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ACTIVE CONTROL OF STRUCTURE'S VIBRATION USING SMART MATERIALS

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Abstract. *The objective of the present study is to propose an alternative for real-time active control of problems of structural vibration using smart materials. PZT (Titanato Zirconato de Chumbo) is a ceramic material that shows a marked piezoelectric effect. It is efficient in converting electrical energy to mechanical energy and was chosen as actuator. PVDF (Polyvinylidene Fluoride) is a highly non-reactive and pure thermoplastic fluoropolymer which was chosen as sensor due its high sensitivity and accuracy. The structure prototype consists of an aluminum beam with clamped-free condition. The piezoelectric sensor and actuator were positioned on opposite surfaces of the beam, close to the clamped side of the structure, considering the criterion of minimum control energy and maximum output energy. An electronic circuit was built to convert the electrical charge of the PVDF sensor to the voltage requirements of the real-time control system hardware used in experiments. Mathematical identification of the structure was performed using the Matlab Identification Toolbox®, in order to obtain the transfer function to model the system. A PD (Proportional plus Derivative) type controller was chosen, because it is simple and efficient for the problem of this study. The vibration control loop was implemented in Matlab Simulink®. Simulations were performed in order to verify the efficiency of the controller and to obtain tuning of proportional and derivative gains.*

Keywords*: smart structures, PID, piezoelectric materials, identification, transfer function*

1. INTRODUCTION

Since the 80s, many researchers have devoted special attention to the optimization of the mechanical response of systems and structures. Most of the studies of these researchers were devoted to the development of adaptive structures, consisting of structural systems capable of modifying their dynamic response according to the instantaneous condition of ambient. These structures have been called Smart Structures (Clark, Saunders and Gibbs, 1998), and their adaptive characteristics are generally related to natural systems, according to a biological analogy (Lammering et al., 1994). Natural Systems have amazing characteristics that smart structures imitate, such as precision, efficacy, functionality, durability and, most important, adaptability.

To provide these qualities, smart structures need three basic elements: sensors, which detect ambient information; actuators, which apply forces to modify the dynamic response of the structure; a control system, that centralizes sensor information and makes decisions about the command signals for actuators so that the response will be close to the desired one. Combination of these elements gives intelligence to the system.

Adaptive structures can be seen in the aeroelasticity area and in the control of structural damage and noise. Smart structures are also used in rotors, cars, buildings, medical machines and tools. Nowadays a lot of research on smart structures is directed at aerospace applications and at the active control of vibrations and noise (Silva, 2005), with sensors and actuators directly fixed in the airplane fuselage.

Several technologies and materials have been investigated and proposed for application to adaptive structures (Lima Jr, 1999), with emphasis on the successful use of piezoelectric materials. Piezoelectric materials can be applied to noise control systems (Flotow and Fuller, 1995), to robot micropositioners (Molter, 2008), to noise control in ducts (Nuñez, 2005), and to structural damage monitoring (Ayres, 1996).

An important application of smart structures is in the control of mechanical vibrations. In some structures, controlled vibrations are desired, as is the case for vibratory conveyors (Santana *et al*., 2003). However, in most situations, vibrations damage the structure, with a consequent risk to human life. For this reason, several studies have been devoted to the reduction of structural vibration.

Traditional methods to reduce mechanical vibrations are based on increased mass and dump of the structure. Silva *et al*. (2004) used a method based on fixing viscoelastic materials to the structure. Several studies have shown that the mechanical vibrations of a structure can be reduced by sensors and actuators, with one or more controllers (Moreira, 1998; Lima Jr., 1999; Bueno, 2007), which confer fast and precise responses.

The objective of the present study was to describe a methodology for the reduction of dynamic structure vibrations using piezoelectric materials. The theory used to choice the materials and controller will be shown in the next sections, as well as the real structure to be controlled, the methodology for mathematical identification of the real structure, and simulations in Matlab Simulink®.

2. SMART MATERIALS: PZT AND PVDF

Piezoelectric materials belong to a class of dielectrics that exhibit a significant deformation of the material in response to application of an electric field, as well as producing a dielectric polarization, an electric field in response to deformation that the material might undergo. These materials can be used as important components of active control to determine stress or strain (piezoelectric sensors distributed through the direct piezoelectric effect) or to act by controlling structure deformation (piezoelectric actuators distributed using the inverse piezoelectric effect). Piezoelectric materials have three axis directions, two approximating an isotropic condition (same properties in all parts of these directions) and the third associated with the direction of polarization, which suffers the piezoelectric effect (Tebaldi *et al.*, 2006). These materials have been widely used in control systems for the detection and suppression of vibrations.

