DAMAGE IDENTIFICATION AND CHARACTERIZATION IN A FLEXIBLE STRUCTURE USING PIEZOELECTRIC SENSOR AND ACTUATOR

Angelo Emiliavaca, angelosite2003@hotmail.com
Abdias Gomes dos Santos, engmec_abdias@hotmail.com
Zoroastro Torres Vilar, zoro.ufcg@gmail.com
Universidade Federal de Campina Grande – UFCG, Unidade Acadêmica de Engenharia Mecânica – UAEM, Av. Aprígio Veloso, 882, Bairro Universitário, CEP: 58429-140, Campina Grande – PB, Brasil

Rômulo Pierre Batista dos Reis, soromulo@hotmail.com
Universidade Federal Rural do Semi-Árido – UFERSA, Dep. de Ciências Ambientais e Tecnológicas, BR 110 - Km 47, Bairro Pres. Costa e Silva, CEP 59.625-900, Mossoró – RN, Brasil

Cícero da Rocha Souto, cicerosouto@hotmail.com
Universidade Federal da Paraíba – UFPB, Departamento de Engenharia Elétrica – DEE, Cidade Universitária, João Pessoa – PB, Brasil.

Carlos José de Araújo, carlos@dem.ufcg.edu.br
Universidade Federal de Campina Grande – UFCG, Unidade Acadêmica de Engenharia Mecânica – UAEM, Av. Aprígio Veloso, 882, Bairro Universitário, CEP: 58429-140, Campina Grande – PB, Brasil.

Abstract. *Mechanical systems subjected to cyclical movements with variable mechanical loads require special attention concerning damage of components caused by fatigue. In many cases, there is the appearance of cracks that propagate until complete failure of the mechanical element. This fact justifies the need of scientific studies combined with technological development that can originate new methods to identify the mechanical damage in an initial phase. The early identification enables the correction before complete failure of the mechanical component. The methods for damage identification and characterization generally use a physical mechanism that acts on the structure, and a mathematical method for data processing and analysis. The most common methods used today are able to identify the defect in the structure, but only in an advanced stage of severity. Those most sophisticated performing better, but the costs involved are usually high. This paper proposes a methodology based on transmission and reception of sinusoidal wave signals applied to a structure using piezoelectric elements. This methodology analyzes how the propagation of the wave emitted in the natural frequency of vibration of the structure is affected by the presence of mechanical defects, identifying and characterizing the failure with respect to its severity. Experimental results were obtained using a single cantilever aluminum beam with two piezoelectric elements bonded, one at each extremity of the beam. In this method, the piezoelectric element near the clamp is used to promote the oscillating motion while the one placed at the free end is used to read the vibration signals. Thus, a piezoelectric element acts as actuator and the other as sensor. A simulation procedure using finite element software was used to determine the natural frequencies of the beam with and without damage. Results are presented for comparison between the values of theoretical and experimental frequencies, also involving the severity of the failure.*

***Keywords**: Piezoelectric Actuator, Piezoelectric Sensor, Mechanical Vibration, Structural Failure, Damage Identification.*

1. INTRODUCTION

The piezoelectric effect was discovered in 1880 in quartz crystals and has since led to numerous investigations for the development of electromechanical transducers. The effect is basically the conversion of mechanical energy into electrical energy, named direct piezoelectric effect. Subsequently, by thermodynamic analysis, it was observed the existence of the inverse piezoelectric effect which consists in the appearance of a deformation of the material in response to an electric field. By 1947 it was discovered that polarized ferroelectric ceramic barium titanate, had the piezoelectric effect, marking the beginning of the generation of piezoceramics. Studies of solid solutions during 50 years have resulted in obtaining ceramics of lead zirconate titanate (PZT), which have become subject of frequent investigations for the optimization of its properties or as motivation for the development of new ceramic compounds. Currently, piezoelectric materials are used as sensors and/or actuators in technological applications, from low frequencies up to frequencies around 10 GHz. For low frequencies applications mainly polycrystalline materials (ceramics, polymers and composites) are adopted and for high frequencies, single crystals and thin films are used. Figure (1) presents a physical model of a piezoelectric rectangular plate highlighting the directions of mechanical deformation and electrical polarization. Conventionally, it has been adopted to represent the directions of deformation and application of voltage indices 1-1 for the length, 2-2 for the width and 3-3 for thickness of piezoelectric plate (Mallik 2005).

