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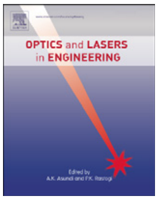

Evaluation of the piezoelectric behaviour produced by a thick-film transducer using digital speckle pattern interferometry

Lucas P. Tendela [a,*], Alejandro Federico [b], Guillermo H. Kaufmann [c]

[a] *Instituto de Física Rosario (Consejo Nacional de Investigaciones Científicas y Técnicas – Universidad Nacional de Rosario), Blvd. 27 de Febrero 210 bis, S2000EZP Rosario, Argentina*
[b] *Electrónica e Informática, Instituto Nacional de Tecnología Industrial, P.O. Box B1650WAB, B1650KNA San Martín, Argentina*
[c] *Instituto de Física Rosario and Centro Internacional Franco Argentino de Ciencias de la Información y de Sistemas (Consejo Nacional de Investigaciones Científicas y Técnicas – Universidad Nacional de Rosario), Blvd. 27 de Febrero 210 bis, S2000EZP Rosario, Argentina*

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ABSTRACT

This paper presents an interferometric measurement of the out-of-plane deflections produced by a piezoelectric transducer, manufactured by thick-film deposition of a ceramic paste over an alumina substrate, when is subjected to a DC electric voltage. It is shown that a digital speckle pattern interferometer with an incorporated phase-shifting facility allows the measurement of nanometer displacements generated by the piezoelectric device. These measurements are used to evaluate the effective piezoelectric charge constant along the polarization direction $(d_{33})_{eff}$ that characterizes the thick-film transducer.

1. Introduction

Lead Zirconate Titanate (PZT) ceramics are typical ferroelectric materials with outstanding piezoelectric properties which are widely used in nondestructive testing and ultrasound for medical images. Its popularity is mainly due to the high piezoelectric response that they exhibit, and also because of their high acoustic and electrical impedance. To manufacture piezoelectric devices on a millimeter scale capable of producing large deflections and high actuation forces, screen printed ceramics can be used, thus allowing to obtain relatively thick-film layers on a ceramic substrate. This process, known as thick-film technology, allows a great geometrical flexibility design [1]. However, thick films exhibit distinct physical behaviour characteristics when they are compared with bulk ceramics. This is mainly due to the effects of the ceramic substrate, as well as the different contributions that result from the composition and sintering process of the film, such as glass and porosity. Therefore, many efforts are currently invested to find adequate choices of active materials, bonding agents and processing conditions to incorporate large piezoelectric effects in thick films. Due to the difficulties presented to control this wide set of choices, there exists a great interest in the use of real-time measurements of static displacement fields as a way of optimizing the manufacture process of thick-film piezoelectric devices.

Atomic force microscopes and scanning near-field optical microscopy have been used for the inspection of microcomponents [2]. However, they are very expensive, require delicate adjustment, use short working distances and measurements are time consuming when typical components need to be qualified in production. Whole-field optical methods provide a promising alternative to the previously mentioned microscopic techniques. The main advantages of these optical methods are their noncontact, nondestructive and whole-field inspection nature. Other important characteristics are their high sensitivity and accuracy, and also the automatic analysis of results.

This paper presents an interferometric evaluation of the static deflections produced by a piezoelectric transducer, manufactured by the deposition of a thick PZT layer over an alumina substrate, when is subjected to a DC electric voltage. It is shown that a digital speckle pattern interferometer with an incorporated phase-shifting facility [3] allows the measurement of nanometer displacements generated by the piezoelectric device. It is also demonstrated that the measured out-of-plane deflections do not replicate the classical piston movement produced by a free sensor due to the clamping effect generated by the substrate. Finally, these measurements are used to evaluate the effective piezoelectric charge constant along the polarization direction $(d_{33})_{eff}$ that characterizes the thick-film transducer.

2. Preparation of the thick-film transducer

A typical paste for screen printing using thick-film technology contains three basic components: an active element that

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[*] Corresponding author. Tel.: +54 3414853200; fax: +54 3414808584.
E-mail address: tendela@ifir-conicet.gov.ar (L.P. Tendela).

