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Active vibration damping of composite structures using a nonlinear fuzzy controller

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ABSTRACT

The present paper presents a comprehensive methodology for the structural active vibration damping using a fuzzy logic control. The proposed application setup consists of a cantilever beam equipped with two pairs of collocated piezoceramic (PZT) actuators and sensors. The investigated carbon composite beam is modeled using a shell 2D-model on Abaqus commercial finite element code. The PZT patches are modeled as additional layers with a coupled electromechanical effect. Experimental data corresponding to the controlled and to the uncontrolled systems are also presented considering fixed frequency and pulse force excitation.

1. Introduction

The notion of suppressing/attenuating structural vibrations is of paramount importance for enhancing safety and improving system performance. Undesirable large-amplitude vibrations often impede the effective operation of various types of structures and systems. It is then practical to introduce structural damping into a dynamic system to achieve a more suitable response. In the past, much of the structural engineering and control research communities gravitated towards use of traditional control methods such as Linear Quadratic Gaussian (LQG), Proportional, Integration, and Derivative (PID), and H-Infinity ($H\infty$). These control algorithms can provide adequate control management for many classes of problems, but this is often at the expense of a strong robust nature. This is mainly due to the sensitivity of traditional controllers to characteristics of the structure itself such as mass, stiffness, and damping. Thus, if the structural properties vary from those used to develop the control algorithm, the effectiveness of many of these control algorithms diminishes significantly. One of the controlling ways, which has been watched an ever-increasing progress, is fuzzy control. In more recent studies, controllers that make use of fuzzy logic have gained acceptance in the research community for their robust nature and ability to account for uncertainties.

Fuzzy logic was first introduced by Zadeh [1] in 1965. The first paper on the fuzzy sets [1] and the theory was quickly branded *fuzzy logic*. The application of fuzzy set theory to vibration control problems was first proposed by Tsoukkas [2] and has been the focus of numerous studies. Most vibration control methods based on fuzzy logic rely on feedback control [2,3] but feedforward control has also been studied [4]. Basically, two fuzzy control systems are used for active vibration control: Mamdani and Takagi–Sugeno (see [5]). People who deal with the Takagi–Sugeno fuzzy controller perform a modal active control called, in this case, fuzzy modal control [5,6]. The latter is carried out by using a decomposed parallel fuzzy control where each controller is associated with a mode and the inputs of each controller match the modal contribution. For a Mamdani-type fuzzy controller the inputs are mainly the displacement and the velocity of the structure or its acceleration [7]. The construction of fuzzy logic controllers (*i.e.* the definition of membership functions and rule base) is either derived from classical PID controller with each input uniformly partitioned [7], or genetic algorithms [8], or neural networks [9,10] or self-organizing method [11] that can also be employed as an adaptive technique for the design of fuzzy logic controller. Despite proven success in many practical situations, fuzzy control is not deemed rigorous due to the lack of formal synthesis techniques that would guarantee the basic requirements for control systems, such as global stability. Basically, a fuzzy controller is a nonlinear controller with more parameters to fix or tune than with a conventional PID controller. These parameters typically have a significant influence on the controlled system itself. Thus, there is a need for a parametric study of the influence of the tunings and the damping on the fuzzy controller. It is worth to mention that in most published studies in the field of vibration control simple models have been used and finite element method formulation and conventional control methods have been systematically used.

In this paper, an attempt is made to develop a more comprehensive structural model and experimentally validate the proposed

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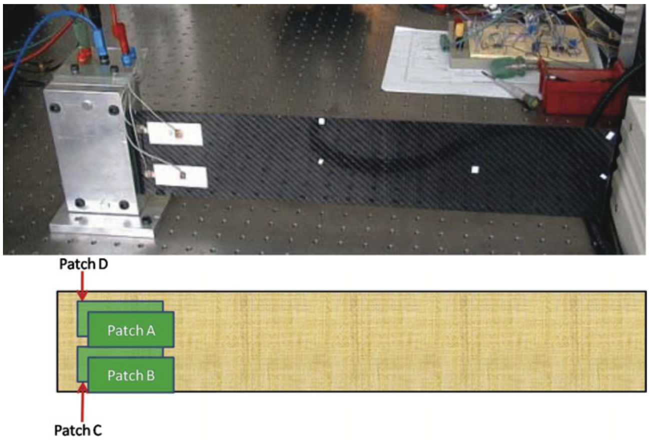

