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Finite Element Analysis of the Local Effect of a Piezoelectric Patch on an Aluminum Plate

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We have been accustomed to traditional materials such as wood, leather, wool . . . and have known the revolution of plastics and composites materials. Recently, we have known other innovations: these of smart materials able to change the shape as the piezoelectric materials. This work deals with the electro-mechanical modeling of these structures by the finite element method. It consists on to model and to simulate deformations in a square aluminum plate subjected to an electric field. This is achieved by using PZT piezoelectric transducers that have such particularity to deform under the influence of an electric field. The study of the deformed aluminum plates equipped with a PZT patch is considered and these types of materials are commonly used in aeronautics and astronautics, which is the context of our study. We have clearly shown the effect of the electromechanical properties of different piezoelectric materials, the transverse piezoelectric coefficient d_{31} and the longitudinal piezoelectric coefficient d_{33} of PZT patch on the final response of the intelligent structure.

Keywords: smart materials, piézoélectricity, aluminum plate, finite elements method.

1. Introduction

In the early 1980's appeared the concept of materials to the evolutionary properties so–called intelligent or smart materials [1, 2] able to better achieve their missions in a changing environment, and better on to ensure their survival. This ambitious concept which naturally involves multi functionality is fairly quickly structured into three categories: the first one concerns the simply sensitive materials capable of providing information on their environment and/or on their own structural condition; the second category is for the materials so-called adaptable capable to change one of their essential characteristics (shape, module,...) under the effect of a locally applied solicitation (electric field, temperature,...); finally, the last category of materials is called adaptive or intelligent both sensitive and adaptable and able to react by themselves at the changing of internal or external variables.

In fact, smart structures are constituted by the assembling of two main functions which are: sensor and actuator [3-5]. These two functions are often provided by different materials which introduces the concept of material/system. There are several types of smart structures, defined in the following four forms:

1. The sensitive structure which includes actuators or sensors capable of bringing information to the system on the environment or on itself,

2. The adaptable structure which includes actuators that can change their characteristics,

3. The structure called adaptive which reacts to a single type of solicitations following a law of well-defined behavior,

4. The so-called intelligent structure reacts to a set of solicitations in terms of sensitivities that are specific to it.

The materials most commonly integrated and taken to intervene in these smart structures [6] are: the electro–rheological fluids, the magnetostrictive and electrostrictive materials, the optical fibers, the shape memory alloys and the piezoelectric ceramic materials.

The multifunctional materials called piezoelectric (PZT) exhibit remarkable features. Because of their ability of electromechanical conversion and their small dimensions, the use of piezoelectric transducers opens the door to a wide variety of applications in structural dynamics.

These piezoelectric elements are coupled to the structure either by gluing on the massive ceramic surface or directly integrated to form an adaptable structure.

When the structure is subject to an external solicitation, the resulting deformations cause the appearance of an electric potential (V) to the terminals of the piezoelectric element (Fig. 1).

In addition, these real adaptive structures are usually of high complexed forms that do not allow an explicit formulation of the solution. Nevertheless, we can approach the solution to a complex problem by the finite element method.

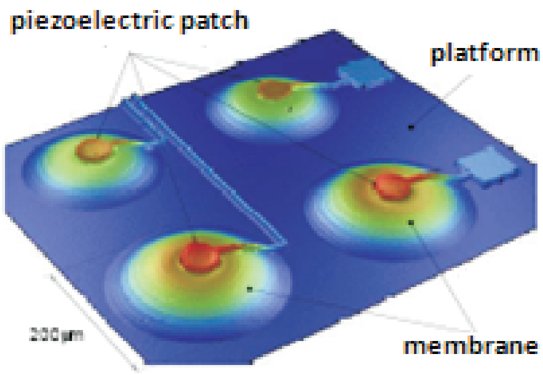

Figure 1 Adaptable structure [7]

Tiersten [8] and Eer Nisse [9] generalized the principle of Hamilton to the linear piezoelectricity. We also mention the work of Yu [10] that extends this principle to the nonlinear. The application of piezoelectric materials [11–13] for the design of smart structures has led many researchers to develop new items. In [14, 15], the authors proposed the formulation of multi physical shell elements for structural composite model plates with one or several piezoelectric layers.