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determines the main electromechanical characteristics of the sintered layer, a support or organic vehicle, and a glass binder that acts as a bonding agent among the particles themselves and the substrate. The active element of the paste was a PZT powder manufactured by Ferroperm (PZ27) [4], which was dispersed in a commercial vehicle to obtain rheological properties suitable for the screen-printing process [5]. The connection between the PZT particles was improved by adding a lead borosilicate glass that also helped to attach the film to the substrate due to the relatively low sintering temperature that was used in the manufacture process. It is important to note that although a low porosity is usually preferred, it is not possible to add a large quantity of glass binder because of the risk of inhibiting excessively the piezoelectric properties of the transducer.

The thick-film ceramic elements were printed on an alumina substrate of 0.6 mm thickness by means of a screen-printing procedure which used a stainless steel screen [1]. Each piezoelectric element had a circular shape with a diameter of 8.5 mm and a thickness $t = 130\ \mu m$. A lower electrode of Au was printed on the alumina substrate before applying the piezoelectric paste and then an upper electrode was made on the fired PZT paste. At the back surface of the transducer, an absorbent block made with epoxy and ferrotungsten was glued to approach the acoustic impedance of the alumina. Each layer was dried at 140 °C during 10 min and then sintered in a belt furnace at 850 °C. As the film thickness diminishes about 30% during the sintering process, the final thickness of the film must be designed taking into account the difference between dry and fired film.

Finally, the PZT film was polarized by heating the sample at 110 °C and an electric field of 3 MVm^{-1} was applied between the electrodes for 30 min. The temperature was lowered to room temperature before turning off the electric field.

Fig. 1 shows a thick-film transducer sintered over an alumina substrate with the external electrical connection that is guided to an inner electrode between the thick film and the substrate.

3. Experimental system and data analysis

The experimental setup used to measure the normal displacement of the thick-film transducer was a conventional out-of-plane interferometer, as shown in Fig. 2. The light beam of a Nd:Yag laser with a wavelength $\lambda = 0.5328\ \mu m$ was first divided into the object and reference beams by a beam splitter (BS). The reference beam was directed to a mirror (M) linked to a piezoelectric transducer (PT), which was controlled by an electronic unit. This phase-shifting facility enables the introduction of a constant phase shift between both beams in order to calculate the wrapped phase map. The reference beam was expanded by the microscope objective (L) and directed through another beam splitter into the CCD camera (Pulnix TM-720), where it was recombined with the light scattered by the object surface. In order to obtain a uniform illumination intensity, a pin hole was used in both object and reference beams. The video camera had a zoom lens (CL) which allows to image a small region of the specimen of $12 \times 12\ mm^2$ in size. Finally, the camera output was fed to a frame grabber (Matrox Pulsar) located inside a personal computer which digitized the images in grey levels with a resolution of 512×512 pixels and 256 grey levels (8-bit). To generate the speckle patterns, the surface of the transducer was covered with a very thin layer of white paint.

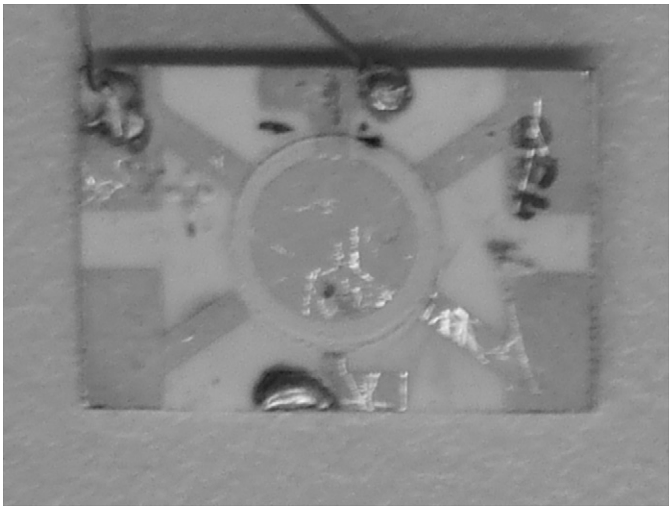

Fig. 1. Thick-film piezoelectric transducer.

