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Experimental Identification of Material Properties of Piezoelectric Patch Transducer

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Abstract. This work is focused on identification of material properties of piezoelectric patch transducers used e.g. for structural health monitoring before attaching to the substrate structure. Two experimental methods were concerned. At first two piezoelectric patches were supplied with a pair of collocated strain gauge rosettes. Both transducers were actuated with the same periodical signal. Significant difference in the results for two transducers was found, however it was claimed to be within tolerance by the producer. As an alternative method a measurement in an optical microscope was chosen. The patch was clamped at one side and actuated by a voltage signal. The displacement of the free end was captured by the microscope and processed in a graphical editor. Finally, a finite element model of the transducer was created and its material data were obtained by calibration with experimental data.

Introduction

Detecting hidden failures in structures or generally structural health monitoring is a present-day trend in a non-destructive testing and reliability assessment, especially with the growing usage of composite structures suffering by debonding and delamination [3]. These structures - equipped with an embedded SHM system - are labelled as 'smart structures' due to involved *smart materials* (e.g. piezoelectric ceramics, magnetostrictive materials etc.) which are used as actuators and sensors. Signals obtained by sensors can be processed for impact or event monitoring (passive approach) [2] or detecting a failure by acoustic methods (active approach) [5].

The piezoelectric materials are most commonly used smart materials. They have a capability to convert mechanical deformation to electric charge (direct piezoelectric effect) and vice versa (reverse piezoelectric effect) and this conversion is supposed to be linear. They are used in shape of cylinders (*stacks)* or *patches*. Transducers used in this work are patches DuraAct P-876.A12 made by Physik Instrumente (PI). When used in various problems, even the patches of the same series provided different results in strain (up to 16% difference). According to the producer, the difference is within tolerance (which is up to 20%). However, some of the methods (especially ones with non-linear effects) need an accurate determination of strain (or voltage) amplitude, therefore every patch needs to be calibrated precisely before attaching to the substrate structure.

As the calibration method two experimental approaches were proposed in this work. Firstly, a lateral compression of the clamped patch was measured by an optical microscope (the maximal longitudinal displacement of free patch is in range of micrometers). After that, these two patches were supplied with pairs of strain gauges. The patches were actuated by a square voltage signal in both cases. These data were provided for a finite element analysis to precise the piezoelectric properties of the numerical model.

Modeling of piezoelectric transducers

Piezoelectric effect. Piezoelectric effect is generally described by a system of constitutive equations

$$\boldsymbol{\sigma} = \mathbf{C}\boldsymbol{\varepsilon} - \mathbf{e}^T\mathbf{E} \ ,$$
$$\mathbf{D} = \mathbf{e}\boldsymbol{\varepsilon} + \boldsymbol{\mu}\mathbf{E} \ , \qquad (1)$$

where **σ** is a stress matrix, **C** is a matrix of elastic coefficients, **ε** is the strain vector, **e** is a piezoelectric matrix for stress-charge form, **E** is an electric field intensity vector, **D** is vector of electric displacements and **μ** is a dielectric matrix with coefficients of an electric permittivity on its diagonal.

The system of equations Eq.1 can be written also as

$$\begin{bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \\ D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & & & & & & e_{31} \\ C_{21} & C_{22} & C_{23} & & & & & & e_{32} \\ C_{31} & C_{32} & C_{33} & & & & & & e_{33} \\ & & & C_{44} & & & & e_{24} & \\ & & & & C_{55} & & e_{15} & & \\ & & & & & C_{66} & & & \\ & & & & e_{15} & & \mu_1 & & \\ & & & e_{24} & & & & \mu_2 & \\ e_{31} & e_{32} & e_{33} & & & & & & \mu_3 \end{bmatrix} \begin{bmatrix} \varepsilon_{11} \\ \varepsilon_{22} \\ \varepsilon_{33} \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \\ E_1 \\ E_2 \\ E_3 \end{bmatrix} . \qquad (2)$$

The piezoelectric problem (e.g. calculated by a finite element method) requires a knowledge of mechanical (elastic matrix **C**), piezoelectric (**e**) and dielectric properties (**μ**) of the active material.

Piezoelectric patches. The patch transducers are commonly produced in a shape of thin layer of piezoelectric ceramic (lead zirconite titanate or PZT) with conductive silver-plated surfaces, where the voltage is applied. The PZT itself is very brittle so the active layer is equipped with a flexible plastic foil (see Fig. 1).

