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Experimental Studies on Adaptive Fuzzy Control of a Smart Structure

KELLY COHEN
RONITH YAFFE
TANCHUM WELLER
JOSEPH Z. BEN-ASHER
Department of Aerospace Engineering, Technion, Israel Institute of Technology, Haifa, Israel, 32000

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Abstract: The present investigation deals with the application of an Adaptive Fuzzy Control Algorithm for active vibration control of an experimental flexible beam. The two-dimensional model of the experimental cantilever beam, given by an orthogonal tetrahedral space truss, represents a slender cantilever aluminum (7075-T6) beam of rectangular cross-section ($1145 \times 60 \times 1.95$ mm^3). A variety of transient disturbances are introduced to excite the first four modes of the beam. The resulting transverse displacements are observed by a single sheet (50×50 mm^2) of piezoceramic material placed at the clamped end of the beam. Active control of the beam is provided by one, two or three identical sheets of piezoceramic material collocated with the sensor. The control moments applied by the piezoceramic actuator are made to emulate the behavior of a discrete dynamic vibration absorber. The virtual absorber is tuned to the fundamental frequency using classical methods and the tuning ratios are time-invariant. However, the uniqueness of this approach is that the damping parameters of the emulated absorber are continuously varied by means of a fuzzy logic control algorithm to provide near minimum-time suppression of vibration. It is demonstrated that application of this methodology allows for its real-time implementation and provides relatively quick settling times in the closed-loop.

Key Words: Fuzzy logic control, flexible structure control, vibration suppression, piezoceramic actuators

1. INTRODUCTION

A major driver to the overall system performance of LFS's (Large Flexible Structures) is the sizing (of such structures) for minimum mass, when subject to both static strength and dynamic requirements. Improved structural characteristics may be achieved by the introduction of adaptive structures whereby the geometry, shape, apparent stiffness, damping, or inertia of the structural modes are controlled (Wada, 1993). Typical LFS facilities are light in weight and extremely flexible and consequently are characterized by a large number of high-density low-frequency structural modes. These higher-order structural systems utilize feedback control laws that are based on system stimulus-response models, embedded sensors to sense their response to operational and environmental stimuli, and actuators to modify their response in such a way as to optimize structural performance.

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LFS control may be based on a passivity design. Such controllers typically consists of a virtual/actual second-order dynamic system comprising of mass, spring and dash-pot elements whose main purpose is to transfer and dissipate the energy of the system, thereby maintaining the stability of the system. The application of passive control laws has so far been applied only to systems having collocated pairs of sensors and actuators. Recently, the passivity approach has been extended to systems having non-collocated input/output pairs by introducing an observer that incorporates the nominal dynamical model of the plant.

Some of the recent research in active control of flexible structures, based on the passivity approach, involves the emulation of dynamic vibration absorbers (Jaung and Phan, 1991). This basic approach has been embraced in this study with a few unique changes. The main modification of this effort is that it introduces, for the first time, an approach which provides continuous tuning of the damping parameter of the emulated absorber by a FLC (Fuzzy Logic Control) algorithm. The main objective of this research effort is to examine the effectiveness of the developed approach, based on experiments conducted on a beam-like cantilever structure subject to transient disturbances. Having stated the goal of this study, an attempt will be made to explain the main reasons as to why variable damping and fuzzy logic were selected.

1.1. Time Variant Damping

Jaung and Phan (1991) proposed an approach for control of flexible structures using a controller that can be described by a set of second-order dynamic equations. They observed some of the basic properties of such a controller, which in fact is a mass-spring-dashpot dynamic system like a DVA (Dynamic Vibration Absorber). These are:

- When a DVA is attached to any mechanical system, including LFS, the damping of the system is almost always augmented *regardless of the system size.*
- The parameters of the DVA are *relatively model-independent and thus insensitive to system uncertainties.*
- *No matter what happens*, the DVA will not destabilize the system because it is an energy-dissipating device.

