Investigation of the Thermal Performance of Piezoelectric Actuators

R. RIMASAUSKIENE, M. MIELOSZYK, T. WANDOWSKI,
P. MALINOWSKI and W. OSTACHOWICZ

ABSTRACT

In this era of new technologies, precision positioning equipment are requested to meet various characteristics, such as small size, versatility, reliability, efficiency, wide operating temperature and speed range, capability of working in vacuum and radiation environment. As it is known, piezoelectric actuators meet most of the requirements. Piezoelectric actuators are small in size, relatively low in cost, and suitable for use in precision positioning systems. However various structures of devices with piezoelectric actuators are used in requires knowing their thermal characteristics.

The experimental research described below disclosed dynamical characteristics of two different piezoelectrical actuators. Measurements were carried out with a help of Laser Scanning Vibrometer and Fibre Bragg Grating (FBG).

INTRODUCTION

Piezoceramical elements became popular in various industries in the second half of 20th century. Characteristics of piezoceramic elements were well researched and employed in piezoelectric actuators and piezoelectric sensors. Actually, it should be mentioned that the choice of piezoelectrical actuators is very wide and their characteristics are actively researched till today [1-3]. Scientific literature tells that piezoceramic is extremely often applied in such areas as medicine, aviation, rail transport, power industry, gas equipment, ultrasonic welding, surface cleaning, drilling and turning as well as other processing industries [4-8].

Ruta Rimasauskiene, Magdalena Mieloszyk, Tomasz Wandowski, Pawel Malinowski, Wieslaw Ostachowicz, The Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Fiszera st. 14, 80-231 Gdansk, Poland

Contemporary requirements for power saving, miniaturization, and adaptation to computer-based management and control systems call for cooperation of science and industry in order to develop piezoceramic products and search for new possibilities of their application [9-10].

Ferroelectric nature of piezoelectric ceramics leads conditions their dependence on ambient temperature or ageing. Constant values make sense only taking into account ageing of piezoelectrics. Temperature dependability of piezoelectrical effect featured by piezoceramic materials limits it usage. In practice, maximum operation temperature must be limited to significantly lower level than Curie point, or otherwise it will accelerate ageing processes [11]. Increased temperature of piezoceramic elements increases power loss, reduces maximum mechanical strength, and irreversibly decreases piezoelectric features until they are completely lost at Curie point.

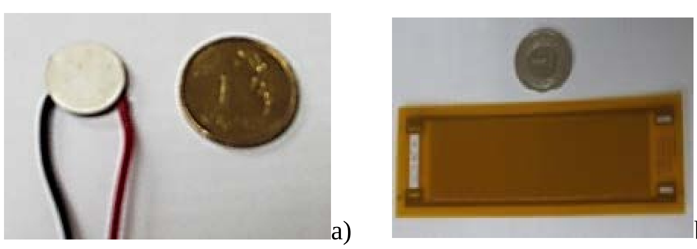
Therefore, it is extremely important to research temperature characteristics of piezoelectric actuators working in various modes. Often piezoelectric actuators are used aiming to obtain maximum displacements that are possible when a piezoelectric actuator operates under maximum excitation voltage and often at the first resonance frequency. The theory suggests that working in such modes extremely increases temperature of piezoceramic elements so that it can reach maximum point. Therefore the development of various devices with piezoceramic elements requires knowing maximum allowable excitation voltages and frequencies. It is important not only for piezoceramic itself, but also for the device where it is used in [12]. High temperatures might cause deformation or other changes of mechanical properties of some materials. This might influence the life time and operational characteristics of the device [13].

The article analyses piezoelectric actuators of some sorts, experimentally researches dynamic characteristics of piezoelectric actuators, and delivers their thermal analysis.

EXPERIMENTAL SECTION

Structure of the piezoelectric actuators

In the paper piezo actuators of two sorts are analysed. It investigates operational characteristics of various devices and finds out their dependence on ambient temperature.



a) b)

Figure 1. Piezoelectric actuators: a) Sonox P502 actuator used for the experiments; b) Macro Fiber Composite (MFC) actuator (type P1) used for the experiments.