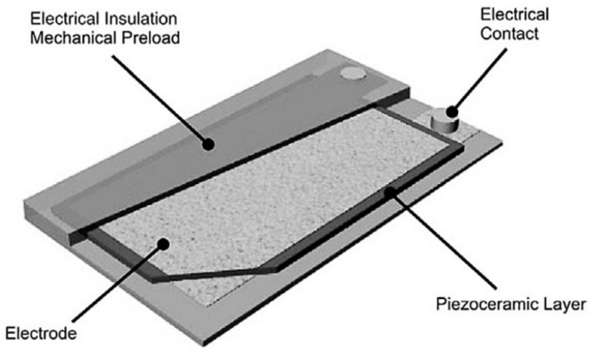

Figure 1. Structure of the piezoelectric patch.

Patch actuators show d_{31}-*effect*, when PZT is polarised through the thickness (*z* or 3 direction), but the main directions of strain are longitudinal (*x*, *y* or 1,2). Glued to the flexible substrate structure the actuator induces bending moment in the place of attachment. The rate of the transducer strain (or hence of bending moment carried to the substrate) is determined by mechanical and piezoelectric properties of the transducer (parameters available in producer's data sheet [6] are presented in Table 1).

Both component materials are supposed to be isotropic. Piezoelectric stress matrix of PZT contains elements e_{31}, e_{32} (identical) and e_{33}. For this type of transducer $E_1 = E_2 = 0$ and $D_1 = D_2 = 0$, thus the piezoelectric constants e_{24} and e_{15} are not concerned in this problem.

Table 1. Material properties of the component materials.

		Units	Piezoelectric ceramic	Polymeric foil
Young's modulus	E	[GPa]	61.8	8.0
Poisson's ratio	ν	[–]	0.3	0.3
Electric permittivity	μ	[Fm^{-1}]	1.062×10^{-10}	–
Piezoelectric constant	$e_{31} = e_{32}$	[Cm^{-2}]	5.6	–
	e_{33}	[Cm^{-2}]	–12.8	–

Finite element model of the transducer. The development and design of the SHM systems requires correct numerical models for simulation of the possible structure states. Various element types with capability of coupled-field effects (e.g. piezoelectricity) are already part of commercial FE systems, e. g. Ansys or Abaqus. The history and state-of-the-art summary of development in this area can be found in [1] and comparison of piezoelectric finite elements available specifically in Ansys 13 is presented in [4].

The FE model of the transducer was created using quadratic bricks with a capability of piezoelectric effect for PZT (denoted as SOLID 226) and structural quadratic bricks for protective foil (SOLID 186). Piezoelectric elements have an additional degree of freedom for an electric potential in each node. The model is loaded statically by an electric potential (electric potential φ = 100 V) applied to outer nodes of piezoelectric material elements. One of the surfaces is grounded (φ = 0). The patch is mechanically supported at one of the shorter edges.

Measurement and calibration

Measurement with microscope. The optical microscopy was chosen as precise and non-contact way to measure a displacement of free patch deformation under static voltage loading. The drawback of this method is impossibility to check the reliability of an attachment of the transducer to the microscope stage.

Two piezoelectric patches DuraAct P-876.A12 of a same production series were attached at one edge and actuated by the square signal in range ±100V. In each extreme position the free end of the patch was captured by an optical microscope Nikon Epiphot 200 (6 times for the first patch and 7 times for the second patch). The position of reference points in each snapshot was found and the resultant values of displacement are presented in table 2. The corresponding longitudinal strains are calculated for half displacement (i.e. in voltage range 0,100 V).

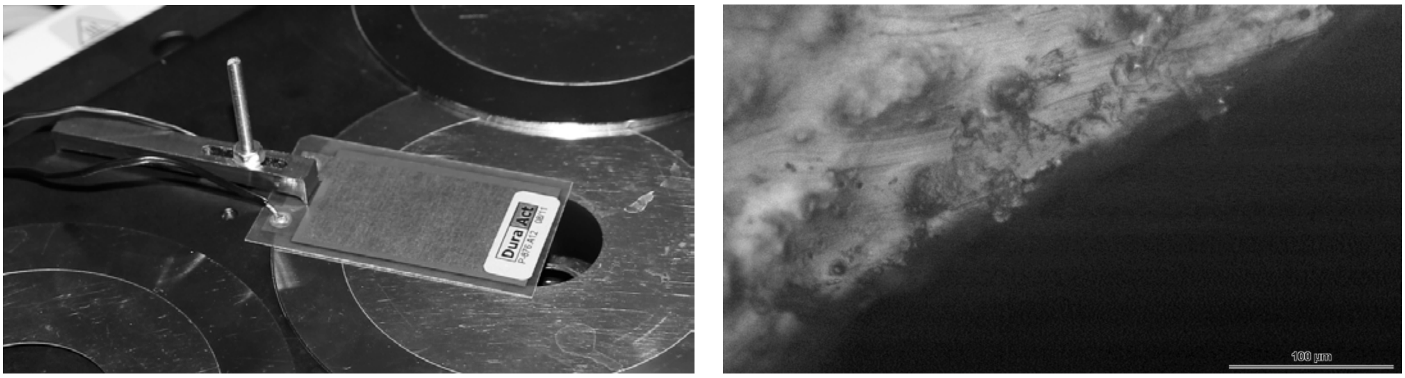

Figure 2. a) Piezoelectric patch attached to the microscope stage b) free end of the patch captured by an optical microscope.