Jaung and Phan's controller (1991) was a LTI (Linear Time Invariant) system and therefore the virtual elements (mass, dashpot, spring) were constant. Den Hartog (1956) formulated the optimal tuning ratio for an absorber attached to a primary structure. Later, Sesak, Gronet and Marinos (1987) showed the applicability of Den Hartog's tuning ratio for the passive vibration suppression of flexible large-space structures, subject to transient disturbances, when a specific mode requires targeting. Optimization techniques were used to reach constant damping of the passive controller. The best strategy for specifying the damping to be introduced was constrained by the requirement for a LTI system. Lifting this *self-imposed* constraint, Shahruz, Langari and Tomizuka (1991) showed that the optimal damping ratio for linear second-order systems that results in a minimum-time response to step inputs was of a bang-bang type. *Variable damping provides enhanced performance*. This approach, however, has not been considered seriously for the control of a complex and challenging system as presented by a large flexible structure for a wide variety of reasons. Some of them are:

- The lack of robustness in view of uncertainties in plant model and external noise.
- The properties of the switch points (how many and when they occur) depend on the character of the transient disturbance, i.e., sensitivity to initial conditions.
- The implementation into a closed-loop system is seldom practically effective.

The incorporation of optimal variable damping requires an approach that enables the integration of the control law into a LFS with relative ease and simplicity, while providing the required robustness characteristics. In the present effort, an appropriate approach based on fuzzy logic is introduced to achieve the desired control.

1.2. Fuzzy Logic Control

One of the gifts of nature is the inherent human capability of making effective decisions based on inexact linguistic information. This all-important characteristic has often lead to the preference of *man-in-the-loop* type control as opposed to *autonomous* controlled machines. Hence, the performance of electromechanical controllers designed for ‘uncertain’ dynamic systems may be improved by their modeling in a manner that emulates human reasoning. A logical system that attempts to capture the spirit of our approximate, imprecise world was introduced by Lotfi Zadeh as the theory of fuzzy sets, which in time proved to be a very powerful tool for dealing quickly an efficiently with imprecision and nonlinearity (Cohen, 1999).

Fuzzy logic, which is the logic on which fuzzy control is based, is a convenient way to map an input space into an output space. The experience of the past decade, with the successful marketing of a wide variety of products based on the FLC (Cohen, 1999), has shown that for certain applications using FLC can lead to lower development costs, superior features, and better end product performance. One of the inherent properties of fuzzy logic systems is that it has the capability of being a universal approximator. This implies that by using *enough* inputs and a sufficient number of rules and fuzzy sets for each input variable, a fuzzy based system can approximate any real continuous nonlinear function to an arbitrary degree of accuracy (Cohen, 1999). The implementation of a variable damping strategy requires such an universal approximator that can successfully emulate the bang-bang type of minimum-time control.

The capability of FLC to emulate time-optimal bang-bang control was attributed, by Thomas and Armstrong-Hélouvry (1995), to what is termed as the *generalized damping* benefit of FLC, thereby providing fast and effective system responses. For large values of system error, the damping effect of the error derivative control is blocked as full control authority to quickly drive the system to zero. On the other hand, as the system error tends to zero, a progressively greater damping effect is introduced. This nonlinear approach is in complete contrast to the trade-off required between the rise time, overshoot, and control effort seen in linear control. Another shortcoming of linear control is that it is far from time-optimal when control authority is bounded.

In another experimental evaluation, Cohen, Yaffe, Weller and Ben-Asher (1996) applied an Adaptive Fuzzy Control Algorithm (AFCA) to a slender cantilever steel beam of rectangular cross-section ($2850 \times 60 \times 4$ mm^3). The laboratory structure was an approximation of a two dimensional version of a cantilever beam-like orthogonal tetrahedral space truss typical of a large space structure. Application of the AFCA provided relatively quick settling times, low overshoots and steady-state error within a few seconds.

