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# ACTIVE CONTROL OF A THIN PLATE USING PIEZOELECTRIC PATCHES: PRELIMINARY RESULTS

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**Abstract:** Due to problems caused by noise and vibration in industrial environment and in human daily life, techniques of active noise and vibration control have received increasing attention lately. More recently, the use of piezoelectric elements in noise and vibration control systems has been investigated. The present paper addresses techniques of active control by employing multiple piezoelectric patches bonded to the surface of thin plate with relatively small dimensions suitable for laboratory tests. A fuzzy control is used in the active control. The paper brings the development of a finite element model of the system and presents some numerical simulations. Experimental implementation is realized aiming at attenuating the vibration modal amplitudes of the plate.

## 1. INTRODUCTION

The existence of vibrations in several types of structures, as originated by external or internal disturbances, causes a reduction in the life time of the system, demands more frequent periodic maintenances, generates noises that disturb the environment and, in certain situations, can cause mechanical fatigue.

Recently, a new proposal for vibration control in flexible structures has been investigated by several researches [1]. The idea is that the response of a structure can be minimized by using active elements, such as sensors and actuators constituted of piezoelectric materials. The piezoelectric ceramics develops an electrical field, when subjected to a force (or pressure) and, conversely, a mechanical deformation results, when the ceramics is subjected to an electrical field. This is the piezoelectric phenomenon, that found application in several areas of the science and technology, particularly, in the control of flexible structures [2].

In [3] the vibration control of a panel type structure by the action of a single-sheet piezoceramic adhesively bonded to the surface of the panel is presented. The control is achieved by means of a digital control law that artificially increases the damping of the modes which dominate the panel response. The results show that panel vibrations may be successfully controlled through the action of distributed piezoceramic actuators. A technique by which the random vibration of a rectangular panel is controlled by means of a pair of thin-sheet piezoceramic actuators is presented in [4]. In that paper a procedure to determine the actuators and sensors locations based on the modes to be controlled is discussed. Experimental results, which demonstrate that significant reductions in vibration levels are achieved globally, are presented.

The fuzzy logic became in the last years an interesting option in the solution of problems for several engineering applications. Its use in control has been important in the last years, because it makes possible to implement control in systems that involve vague, imprecise and no appropriately quantified information. Unlike the classical control theory, of which main requirement is the knowledge of the system models to be controlled (exact equations and numerical values), the fuzzy logic allows to work with complex systems using a high abstraction, based on the knowledge and experience of the designer about the system. Fuzzy logic control has a smaller number of steps to be implemented, as compared to classical control. As a result, the fuzzy control reduces the development time. Another important characteristic is the robustness of the solution, which provides a good performance even in the presence of variations and uncertainties in the parameters of the physical systems [2].

This work proposes the control of a system constituted by a thin steel plate with bonded piezoelectric actuators. It is aimed at reducing the level of plate vibrations by using a simple active controller based on fuzzy logic. In this preliminary stage, the controller should be able to reduce vibration level in the case a mode is excited.

## 2. EXPERIMENTAL SET-UP

The system to be controlled consists of a thin plate of steel with bonded piezoelectric actuators. The geometry of the plate is defined as follows: 400 mm length, 300 mm wide and 1 mm thickness. Two piezoelectric actuators QP-10N, ACX (*Active Control eXperts*), are used, whose dimensions are: 45.974 mm × 20.574 mm × 0.254 mm [5]. The location of the actuators in the plate is determined according to the vibration mode to be controlled, and will be discussed in the following. The supply of the piezoelectric actuators is provided by a single power amplifier, QuickPack Power Amplifier – Model EL 1224, ACX [5]. An electrodynamic shaker is rigidly coupled to the centre of the plate, being responsible for exciting the plate continually in a given frequency. The borders of the plate are free. Two proximity probes are used to measure the vibration signals of the plate. Only one of these sensors is used in the control loop. The other sensor is used to monitor the vibration of the plate in a different position. The experimental set-up is shown in the Figure 1. The system consists of the steel plate, piezoelectric actuators (bonded to the plate), electrodynamic shaker and proximity probes.