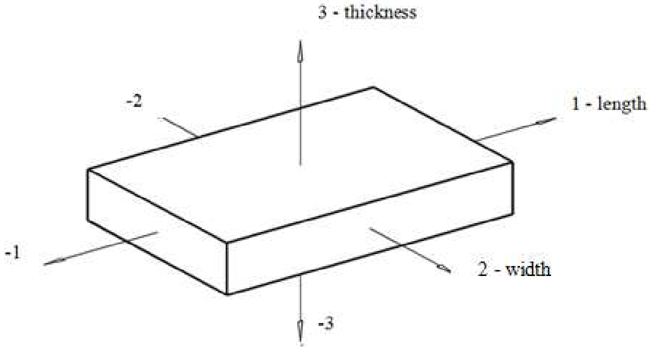


Figure 1. Directions of deformation and polarization of a piezoelectric plate.

The use of piezoelectric materials has increased significantly over the past decade, by new technological applications as actuators, sensors and generators of electricity.

Compared with other conventional actuators, like shakers and speakers, the piezoelectric actuators demonstrate superior characteristics, due to its lightweight and small size (Gardonio et al., 2003, Gardonio et al., 2004). Thus, several studies with smart panels have been developed in an attempt to reduce vibrations and/or noise using piezoelectric actuators (Souto, 2008, Park et al. 2000). However, it is not always possible to get adequate levels of reduction, and in this case, some researchers have studied the possibility of using hybrid actuators formed by PZT and PVDF (Fluoride polivinidileno) (Kaizuka & Tanaka, 2006).

When used as a sensor, the piezoelectric elements perform well, especially for being able to detect small variations of deformation. As actuators, it can be used in a relatively large range with respect to the frequency, with reasonable force capacity. The direct piezoelectric effect of these materials has now been well explored with the intention of generating electricity.

In this context, this work propose a methodology for damage identification and characterization based on transmission and reception of sinusoidal wave signals applied to a structure using piezoelectric elements. Basically, this methodology analyzes how the propagation of the wave emitted in the natural frequency of the structure is affected by the presence of mechanical defects, identifying and characterizing the failure with respect to its severity.

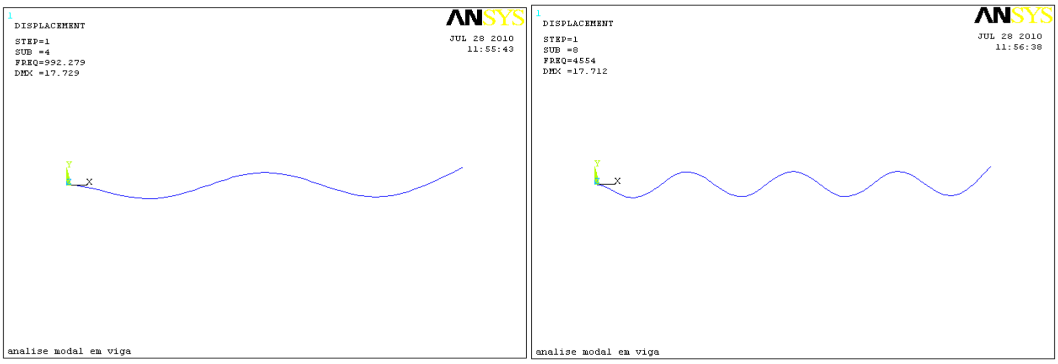
2. MATERIALS AND METHODS

The methodology used for the development of this work is divided into two main parts: simulation (theoretical model) and experiment. For simplicity, the mechanical system chosen was a single cantilever aluminum beam whose dimensions are optimized by the simulation process.

2.1 Simulation

A model for the studied beam was created and simulated using finite element method (FEM) in commercial software. The clamped end only allowed movement of translation with respect to its vertical axis. To define the geometry of the system, several analyses were performed by varying gradually the dimensions of the beam. In theses analysis the main variables of interest were the values of the natural frequency of the structure, which is directly related to its geometry, and the behavior of the vibration modes. This procedure allows determining the best location for the piezoelectric sensor aiming greater strain for the various frequencies analyzed.