2. OBJECTIVE OF THIS STUDY

The present study involves additional tests on the AFCA, whose development is presented in Cohen, Weller, and Ben-Asher (1996), to actively control the structural vibrations of an additional experimental model designated "LFS1-P" in view of transient disturbances. The experimental studies on "LFS1-P", conducted at the Aircraft Structures Laboratory, Faculty of Aerospace Engineering, Technion, observe and address the behavior of LFS1-P as reflected by the following characteristics:

- Closed-loop response including rise time, overshoot, settling time, logarithmic decrement, steady-state error and actuator input required.
- Sensitivity of the closed-loop performance and control voltage to the length of the actuating piezoceramic patch.
- Robustness of the control system to an externally initiated change in the temporal dynamics of closed-loop model. This perturbation will be introduced by the addition of a discrete mass.

3. DESCRIPTION OF THE "LFS1-P" & CONTROLLER

The "LFS1-P" is a slender aluminum alloy (7075-T6) cantilever beam of rectangular cross-section whose dynamic characteristics represent a flexible structure. The basic properties of this proof-of-concept model are:

- Length – 1145 mm.
- Width – 60 mm.
- Thickness – Varies 1.27–1.95 mm.
- Material – Aluminum alloy (7075-T6).
- Boundary Condition – Fixed-Free (Cantilever).

The measured open loop frequencies of "LFS1-P" are presented in Table 1.

A variety of transient disturbances is introduced to excite the first few modes. The experimental structure is equipped with a piezosensor/piezoactuator pair. The transducers are comprised of one or more rectangular (54.6 mm $\times$ 54.6 mm) PZT patches attached as close as possible to the clamped end of the cantilever. These patches, designated as PSI-5A-S3, are piezoceramic sheets manufactured by Piezo Systems, Inc., Massachusetts, USA.

The controller proposed by Cohen, Weller and Ben-Asher (1995), provided continuous tuning of the damping parameters of the above-described emulated absorber. These parameters could be adapted to provide fairly fast control for large deviations of the measured state of the plant from the desired state, and a minor amount of control for small deviations. Thus, non-linear control actions, corresponding to a *lightly* damped absorber that fully utilize the range of actuator displacements, send the Plant State hurtling towards the desired state. On the other hand, in the vicinity of this desired state, the absorber is *heavily* damped.

Table 1. Natural Frequencies for Nominal and Perturbed “LFS1-P”

Mode Number	Frequencies of Nominal LFS1-P (Hertz)	Frequencies of Nominal LFS1-P (Rad./Sec.)	Frequencies of Perturbed LFS1-P (Rad./Sec.)
1	0.65	4.1	3.64
2	4.8	30.2	26.69
3	14.0	88.0	86.35
4	27.0	169.6	163.28

Heuristic rules, based on **well-experienced** structural engineering insight, coupled with fuzzy reasoning, provide crisp values for the *lightly* and *heavily* damped cases. The main advantages of using a fuzzy approach are the relative ease and simplicity of implementation and the robustness characteristics of the approach. The methodology for the controller development is detailed in Cohen et al. (1997) and Cohen (1999), and its effectiveness is demonstrated by applying it to several benchmark problems using MATLAB® simulations.

4. EXPERIMENTAL SET-UP AND TESTING PROCEDURES

The experimental structure “LFS1-P”, shown in Figure 1, was subjected to a wide variety of transient disturbances in the form of arbitrary “hits” or “flicks” produced by a ruler and directed at different locations along the structure. Even though there was no self-imposed requirement to simulate any particular type of disturbance, the “flicks” were primarily aimed at exciting as many modes as possible. In addition, the closed-loop response was observed for many different initial conditions to ensure that the quality of the resulting performance was unnoticeably dependent on the type of disturbance.

The experimental set-up used for the testing of the “LFS1-P” may be explained by closely examining a typical “response to stimuli”. To simplify matters, the explanation of the process is divided into two loops, namely, an outer loop and an inner loop. The outer loop follows the trail of the signals popping in and out of the hardware devices, whereas, the inner loop portrays the input/output processing of information by the computer.

5. THE OUTER LOOP

A block diagram of the outer “hardware” loop is shown in Figure 2. The setup devices consist of the:

- PZT sensor, which is comprised of a patch of piezoceramic material (Cohen, 1999).
- Amplifier: Model KEPCO BOP 500 M; Voltage range $= 500$ Volt.
- Computer: Pentium 100 MHz Personal Computer.
- A/D and D/A converters: DT 3003, 12bits, PCI board.
- PZT Actuator, comprised of one, two or three patches of piezoceramic material.