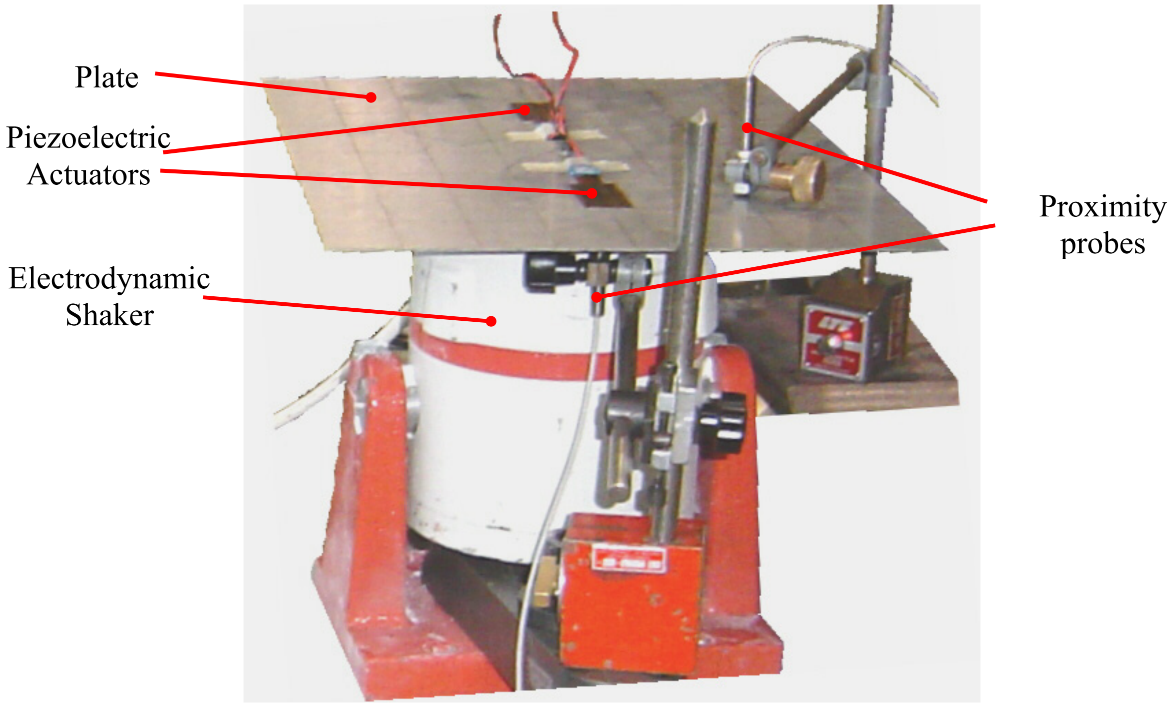



*Figure 1: Experimental set-up.*

A scheme of the control system used is shown in Figure 2. The control algorithm and the data acquisition system are incorporated to the computer. The control algorithm was developed in Matlab/Simulink® and was compiled and loaded in a dSpace® board, model DS1102. The control scheme is shown in Figure 7.

The control signal, calculated as a function of the sensor input, leaves the acquisition system, goes to the low-pass filter and then to the power amplifier for the piezoelectric actuators. This power amplifier is responsible for introducing a gain of 20 times to the input signal, to supply the actuators. A proximity sensor, placed below the centre of one of the actuators, is used to measure the displacements of the plate, and its signal goes to a conditioner and a summation system before going to the acquisition system. The summation system is required to subtract the constant voltage due to the air gap between the sensor and the plate. The signal from the other sensor is acquired for subsequent analysis. During the control process the plate is excited in its centre by a sinusoidal displacement with constant amplitude and constant frequency, by means of the electrodynamic shacker driven by a sinusoidal signal at the desired frequency and a power amplifier.