The piezoelectric actuators investigated can be used in various areas therefore the experiment involved actuators of various structures and dimensions. Different piezoelectric actuators achieved various displacements that varied from few to several thousand nanometres. They also differed in their thermal characteristics.

First the *CeramTec SonoxP502* actuator (diameter10 mm, thickness 0.5 mm) (Fig. 1 a) was analysed. Actuators are mainly used in mixed systems where piezoceramic elements are used as an ultrasonic-transducer on one side and as a receiver on the other side. *Sonox P502* is made of specifically created materials with a high rate of thermal and temporal stability. Standard electrodes are made of silver or nickel-gold plated.

The second actuator was made with Macro Fibre Composite (MFC) elements offering high performance, flexibility, and reliability features in cost effective devices. The MFC consists of rectangular piezoceramic rods sandwiched between an adhesives, electrodes, and polyimide film. The electrodes are attached to the film in an interdigitated pattern that transfers the applied voltage directly to and from the ribbon shaped rods. Under the voltage it will bend or distort materials, counteract or generate vibrations. If no voltage is applied it can serve as a very sensitive strain gauge, sensing deformations, noise, and vibrations.

The MFC is available in d_{33} operational mode, a unique feature of the *Macro Fiber Composite*:

- MFC P1 type (d_{33} effect) can elongate up to 1800 ppm if operated at the maximum voltage rate of -500V to +1500 V (Fig. 1 b).

Experimental equipment

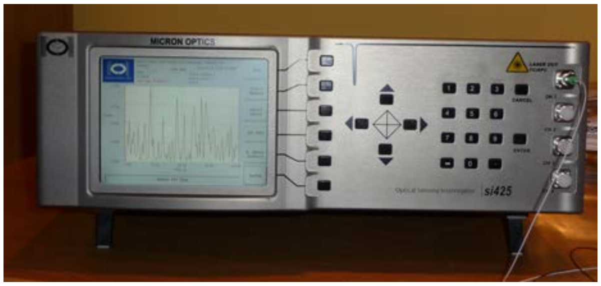
The experimental analysis of dynamic characteristics of piezoelectric actuators aimed to find out what frequency would allow achieving the largest displacement of piezoelectric actuator surface and what shapes of the piezoelectrical actuator surface are at various resonance frequencies. The experiment disclosed thermal characteristics of all piezoelectric actuators in various working conditions.


a)

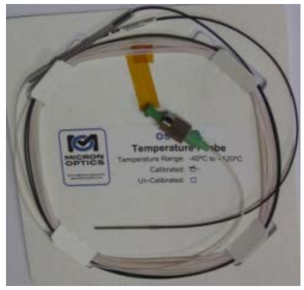
b)

Figure 2. Polytec 3D laser vibrometer: a) three scanning heads for 3D vibration measurement; b) control unit.

In order to determine these parameters experiments at the experimental stand (Fig. 2), consisting of a programmable signal generator (TTi TG4001 Arbitrary Function Generator 40MHz, high voltage amplifier (1 kHz - 150 kHz frequency zone), Polytec 3D laser vibrometer (frequency response up to 1.5 MHz, displacement measurement range as low as 1 nm) and a computer with installed PSV 8.8 software were carried out.



a)



b)

Figure 3. Thermal measurements devices: a) interrogator for FBG sensors; b) temperature probe.

During the experiment with Fibre Bragg Grating (FBG) the experimental stand consisted of an interrogator (Micron Optics, si425-500) (Fig. 3a) and FBG temperature probe (os4200) (Fig. 3b). The FBG sensor was dedicated to measure the temperature variations of the surface of piezoelectric actuators.

RESULTS AND DISCUSSIONS

At the beginning the researchers aimed to identify resonance frequencies of piezoelectric actuators having excited them by maximum voltage. With a help of laser vibrometer, resonance frequencies and surface displacements were determined.