Fig. 1. Cantilever beam with four piezoelectric patches.

fuzzy logic controller (FLC) for active vibration damping. The proposed application setup consists of a cantilever beam equipped with four piezoceramic (PZT) patches. The carbon composite beam is modeled using a shell 2D-model on Abaqus commercial finite element code and the PZT patches are modeled as an additional layer with a coupled electromechanical effect. Li et al. [12] investigate the design of-synthesis controller for vibration control of a plate with piezoelectric patches. A numerical model accounting for the coupling between the PZT actuators and host plate is derived. In this contribution Li et al. [12] have shown that the established model provides a useful tool for the controller design, pointing to a straightforward extension to the case of multi-layer composite laminates and other composite structures.

2. Fuzzy controller design for vibration damping

The main task during the construction of a fuzzy controller is to define control rules. The error and the change of error are two variables commonly used in the design of fuzzy controllers. The time response E from sensor A and its corresponding rate variable $\dot{E}$ from sensor D are the controller inputs (see Fig. 1). The voltage applied to the voltage amplifier is the output of the controller sent to the actuator C. In the proposed application, a triangle-shaped membership function (Figs. 2 and 3) is used to convert the input variables (error and error rate) into linguistic control variables and an output membership function is used to convert linguistic control to electric potential values applied to the actuator C after voltage amplification.

Notice that the fuzzy inference method uses the max–min product composition to enforce fuzzy control rules. The centroid of area method was utilized in order to defuzzify the output variable. The membership function breakpoints are initially chosen arbitrarily. The membership function parameters are then adjusted to produce the best performance for excitation inputs. Breakpoints of membership functions of E and $\dot{E}$ are chosen initially to trigger excitations. The parameters of membership function u are then adjusted to achieve the best performance for reference inputs in the remainder of the operating range. However, modifying the breakpoints of membership functions E, $\dot{E}$ and u changes the input rate based on the output at each time step. Hence, the breakpoints of membership functions E and $\dot{E}$ can be changed to affect performance over a range of reference inputs while the breakpoints of u can be adjusted to influence performance in a certain operating region for each response; these breakpoints are limited by the controller gain output.

As previously mentioned, the developed fuzzy controller will be tested on a cantilever composite beam (Fig. 1). For this purpose, the rule base is the core of the controller and must be carefully designed. We recall that the number of membership functions depends on the discretization of the output domain and on the nonlinearity of the system to be controlled. Furthermore, we should keep in mind that the fuzzy controller should be translated in an understandable natural language and that it does not make sense to consider fuzzy sets that do not significantly improve the performance of the controller. Within the scope of this application, the rule base is derived from the conventional Proportional Derivative (PD) controller. Nevertheless, some variations can be developed that involve some differences with regard to the performance of the controller itself. Since the uniformity of partitions influences the accuracy of the controller, fine discretization is needed in the neighborhood of the equilibrium point. In addition, the overlap between membership functions influences the time needed by the controller to reach a stable state. A common practice is to consider a cross-point level of 0.5 for two adjacent membership functions.