An analogical low-pass filter of the RC type, with cut-off frequency at 300 Hz was used to filter the output of the acquisition system, because the sampling rate of 2 kHz introduces high-frequency components, which are passed forward to the actuators. It is not desirable to have these high-frequency components exciting the plate, because it is very sensitive to them.

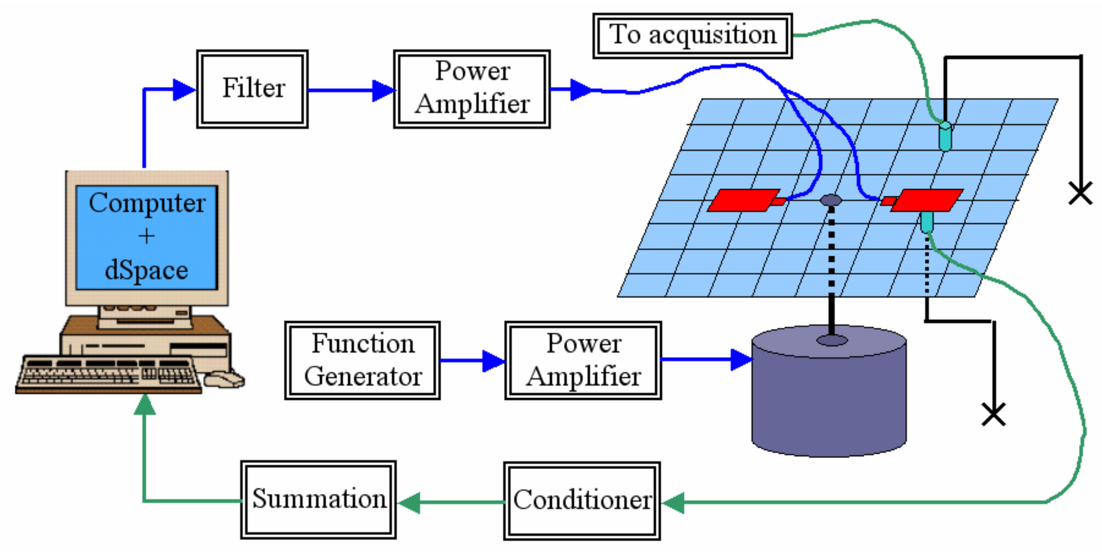



*Figure 2: Scheme of the control system.*

## 3. SIMULATION RESULTS

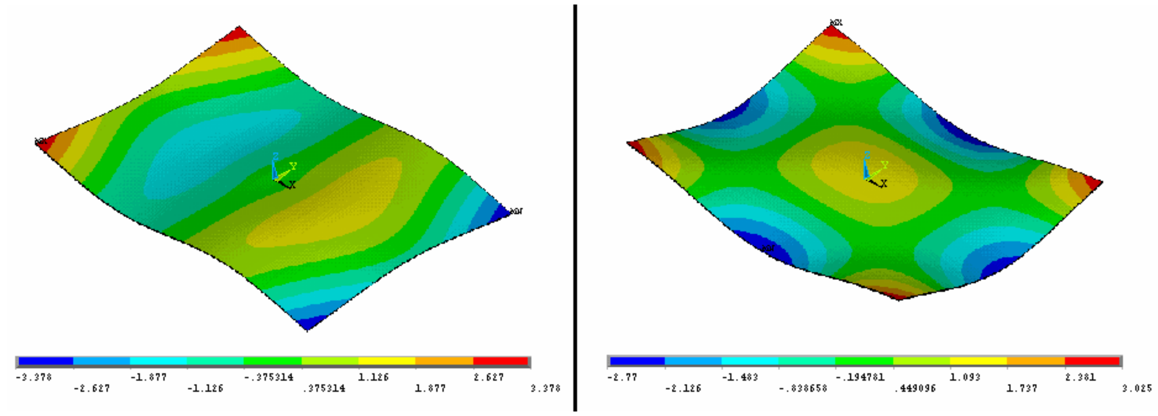
A finite element model of the plate with bonded piezoelectric actuators was developed in Ansys®. The Solid 45 element was used for modelling the plate and the Solid 5 element was used for the piezoelectric ceramic. The displacements of the centre of the plate are restricted along the horizontal directions (X and Y). This way it is possible to approximate numerical simulation to the experimental case (steel plate coupled to a shaker in the centre).