Arthur Von Hiffel produced the first synthesized piezoelectric material in the 1940's, after polarizing barium titanate (BaTiO3) by applying an external electric field. But it was in 1954 that Jafett discovered the piezoceramic of wider current application, composed of lead zirconate titanate and known as PZT. Due to their ceramic nature, PZTs have good stiffness and often the same order of the basic structure, which results in an excellent conversion of electrical energy to mechanical energy. This makes these materials effective actuators for a wide variety of applications. Piezoceramic materials are effective over a wide frequency range and the dual property displayed by these materials makes them extremely advantageous for application to control system troubleshooting (Dosch, Inman, and Garcia, 1992).

Faria (2006) cited the following advantages for polycrystalline ceramics: less costly manufacturing, possibility of being manufactured in a wide variety of compositions, allowing control and change of their physical properties, and possibility to be built in several geometries. As disadvantages, Faria (2006) noted: greater dependence of their electromechanical properties on temperature, formation of unwanted phases during their production, variation of their properties with time (aging).

One of the most important operating limitations of piezoelectric ceramics is the fact that exposure of the material to temperatures higher than a certain threshold, called Curie temperature, causes it to lose the polarization acquired during its manufacture, and thus seriously damages their piezoelectric properties. Likewise, in a reverse application, when the material is subjected to an electric field exceeding a certain limit, called the coercive field, depolarization occurs. The limits of temperature and electric field vary for each material and structure (Faria, 2006). The piezoelectricity of a ceramic material is based on a large number of randomly oriented crystal grains, each with its own electric dipole. This random orientation of grains results in reciprocal cancellation of electric dipoles. To start the piezoelectric effect in a ceramic material, its temperature is raised to a level just below the Curie temperature and then subjected to a high electric field of the order of a few kilovolts. This process is known as "poling". Once the material is polarized, electric dipoles are aligned with the applied electric field and the material will possess piezoelectric properties.

Although favorable in many applications, piezoceramic materials are difficult to mold with complex shapes because of their fragility. The alternative materials used in these cases are piezoelectric polymers such as PVDF film or polyvinylidene fluoride, discovered by Kawai in 1960, which became marketable only in 1980. These materials have the consistency of a plastic wrap, and can be affixed on the structures in virtually any geometry. They have low density and are very flexible, have high sensitivity and accuracy in measurements and therefore are mainly used as sensors. Direct application of PVDF films as actuators has been limited because their electromechanical coupling coefficients are lower than those of PZTs. Moreover, they are difficult to polarize, and their low dielectric constant along with their thinness complicates their application in detection circuits. However, the dielectric strength of PVDF films is higher than that of PZT and they can be exposed to higher electric fields (Tebaldi *et al.*, 2006).

3. REGULATORY SYSTEM CONTROL

The problems of structural vibration control discussed in the present study can be treated using a regulatory system. In this study we looked for a simple and easy-to-implement control method such as those using PID controllers.

In essence, regulatory systems have a fixed set point, in which a reference is established. In the case of control of beam vibrations we can ensure that the beam is static when the PVDF sensor reports a null response. Thus, the controller has the function to cancel the vibration caused by the entry disturbance in the structure.

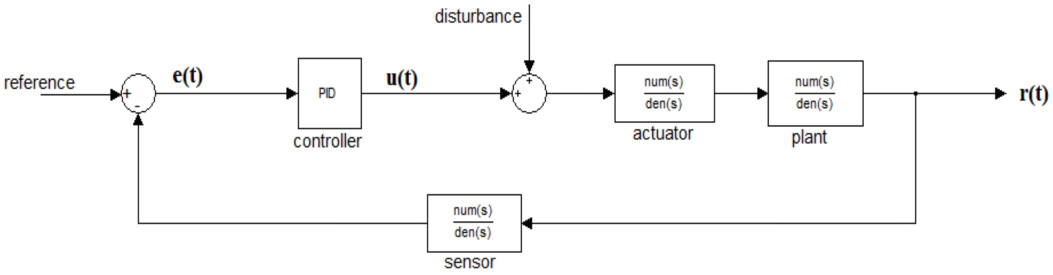

Figure 1 – Block diagram for regulatory systems

Figure 1 shows the general block diagram of a control loop for a regulatory system. The controller detects the error signal acting on the system, and, according to its internal parameters, produces a control signal for the actuator, that acts directly on the process to be controlled. A sensor reads the variable to be controlled, transforms it in an appropriate manner, and sends it to the controller to determine the error signal again. In an automatic controller in real time, the system repeats this process continuously.