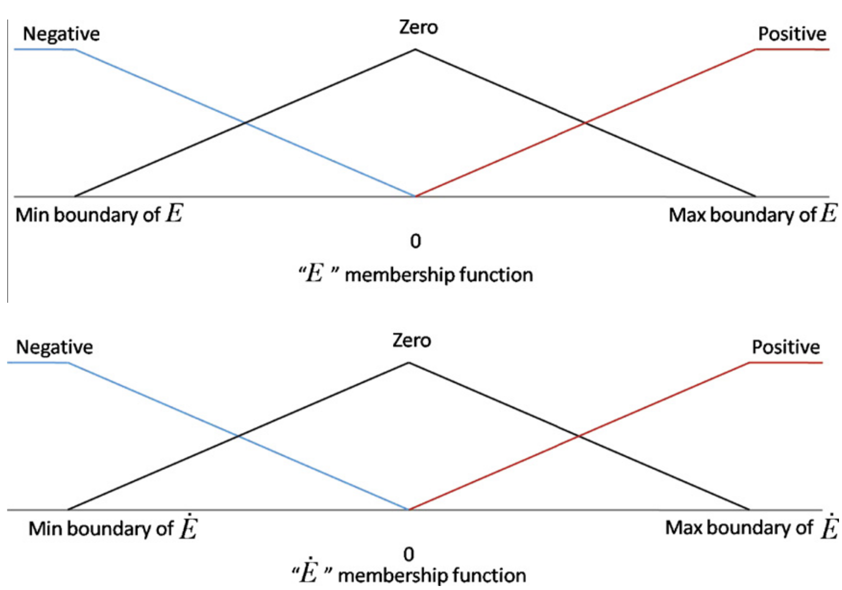

Fig. 2. Membership functions for input variables E and E.

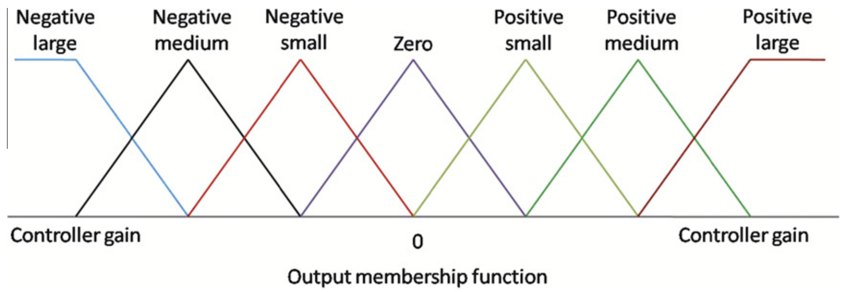

Fig. 3. Membership function for control output *u*.

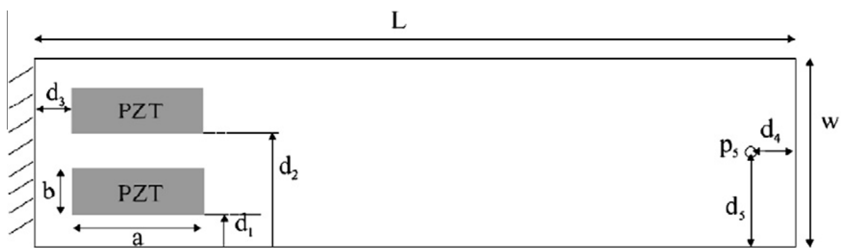

Fig. 4. Sketch and geometrical description of the beam.

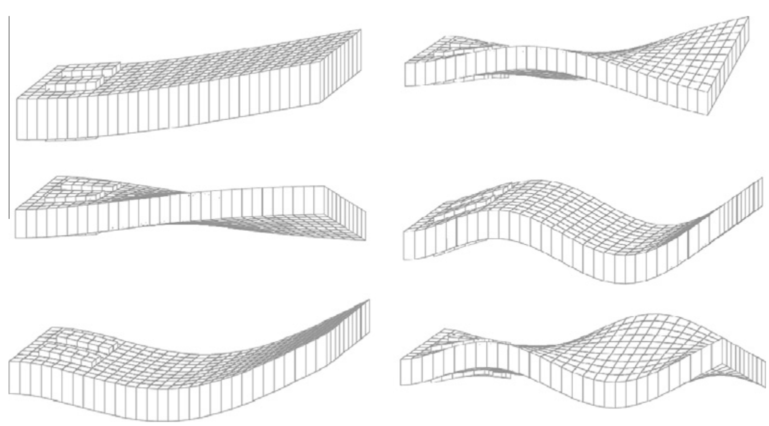

Fig. 5. First six mode shapes.

Table 1
Geometrical and electro-mechanical properties.

Composite	Young modulus: E_x = 41.5 GPa Young modulus: E_y = 41.5 GPa Young modulus: G_xy = 3.35 GPa Poisson ratio: ν_xy = 0.042 Density: ρ = 1490 kg/m^3
PZT patches	Young modulus: E = 65 GPa $d_31 = d_32 = -205 \times 10^{-12}$ (m/V) Poisson ratio: ν = 0.3 Density: ρ = 7800 kg/m^3 ϵ_r: 2600 F m^{-1}
Geometry a = 55 mm b = 25 mm d_4 = 5 mm d_5 = 50 mm	L = 463 mm d_1 = 13 mm d_2 = 64 mm d_3 = 15 mm w = 100 mm and thickness = 1.3 mm height

Table 2
Undamped natural frequencies.