### 3.1 Modal Analysis

A modal analysis of the steel plate alone (without the piezoelectric actuators) was conducted aiming at choosing the mode to be controlled. The first 14 vibration modes of the plate are presented in Table 1. For illustration purposes two vibration modes are presented in Figures 3(a) and 3(b).

*Table 1: Frequencies of the vibration modes of the plate.*

| Mode | Frequency (Hz) | Mode | Frequency (Hz) |
|---|---|---|---|
| 1 | 27.9 | 8 | 136.1 |
| 2 | 33.0 | 9 | 176.9 |
| 3 | 61.4 | 10 | 185.8 |
| 4 | 69.8 | 11 | 191.3 |
| 5 | 80.9 | 12 | 218.2 |
| 6 | 106.0 | 13 | 219.3 |
| 7 | 126.9 | 14 | 267.7 |




(a) (b)

*Figure 3: (a) 6th vibration mode – frequency 106 Hz;*
*(b) 8th vibration mode – frequency 136 Hz.*

The vibration modes shown in Figures 3(a) and 3(b) were chosen to be controlled separately. However, in the frequency corresponding to the 8th vibration mode (136 Hz – numerical value) it was verified experimentally that the gain of the system was too low. Consequently, the interest was concentrated on reducing the vibrations of the 6th mode shape, whose frequency is approximately 106 Hz.

### 3.2 Harmonic Analysis

A harmonic analysis of the 6th vibration mode of the plate was accomplished to find the best location of the piezoelectric actuators. The plate was excited in the centre by a harmonic force of 10 N (peak value) in the frequency of 106 Hz. The total deformation of the plate in the harmonic analysis is shown in Figure 4. The larger bending deformation for the 6th mode and the highest surface strains occur in the areas where two rectangles represent the piezoelectric actuators. Therefore the actuators are symmetrically located with respect to the length of the plate, so that the centres of these actuators are a 100 mm distant from the centre of the plate.

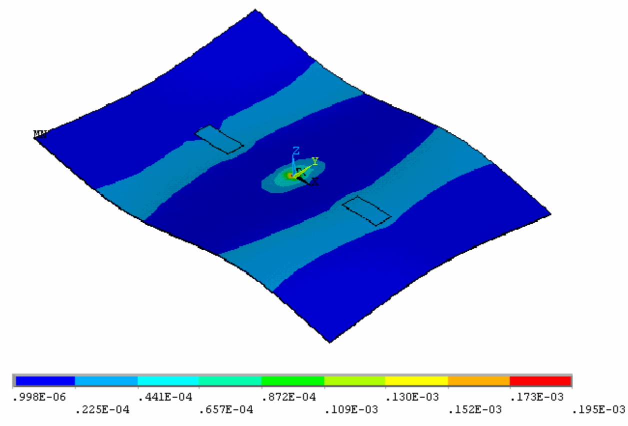



*Figure 4: Total deformation of the plate – harmonic analysis at the frequency of 106 Hz.*

## 4. EXPERIMENTAL RESULTS

In laboratory conditions, first the vibration modes of the plate without the piezoelectric actuators were verified experimentally, then the tests with the fuzzy active controller were accomplished.