In [16], the author proposed a state of the art of multi physics elements taking into account the presence of piezoelectric materials, whatever their kind: beam, plate, shell or volume.

In this work, we propose to study the nonlinear electromechanical behavior of a clamped aluminum plate using the finite element method. This structure is instrumented by two piezo-laminate sensors located in the center of the plate (Fig. 2). The model can simulate two different excitation devices, namely: a force perpendicular to the plane of the plate and the piezo-laminate or an electrical voltage applied to the PZT pellets.

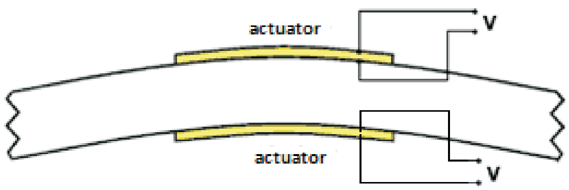

Figure 2 Mounting actuator/actuator virtually co–located

2. Finite element modeling of a the adaptable structure

2.1. *Assumptions and boundary conditions*

Consider a square plate of side equal to 36mm and a thickness of 1mm determined by its 4 edges fitted in the center of two piezoelectric pellets square dimension of 10mm and 0.5mm thick Fig. 2 and 3. Two electrodes, connected to an external generator, can create in the layer of piezoelectric material (PZT) an electric field directed along z Fig. 2. This allows to polarize the PZT layer on one hand and secondly to deform it in the longitudinal direction to cause the vibration of the system. Similarly, the actuator applies to structure a bending moment proportional to the voltage applied to its terminals. These piezoelectric transducers allow the conversion of mechanical energy into electrical energy and vice versa (direct and inverse piezoelectric effects). Thus, because of these effects, the bending moments can be measured and applied (because they are proportional to the voltages respectively measured and applied).

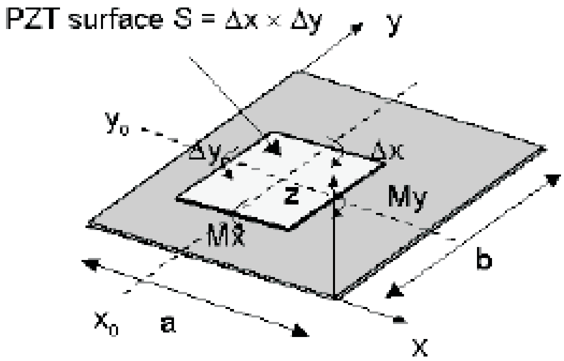

Figure 3 Square plate in Aluminum excited by piezoelectric ceramic pellets square

The geometry of the pellets was meshed with SOLID5 elements whose degrees of freedom are the displacements along x, y and z and the electric potential. The aluminum plate was meshed with elements SOLID45 whose degrees of freedom are the displacements along x, y and z. The electric potential nodes of the interface between the piezoelectric elements and the Al plate are set at zero to simulate the electrical ground. It is configured to be common to all nodes of the upper surfaces of the pellets to simulate electrode and paralleling of piezoelectric elements. The complete mesh system in Ansys is represented in Fig. 4. The Ansys software allows to calculate the responses of structure combining elements of purely mechanical and piezoelectric elements. The conditions supporting plane of the plate are simulated by blocking the movement of nodes on the outer edge of the plate.