For a controller with PID action, its response is given by the following equation:

$$u(t) = K_p e(t) + \frac{K_p}{T_i}\int_0^t e(t)dt + K_p T_d \frac{de(t)}{dt} \tag{1}$$

Where *u(t)* is the controller response, and *e(t)* is the temporal error signal that feeds the controller, *Kp* is the proportional gain error, *Ti* is the integral time constant, and *Td* is the time constant of the derivative part. Transfer Function in the Laplace domain is given by Eq. 2:

$$\frac{U(s)}{E(s)} = K_p(1+\frac{1}{T_i s}+T_d s) \tag{2}$$

Individually, each part of the controller has the following functions (Ribeiro, 2005):

1. The proportional action stabilizes the process, leading to a correction proportional to the instant value of the error. It is primarily responsible for process stability.
2. Integral is an auxiliary action that eliminates the permanent offset (steady-state error) between the current measurement and the reference, producing a correction proportional to the length of the error, after the proportional action.
3. Derivative is an additional action that hastens the correction, generating an action proportional to the error change rate, before the proportional action. It should be used in processes with large inertia and suffering sudden changes, but should be avoided when there is much noise in the system, because the action would amplify this noise, thus damaging the system.

The design of vibration active control in this case consists of a proposed regulatory scheme, whereby vibration of the beam becomes zero. To ensure this situation of zero vibration, the PVDF sensor signal (or error signal) must be zero. Thus, the reference applied to the system to find the error that will feed the controller is zero, which represents the static system.

The block diagram in Figure 2 represents the active control system of a free cantilever beam. When applying a disturbance to the beam without control, we observe that the value of sensor output fluctuates around zero amplitude, as observed in Figure 3, until it stabilizes at zero. The damping factor of the beam and its friction with the air and the crimping during vibration are responsible for the stabilization of the beam around zero.

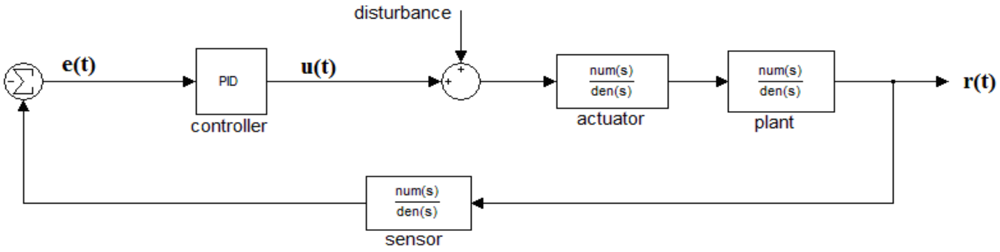

Figure 2 - Block diagram of the beam vibration control system

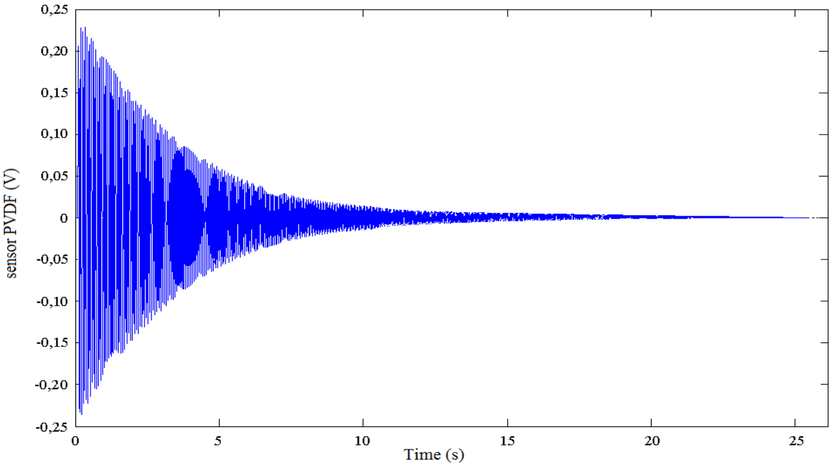

Figure 3 - Typical sensor output for a beam without control, with any input signal

The integrative part is mainly responsible for decreasing the steady-state error. The controller does this by adding the areas below the graph of the error between the curve and the abscissa axis. As mentioned, the system oscillates around zero, and the output of the system tends to zero in steady state, so the use of the integrative part is not justified. The derivative part is responsible for decreasing the time to fix the system by adding a restriction of the feedback system, which generates a response with some delay controlled by the constant derivative. Thus, as the goal is to stabilize the beam within the shortest time possible, it is interesting to use the derivative part. According to these responses, the controller being used in the control system is the PD. According to eq. 3, the controller is given by:

$$u(t) = K_p e(t) + K_p T_d \frac{de(t)}{dt} \tag{3}$$

There are several methods for tuning the proportional and derivative constants, K_p and T_d respectively, among them the method of Ziegler-Nichols and the relay. For the present study, these parameters were determined using the empirical method of analysis of responses in the simulations. In industry, the method based on trial and analysis of the response is the one most frequently used.