The results of these simulations come to a beam with 169 mm of free length, 28 mm in width and 1 mm of thickness. Figure (2) shows the behavior of the optimized beam in the fourth and eighth vibration modes with its associated natural frequencies. These modes were taken as reference because are considered be most influenced by the existence of the mechanical fault.



(a) (b)

Figure 2. Vibration modes of the single cantilever aluminum beam. (a) Fourth mode - 992 Hz. (b) Eighth mode - 4554 Hz.

Once defined the geometry of the beam, it was necessary to choose which type of failure would be introduced and how to characterize its severity, and then start the investigation of the theoretical behavior of the beam after the introduction of the failure. Thus, the failure was characterized as a reduction of cross section in the center of the beam by gradually varying thickness up to 70% of the initial value, keeping the width of fault in 1 mm. Based on these parameters it was possible to characterize the failure severity of two ways, one based on the geometry (thickness reduction in a particular section) and another in mass (mass removal in the particular section).

2.2. Experiment

From the parameters obtained in the simulation it was developed an experimental test bench based on an aluminum beam bolted to a steel block.

To start the experimental procedure, impact tests were carried out before and after bonding of the PZTs in order to verify the compatibility of the experiment with the simulated model, as well as to obtain an initial vibration signature of the structure. During this procedure it was employed one accelerometer placed at the free end of the beam and the signal was monitored through an acquisition board compatible with the LabView software. The results of the signal in the time domain and its corresponding signal in the frequency domain after applying the fast Fourier transform (FFT) are shown in Fig (3).

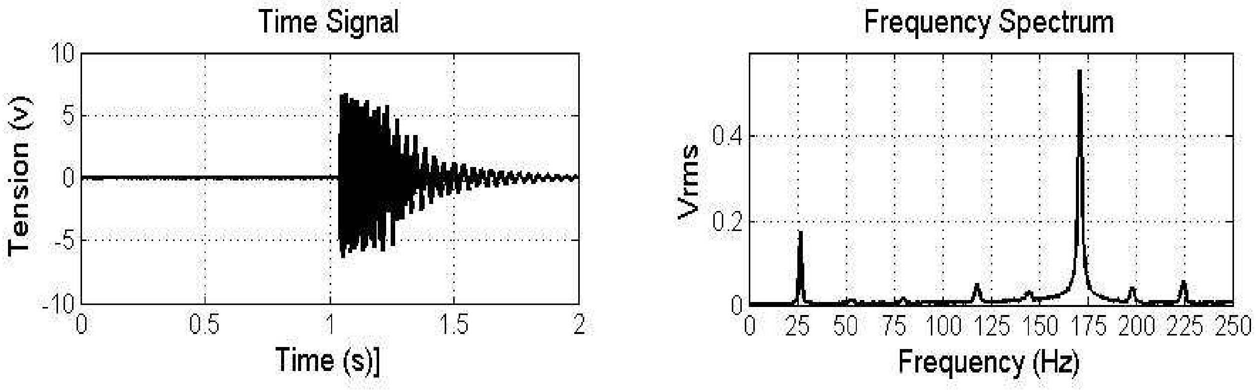


Figure 3. Signal vibration of the beam without failure in the time and frequency domains, respectively.

Based on the data from measured frequencies it was possible to verify that the experiment was consistent with the model. Following the proposal of the work, it was installed two PZT plates with dimensions of 32 mm in length and 28 mm wide, one next to the clamp and another on the free end of the beam. In this case, the PZT plate near to the clamp acted as a transmitter of the sine wave frequency and the other as receiver of this wave. The PZT actuator was powered by a sine wave generator with peak to peak amplitude of 10 V. To measure the wave applied to the PZT actuator as well as to measure the response of the PZT sensor, it was used a digital oscilloscope with adjust to measure the frequency and amplitude of the signals. Figure (4) illustrates the experimental test bench above described.