Mode	Natural frequencies (Hz)		Experiment
	Without PZT patches	With PZT patches	
1	5.1715	6.3292	6
2	23.812	25.092	–
3	32.486	36.831	33
4	77.216	80.766	–
5	91.399	99.146	92
6	146.82	152.70	–

3. Modeling

A fuzzy controller is a nonlinear controller with more parameters to fix or tune than with a conventional PID controller. These parameters typically have a significant influence on the controlled system itself. Thus, there is a need for a parametric study of the influence of the tunings and the damping on the fuzzy controller. The implementation of controllers in a Matlab-based environment starting from a finite element model of the structure is then developed. The proposed application setup consists of a cantilever beam equipped with four PZT patches. These MFCs patches can be used as sensor (short-circuited condition, charge measured), or as actuators (voltage applied to the MFC) see (Fig. 4). The properties of the piezoelectric material (PZT 5A1 Navy Type II) are given by the manufacturer (Ceramtec). The properties of the epoxy are given

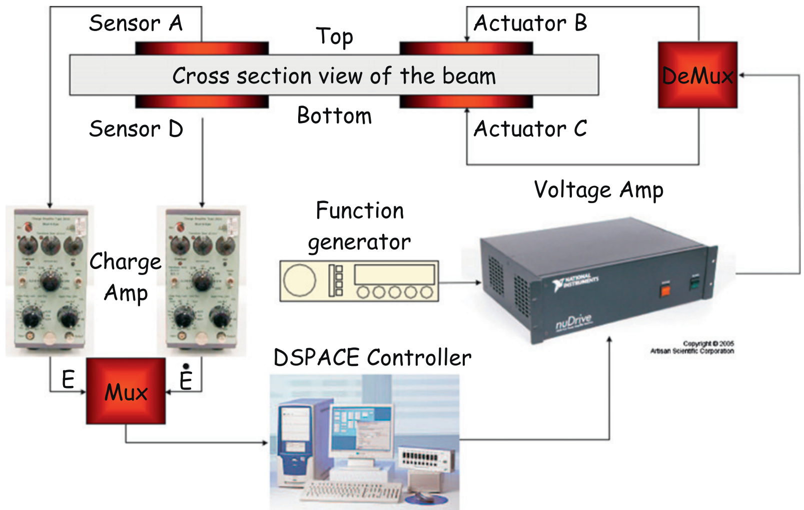

Fig. 6. Experimental procedure and used devices.

by Smart-Material (the relative permittivity is found on the internet for a typical epoxy) (Table 1).

Mechanical modeling has been performed both using Abaqus FEM commercial code. The carbon composite beam is modeled using a shell 2D-model and the PZT patches are modeled as an additional layer with a coupled electromechanical effect. After a convergence study a regular mesh is chosen, with a first order through-the-thickness expansion (Fig. 5).

Almost all the calculated frequencies slightly increase if the patches are considered in the analysis (the structure is more rigid). It is clear that the stiffening effect due to the electromechanical coupling is negligible in this case study and the reason is in the fact that the piezoelectric patches represent a very small when compared to entire structure. It is worth to mention that some natural frequencies cannot be detected from the experiment: transverse translation of the patch *A*, for instance, is not significantly excited by modes two, four and six. The contrary occurs for modes one, three and five, which are regularly detected during the test. It comes out from this first analysis that high order theories have no impact on the prediction of co-located transfer functions such as that between a sensor and an actuator placed on the same location on the plate. Tools have been developed in order to build reduced state-space models from full finite element models of active structures (mainly thin structures with piezoelectric actuators and sensors), and apply control strategies Tables 1 and 2.

4. Experimental implementation and validation

In this section, a description of the experimental setup is provided (Fig. 6). We consider a cantilever beam clamped at one end and free at the other. The beam is equipped with two collocated pairs of piezoelectric patches. The pairs are located close to the clamped end of beam as depicted in Fig. 1. In this application, one collocated pair of patches PZT is used as sensors for measuring the error and error rate. In order to get a robust controller, a collocated pair of actuator and sensor is required [13].

