both cases, all the vibrational energy is dissipated as the beam returns to its undisturbed state throughout its length.
- The equivalent damping ratio of the response of the closed-loop system in Phase One is slightly higher than

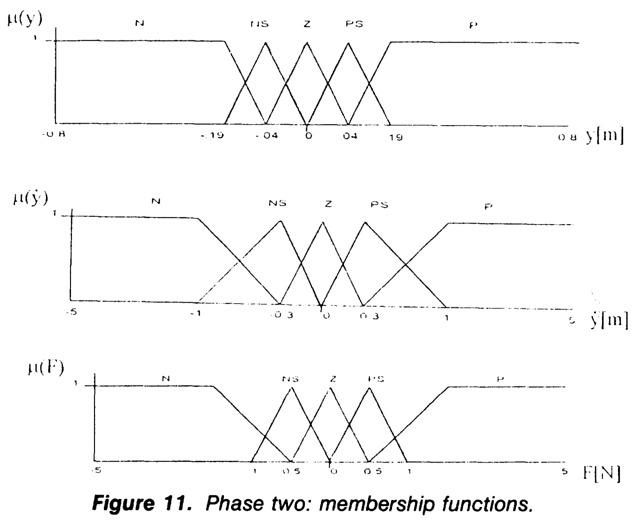

Figure 11. Phase two: membership functions.

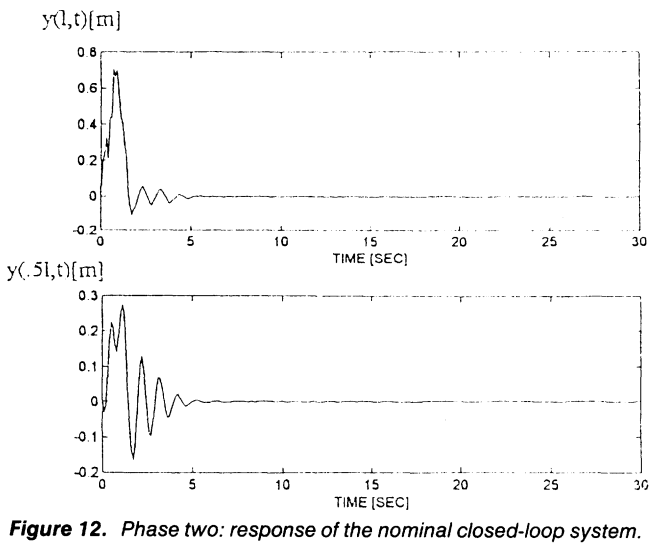

Figure 12. Phase two: response of the nominal closed-loop system.

that observed in Phase Two. However, the average equivalent time constant [as defined by Van De Vegte (1994) as the reciprocal of the product of the frequency of transient oscillations and the damping ratio] of the Phase One response is substantially lower than that achieved in the Phase Two response. This reduces the settling time of the response in Phase Two, relative to Phase One, by about 2 seconds.

CONCLUSIONS AND RECOMMENDATIONS

- The present effort describes the development of two fuzzy controllers which are based on actively controlled, adaptive, dynamic vibration absorbers.
- The control algorithm assumes no a priori knowledge of the temporal plant model.
- The controller developed in Phase One requires the solving of the 2-DOF differential equation of the virtual absorber at every time step. The controller developed in Phase Two, mimics the Phase One controller using only fuzzy logic input/output mapping, and is, therefore, computationally superior. In addition, the Phase Two controller provides enhanced performance which is emphasized by shorter settling times.
- The controllers are applied to an Euler-Bernoulli cantilever beam which is subjected to an initial unit impulse disturbance.
- MATLAB simulations of the closed-loop transient response demonstrate quick settling times, a high rate of vibrational energy dissipation and no control spillover to the higher modes.
- The controller presented may further be developed and tested for the vibration suppression of higher order beam models having different boundary conditions and which include coupling between the bending and twisting modes. Future research plans should include experimentation and performance comparisons with other classical control laws.

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