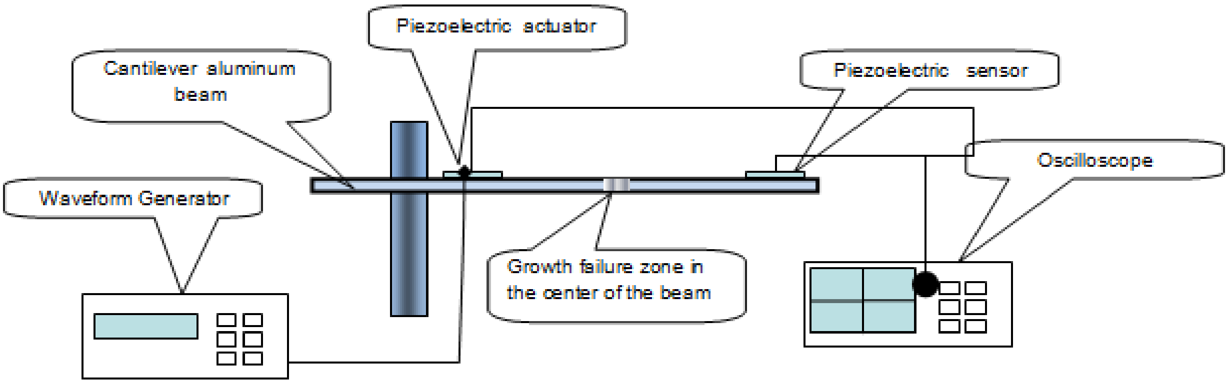


Figure 4. Schematic illustration of the experimental test bench.

The acquisitions of natural frequencies were performed on five sets, verifying the repeatability of results. Then, it was carried out weighted average of five sets of signals. The frequency range analyzed was from 20 Hz to 30 kHz.

Adopting for the model simulated a perfectly isotropic structure, with constant width, thickness and density, it were obtained the theoretical numerical results. Likewise, through the experimental procedure it was obtained the experimental results of natural frequencies of vibration modes, evaluated at points of tension peaks in the response of PZT sensor. Figure (5) show the comparative results between the experiment and model.

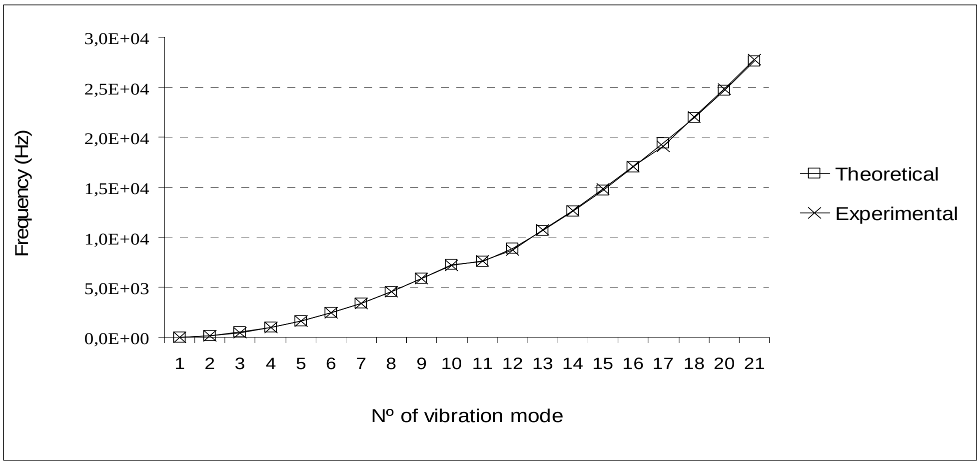


Figure 5. Natural frequencies of the beam without failure determined by the theoretical model in comparison with experiments.

Table (1) summarizes the values of theoretical and experimental natural frequencies of the beam and the relative error associated with taking as reference the theoretical values.

Table 1. Theoretical and experimental natural frequencies of the cantilever beam without failure.

