Vortragsankündigung

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Piezoelectric ceramic discs, plates and bars for electrical signal transformation

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Abstract:
Piezoelectric ceramic resonator with segmented electrodes may serve as a transformer of AC electrical signals. Transformation parameters depend on the shape of ceramics body, its material, electrode pattern, vibration mode, driving frequency and voltage amplitude etc. Different shapes of transformers (bar, plate and discs) used in the transformer design are briefly described. Transformation parameters like efficiency and gain as a function of frequency and load are presented e.g. for the set of disc ceramic transformers with various electrode patterns on homogeneously polarized discs. As an example, Rosen type transformer made from the soft and hard PZT is presented for comparison. Ceramic body of the transformer might be modified by the domain engineering or by the co-sintering of soft and hard PZT materials. Some results are presented also for the analytical and numerical calculations for piezoelectric transformers and for the measurement of properties.

Alle Interessenten sind herzlich eingeladen.

Dr.rer.nat. G. Suchaneck
Evaluation of Polarization of Embedded Piezoelectrics by the Thermal Wave Method

Gunnar Suchaneck, Agnes Eydam, Wenguo Hu, Burkhart Kranz, Welf-Guntram Drossel, and Gerald Gerlach

Abstract—This work demonstrates the benefit of the thermal wave method for the evaluation of the polarization state of embedded piezoelectrics. Two types of samples were investigated: A low-temperature co-fired ceramics (LTCC)/lead zirconate titanate (PZT) sensor-actuator and a macro-fiber composite (MFC) actuator. At modulation frequencies below 10 Hz, the pyroelectric response was governed by thermal losses to the embedding layers. Here, the sample behavior was described by a harmonically heated piezoelectric plate exhibiting heat losses to the environment characterized by a single thermal relaxation time.

I. INTRODUCTION

T

ransient methods for the determination of the thermal or pyroelectric properties of thin films after pulse or periodic heating have been known for more than 140 years [1]–[6]. Periodic heating of the sample by a modulated light beam is most widely used in high-resolution measurements [2]–[6]. The intensity-modulated light beam is absorbed in the sample and generates well-defined thermal waves, which propagate in the sample and cause local changes in temperature, thermoelastic strains, pyroelectric response, etc. Modulation of the laser beam is performed in different ways: Trapezoidal (dynamic method [4]), triangular (alternative thermal wave method [5]), rectangular (square wave method [6]–[8]), and sinusoidal modulation [6], [8]–[11], which was later called the laser intensity modulation method (LIMM) [11].

By traveling through the sample, the thermal wave is both attenuated and retarded in phase in accordance with a complex wave vector k:

\[ k = (1 + i) \sqrt{\frac{\omega}{2\alpha}} \]  

(1)

which is determined by the circular frequency of heat modulation \( \omega \) and the thermal diffusivity \( \alpha \). Therefore, the main difficulty for the evaluation of embedded piezoelectrics is that, because of the exponentially decaying thermal wave, the signal of the detector is weak, thus increasing measurement uncertainty.

Embedded piezoelectrics are currently finding increasing applications for structural actuation and sensing, e.g., for flexure or distorting materials, counteracting vibrations, or generating vibrations. They are very sensitive strain gauges to sense deformations, noise, and vibrations as well as excellent devices to harvest energy from vibrations [12]. During fabrication, such sensor-actuators are subjected to many thermal and mechanical stresses, leading to partial depolarization of the piezoelectric properties. Therefore, the development of a nondestructive technique for polarization evaluation of embedded piezoelectrics is an important task for mass fabrication of such devices.

In this work, we demonstrate that the thermal wave method is a promising approach for the nondestructive evaluation of the polarization state of embedded piezoelectrics in integrated sensor-actuator modules. We evaluate the polarization state of 1) lead zirconate titanate (PZT) plates embedded into low-temperature co-fired ceramics (LTCC) [13], and 2) piezoceramic PZT rods of a macro-fiber composite (MFC) embedded into epoxy resin.