This loop may be described by examining the sequence of a typical response to a transient disturbance as follows:

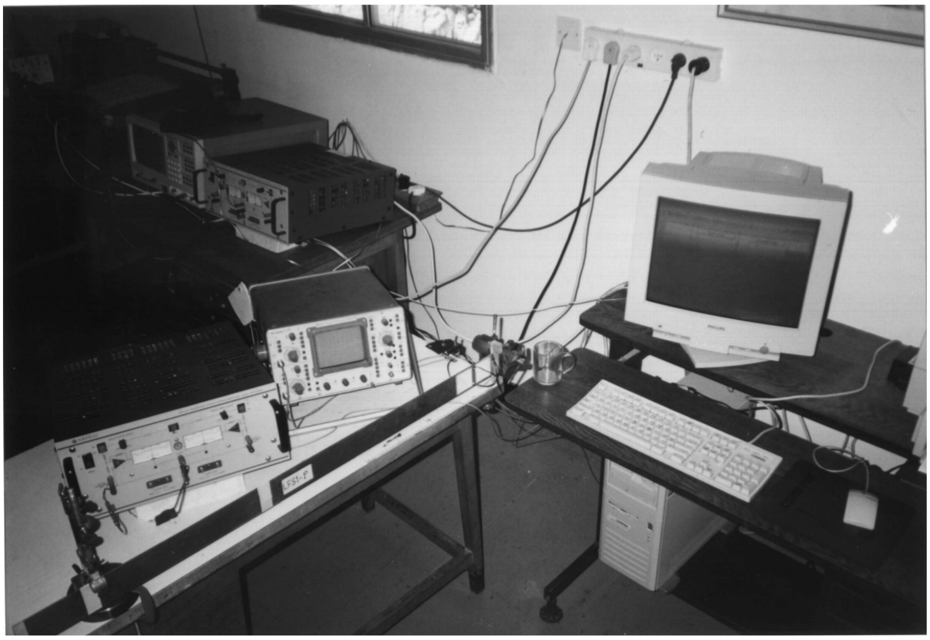

Figure 1. The “LFS1-P” at the Aircraft Structures Laboratory, Technion

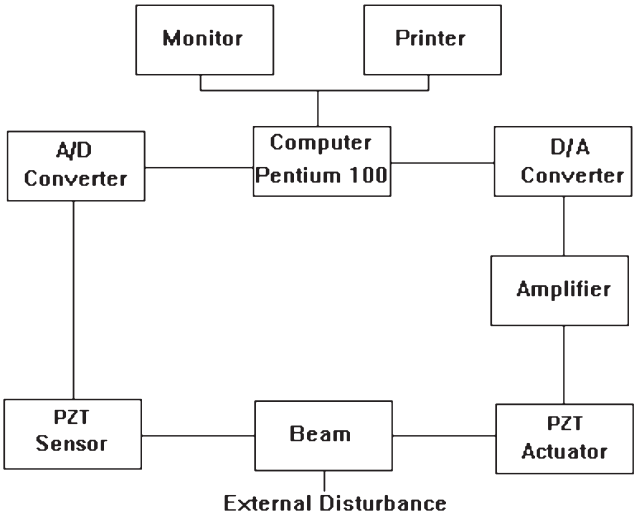

Figure 2. The Outer Loop – Block Diagram

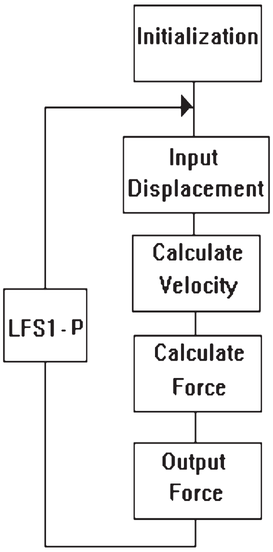

Figure 3. The Inner Loop – Block Diagram

- An arbitrary transient disturbance is applied to the “LFS1-P” by extending a “flick”.
- The PZT sensor positioned near the clamped end of the beam, translates the measured strain into a continuous analogue voltage signal.
- The PZT sensor is sampled at a rate of 1700 readings per second.
- The signal enters an A/D converter, which converts the amplified analogue signal into a digital one, for subsequent computer processing.
- Inside the Pentium 100 MHz Personal Computer the digital signal undergoes processing, described in Figure 3, which results in a digital signal that represents the value of the actuator command required to control the “LFS1-P”.
- The histories of the input and output digital signals are displayed on a 17-inch SVGA color monitor. In addition, at any appropriate time a command may be sent by the operator for a hard copy printout of the above information.
- The command to the actuator, expressed by a digital signal, undergoes conversion to an analogue signal via the D/A converter.
- The resulting analogue signal is amplified.
- The amplified signal commands the PZT actuator, which is collocated with the PZT sensor as shown in Figure 1.
- The beam experiences a discrete force that emulates the working of an adaptive dynamic vibration absorber tuned to the fundamental frequency. The beam responds to the control command and the PZT sensor subsequently picks up this response.

6. THE INNER LOOP

Once the basic functioning of the Outer Loop has been appreciated, a closer look needs to be taken at what takes place during the above mentioned computer processing. Before proceeding, we may recollect that the controller has been developed off-line, based on the procedure described above. All off-line simulations were conducted on a MATLAB® platform.

The Inner Loop, schematically illustrated in Figure 3, may be described by examining the sequence of a typical response of the "LFS1-P" to a transient disturbance:

a. After closing the control loop, the computer is fed with a measurement of the transverse displacement as described in the Outer Loop.
b. The transverse velocity is calculated by means of an estimator. This calculation is performed at a sampling rate of 1700 Hertz.
c. The inputs consisting of the measured transverse displacement and the calculated transverse velocity are fed into the Adaptive Fuzzy Control Algorithm, as detailed in Cohen (1999), where the following processes take place:
   - Fuzzification of the inputs using five triangular and trapezoidal membership functions for each of the two inputs and the output.
   - Inferencing of a control action that involves the firing in parallel of the 25 fuzzy rules.
   - Defuzzification to obtain a crisp value for the damping of the virtual DVA.
   - The equations of motion that constitute the virtual DVA are solved using Runga Kutta methods, and the force applied by the DVA is subsequently computed.
d. The above computed force is transformed into an equivalent pin force, applied by the PZT actuator by providing an equal amount of internal strain energy. The mathematical mapping describing the adaptation of the fuzzy-based controller to piezo-ceramic sensors/actuators are developed in Cohen, Yaffe, Weller and Ben-Asher (1997).
e. The calculated actuation command calculated is finally translated into a signal that flows from the computer into the Outer Loop.

The cycle time for an input displacement to be translated into a control command is about 0.6 msec.

6.1. Nominal and Perturbed Plant

In the experimental studies, the performance robustness of the AFCA was examined in view of additional non-structural mass in the form of discrete weight (approximately 50 g) applied to the free end of the "LFS1-P". The nominal "LFS1-P" did not have any non-structural mass. Its first four natural frequencies are presented in Table 1. It is a known fact that the addition of a discrete weight, at the free end of a cantilever beam, increases the modal density and alters the mode shapes. Table 1 also compares the calculated natural frequencies of the nominal "LFS1-P" to those obtained for the perturbed structure. The addition of the non-structural mass at the free end of the cantilever causes a decrease of the fundamental frequency by about 10% (as seen in Table 1).