Number of Mode	Frequency Theoretical (Hz)	Frequency Experimental (Hz)	Error (%)
1	28.863	27.66	4.17
2	180.87	178.1	1.53
3	506.42	490.7	3.1
4	992.28	972.02	2.04
5	1640.1	1637.8	0.14
6	2449.7	2463.8	0.58
7	3420.8	3425	0.12

8	4553.4	4538.8	0.32
9	5847.1	5859	0.2
10	7301.9	7165.4	1.87
11	7549	7622	0.97
12	8917.4	8722.4	2.19
13	10693	10756.8	0.6
14	12629	12692.8	0.51
15	14725	14839.4	0.78
16	16981	17056.8	0.45
17	19395	19120.8	1.41
18	21968	22065.4	0.44
20	24700	24805	0.43
21	27589	27746.4	0.57

Verified the compatibility of the model with the experiment without any damage, a failure was introduced in the central position with respect to the beam length by conventional machining, with a width of 1 mm and initial depth of 0.1 mm along the beam thickness.

To analyze a range of defects severity in the beam, acquisition of natural frequencies were made in blocks of five samples for each depth of the fault, then considering the average of the samples. Damages were introduced gradually, starting with a failure of 1 mm wide and 0.1 mm in depth, where after the acquisition of each set of data has increased the severity with gradual reductions in depth using steps of 0.1 mm for each failure, achieving a final reduction in cross-section of 0.7 mm. Figure (6) shows photographs of the procedure used to introduce the failure and the experimental test bench illustrated in Fig. (4).

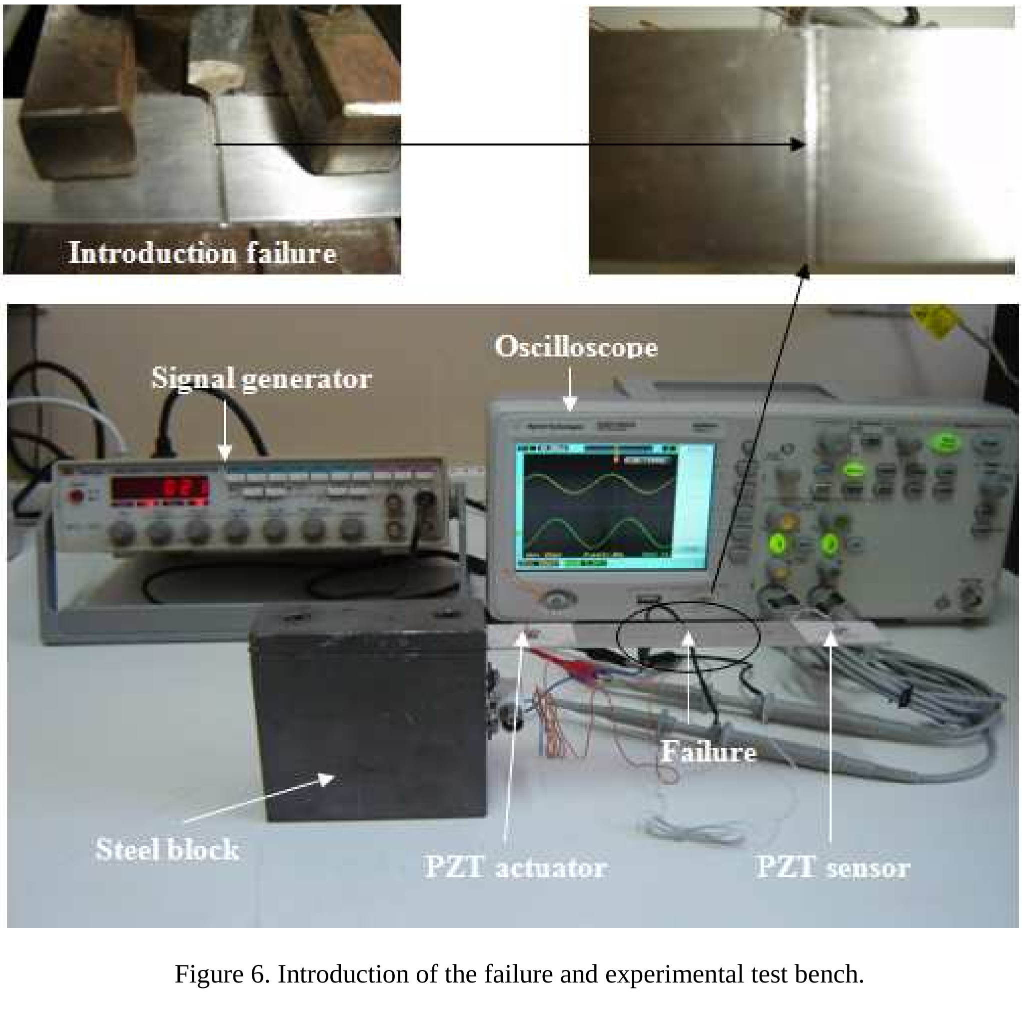


Figure 6. Introduction of the failure and experimental test bench.