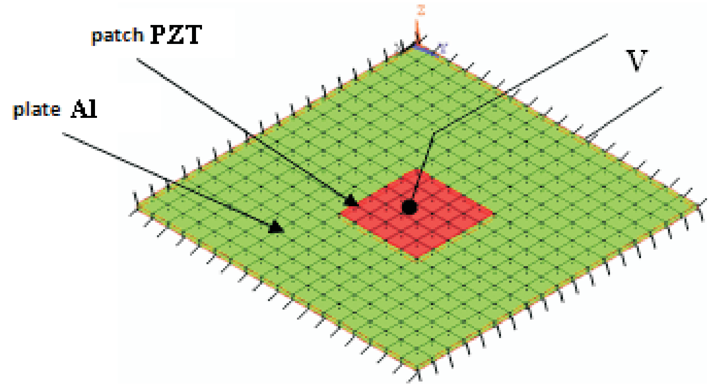

Figure 4 Finite element mesh of the intelligent structure and boundary conditions imposed

2.2. *Constitutive law*

The study of a piezoelectric system is a coupled field problem. In fact, the field of mechanical displacements and forces and the field of electrical tensions and intensities are dependent to each other. These piezoelectric materials are governed by the fallowing electromechanical behavior equations:

$$\left\{ \begin{array}{c} \sigma \\ d \end{array} \right\} = \left[\begin{array}{cc} C^E & e \\ e & -\varepsilon^e \end{array} \right] \left\{ \begin{array}{c} \varepsilon \\ -E \end{array} \right\} \tag{1}$$

With σ is the stress tensor, d: vector of electric intensity, ε: strain vector, C^E: elasticity matrix, e: piezoelectric matrix and ε^e: permittivity matrix.

2.3. *Study materials*

The aluminum is a material suitable for the aerospace industry for its many advantages: light, high mechanical properties, robust, resistant to corrosion and allows a wide variety of forms, multiple solutions. It has been chosen as the basic material of our structure. For the actuators, it has been selected the PZT which are placed in the center of the plate. The mechanical and electrical properties of different selected materials are presented in Tables 1-4.

3. Results and discussion

The simulation allows us to calculate the deflection of the adaptable structure for a given voltage. The results are illustrated in the form of maps and graphs that give the influence of chosen parameters on the static response of the model.

3.1. *Sensitivity to different actuators*

Figs. 5 and 6 in terms of the iso values of displacement U_z and of stress σ_{zz} show the response of the adaptable structure for different PZT actuators. The influence of the electromechanical properties of PZT is significant: about 20% increase of

Table 1 Tensor of mMonocrystal PMN-0.25PT

37.5	-18.9	-15.7	0	0	0	0	0	-386
-18.9	37.5	-15.7	0	0	0	0	0	-386
-15.7	-15.7	35.3	0	0	0	0	0	843
0	0	0	15.3	0	0	0	152	0
0	0	0	0	15.3	0	152	0	0
0	0	0	0	0	17.4	0	0	0
0	0	0	0	152	0	1.41	0	0
0	0	0	152	0	0	0	1.41	0
86	-386	843	0	0	0	0	0	2.86

Table 2 Tensor of Ceramic PMN-0.25PT

11.9	-3.55	-5.02	0	0	0	0	0	-100
-3.55	11.9	-5.02	0	0	0	0	0	-100
-5.02	-5.02	13.78	0	0	0	0	0	247
0	0	0	33.4	0	0	0	249	0
0	0	0	0	33.4	0	249	0	0
0	0	0	0	0	30.9	0	0	0
0	0	0	0	249	0	1.15	0	0
0	0	0	249	0	0	0	1.15	0
-100	-100	247	0	0	0	0	0	1.73

Table 3 Tensor of Monocrystal PMN-0.40PT

13.1	-1	-6.94	0	0	0	0	0	-128
-1	13.1	-6.94	0	0	0	0	0	-128
-6.94	-6.94	16.14	0	0	0	0	0	272
0	0	0	22.9	0	0	0	371	0
0	0	0	0	22.9	0	371	0	0
0	0	0	0	0	16.9	0	0	0
0	0	0	0	371	0	2.58	0	0
0	0	0	371	0	0	0	2.58	0
-128	-128	272	0	0	0	0	0	0.99

Table 4 Characteristics of the Plate Aluminum and Piezoelectric Transducers

Material	Aluminum plate	PZT Actuator
Length (l)	36 mm	10 mm
Width (b)	36 mm	10 mm
Thickness (h)	1 mm	0.5 mm
Young's Module (E)	69 GPa	-
Poisson's coefficient (ν)	0.3	0.3
Density (ρ)	2700	7700-8070

the arrow between two patches (PZT-0.25PT single crystal or ceramic PZT-0.40PT single crystal).