### 4.1 Modal Analysis of the Plate

The plate was excited by the shaker by using a white noise signal for the verification of the natural frequencies without piezoelectric actuators. The proximity sensor was positioned in several points of the plate and the natural frequencies were identified analysing the frequency response functions (FRFs) of the system. For both experimental and numerical results, the frequency values have shown to be very close in the spectrum. This is more evident for the lower frequencies. The vibration modes corresponding to the identified natural frequencies were verified experimentally. The plate was excited at its centre by using a sinusoidal signal at each identified natural frequency. A uniform layer of chalk powder was used to cover the plate before beginning the test. The chalk powder on the plate tends to accumulate at the nodal lines of the modal shape corresponding to the frequency used, as shown in Figures 5(a) and 5(b). By comparing figures 5(a) and 3(a) and also figures 5(b) and 3(b), good correlation is observed.

(a) (b)

*Figure 5: (a) 6th vibration mode – frequency 99 Hz; (b) 8th vibration mode – frequency 138 Hz.*

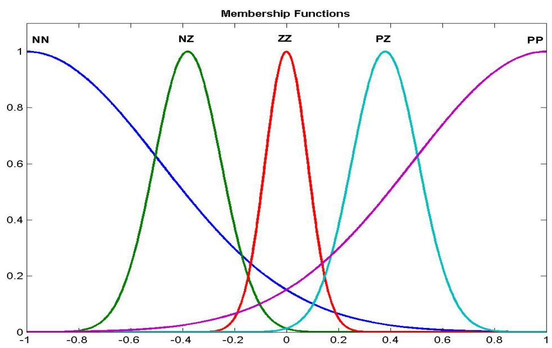
To reduce the vibration level of the plate in the frequency of 99 Hz was adopted as objective for the fuzzy active controller, because the vibration mode corresponding to this frequency is very symmetrical. This configuration is compatible with the position of the two actuators, which can be fed by the same voltage, but opposite in sign.

### 4.2 Fuzzy Control

One of the advantages of the fuzzy controller is that mathematical models are not necessary. In the present contribution, a simple fuzzy controller with two inputs and one output was designed. The controller inputs are the following: 1) the signal error between a zero reference and the signal of the proximity probe, and 2) the signal corresponding to the time derivative of the error.

Five membership functions of gaussian type were used for each input. These functions can be seen in Figure 6 and they are vaguely defined as: NN (very negative), NZ (negative), ZZ (null), PZ (positive) and PP (very positive). The output of the fuzzy controller correspond to the Sugeno type of zero order with five constant value functions: NN = –1.0; NZ = 0.5; ZZ = 0.0; PZ = 0.5; and PP = 1.0. The range of the input and output values of the fuzzy controller are normalized between –1.0 and +1.0.

The designed controller has scale factors of 2 and $3.10^{-3}$ for the input error and error variation, respectively. A scale factor of 5 is used for the output. For this output gain, the maximum voltage in the piezoelectric actuators is 100 V, considering the power amplifier gain (20 times). The rule base of the designed fuzzy controller is shown in Figure 6. The first rule of the table states: if the error is NN (very negative) and the variation of the error is NN (very negative), then the control output is PP (very positive). More details regarding fuzzy controllers can be found in [6].




*Rule Base*

| | | Error Variation | | | | |
|---|---|---|---|---|---|---|
| | | NN | NZ | ZZ | PZ | PP |
| Error | NN | PP | PP | PZ | PZ | ZZ |
| | NZ | PP | PZ | PZ | ZZ | NZ |
| | ZZ | PZ | PZ | ZZ | NZ | NZ |
| | PZ | PZ | ZZ | NZ | NZ | NN |
| | PP | ZZ | NZ | NZ | NN | NN |