Table 2. Measured coordinates and values of displacement for two piezoelectric transducers.

	PATCH 1			**PATCH 2**		
	Coordinates [px]	Displacement [px]	[μm]	Coordinates [px]	Displacement [px]	[μm]
1	[1107, 87]	167.2633	11.3016	[992, 310]	163.8566	11.0714
2	[1031, 236]	164.1371	11.0903	[1072, 167]	166.4121	11.2441
3	[1106, 90]	165.9217	11.2109	[994, 314]	159.7060	10.7909
4	[1033, 239]	164.1280	11.0897	[1069, 173]	161.9413	10.9420
5	[1106, 92]	164.1280	11.0897	[993, 316]	161.0590	10.8824
6	[1033, 239]			[1069, 174]	162.4131	10.9739
7				[992, 317]		
Average		165.1156	11.1565		162.2237	10.9611
Max. + variance		0.14511 =	1.3007 %		0.283 =	2.582 %
Max. – variance		–0.066731 =	–0.5981 %		–0.17012 =	–1.552 %
Calculated longitudinal strain (Δl/l)			1.1156×10^{-4}			1.0961×10^{-4}

In case of these two particular patches the mutual percentage difference between average values of displacement was 1.75%. Maximal variances were +2.5% and –1.5%.

Measurement with strain gauges. The values obtained by optical microscopy were compared to the results of standard strain gauges. This way of measurement is less proper for calibration because of damaging the polymeric foil by an adhesive and higher price.

The same two piezoelectric transducers were supplied with a pair of collocated strain gauge rosettes HBM 6/350 RY91(see Fig. 3). Each patch was actuated by a square signal with amplitude ±100 V. The responses of all strain gauges were recorded and are depicted in figure 4.

Figure 3. Piezoelectric patch with applied strain gauge rosette.