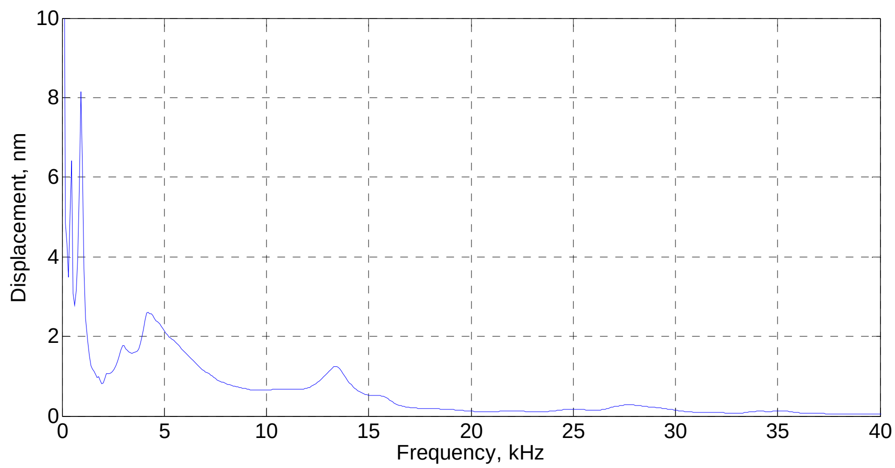


Figure 4. The dependence of piezoelectric actuator Sonox P502 surface's displacement on frequency (U=±200 V).

It was defined that maximum displacements occur at the first resonance frequencies. Therefore the article delivers the analysis of the first four resonance frequencies, i.e. discloses surface shapes and thermal characteristics of piezoelectric actuators at these four frequencies. It should be mentioned that piezoelectric actuators were not fixed; the researchers fixed only the electrodes.

First, the researchers analysed piezoelectric disc *Sonox P502* by the company *CeramTec*. The dependence of piezoelectric actuator *Sonox P502* surface's displacement at various frequencies (voltage ± 200 V) was found (Fig. 4). The shapes of the surface of piezoelectric disc were found working at the first four resonance frequencies (Fig. 5).

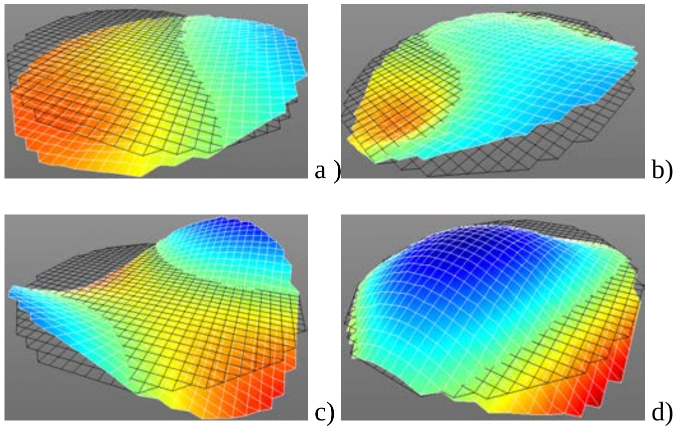


Figure 5. Shapes of the surface of piezoelectric actuator Sonox P502: a) frequency 0.93kHz; b) frequency 4.22kHz; c) frequency 13.36kHz; d) 27.73 kHz.

Figure 4 shows that working at the first resonance frequency 0.93 kHz (voltage ±200 V) delivered the biggest displacement (about 8.15 nm) of the surface of piezoelectric. If piezoceramic element is working under the highest excitation voltage at the first resonance frequency, the temperature is not growing rapidly. After 1.5 minutes it achieved 35°C and became stable (Fig. 6 a). But working continuously at the second resonance frequency temperature was growing extremely rapidly and the electrodes felt down after 20-30 seconds. The temperature was too high for the electrode welding solder and they were disconnected. It was a problem of our research.