The position configuration of PZT patches of actual setup, the pole–zero distance is very small, which results in a poor performance of the controller. Fig. 7 illustrates the transfer functions measured between actuator *C* and each of the three other patches (*A*, *B* and *C*) operating as sensors; one can easily determine the

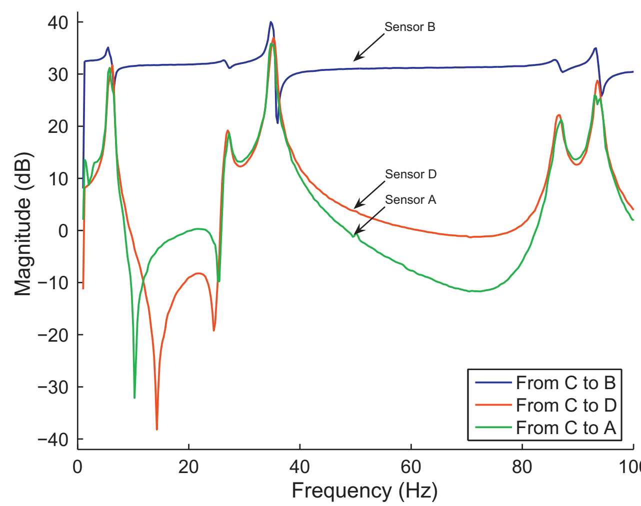

Fig. 7. Measured open-loop frequency response using one patch as actuator and the other three as sensors.

pole–zero distance for the first eigenfrequency. For patches (*C*,*B*), the phase remains in a 180° band, stability is therefore guaranteed, but the pole–zero distance is very small. For patches *C*, *A* or *C*, *D*, (see Fig. 6) the pole–zero distance is much larger for the first mode but there is a loss of stability after the first mode shape due to the second mode shape, which is torsional. For this torsional mode, there is a sign change between the actuator and the sensor, causing a change of phase larger than 180°. For this reason, the pair of patches *A* and *D* provides input for the controller (error and error rate respectively). Actuator *C* is candidate for the controller while actuator *B* is subject to excitation input.

5. Results and discussion

The fuzzy logic controller application requires measuring the time response *E* and its rate $\dot{E}$. The use of a simple derivative in the DSP device in order to compute $\dot{E}$ was problematic because of noise amplification when computing the derivative of a signal. To overcome this issue, we used an external device to calculate

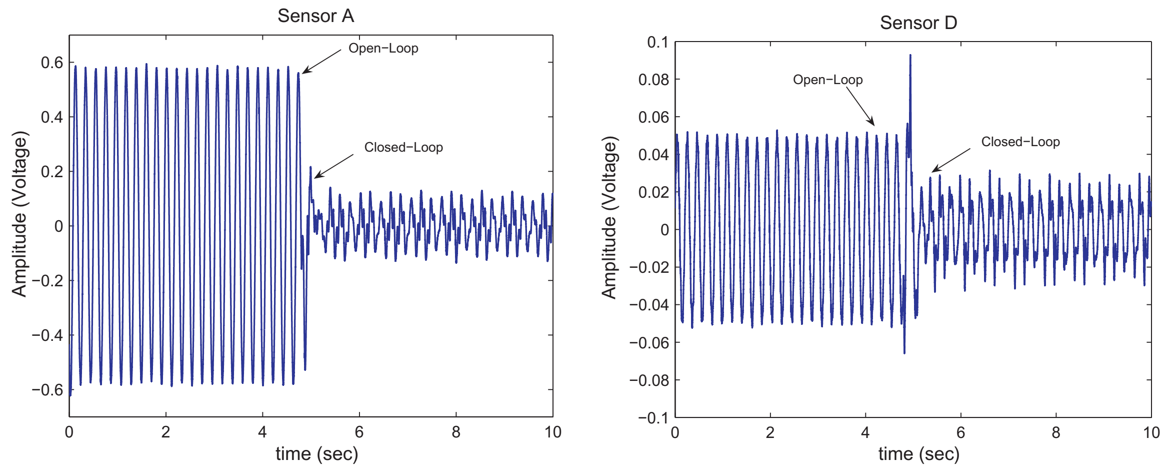

Fig. 8. Measured time response for sensors and output voltage with fixed frequency excitation input voltage at the moment of turning on the fuzzy logic controller.