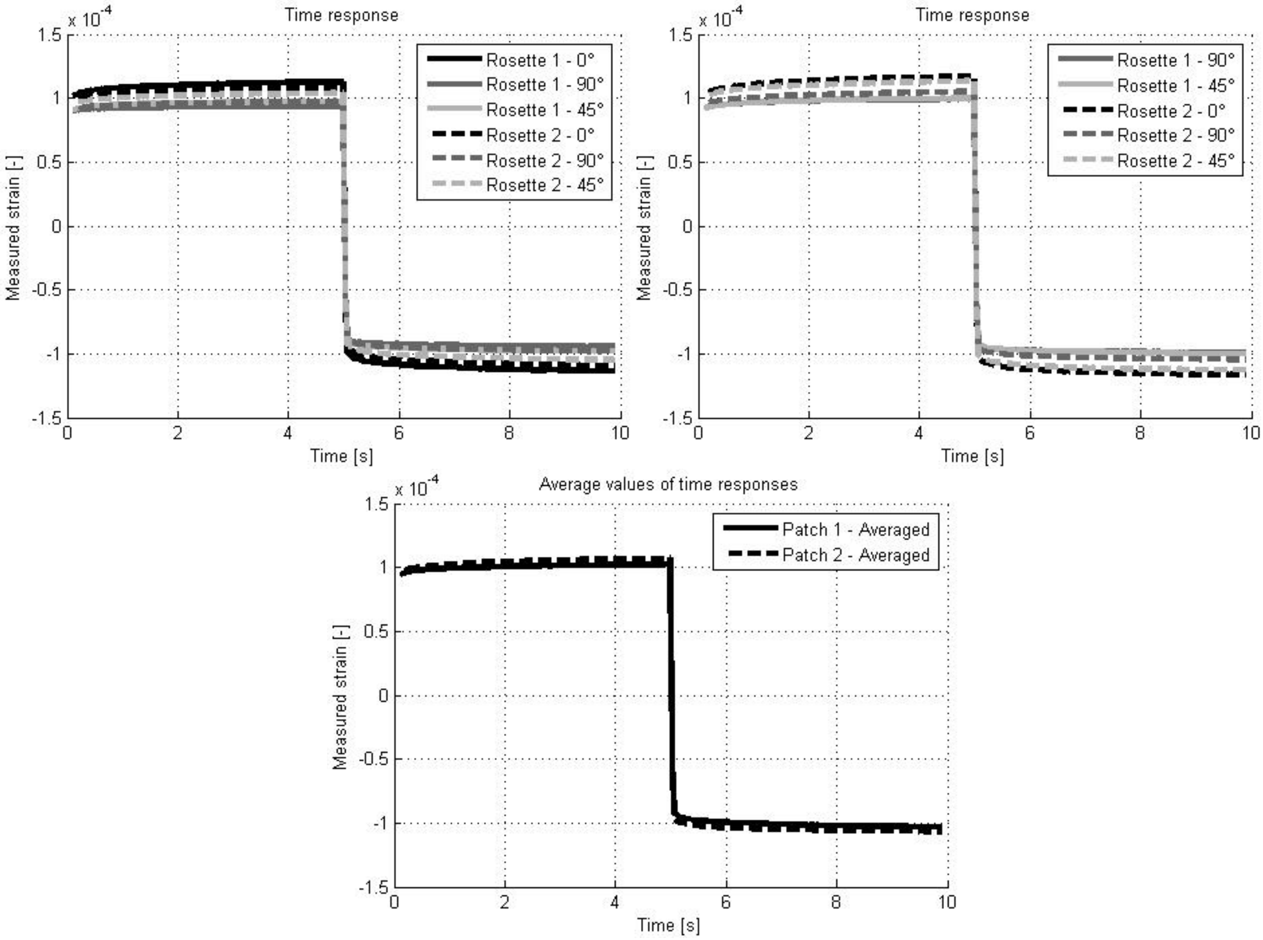

Figure 4. The time responses of strain gauges of patch 1 (a) patch 2 (b) and comparison of the average amplitudes (c).

Table 3. Values obtained by individual strain gauges in a reference time $t = 4.5$ s.

		PATCH 1	PATCH 2
Rosette 1	0°	1.123×10^{-4}	–
	90°	0.934×10^{-4}	0.990×10^{-4}
	45°	0.972×10^{-4}	0.959×10^{-4}
Rosette 2	0°	1.083×10^{-4}	1.166×10^{-4}
	90°	0.972×10^{-4}	1.046×10^{-4}
	45°	1.037×10^{-4}	1.131×10^{-4}
Comparison			
Longitudinal strain		1.103×10^{-4}	1.166×10^{-4}
		+ 5.7%	
Transverse strain		0.953×10^{-4}	1.0018×10^{-4}
		+ 5.1%	
Diagonal strain		1.0045×10^{-4}	1.045×10^{-4}
		+ 4.0%	
Strain gauges – total average		1.02×10^{-4}	1.066×10^{-4}
		+ 4.5%	

Numerical results. At first the static analysis of the piezoelectric transducer using the producer's material data was performed. The resultant strain (x-direction) was 0.495×10^{-4} which is 55% less than the value measured by strain gauges. Then the piezoelectric stress matrix coefficients $e_{31} = e_{32}$

and e_{33} (calculated to keep their mutual ratio) were set to match the experimental results. The values of these parameters are presented in Table 4).

Table 4. Table of found piezoelectric constants to match the experimental results (reference values are underlined).

Piezoelectric constant e_{31}	Piezoelectric constant e_{33}	Elastic strain ε_x	Elastic strain ε_y	Displacement (free end) u_x	Criteria
[Cm^{-2}]	[Cm^{-2}]	[–]	[–]	[μm]	
5.60	–12.80	0.495×10^{-4}	0.537×10^{-4}	2.51	Original values
12.45	–28.46	1.11×10^{-4}	1.19×10^{-4}	<u>5.58</u>	Microscopy - patch 1
12.34	–28.21	<u>1.10×10^{-4}</u>	1.18×10^{-4}	5.53	Strain gauge (*x*) - patch 1
– 0.8 %					
12.23	–27.95	1.09×10^{-4}	1.17×10^{-4}	<u>5.48</u>	Microscopy - patch 2
13.07	–29.87	<u>1.16×10^{-4}</u>	1.125×10^{-4}	5.86	Strain gauge (*x*) - patch 2
+ 6.8 %					

Summary

Two experiment approaches were presented to find piezoelectric constants of the patch transducer. The optical microscopy was proved to be a proper method of calibration with variances in one measurement not exceeding 2.5 %. In comparison with standard strain gauges the results matched for the first patch, but there was greater difference for the second patch 6.8 %. Experiments with a higher number of piezoelectric patch transducers are needed to verify this methodology.

Acknowledgements

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