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Use of piezoelectric fibers in low power consumption smart sensors

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Abstract: This paper is devoted to FEM and laboratory experiments of piezo smart sensors, which are going to be used for measuring strains in locations where low energy consumption is essential. It begins with a short description of piezoelectric phenomena followed by PZT material introduction. Next chapter is a description of preliminary FEM model, which is going to be used as a baseline for laboratory experiments, which are described in Chapter 5.

Keywords: Piezoelectric; PZT; FEM; Stress Analysis

1. Introduction

In recent years there is a need to increase development of smart and low weight and low energy consumption sensors and actuators for engineering applications. One reason is produce sensors which are independent from external energy sources, or their energy consumption is negligible. Therefore such sensor could be used in currently unreachable (for traditional sensors) locations of engineering structures. Only requirement is to provide some way for data acquisition. One solution could be real time transmission to recorder realized by wiring or wireless (for example cell telephony), second is to implement recorder together with sensor and read measurements with some lower frequency (e.g. during maintenance).

The second reason is the desire to minimize such mass and size, so that the sensor can be become an integral part of the structure. This is essential in fields of aviation, medicine, robotics and automotive.

All these requirements can be met by piezoelectric materials. When mechanical force is applied to piezo-material, due to the direct piezoelectric effect, an electrical voltage is generated. Such sensor does not require external power supply. Instrumentation like signal amplifier and data collector could be supplied by solar panels. Significantly less power consumption and more temperature independent characteristics of piezo materials are main advantages against traditional resistive strain gauge.

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Although due to inverse piezoelectric effect it can induce force, when electric field is applied. Different applications of piezoelectric materials makes them appropriate for the development of systems that such sensor-active vibration damper.

2. Basis of piezoelectric theory

Piezoelectric phenomena is based on an unusual characteristic of certain crystalline minerals, when a mechanical force is applied, the crystals became electrically polarized. Tension and compression generated voltages of opposite polarity, both relative to the applied force (Fig. 2b – disc compressed, generated voltage has same polarity as polling voltage, on Fig. 2c disc is stretched, generated voltage has opposite polarity to polling voltage) [2]. The opposite relationship is also confirmed, when piezo material is exposed to an electric field it lengthening or shortening according to the polarity of the field, and it is also relative to the strength of the field. First behavior is labeled the direct piezoelectric effect and second one the inverse piezoelectric effect.

The magnitudes of piezoelectric voltages are small, and often require amplification (for example a typical fiber of piezoelectric ceramic will increase or decrease in length by only a small fraction of a milimeter) piezoelectric materials are adapted to many range of applications. In the 20th century metal oxide-based piezoelectric ceramics and other man-made materials enabled designers to employ the piezoelectric effect and the inverse piezoelectric effect in many new applications. These materials generally are physically strong and chemically inert, and they are relatively cheap to manufacture. Shape and dimensions of a piezo ceramic element can be manufactured to meet the requirements of a specific purpose. Ceramics manufactured from formulations of lead zirconate/lead titanate exhibit greater sensitivity and higher operating temperatures, relative to ceramics of other compositions. All those advantages make PZT materials currently the most widely used piezoelectric ceramics [2].

3. Piezoelectric PZT

Currently most piezoelectric ceramic sensor formulations are also based on PZT, which is compound of 52±54 mole % lead zirconate ($PbZrO$ 3) and 46±48 mole % lead titanate ($PbTiO3$). The addition of dopants to PZT can have a strong impact on its properties. As a result, PZTs such as those designated as 5A and 5H have large piezo-electric coefficients, large permittivity, high electrical losses, large electromechanical coupling factors, very high electrical resistance [4]. Stock PZT fibers are usually not polarized, like it is shown on Fig. 1a. Typically polarization is performed by exposing the element to a strong, direct current electric field (Fig. 1b) (e.g. for electrodes spaced 1mm apart on PZT 5 it is 2kV). Polarization of PZT 5 should take 15 minutes and be performed at room temperature.When the electric field is removed polarizing configuration is near alignment (Fig. 1c) [2].

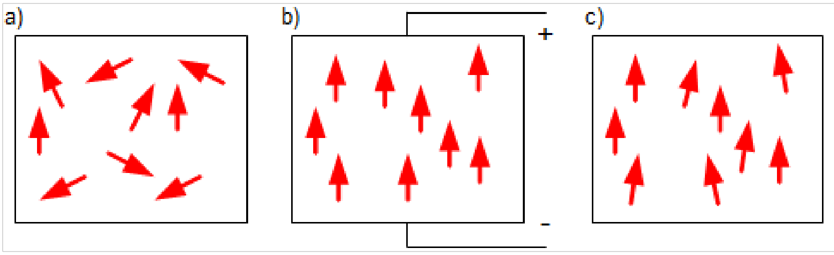

Fig. 1. Polarization of piezoelectric: a) Disk before polarization, b) DC field polarization, c) Disk after.