4. EXPERIMENTAL IDENTIFICATION SYSTEM

4.1. Trial bench

The bench for experimental tests consists of an aluminum beam fixed in order to obtain the clamped-free condition. The piezoelectric elements are the PVDF sensor and the PZT actuator, co-positioned on opposite sides of the beam, and set near the point of crimp, as can be seen in Figure 4. This position for a clamped-free beam was studied by Abreu (2003) and considers the criterion of minimum effort and maximum controller output energy using graminians of controllability and observability. Figure 5 shows the real thing.

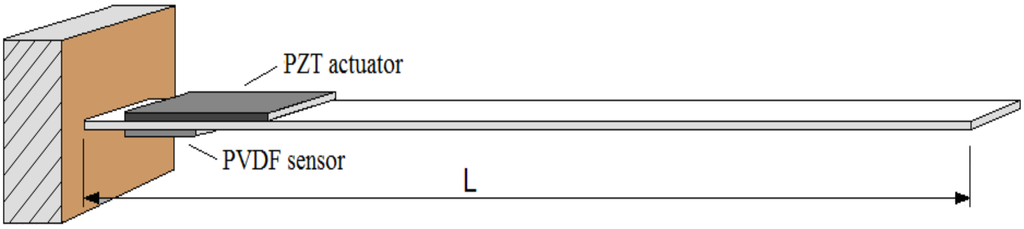

Figure 4 – Schematic presentation of the bench

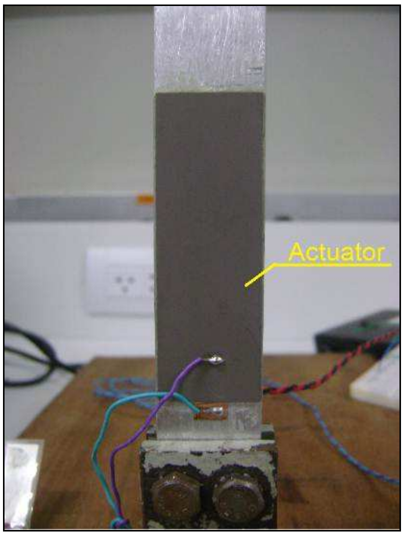

Figure 5 – PZT Actuator in the vertical beam

4.2. Electronic circuit for the sensor

To measure the potential difference of the sensor, an electronic circuit was built, like those used by Lima Jr. (1999) and Abreu (2003). The OPA129 operational amplifier used in the constructing of the circuit has high impedance and low input current. When connected in parallel to a capacitor, it converts the charge generated by the sensor into electrical voltage.

A voltage amplifier circuit was added to the output circuit using the UA741 operational amplifier. Figure 6 shown the complete circuit.

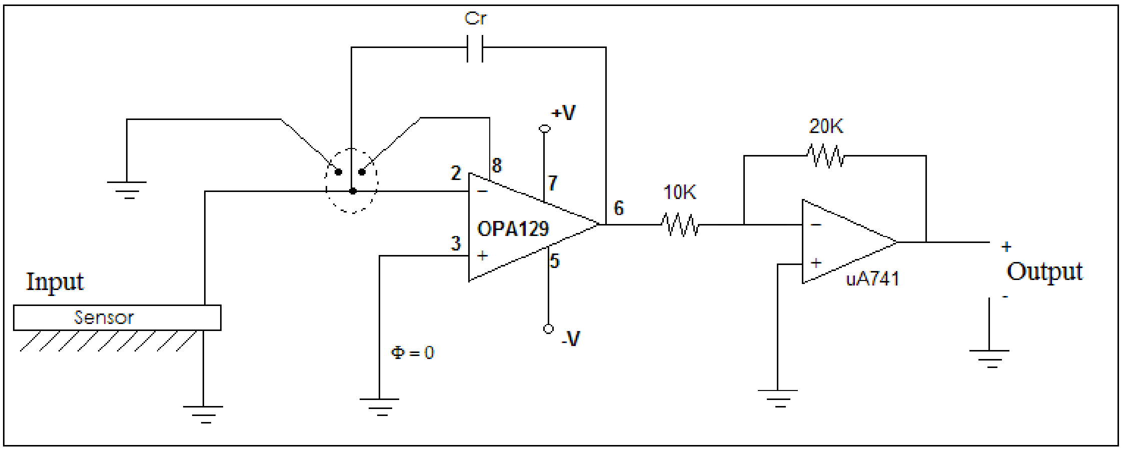

Figure 6 – Electronic circuit for the PVDF sensor

4.3. Identification test

Regarding the problem of active control of beam vibration, using experimental analysis, one can obtain a model (mathematical equation) capable of representing the behavior of the system. The model must reveal the effect caused in the beam in response to a certain input made in the actuator. In other words, it is the relationship between input and effect in the actuator beam perceived by the sensor. This model allows verifying the efficiency of the driver, facilitates the tuning of its parameters, and allows estimating the output of the system subjected to different disorders. One factor to be considered is the electronics of PVDF sensor, which is included into the system response. Figure 7 illustrates the layout of the experimental setup to test the identification of the beam.