An LTCC/PZT module consisting of a previously sintered PZT plate (Sonox P53, CeramTec GmbH, Plochingen, Germany) with a size of 25 × 10 × 0.2 mm embedded in the center of a 45 × 20 × 0.7 mm sintered LTCC module (HeraLock Tape-HL2000, Heraeus, Hanau, Germany) was chosen as the first sample. Sample fabrication was previously described in detail elsewhere [13]. The sample capacitance was 30 nF and the dielectric loss tangent about 2% at 10 kHz. The second sample was a commercial M-8528-P2 piezoelectric actuator (Smart Material Corp., Sarasota, FL) with an overall length of 105 mm, an active length of 85 mm, an active width of 28 mm, a thickness of about 0.3 mm, and a sample capacitance of 170 nF.

II. THEORY

A. Analytical Solution

By traveling through the top layer of the module packaging, higher harmonics of a square wave disappear and the thermal wave gradually becomes sinusoidal [14]. Therefore, we analyze in the following the thermal problem of a harmonically heated piezoelectric plate exhibiting heat losses to the environment, characterized by a single thermal relaxation time:

\[ \tau_{\text{th}} = \frac{\varepsilon \rho \cdot d_f}{2H}, \]  

(2)
where \( c, \rho, \) and \( d_f \) are specific heat, density, and thickness of the plate, respectively. \( H \) is the thermal conductance at the interface which is (e.g., in the case of radiation losses) determined by the Stefan-Boltzmann law, yielding in linear approximation:

\[
H \approx 4\varepsilon\sigma_{SB} \cdot T_0^3,
\]

where \( \varepsilon \) is the emissivity and \( \sigma_{SB} \) is the Stefan-Boltzmann constant. The steady-state periodic solution of this problem in the form of an infinite series is given by [14], [15]

\[
\Theta(z) = \Theta_\infty \left[ \frac{\tau_{th}}{1+i\omega\tau_{th}} \right] + 2 \cdot \sum_{n=1}^{\infty} \cos \left( \frac{n\pi z}{d_f} \right) \left[ \frac{\tau_d/n^2}{1+i\omega\tau_d/n^2} \right] \exp(i\omega t),
\]

where \( \Theta = T - T_0 \) (where \( T_0 \) is the temperature of the environment, \( \Theta_\infty = \Phi_0/cd_f \) is the asymptotic value of \( \Theta(t,z) \) at \( t \to \infty \)), \( \Phi_0 \) is the heat flux absorbed by the plate surface, \( \tau_d = d_f^2/\pi^2 \alpha \) is the heat diffusion time, and \( \alpha \) is the thermal diffusivity of the plate. The pyroelectric response of the piezoelectric plate yields [15]

\[
I_-(\omega) = \frac{\Phi_0 A}{\varepsilon\rho \cdot d_f} \left[ p_0 \frac{i\omega \tau_{th}}{1+i\omega\tau_{th}} + \sum_{n=1}^{\infty} p_n \frac{i\omega \tau_d/n^2}{1+i\omega\tau_d/n^2} \right] \exp(i\omega t),
\]

where \( A \) is the plate area and

\[
p_0 = \frac{1}{d_f} \int_0^{d_f} p(z) \, dz,
\]

\[
p_n = \frac{2}{d_f} \int_0^{d_f} p(z) \cos \left( \frac{n\pi z}{d_f} \right) \, dz
\]

are the average and spatially dependent parts of the pyroelectric coefficient. Note, that in the case of square wave modulation with a period \( T = 2\pi/\omega_0 \), (4) is

\[
\Theta(z) = \Theta_\infty \left[ \frac{\tau_{th}}{1+i\omega\tau_{th}} \right] + 2 \cdot \sum_{n=1}^{\infty} \cos \left( \frac{n\pi z}{d_f} \right) \left[ \frac{\tau_d/n^2}{1+i\omega\tau_d/n^2} \right] \times \sum_{m=1}^{\infty} \frac{(-1)^{m-1}}{2m-1} \exp(i\omega_0 t).\]

B. Numerical Simulation

A transient thermal analysis of the more complicated MFC actuator was performed using the finite element modeling package Ansys 11.0 (Ansys Inc., Canonsburg, PA). The actuator consists of an array of elements with a total area of 2380 mm². The geometric model of one of the modeled periodic MFC elements is shown in Fig. 1.