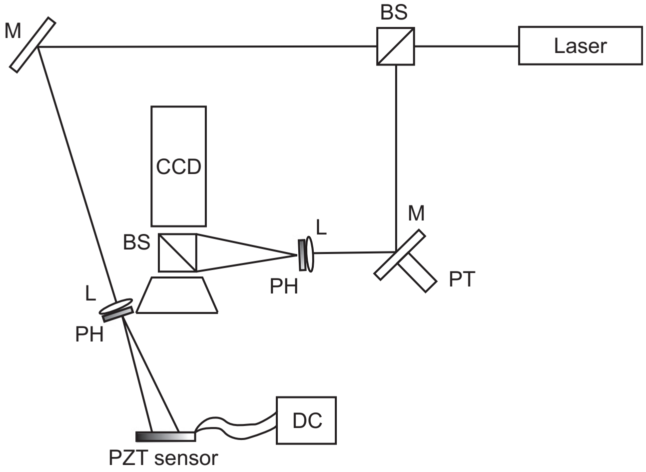

Fig. 2. Optical arrangement of the out-of-plane digital speckle pattern interferometer.

The experimental procedure used to record the pair of speckle interferograms to be correlated was as follows. First, the thick- film transducer was subjected to a selected DC electric voltage and a set of four phase-shifted speckle interferograms was acquired and stored in the computer. Then, the same DC electric voltage but with an inverse polarity was applied to the thick-film device and a new set of four phase-shifted speckle interferograms was acquired and stored in the computer. Afterwards, the corresponding wrapped phase distribution $\Delta\phi$ was calculated using the Carré phase-shifting technique [3], which is based on the processing of the two sets of four phase-shifted speckle interferograms. This technique evaluates the difference of phase and gives a significant improvement in the quality of the reconstructed phase maps. In order to improve the signal-to-noise ratio of pixels having very low-intensity modulation, a local smoothing kernel of $3\ \times 3$ pixels was also used.

It is important to note that the pair of speckle interferograms to be correlated generated less than a fringe because the out-of-plane displacement produced by the thick-film transducer lies in the nanometer scale. Therefore, as the wrapped phase distribution did not present the usual 2π phase discontinuities, it was not necessary to apply a phase unwrapping algorithm.

Then, the out-of-plane displacement component w was computed from the wrapped phase map $\Delta\phi$ by means of [3]

$$w = \frac{\lambda}{4\pi}\Delta\phi \tag{1}$$

4. Experimental results

As a typical result, Fig. 3 displays the wrapped phase map produced by a thick-film transducer for an applied voltage of 314 V. Fig. 4 shows the 3D plot of the out-of-plane displacement component w evaluated from Eq. (1) using the wrapped phase map $\Delta\phi$ displayed in Fig. 3. As the transducer edges remain fixed by the substrate, it is observed that the out-of-plane displacement component does not replicate the classical piston movement produced by a free device.

Fig. 5 shows a plot of the out-of-plane displacement component along a line crossing the center of the transducer and determined from the values displayed in Fig. 4.

As previously mentioned, in a thick-film PZT transducer obtained by screen printing there are various factors that modify the elastic and piezoelectric characteristics from those of the bulk material. We can mention three main causes: the glass binder phase that was added when the paste was prepared to achieve better consistency in the sintered film, the porosity resulting from the relatively low temperature of sintering and the low quantity of glass in the film, and finally the clamping introduced by the substrate which is a characteristic of this technology. Taking into account that from the properties of the bulk materials it is quite difficult to determine separately the effect of these factors on the electromechanical behaviour of the transducer, the manufacture process can be optimized through the determination of the effective piezoelectric charge constant along the polarization direction $(d_{33})_{eff}$ given by the sintered device. It should be noted that the poling electric field can also affect the $(d_{33})_{eff}$ value because the electric field must go through the pores inside the film during the polarization process and some regions could remain partially polarized. Therefore, for all these reasons the d_{33} value of the bulk material will always be much higher than the effective piezoelectric charge constant measured from the thick-film transducer.