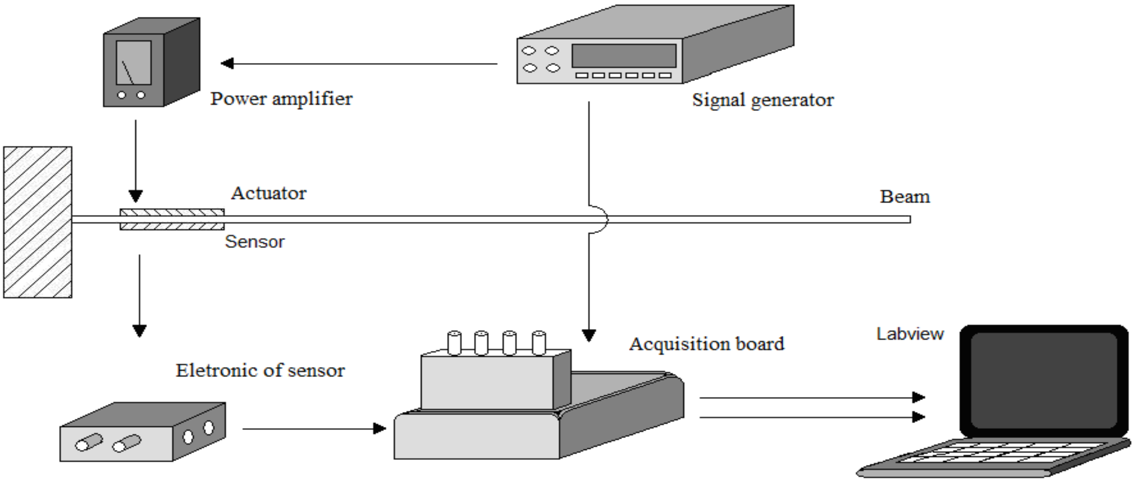

Figure 7 - Schematic presentation of the experimental assembly for model identification

With the test, a transfer function can be determined, which will be able to provide the mathematical relationship between an input applied to the PZT actuator and the beam response, measured by the PVDF sensor. For the identification of the system, the System Identification Toolbox of Matlab® was used, which provides an automatic approach to get the system model. For the system in question, the model that produced the best results was that based on the linear equation of differences (ARX), which relates the input and output as follows:

$$y(t) + a_1\, y(t-1) + \ldots + a_{na}\, y(t-na) = b_1\, u(t-nk) + \ldots + b_{nb}\, u(t-nk-nb+1) \quad (4)$$

where:
na: number of poles
nb: number of zeros + 1
nk: pure time delay (dead time of the system)

Figure 8 shows part of the experimental step response measured, and part of the step response simulated using the model identified in the time domain.

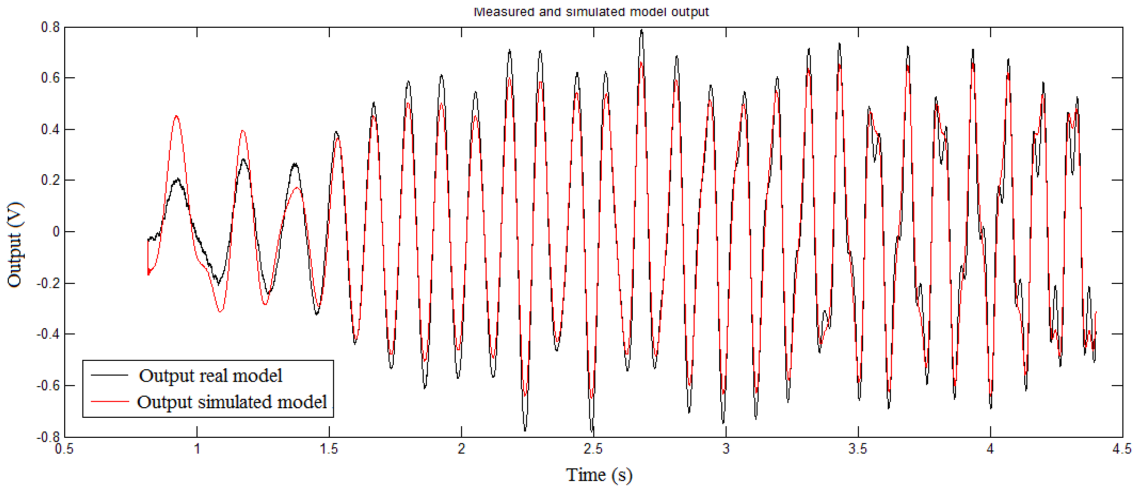

Figure 8 - Comparison between the experimental step response measured, and step response simulated with the identified model

Equation 5 features the transfer function (Gv), that represents mathematically the identified system and was used to do the simulations:

$$Gv(s) = \frac{1.311s + 8.547}{s^3 + 19.26s^2 + 2558s + 48400} \quad (5)$$

5. SIMULATION OF THE CONTROL SYSTEM IN SIMULINK ®

With the system model (Eq. 5) and PD controller (Eq. 3), simulations were performed to check if the driver actually meets the requirements of the main project, which is to decrease the vibration magnitude of the beam response, subjected to a disturbance. The control system should direct the beam to stabilize faster. Figure 9 shows the block diagram representing the control mesh used to simulate the system.