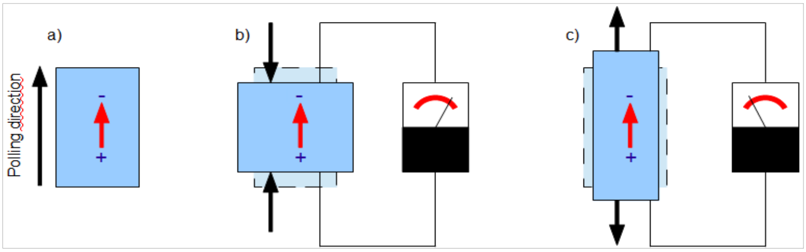

Fig. 2. Generating voltage by piezoelectric: a) Disk after polarization, b) Disc compressed, c) Disk stretched.

4. Modelling of pieso sensor

Full model of piezo fibers and specimen plate were modeled although for the purposes of this article only half symmetric model could be used. It was decided to use the full because of the possibility of using it later for unsymmetrical load cases and because full model can be easily implemented to more extended analysis.

All calculations were performed in FEM software ANSYS 13 Mechanical APDL.

Model is fully parametric and will be adjusted after real test of specimens. On Fig. 3. main components are presented:

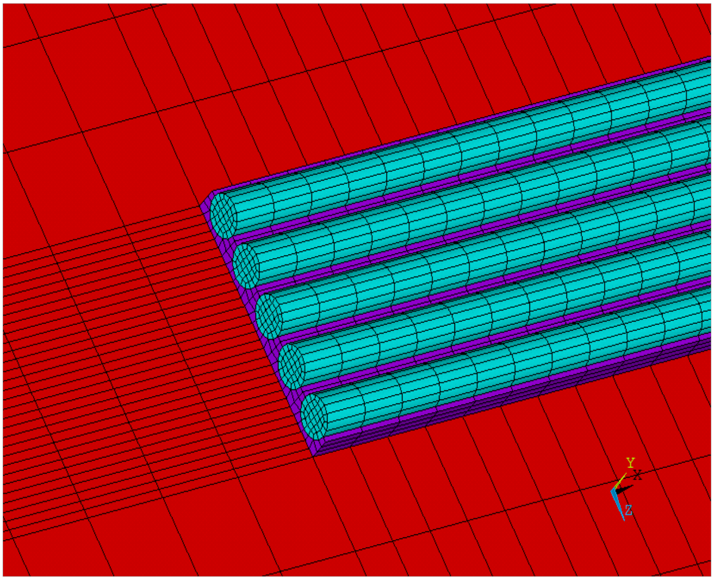

Fig. 3. FEM model of piezo smart sensor on measured object.

- red – measured object
- violet – glue
- blue – piezo fibers

Currently Ø 0.8mm, 50mm length piezo fibers are used. All used FEM elements are 20-node solids (SOLID226 for piezo material and SOLID186 for rest components). Fibers are connected to specimen by glue, which currently has same mechanical properties as measured specimen. In final model mechanical properties and elements behavior will be adjusted to represent real glue mechanics.

Piezo element length in X direction, which is also polling axis, is equal to gap between electrodes. Such a solution is forced by the way in which ANSYS formulates the elements. Modelled material properties are similar to PZT5A1 [8],which main piezo and mechanical properties are listed below:

$d_{33} = 440*10^{12}$ C/N	$g_{33} = 25.5*10\text{-}3$ Vm/N	$S_{11}{}^{E} = 18.5*10^{12}$ m/N
$d_{31} = -185*10^{12}$ C/N	$c_{33}{}^{D} = 15.7*10^{10}$ N/m^2	$S_{11}{}^{E} = 18.5*10^{12}$ m/N
$d_{15} = 560*10^{12}$ C/N	$c_{55}{}^{D} = 6.5*10^{10}$ N/m2	

Electrodes are presented on Fig. 4, same configuration of electrodes will be used in real tests, both for polling and reading voltages during experiments. In real model first electrodes will be made from cooper wires, but finally they will be etched in order to obtain manufacturing high precision.

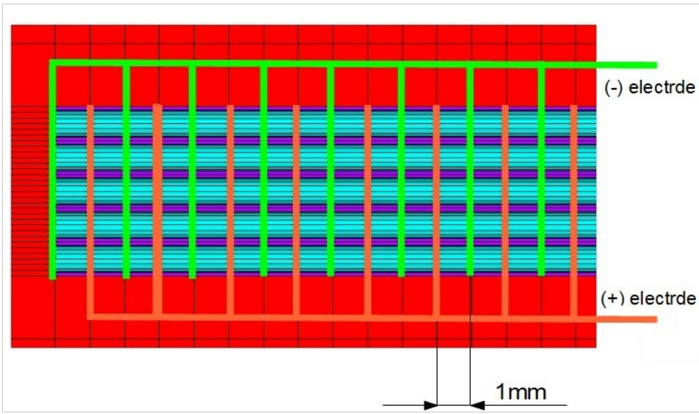

Fig. 4: Electrodes modeled in FEM.