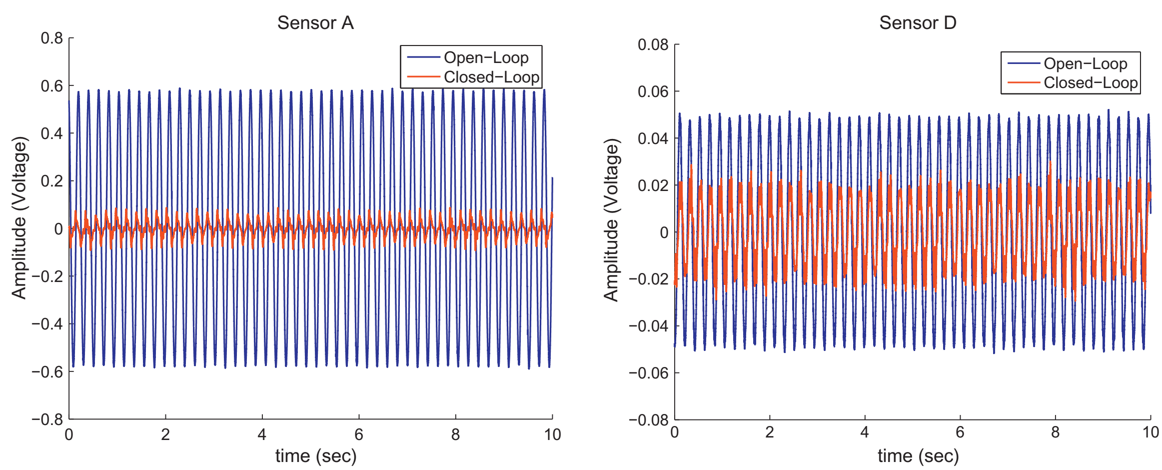

Fig. 9. Measured time response for sensors and output voltage with fixed frequency excitation input voltage for the controlled and for the uncontrolled systems.

the structural response time and its derivative for each degree of freedom (DOF) of the structure using a collocated actuator/sensor pair. In this study, time response error E and error rate $\dot{E}$ are read from two collocated PZT patches A and D.

The time response E is measured by sensor A and its negative rate is measured by sensor D (because of opposing polarization axes of sensors A and D. Two charge amplifiers are employed in order to measure the time vibration response. The charge amplifier converts an input charge to a voltage output by integration. The advantage of using charge amplifiers is to allow several integrator orders (m/s^2, m/s, m with respect to the conventional accelerometer conversion charge output). Two types of structure excitation were considered: the first type involves fixed frequency voltage being applied as input to actuator B, while the second type involves pulse excitation force applied at the free end of the beam.

5.1. Fixed frequency excitation

This section uses the system model to examine the closed-loop effects of the fuzzy logic controller. A fixed frequency excitation is supplied as input voltage. The voltage excitation frequency of sensor B is chosen to be close to the resonance frequency of the structure. Figs. 8 and 9 illustrate the time response output of sensors A and D. Fig. 8 illustrates the time response at the moment when the fuzzy logic controller is turned on and Fig. 9 shows the responses of the controlled and the uncontrolled systems. In these figures, the closed-loop controller reduced the magnitude of structural vibration by nearly 60% compared to the open-loop controller.

5.2. Pulse excitation

In this section, we evaluate the performance of the fuzzy logic controller when an impulse excitation force is applied at the free end of the beam.

Despite the weak control authority of the transfer function in our experimental setup, the fuzzy logic controller showed some effectiveness in vibration control. Fig. 10 illustrates the time response of sensors A and D with open loop and with closed-loop controllers. From Fig. 9, one can see that the implemented controller is capable of damping structural vibration even for large impulse forces.