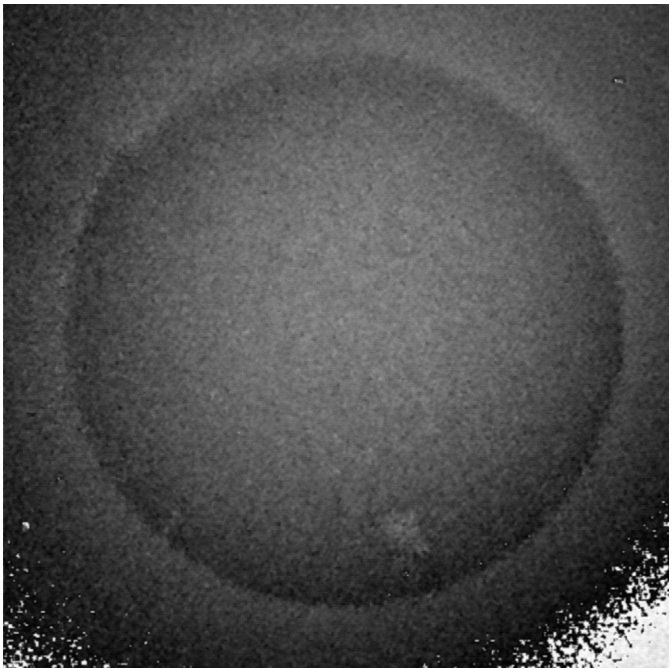

Fig. 3. Wrapped phase map produced by the thick-film transducer for an applied voltage of 314 V.

If ε_k is the strain tensor written in matricial form due its symmetry, being $k=1,\ldots,6$, and E_i with $i=1,2,3$ is the electric field component, the equation describing the piezoelectric effect can be expressed as [6]

$$\varepsilon_k = d_{ik}E_i \tag{2}$$

where d_{ik} is the piezoelectric charge constant.

Therefore, the effective piezoelectric charge constant $(d_{33})_{eff}$ from a clamped thick-film disc, polarized along the three direction which is parallel to the normal to the disc surface, can be obtained from Eq. (2) as

$$(d_{33})_{eff} = \varepsilon_3/E_3 \tag{3}$$

where $\varepsilon_3 = w/t$ and $E_3 = V/t$ being V the DC voltage applied to the transducer.

As from Eq. (3) it is seen that the effective piezoelectric charge constant $(d_{33})_{eff}$ does not depend on the thickness of the transducer, its value can be determined from

$$(d_{33})_{eff} = w/V \tag{4}$$

Evaluating the difference between the maximum out-of-plane displacement component obtained from Fig. 5 by means of a curve-fitting algorithm and the deflection measured at the transducer edge, and taking into account the applied DC voltage $V=314$ V, the effective piezoelectric charge constant calculated from Eq. (4) resulted $(d_{33})_{eff} = 270 \times 10^{-12}$ N/C. This result compares quite well with the value $(d_{33})_{eff} = 297 \times 10^{-12}$ N/C which was determined in other thick-film transducers produced using the same piezoelectric material and similar manufacturing conditions, through the measurement of the permittivity and other electromechanical parameters [5]. It is noted that due to the previously mentioned reasons, the thick-film transducer is less active piezoelectrically than the bulk ceramic material, as from the PZ27 data sheet $d_{33} = 425 \times 10^{-12}$ N/C [4].