Both real and FEM test will be performed in 4-point bending load condition. Thus it is easy to verify the results, due to the fact that the stress state in the area of the sensor is pure bending. Loads are presented on Fig. 5.

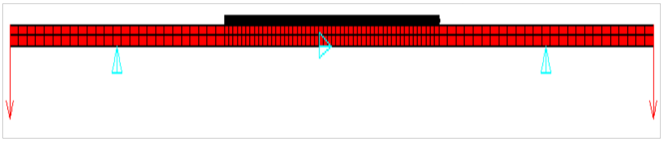

Fig. 5: 4-point bending load configuration.

On Fig.6 are presented voltages on piezo-elements reached due to load condition from Fig.5. Characteristic of result is appropriate, zero and peak values occurs in places where are minus and plus electrodes.

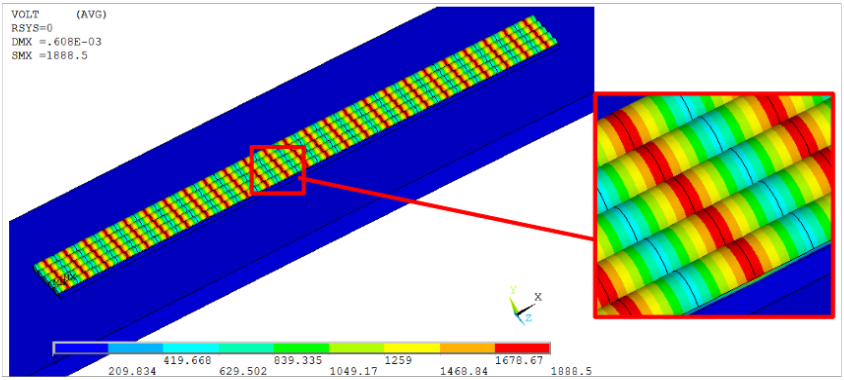

Fig. 6: Voltage results on piezo-elements.

Good behavior of SOLID226 is observed and lead to use ANSYS software also in future experiments as a reference for laboratory test. After that correction function will be applied to FEM model.

Results are also linear as shown on Fig. 7. Red chart is a function of voltage generated due to loading, blue present strains in measured object in area of piezo-fibers.

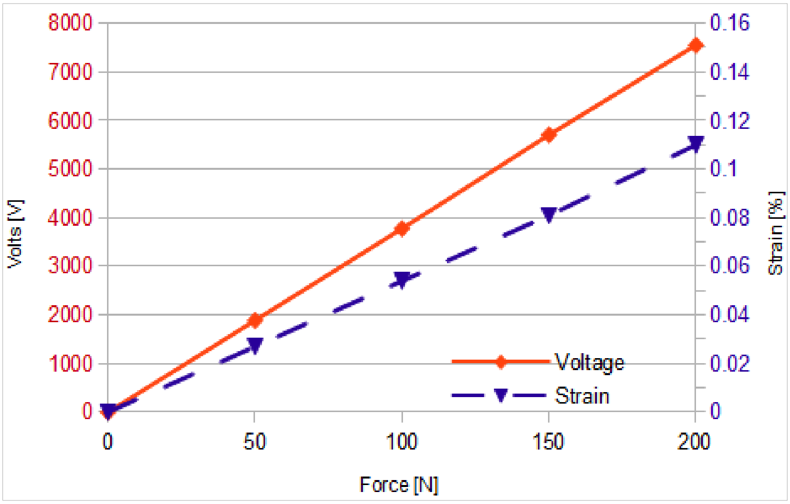

Fig. 7: Obtained voltage and strains as a function of applied force.

5. Planned experiments

In nearest future series of laboratory test are planned. At the beginning possibility of polling piezo-fiebers by one side electrodes will be investigated. There is a tread, that electric field generated by this method may not polarize 100% of piezo-material. Then two side electrodes will be used. Second goal is to obtain real voltage values. It is difficult because of the short duration phenomena, its high voltage and a very low current. Then after series of test where glass fiber composites will be used (due to its electrical non-conductivity) correction function will be applied to FEM model. All test will be performed on typical testing machine.

6. Summary

Piezoelectric materials are promising in the field of mechanical measurement. They have a lot of advantages like thermal linearity, low power consumption and they can also be used as actuators. Main disadvantage is their high density (from 5000 to 8000 kg/m^3) and fragility, also they are not suitable for point measurement, due to its construction. However piezoelectric materials every day increase their presence in many engineering areas and they will continue their growth together with improved material properties and better knowledge about piezoelectric phenomena.

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