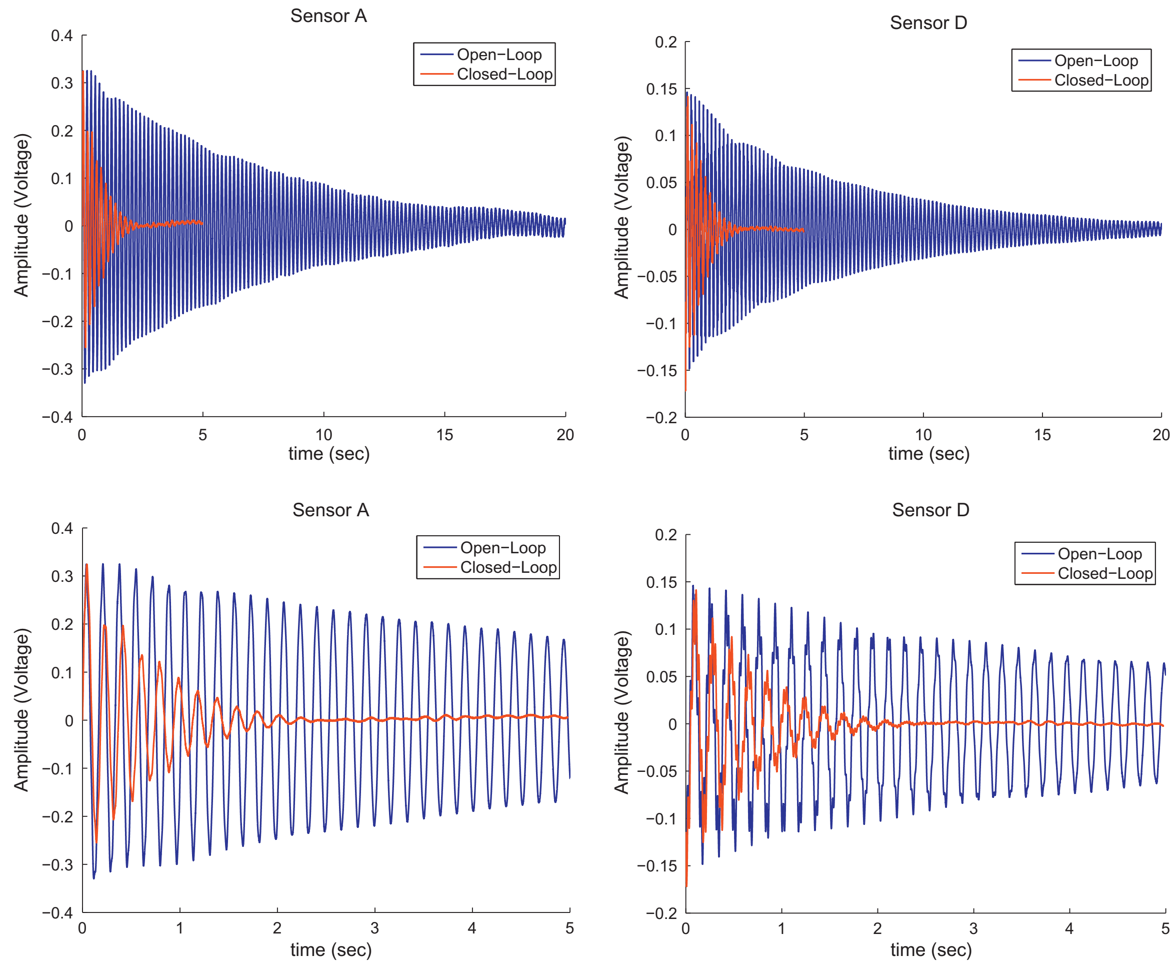

Fig. 10. Measured time response for sensors and output voltage with pulse excitation input force for the controlled and for the uncontrolled systems.

6. Conclusion

The experimental validation of a nonlinear fuzzy controller was carried out on a cantilever composite beam equipped with two collocated pairs of piezoelectric patches. One sensor was used to measure the error and another one to measure the error rate. Several tests were conducted on the considered structure in order to evaluate the performance of the proposed controller. Experimental data corresponding to the controlled and to the uncontrolled systems were presented considering fixed frequency and pulse force excitation. A tool has been developed in order to assess the impact of different parameters on the performance of control strategies. The approach is fully automatic, and allows to assess the robustness of the control strategies adopted. Further research is needed in order to investigate the robustness of the controller with respect to various parameters like the type of input/output memberships and the fuzzy rule base.

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