The piezoceramic macrofiber is embedded into epoxy resin at both sides. It is located between two copper electrode strips of the electrode structure and covered by a Kapton film (DuPont de Nemours, Neu-Isenburg, Germany). A Ni layer covering the total surface area of the rectangular piezoceramic rod provides better adhesion of the copper electrode and a more homogeneous electric field inside it.

The initial temperature of the MFC was set to \( T_0 = 20^\circ C \). Two load steps were created for transient analysis: In the first load step, a heat flux of 780 W/m², provided by the laser array, was applied to the top of the sample for one half-period. In the second load step, the heat flux was set to zero for another half-period, and so on. The element’s backside was assumed to be an ideal heat sink. Heat conduction in the sample was simulated using the thermal properties compiled in Table I. Ideal thermal contact was considered at internal interfaces between materials of different thermal conductivity. Radiation losses estimated using (3) were negligible. The analysis was performed for modulation frequencies of 1, 3, 10, 100, and 1000 Hz.

### III. Experiment

The measurement of the PZT P53 plate’s pyroelectric coefficient was carried out by heating the sample periodically at the bottom electrode by means of a Peltier element and controlling the temperature change by a

<table>
<thead>
<tr>
<th>Material</th>
<th>Density, g/cm³</th>
<th>Thermal conductivity, W/mK</th>
<th>Specific heat, J/gK</th>
</tr>
</thead>
<tbody>
<tr>
<td>Epoxy resin</td>
<td>1.97 [18]</td>
<td>0.495 [18]</td>
<td>0.97 [18]</td>
</tr>
<tr>
<td>Cu (20°C)</td>
<td>8.94 [19]</td>
<td>305 [19]</td>
<td>0.386 [19]</td>
</tr>
<tr>
<td>Ni</td>
<td>8.908 [20]</td>
<td>90.7 [20]</td>
<td>0.44 [20]</td>
</tr>
</tbody>
</table>
The pyroelectric current was recorded by an SR850 lock-in amplifier (Stanford Research Systems, Sunnyvale, CA). The value obtained was 120 μC/m²∙K.

The sensor-actuator samples were periodically heated by an array of 6 semiconductor lasers (LCU98A041A, Laser Components GmbH, Olching, Germany) square-wave modulated with frequencies of up to 1 kHz each with a power of 14 mW at a wavelength of 980 nm. Polarization was determined obtaining the pyroelectric current spectrum. The pyroelectric current was transformed into a voltage by a current-voltage-converter and amplitude and phase were determined by an impedance-phase analyzer (Solartron 1260, Solartron Analytical, Farnborough, UK). The current spectra were corrected by laser power measurements using internal photodiodes of the lasers. To reduce noise, up to 100 measurement repetitions were used for averaging.

IV. RESULTS AND DISCUSSION

Fig. 2 shows the pyroelectric current amplitude of the piezoelectric LTCC/PZT module in dependence on frequency for 50 measurement repetitions in comparison with a fit to (5) performed using data in Table II. Above 0.6 Hz, the thermal wave is confined within the sample, at frequencies above 10 Hz, only the top LTCC layer is heated. The pyroelectric response below 10 Hz is determined by thermal losses induced by heat conduction and radiation to the surroundings. The estimated value of the thermal relaxation time τth is 0.135 s, resulting in a thermal conductance of 3650 W/m²-K; i.e., about 1825 W/m²-K at both the top and the bottom surface. Beyond a frequency of 10 Hz, the pyroelectric response is described by a pyroelectric capacitor periodically heated by thermal waves from the LTCC top layer absorbed in the PZT plate top electrode. Above 100 Hz, the penetration depth of the thermal wave into LTCC becomes less than 60 μm. This is in the order of the laser light absorption depth of about 25 μm determined by optical transmission measurements on thin LTCC samples. Consequently, the model of light absorption in a very thin surface layer is no longer valid. For capacitive loads as large as 30 nF, the performance of the preamplifier also degrades at frequencies above 200 Hz.