The electro-mechanical equations that govern the behavior of the “LFS1-P” actuator patch, described in detail by Cohen, Yaffe, Weller and Ben-Asher (1997), point to the relationship between the length of the actuator patch and the applied voltage command required to produce an equivalent point force. Experiments on structural vibration control, using PZT transducers conducted by Yousefi-Koma and Vukovich (1996), show the effect of an actuator patch on the closed-loop performance. Furthermore, for a longer piezoceramic patch, a smaller control voltage was required to achieve greater damping. To examine the effectiveness of the developed AFCA to the length of the piezo-actuator, three cases were considered, namely:

6.1.1. Case 1

A single rectangular (54.6 mm $\times$ 54.6 mm) PZT patch attached at a distance of 15mm from the clamped end of the cantilever. The single actuator patch is collocated with a similar PZT patch used as a sensor.

6.1.2. Case 2

Two rectangular (54.6 mm $\times$ 54.6 mm) PZT patches are attached together, to form a patch that is twice as long, at a distance of 15mm from the clamped end of the cantilever. The PZT sensor patch is identical to CASE 1.

6.1.3. Case 3

Three rectangular (54.6 mm $\times$ 54.6 mm) PZT patches are attached together, to form a patch that is three times as long, at a distance of 15mm from the clamped end of the cantilever. The PZT sensor patch is identical to CASE 1.

7. EXPERIMENTAL RESULTS

The performance of the “LFS1-P” during the experiment were observed in the monitor attached to the Pentium Personal Computer. A plot of the open-loop response is presented in Figure 4, whereas Figure 5, for Case 1, illustrates the sensor output for the nominal “LFS1-P”, which plots the time history of the measured transverse displacement as picked up by the PZT sensor.

The application of the AFCA to the nominal “LFS1-P”, provides damping augmentation in view of the transient disturbance leading to improved settling times with respect to the open-loop response space (see Figure 5). When the control force is turned off shortly after the dying out of the vibrations, 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 was found to be insensitive to the type of transient disturbance as detailed in Cohen (1999).

Next, the effectiveness of the developed AFCA to the length of the piezo-actuator, in CASE 2, was examined. In comparison to the results obtained in CASE 1, substantial improvement in the damping was obtained (see Figure 6). Furthermore, the results obtained for CASE 2 are promising considering that the ratio of the length of the actuator patch to the beam length is less than 10%. Finally, for CASE 3, considerable improvement in the damping was obtained (see Figure 7). The controller suppresses the flexural vibration quickly, and

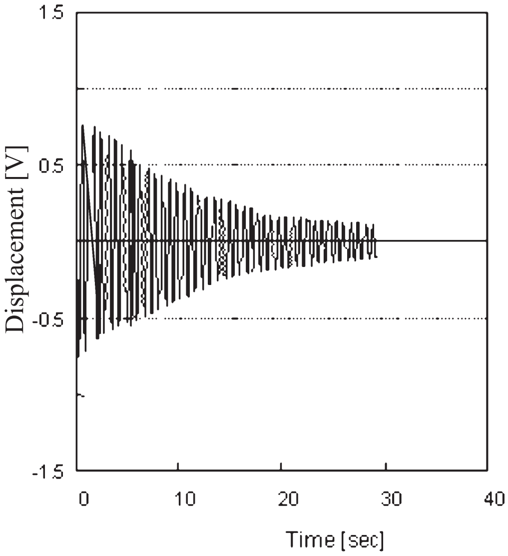

Figure 4. Open-loop response of the “LFS1-P” to a transient disturbance

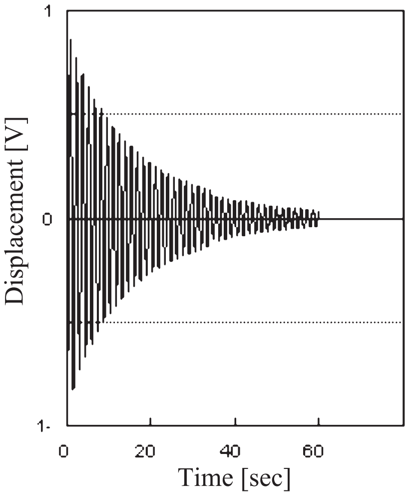

Figure 5. Closed-loop response of the “LFS1-P” to a transient disturbance – Case 1