*Figure 6: Membership functions of the fuzzy controller and rule base.*

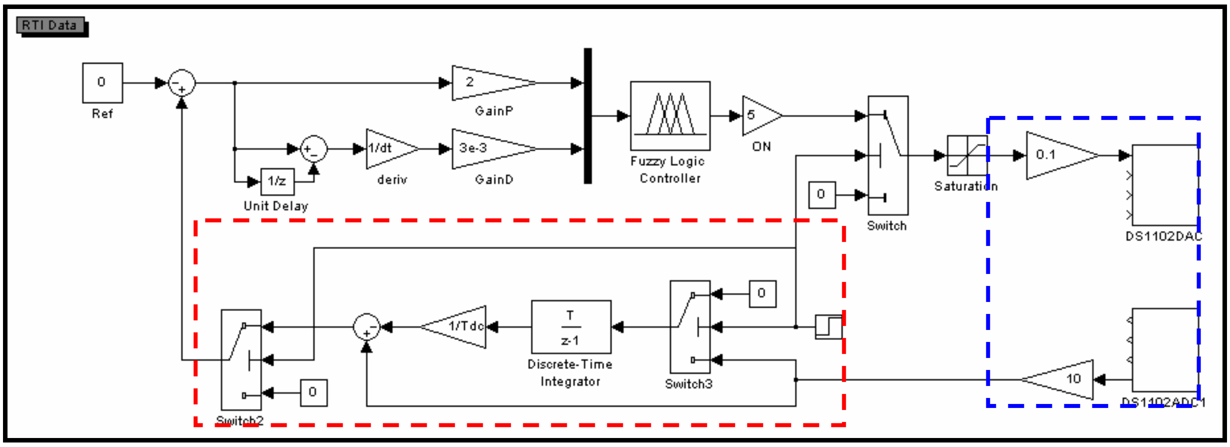



*Figure 7: Scheme of the implemented fuzzy control.*

A scheme of the implemented fuzzy controller is shown in Figure 7. The blocks encompassed by the red rectangle are responsible for estimating the average value of the proximity probe signal. This value will later be subtracted from the acquired signal. The acquired signal has not a zero value at the equilibrium position of the plate. The blue rectangle encompasses the blocks responsible for the input and output process of the signals. The other blocks in the figure refer to the fuzzy controller system.

The response of the controlled system in the frequency of 99 Hz is shown in Figure 8. The controller starts to operate for t = 0.3 s (see Figure 8). The Power Spectral Density (PSD) of the system without control and of the controlled system is presented in Figure 8. It is possible to observe that the controller reduced the vibration level by 17.6 dB (7.6 times). Also, the controller was able to reduce the vibration level in the frequency of 198 Hz (one of the harmonics of the system response).

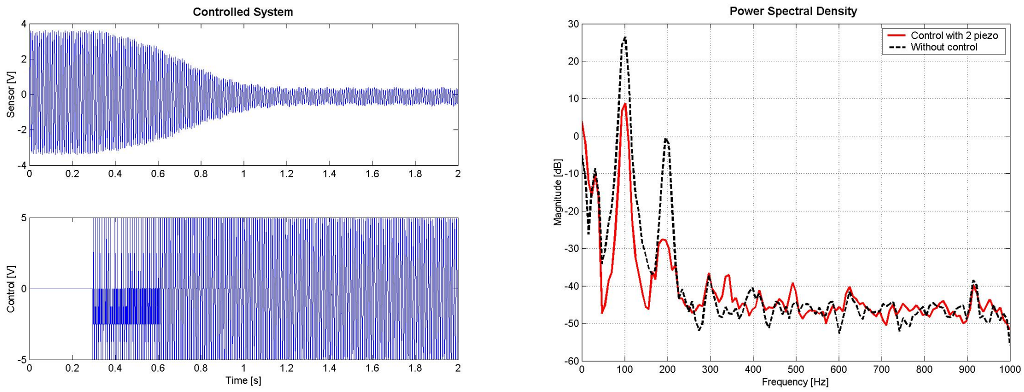
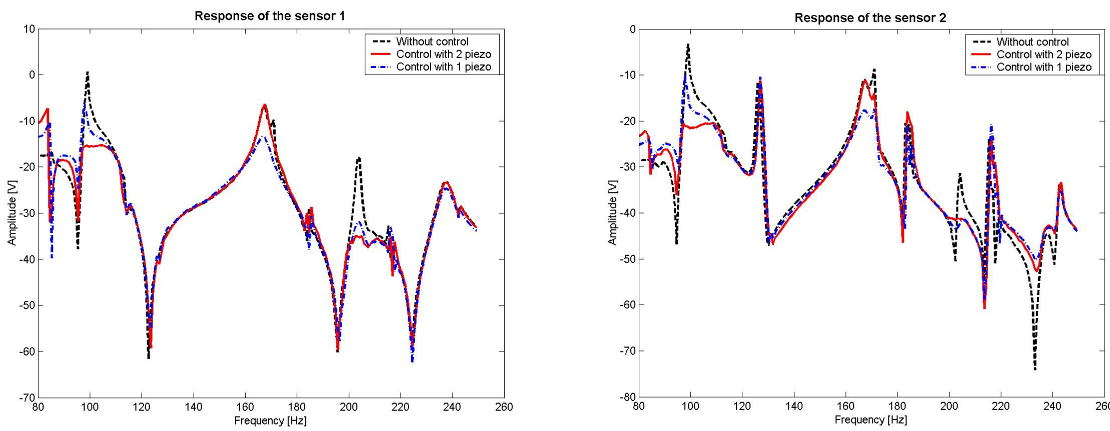