Fig. 3 shows the simulated time dependence of the temperature difference Θ in the center of the different macro-fiber composite actuator materials calculated for a modulation frequency of 10 Hz. The values for the Ni adhesion layer were omitted because they are practically the same as for the Cu electrode. The Ansys simulation reveals the presence of a transient heating-up period before reaching the steady state. This was accounted in the measurements. Inside the PZT piezoceramics, the thermal excitation becomes nearly sinusoidal and shifted in phase, as is known for harmonic excitation [14].

Fig. 4 demonstrates the calculated temperature distribution in the center of the piezoceramic rod. A significant blurring of the temperature field by the metallic electrodes is seen. On the other hand, the horizontal component of the temperature gradient at the piezoceramics/epoxy resin interface remains small, e.g., heat conduction through this interface can be neglected. Thus, the pyroelectric response of the MFC actuator is well described by (5), see Fig. 5.

<table>
<thead>
<tr>
<th>Material</th>
<th>Effective area, mm²</th>
<th>Thickness, mm</th>
<th>Pyroelectric coefficient, μC/m²-K</th>
</tr>
</thead>
<tbody>
<tr>
<td>PZT plate</td>
<td>250</td>
<td>0.2</td>
<td>120</td>
</tr>
<tr>
<td>Macrofiber-array</td>
<td>~1100*</td>
<td>0.18</td>
<td>120</td>
</tr>
</tbody>
</table>

*Part irradiated by the laser array.
Here, the model curves were drawn again using the data in Table II. The pyroelectric coefficient of the PZT macrofiber rods was assumed to be equal to that of the PZT plate. Consequently, an expensive finite element modeling of this complex thermal problem may be avoided. The thermal relaxation time equals 0.14 s, yielding an effective value of thermal conductance of 3175 W/m²·K for the whole structure. We attribute the discrepancy between measured data and the model above 200 Hz to preamplifier performance degradation at higher frequencies. Note, that the capacitive load is much larger for the MFC sample (170 nF) compared with the LTCC/PZT one (30 nF).

With regard to (5) and (7), the spatial polarization distribution provides a small contribution to the imaginary part of the pyroelectric current in the frequency range of $\frac{1}{\tau_{th}} < \omega < \frac{1}{\tau_{d}}$, given by

$$I_{\omega} = \frac{\Phi_{p} A}{c \rho \cdot d_{f}} \sum_{n=1}^{\infty} p_{n} \frac{i \omega \tau_{d}/n^{2}}{1 + i \omega \tau_{d}/n^{2}} \approx \frac{\Phi_{p} A}{c \rho \cdot d_{f}} \sum_{n=1}^{\infty} p_{n} \frac{\tau_{d}}{n^{2}}.$$  

(9)

Taking into account that $\cos(n\pi z/d_{f}) < 1$ we get

$$\text{Im} I_{\omega} < 2 \frac{\Phi_{p} A}{c \rho \cdot d_{f}} \omega \tau_{d} \cdot p_{0} \cdot \sum_{n=1}^{\infty} \frac{1}{n^{2}} = 2 \frac{\Phi_{p} A}{c \rho \cdot d_{f}} \omega \tau_{d} \cdot p_{0} \cdot \zeta(2)$$

$$= \frac{\pi^{2}}{3} \frac{\Phi_{p} A}{c \rho \cdot d_{f}} \omega \tau_{d} \cdot p_{0},$$

(10)

where $\zeta$ is the Riemann Zeta function. Consequently, no information about the polarization profile can be extracted within a frequency region determined by

$$\frac{\pi^{2}}{3} \omega \tau_{d} \ll \frac{\omega \tau_{th}}{1 + (\omega \tau_{th})^{2}} \approx \frac{1}{\omega \tau_{th}}.$$  

(11)

In our case, information about the polarization profile of the LTCC/PZT actuator’s piezoelectric plate can be extracted within a frequency range of 3 Hz < $f$ < 20 Hz. The derivation of the polarization profile of embedded piezoelectrics by thermal wave methods is the subject of a forthcoming paper.