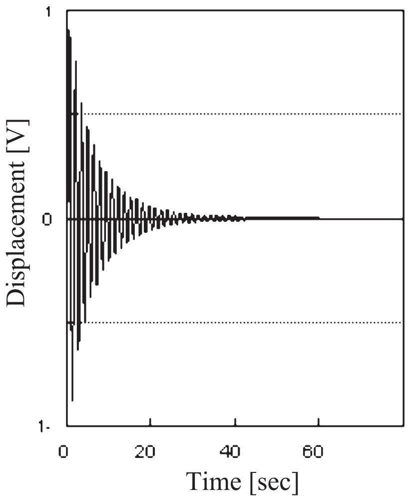

Figure 6. Closed-loop response of the “LFS1-P” to a transient disturbance – Case 2

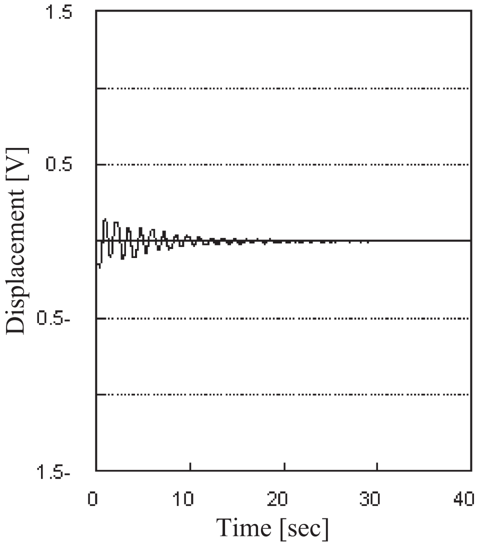

Figure 7. Closed-loop response of the “LFS1-P” to a transient disturbance – Case 3

a greater damping is obtained at the expense of smaller control voltage. This result was expected and is similar to that reached by Yousefi-Koma and Vukovich (1996).

To demonstrate the robustness of the control system to changes in the temporal dynamics of the ”LFS1-P” (CASE 2), the transient disturbance response to a perturbed plant was experimentally obtained. A discrete, non-structural weight of approximately 50 gm. was attached to the free end of the beam, reducing the fundamental frequency of vibration by about 10%. For the perturbed structure, the developed controller provided similar settling times and rates of vibrational energy dissipation (Cohen, Yaffe, Weller and Ben-Asher, 1997).

8. CONCLUSIONS

1. The present effort describes the experimental testing of an adaptive fuzzy-control algorithm on a laboratory model of a large flexible structure. The laboratory model, designated “LFS1-P”, is comprised of an aluminum slender cantilever beam, which is subjected to a transient disturbance. The structure is equipped with transducers, which are comprised of one or more rectangular PZT patches attached at its clamped end.
2. The controller introduces an active “soft shunting” action that causes the piezo-transducers to emulate a dynamic vibration absorber whose damping is variable. Non-linear control actions, corresponding to a *lightly* damped absorber with a *large* mass ratio, send the Plant State hurtling towards the desired state. On the other hand, in the vicinity of this desired state, the absorber is *heavily* damped, having a *small* mass ratio.
3. Experimental results of the closed-loop system for CASE 3 demonstrate quick settling times and a high rate of vibrational energy dissipation. When compared to CASE 1 and CASE 2, the CASE 3 closed-loop system enables quick suppression of the flexural vibration and greater damping at the expense of smaller control voltage.
4. The robustness of the control system to changes in the temporal dynamics of the cantilever beam is examined by observing the transient disturbance response to a perturbed plant. The AFCA provides satisfactory settling times and rates of vibrational energy dissipation.

9. RECOMMENDATIONS

1. The size of the PZT patch was found to have a distinct effect on the closed-loop performance of the system. Further research may include analytical and experimental research into the optimization of PZT sensor/actuator size and location.
2. The experimental testing of the “LFS-P” was limited to 2-D transverse bending. The algorithm may be further tested by adding a substructure that introduces bending/torsion coupling.
3. The controller presented may further be developed and tested for the vibration suppression of structures having an increased complexity and possessing very high modal densities at the lower frequencies.
4. Future research plans should include performance comparisons with other classical control laws.

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