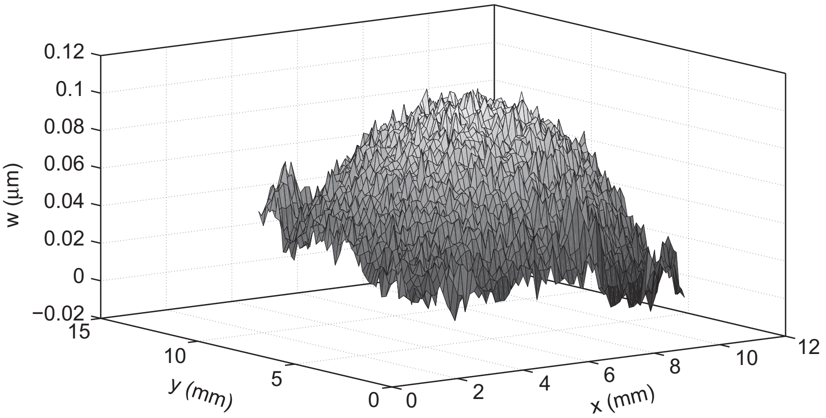

Fig. 4. Out-of-plane displacement component determined from the wrapped phase map shown in Fig. 3.

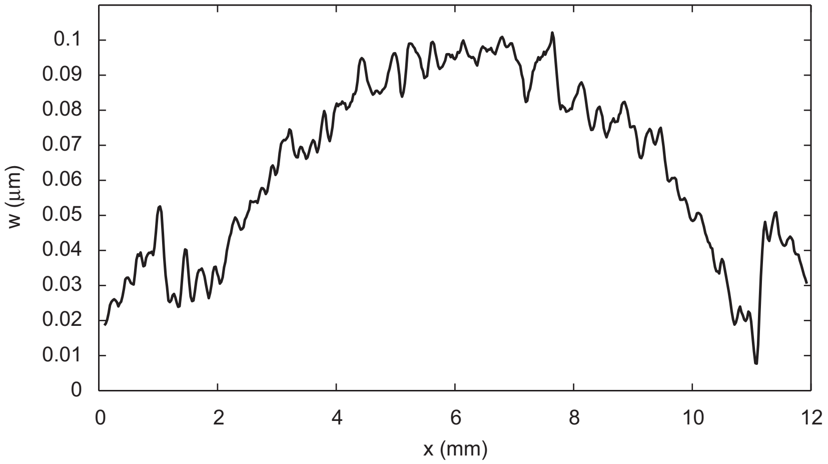

Fig. 5. Out-of-plane displacement component along a line crossing the center of the thick-film transducer, obtained from Fig. 3.

5. Conclusions

This paper presents the application of the digital speckle pattern interferometry technique to the evaluation of the electromechanical properties produced by a thick-film piezoelectric device manufactured with screen-printing deposition over a ceramic substrate. The experimental work presented here clearly demonstrates that the mentioned whole-field optical technique, with the addition of a phase shifting facility for automating data analysis, allows the measurement of displacement fields in the nanometer scale if in-plane displacements or decorrelation are not introduced by the object deformation. As expected, it is also demonstrated that the measured out-of-plane deflections produced by the piezoelectric transducer do not replicate the classical piston movement produced by a free sensor due to the clamping effect generated by the substrate. Evaluating the maximum out-of-plane deflection generated by the transducer for a known DC voltage, it is shown that digital speckle pattern interferometry enables quite easily the determination of the effective piezoelectric charge constant $(d_{33})_{eff}$ that characterizes the thick-film ceramic. As known, this constant has a much lower value than the one generated by a bulk ceramic of the same material due to the glass binder used to achieve better consistency in the sintered film, the porosity resulting from the relatively low sintering temperature and the clamping introduced by the substrate.

The screen-printing technology to manufacture thick-film piezoelectric transducers has great flexibility, allowing batch production and facilitating the fabrication with different formats and geometries including several substrates. Therefore, the interferometric measurement of the effective piezoelectric charge constant presented in this work would enable the optimization of the different parameters used in the fabrication procedure of the thick-film ceramic to obtain transducers with good electromechanical responses. In this way it will be possible to analyze the influence of different glasses, variations in the composition of the paste, the residual porosity, the sintering temperature and various other fabrication parameters, which will ultimately define the utility of the piezoelectric device for each application. Finally, the DSPI testing applied in this work will also enable the evaluation of the electromechanical response of individual thick-film piezoelectric transducers to form bidimensional arrays with different geometries.

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