V. Conclusions

The thermal wave method was demonstrated to be a simple and nondestructive means for the evaluation of the polarization state of embedded piezoelectric components in integrated sensor-actuator modules. Pyroelectric response at frequencies where the sample behaves as a pyroelectric capacitor which is periodically heated by the embedding material allows quantification of depolarization effects resulting from mechanical and thermal stresses arising during sensor-actuator module fabrication. On the other hand, the determination of the thermal relaxation time of the embedded piezoelectrics enables disclosure of lamination failures.

REFERENCES


Agnes Eydam received her diploma degree in electrical engineering from the TU Dresden, Germany, in 2010. She is currently working toward the Ph.D. degree at the Solid-State Electronics Lab of TU Dresden. Her research interest is polarization determination of integrated piezoceramics as part of process control and nondestructive device evaluation.

Wengu Hu received his bachelor degree from Tongji University, China, in 2006. He obtained his diploma degree in electrical engineering at TU Dresden in 2010. His research interest at the Solid-State Electronics Lab at TU Dresden was measurement technology.

Burrhhard Kranz received his diploma degree in the field of applied mechanics from TU Dresden in 1993. Since 2001, he has worked at the Fraunhofer Institute of Machine Tools and Forming Technology (IWT) as a research assistant. He is engaged mainly in finite element simulations in conjunction with applications of piezoelectric materials.

Well-Guntram Drossel studied technical acoustics at TU Dresden and received his Ph.D. in the field of metal forming from TU Bergakademie Freiberg in 1998. Since 1999, he has been involved in the Fraunhofer Institute of Machine Tools and Forming Technology (IWT) at different positions. Currently, he is one of the chief engineers of Fraunhofer IWT. Dr. Drossel is a lecturer at the TU Chemnitz. His main research activities are in the fields of mechatronics, system technology, and functional integration. He is a corporate member of the International Academy for Production Engineering (Collège International pour la Recherche en Productique, CIRP).

Gerald Gerlach received the diploma degree in information technology and the doctoral degree in electrical engineering from TU Dresden, Germany, in 1985 and 1987, respectively. He worked as a senior engineer at two companies in the measurement devices industry. In 1993, he became a professor at the Department of Electrical Engineering of TU Dresden. Since 1996, he has been the head of the Solid-State Electronics Laboratory. From 1994 to 2000, he served as Deputy and as Dean of the Department of Electrical Engineering and Information Technology, respectively. From 2007 to 2010, he was Chairman of the German Society for Measurement and Automatic Control (GMA). Dr. Gerlach’s research includes solid-state sensors, especially pyroelectric infrared sensors and systems and piezoresistive sensors for pH and chemical concentration measurement, micromachining technology, and modeling and simulation of heterogeneously coupled systems such as sensors and actuators. He is author or coauthor of four textbooks and editor of a book series in the field of sensor technology. He authored more than 350 technical publications in scientific journals and conference proceedings and holds more than 40 patents.

Gunnar Suchaneck received his Ph.D. in physico-mathematical sciences from the Electrotechnical University–LETI, St. Petersburg, Russia, in 1983. Since 1984, he has been a Senior Scientist at TU Dresden; since 1997 he has been with the Solid-State Electronics Lab there. His current research interests include solid-state sensor technology, IR- and UV-thin film sensors, thin film sensors based on PZT thin films, and solid oxide fuel cells. He has coauthored more than 250 technical publications in books, scientific journals, and conference proceedings, and has coauthored 15 patents.