3. RESULTS AND DISCUSSION

The simulations predict that for most vibration modes of the beam there is a reduction of natural frequency as the failure increases. This fact is shown in Fig (7), demonstrating that the relative change in natural frequency of the damaged structure increases with increasing the failure severity.

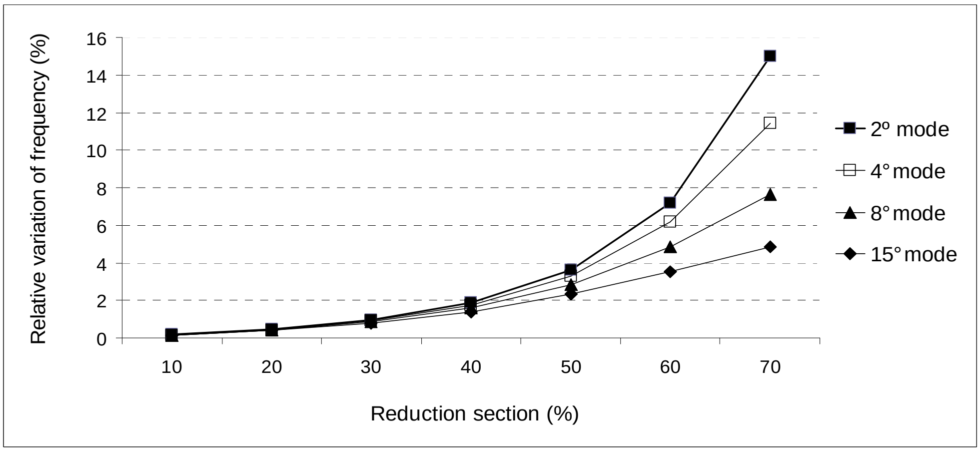


Figure 7. Relative variation of natural frequency in the theoretical model due to the increase of the failure.

The criterion for selection of vibration modes used for the experimental observations of the behavior of the beam in terms of frequency variation, and subsequent analysis of its structural integrity, was based on the FEM model that showed the modes 2, 4, 8 and 15, which already had a relative variation of frequency of about 1% for a section reduction close to 30%. As can be verified in Fig (7), for variations of frequency above 2% was only possible to detect a reduction in section above 40% and for 5% relative variation was possible to detect a reduction above 50%. For the damaged beam, Tab (2) shows the values of the selected vibration modes with their theoretical natural frequencies.

Table 2 - Selected vibration modes and associated theoretical natural frequencies as a function of the damage severity level.

	Damage severity														
	0	10%		20%		30%		40%		50%		60%		70%	
Mode	F (Hz)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)	F (Hz)	ΔF (%)
2	178,1	177,28	0,46	176,92	0,66	176	**1,18**	174,5	**2,02**	170,48	**4,28**	164,14	**7,84**	148,52	**16,61**
4	972,02	968,66	0,35	965,14	0,71	961,04	**1,13**	951,46	**2,12**	930,84	**4,24**	899,68	**7,44**	839,18	**13,67**
8	4538,8	4529	0,22	4511,4	0,60	4486	**1,16**	4446,4	**2,04**	4369,2	**3,74**	4260,4	**6,13**	4103,4	**9,59**
15	14839,4	14704,6	0,91	14708,8	0,88	14668,4	**1,15**	14573,2	**1,79**	14450	**2,62**	14300,8	**3,63**	14123,2	**4,83**

Based on the experimental results it was observed that the relative variation of the frequency of the 2nd mode did not represent an absolute change significantly, whereas the value of the frequency is so low compared to other frequencies evaluated and their variations with reference to the absolute structure without damage. From the modes 4, 8 and 15, changes were relevant with respect to variations in natural frequencies for lower levels of failure severity, as shown in Fig. (8).