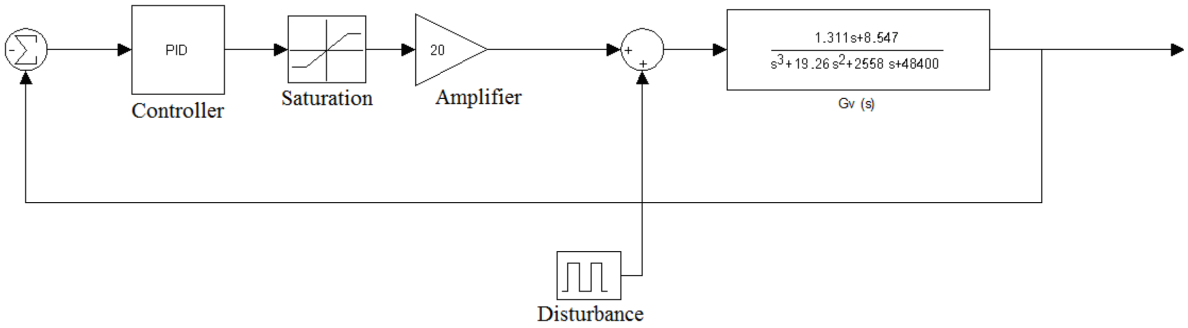

Figure 9 - Block diagram of the control system

The "Controller" block contains a PD controller, where the proportional and derivative gains were set. During the execution of several simulations for different values of proportional and derivative gains, the best observed combination was 100 and 5, respectively. These values resulted in the minimum settling time. The function of the “saturation” block is to limit the control signal, as in the real system. The “Gain” block represents the power amplifier that was used in experimental tests, which provides a gain of 20 in the control signal.

5.1. System response to a step input

Figure 10 shows the step responses of the controlled system and the system without control. It can be seen that while the beam without control vibrates a long time, the vibration of the controlled beam ceases quickly.

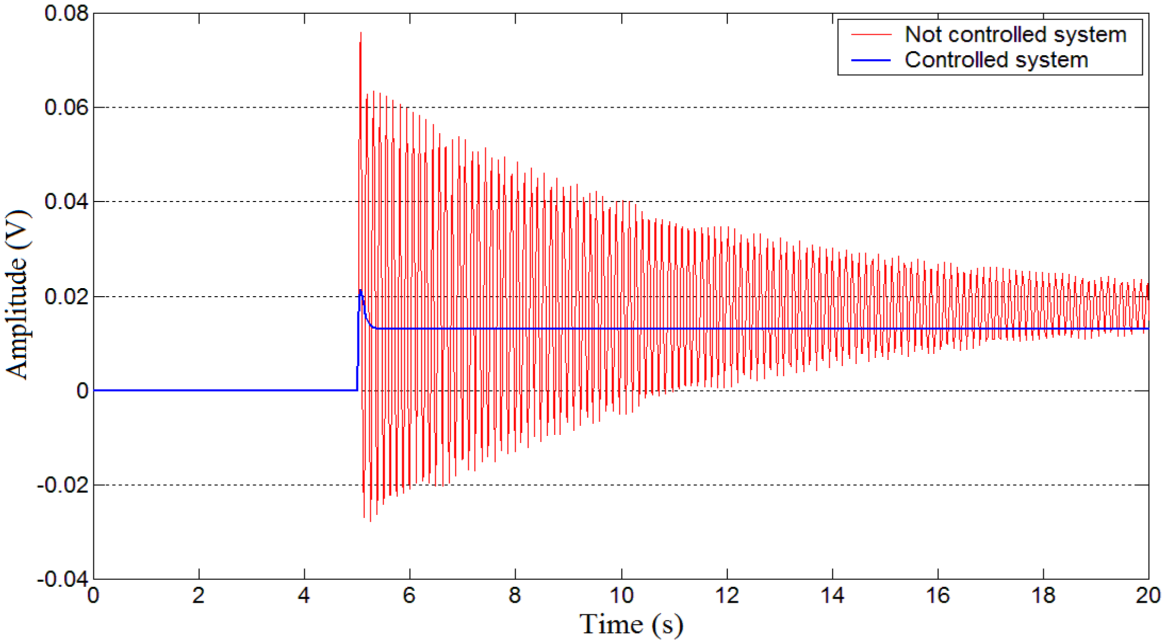

Figure 10 - Response of the free system and controlled system to a step input

Figure 11 shows the control signal, and the step response (x100) of the controlled system. We can see the opposition of the signs: while the controlled beam has a positive outlet, the control signal has a negative sign. This fact indicates the correct control action in order to stop the vibration of the beam, while the beam is suffering a continuous disturbance.