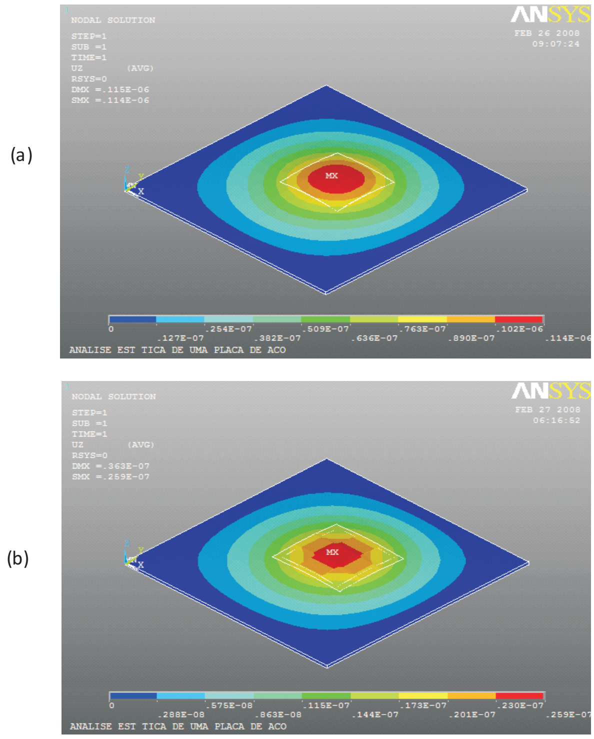

Figure 5 Finite element simulation of the static deflection of the membrane under the action of PZT polarized voltage 10V: (a) monocrystal PZ -0.40PT, (b) ceramic PZT-0.25PT

In Fig. 6, we observe that the axial stresses are much higher in the actuators by extension than in the elastic. As expected, to flex the plate, the actuator stuck on the top surface of the plate is in compression while the one of the other surface is in traction.

The response plotted on the graph in Fig. 7 shows the evolution of the arrow for an applied voltage of 10V. It is nearly identical in the couple PZT of type PMN (0.40PT monocrystal & 0.25PT ceramic), of the order of 0.114 nm. We obtained an arrow greater 2.5 times than the first for the ceramics PZT-0.4PT.

3.2. *Sensitivity of the transverse coefficient* d_{31}

Figure 8a shows the evolution of the arrow induced by tension of 10 V for different values of the piezoelectric coefficient d_{31}. We observe that the three values of d_{31} lead to similar results. The influence of this parameter is minimal: about 1% increase in the deflection for a 10% change in the value of d_{31}.

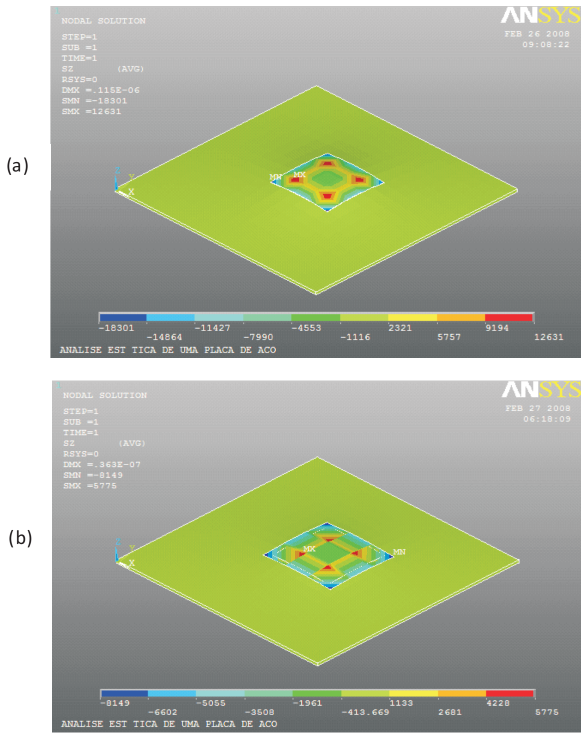

Figure 6 Isovalues of axial stresses of the aluminum plates actuated by extending at a tension of 10 V: (a) monocrystal PZT-0.40PT, (b) ceramic PZT-0.25PT