*Figure 8: System response for the excitation at 99 Hz.*

In Figures 9(a) and 9(b) the frequency response functions of the system without control, the controlled system with a single piezoelectric actuator and the controlled system with two actuators driven by a single control signal are shown. For the controlled system with one and two actuators the same fuzzy controller is used. The response of the sensor used in the control loop (sensor 1) is shown in Figure 9(a). Figure 9(b) shows the frequency response function of the sensor 2 whose centre is located at (100 mm, 75 mm) on the XY plane. The signals used to estimate the FRFs shown in Figure 9 are respectively the input signal of the shaker power amplifier and the output of the summation device (see Figure 2).




(a) (b)

*Figure 9: Frequency response of the system: without control, controlled with one actuator and controlled with two actuators.*

Analysing the results shown in Figure 9 interesting behaviour is detected. In the region close to 99 Hz, the vibration mode for which the controller was designed, the controller with a single actuator reduces the vibration level of the plate. However, when two actuators are used simultaneously the reduction is more effective. The use of two piezoelectric patches is more effective for this mode, because the excitation voltage applied to one piezoelectric is inverted with respect to the voltage applied to the other (see vibration mode in Figure 3(a)).

A resonance is shown by sensor 2 at 125 Hz, which is an antiresonance (nodal point) for sensor 1. As the actuator is applied according to sensor 1, the resultant effect on this mode shape is obviously null. A similar situation occurs also at the frequency of 185 Hz. In the frequency equal to 167 Hz, the use of a single actuator reduces the vibration level. However, with two actuators no modification in the FRF is verified. Probably the system is modulated in two mode shapes, because the spectrum shows the existence of two close frequencies. In this frequency one actuator competes with the other and, to obtain good performance, the voltage polarization of one of the piezoelectric actuators should be inverted. Close to 203 Hz, both the controllers with one and two piezoelectric actuators showed good performance. Experimentally, the modal shape in this frequency corresponds to the modal shape shown by Figure 10. For this modal shape the location and voltage polarization of the piezoelectric actuators are appropriate. However, the controller should be designed again if higher reduction in the vibration level of the plate is desired.