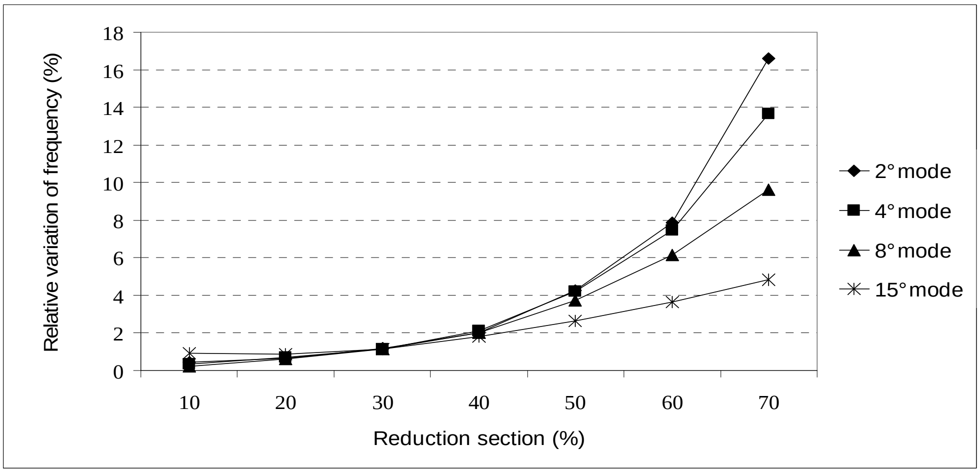


Figure 8. Relative variation of natural frequency as a function of failure severity in the experimental test bench.

4. CONCLUSIONS

The results of this study demonstrate the efficiency of the proposed methodology using the PZT as an actuator and sensor for structural health monitoring. It has been shown that this methodology can be applied for monitoring of structures for which 30% of reduction in cross-section thickness does not represent a critical situation. This minimum value of severity was established based on a relative variation of about 1% between the natural frequencies of the structure with damage in relation to the full structure. In absolute values this represents, for vibration modes like the eighth, a variation of the order of 52 Hz. Therefore, this methodology can be used to identify mechanical faults in structures before a critical stage through a constant monitoring using PZT plates.

5. ACKNOWLEDGEMENTS

The authors thank the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), Brazilian office, for sponsoring the INCT of Smart Structures in Engineering (INCT grant 574001/2008-5) during the course of these investigations.

6. REFERENCES

Gardonio, P.; Bianchi, E.; Elliott, S. J., 2003, “Smart Panel With Multiple Decentralized Units for the Control of Sound Transmission. Part II: Design of the Decentralized Control Units”. Journal of Sound and Vibration, Vol. 274, pp. 193–213.

Gardonio, P.; Bianchi, E.; Elliott, S. J., 2004, “Smart Panels With Velocity Feedback Control Systems Using Triangularly Shaped Strain Actuators”. Acoustical Society of America, Vol. 117, pp. 2046 – 2064.

Kaizuka, T.; Tanaka, N., 2006, “Active Boundary Control of a Rectangular Plate Using Smart Modal Sensors”. Smart Materials and Structures, Vol. 15, pp. 1395-1403.

Mallik N.; Ray, M. C., 2005, “Exact Solutions for the Analysis of Piezoelectric Fiber Reinforced Composites as Distributed Actuators for Smart Composite Plates”. International Journal of Mechanics and Materials in Design, Vol. 2, pp. 81-97.

Park, G.; Cudney, H. H.; Inman, D. J., 2000, “An Integrated Health Monitoring Technique Using Structural Impedance Sensors”. Journal of Intelligent Material Systems and Structures, Vol. 11, pp. 448 – 455.

Souto, C. R.,2008, “Controle Ativo de Vibração em Placas Usando Atuadores Piezoelétricos - Aplicação a Atenuação de Ruídos em Ambientes Fechados”. Tese de Doutorado, UFPB, Brasil. In portuguese.

7. RESPONSIBILITY NOTICE

The authors are solely responsible for the printed material included in this work.