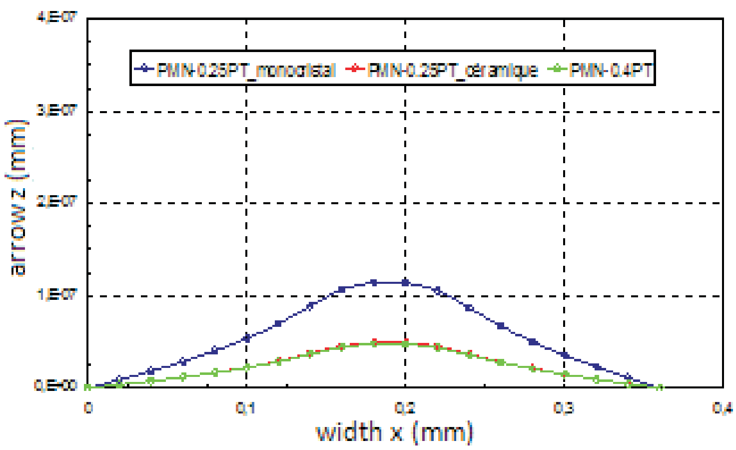

Figure 7 Sensitivity of the response of PZT on the arrow

3.3. *Sensitivity of the longitudinal coefficient d_{33}*

The response in the Fig. 8b shows the evolution of the arrow depending on the change in the value of the piezoelectric coefficient (d_{33}). This plays an important role in the flexural behavior of the structure. Indeed, when the plate put under tension, the coefficient (d_{33}) reflects the expansion or contraction of the patch PZT in the normal to the axis of polarization plane. If the value of the d_{33} evolves, the plate undergoes most important deformations.

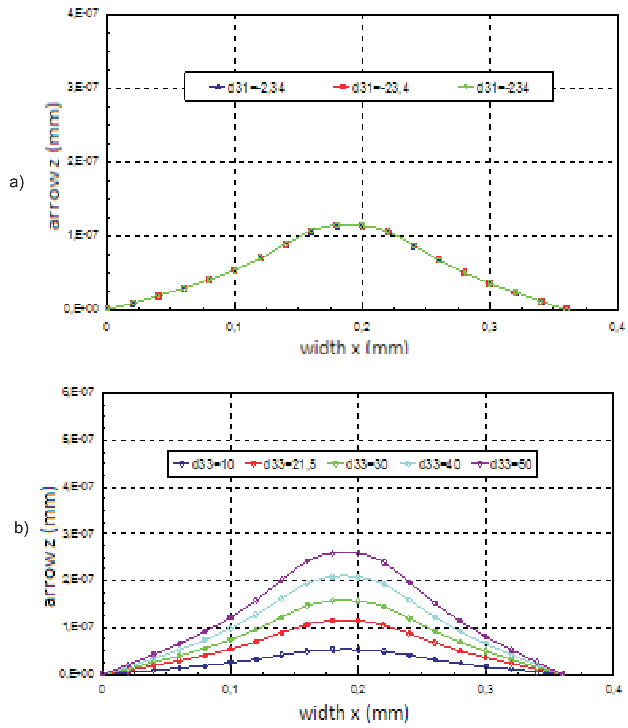

Figure 8 Sensitivity of the piezoelectric coefficient on the arrow: (a) transversal (b) longitudinal

4. Conclusion

The work presented in this article concerns the study of a modeled finite element of the deformation of an inert structure with piezoelectric elements. This modelization is used to describe the influence of different parameters on the final response of the adaptable structure. It comes out that the sensitivity analysis is significantly influenced by the electromechanical properties of PZT and piezoelectric coefficient (d_{33}) actuators. However, the coefficient d_{31}has almost no influence.

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