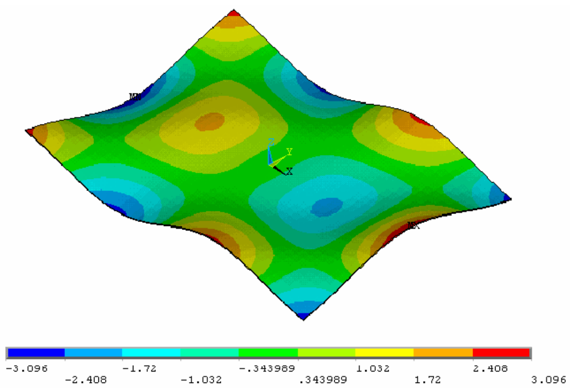



*Figure 10: 13th vibration mode;*
*numerical frequency: 219 Hz – experimental frequency: 203 Hz*

Adaptive systems, which optimize the scale factors of the fuzzy controller (range of inputs and outputs), the membership functions and/or the rule base, can be used to improve the performance of the fuzzy controller and to facilitate the design process. In [7] a fuzzy adaptive controller with a structure similar to a PID (proportional-integral-derivative) controller was developed. The scale factors of the fuzzy controller are adapted continuously along the process and the controller is stable for all tested cases. In [2] and [8], fuzzy controllers were implemented in low cost microprocessors, such as PIC16F877 from *Microchip*, and applied to the vibration control of a flexible beam with piezoelectric actuators incorporated. In [8] an adaptation mechanism is responsible for optimizing the scale factor of the controller input.

## 5. CONCLUSIONS

The use of a simple fuzzy was shown to be efficient for the control of a plate vibration mode. When the plate is excited at various frequencies the active control can become uneffective due to one or a combination of the following reasons: the voltage polarization applied to the piezoelectrics is not correct; and the position of the piezoelectrics is not optimal for that particular mode to be controlled; the controller is not adequate. The design of more complex fuzzy controllers can be considered for the simultaneous control of several modal shapes of the plate.

In this work, two actuators were used as driven by a single control signal and a single sensor was used in the control loop. Only few modes of the plate can be controlled by using this set-up: only the modes for which position and voltage polarization are suitable. In more complex situations for which several modes have to be controlled simultaneously, it is necessary to use various sensors and actuators fed by independent power amplifiers. Both fuzzy and robust control techniques should be investigated as potential candidates for those cases [9].

The finite element modelling of the plate with and without bonded piezoelectric actuators was an effective tool in the understanding of the dynamic behaviour of the system. The position of the actuators and the design of the controller strongly depend on the dynamic behaviour of the plate.

## 6. ACKNOWLEDGEMENTS

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## 7. REFERENCES

[1] G.W. Taylor, J.J. Gagnepain, T.R. Meeker, T. Nakamura and L. A. Shuvalov, Piezoelectricity – Ferroelectricity and Related Phenomena, Gordon and Breach Science Publishers, Vol. 4, 1985.

[2] G. L. C. M. Abreu and P. M. Cardoso, Applications of Fuzzy Controllers in Micro-Controllers to the Control of Vibrations in Flexible Beam Type Structure (*in Portuguese)*, Proceedings of COBEM 2001, Vol. 15, 184-193, Brazil, 2001.

[3] J. D'Cruz, The Active Control of Panel Vibrations with Piezoelectric Actuators, Journal of Intelligent Material Systems and Structures, Vol. 4, 1993.

[4] J. D'Cruz, Global Multivariable Vibration Control with Distributed Piezoceramic Actuators, Journal of Intelligent Material Systems and Structures, Vol. 6, 1995.

[5] Mide Technology Corporation, www.mide.com.

[6] R. E., Uhrih and L. H. Tsoukalas, Fuzzy and Neural Approaches in Engineering, John Wiley & Sons, New York, USA, 1997.

[7] P. M. Cardoso, J. F. Ribeiro, R. L. Teixeira and I. J. C. Nuñez, A New Adaptive Fuzzy PID Controller applied to Mechanical Systems Control (*in Portuguese*), CONEM2002, Brazil, 2002.

[8] I. J. C. Nuñez, J. F. Ribeiro and P. M. Cardoso, Adaptive Fuzzy Control of a Flexible Beam Through Microcontrollers (*in Portuguese*), CONEM2002, Brazil, 2002.

[9] H. Kwakernaak and R. Sivan, Linear Optimal Control Systems, John Wiley & Sons, ISBN 0-471-51110-2, 1972.