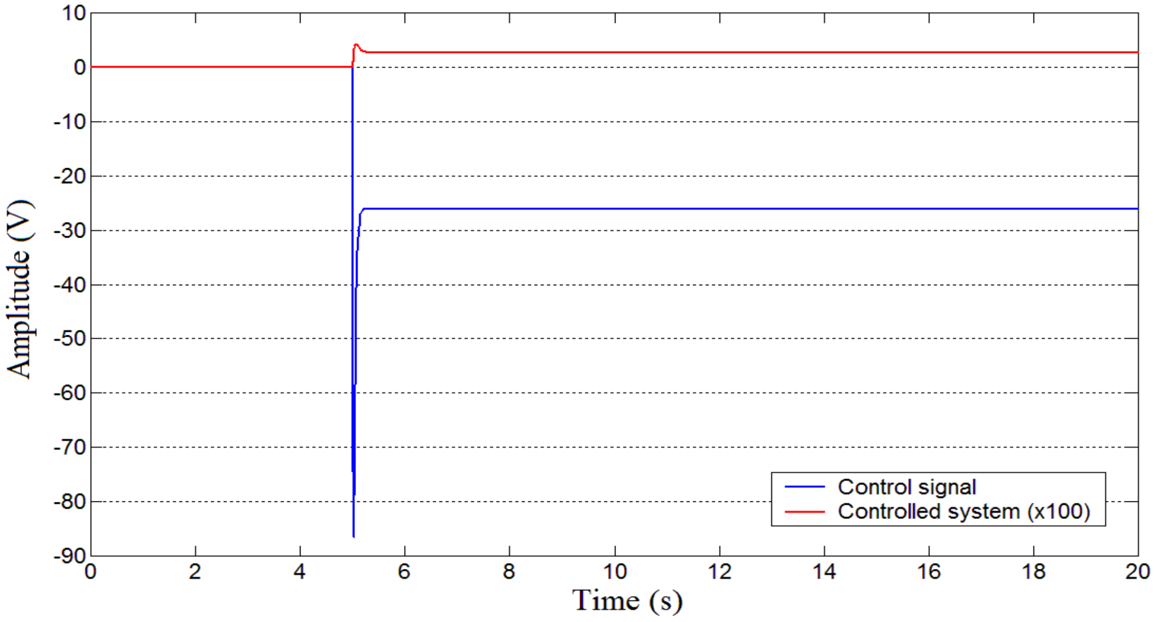

Figure 11 - Control signal and response (x100) of the controlled system to a step input

5.2. System response to the impulse

To check the system response to an impulse input, the block diagram of the Fig. 9 was used, with a 100 V disturbance impulse input. Figure 12 shows the simulated response of both free system and controlled system. It can be seen that after 20 seconds, the free beam is still vibrating considerably when compared to the controlled beam. The controlled beam has an initial overshoot, but stabilizes in less than 1 s.

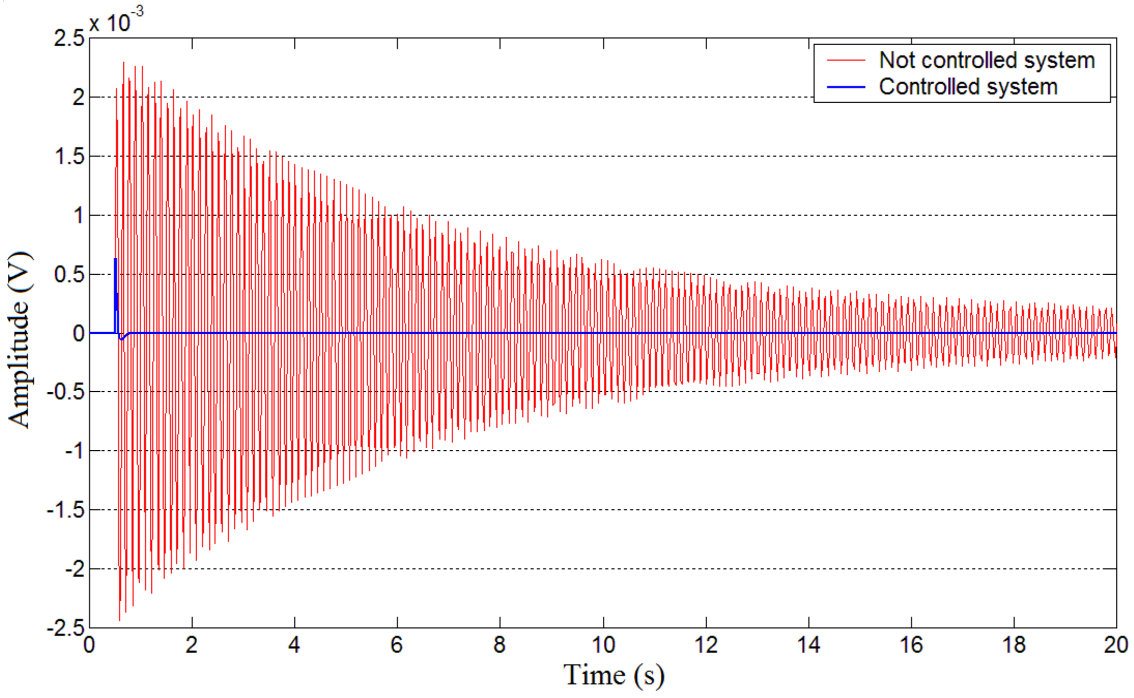

Figure 12 - Response of the free system and the controlled system to the impulse

Figure 13 shows the control signal and the impulse input response (x100) of the controlled system. It can be seen the action of the control system. At the first moment, when the response is positive, the control signal acts in the opposite direction, with high amplitude. Subsequently, the control signal acts stabilizing the beam. This fact also indicates the good functioning of the feedback loop in order to stop the beam displacement.

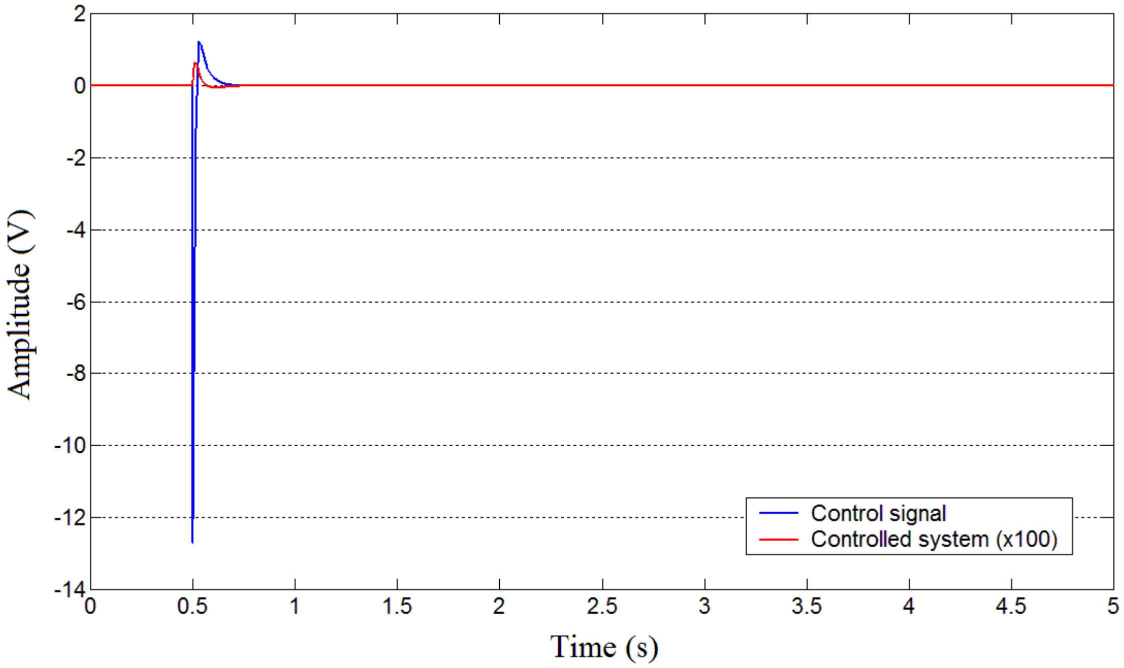

Figure 13 - Signal of control and impulse input response (x100) of the controlled system

6. CONCLUSIONS

A simple method was proposed for the active control of structural vibrations using smart materials. Among the materials most frequently utilized to solve this problem, the PZT piezoelectric ceramic and PVDF polymer proved to be relatively easy to use as actuator and sensor, respectively. The criterion used to position the elements was shown to be satisfactory. An identification test permitted to obtain a good mathematical model of the system. The PD controller demonstrated good efficiency in the control of structural vibration. In simulations, for the step and impulse inputs, vibration ceased very fast, with highly satisfactory stabilization. In practical implementation, there are limitations in the available power from amplifier, and limitation in the transference of force of PZT actuator to the beam, but good results can be expected.

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