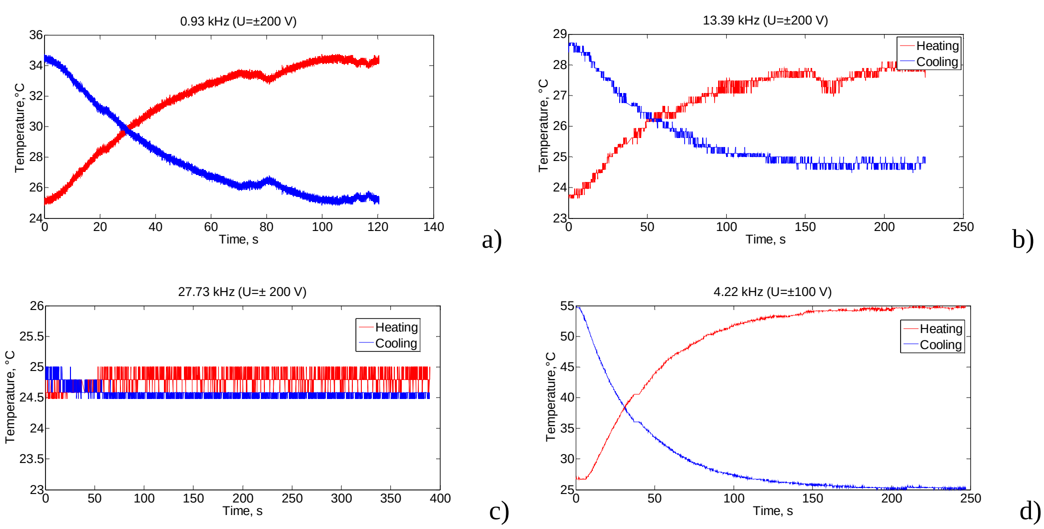


Figure 6. The dependence of temperature on time: a) frequency 0.93 kHz, voltage ±200V; b) frequency 13.39 kHz, voltage ±200 V; c) frequency 27.73 kHz, voltage ±200 V; d) frequency 4.22 kHz, voltage ±100 V.

Theory suggests that different dielectric ceramic bodies are heating up at different excitation voltages. If cooling of piezoceramics elements is not ensured, the increased temperature increases losses and causes thermal destruction of polarity. The best mechanical and piezoelectric properties of piezoceramics *Sonox P502* are kept when it is working up to 160°C. Therefore, the experiment at the second resonance frequency was repeated by keeping different excitation voltages (±100 V).

At the third frequency (13.39 kHz), temperature reached 28°C in 200 s and became almost linear (Fig. 6 b). It should be noted, that on the same time it was cooling down, like in the experiment with the first resonance frequency. During the experiment with the fourth resonance frequency, thermal dependence remains almost constant (Fig. 6 c). The same process was observed at next frequencies too.

In the next steps of the thermal analysis the excitation voltage was changed from ±200 V to ±100 V. It must be said that such a big change of voltage was not very useful, since the displacement of the surface of piezoelectric actuator became about smaller at 1 nm. But from the other side, it was the possibility to find thermal characteristics of piezoelectric disc *Sonox P502* at the second resonance frequency. Curves in the Figure 6 d show that temperature was growing quite fast and reached 55°C in 150 s. Cooling lasted for the same time. At the third resonance frequency (13.39 kHz), temperature reached just 26°C. It means the temperature changed only by 1.5°C. At the fourth resonance frequency, temperature acted seemingly as in case with the voltage of ±200 V. It means that, working at the first three resonances, frequencies temperature is growing, but it is possible to achieve the biggest displacement of the piezoelectric actuator's surface.

Experimental results of piezoelectric disc *Sonox P502* made clear that the best way to get the biggest displacement for the system is to use the first resonance frequency. It is possible to conclude that cooling of piezoelectric actuator must be ensured. Otherwise it is not possible to work in the best working modes, since they will destroy piezoceramic elements.

Next analogical experiment was conducted with MFC (P1 type) actuator (Fig. 1 b). It disclosed the displacement of the actuator's surface at various resonance frequencies (Fig. 7). Peak voltage (-1000÷500 V) was applied on this piezoelectric actuator too. The biggest displacements at the first four resonance frequencies were obtained. Figure 8 delivers shapes of the surface MFC actuator.

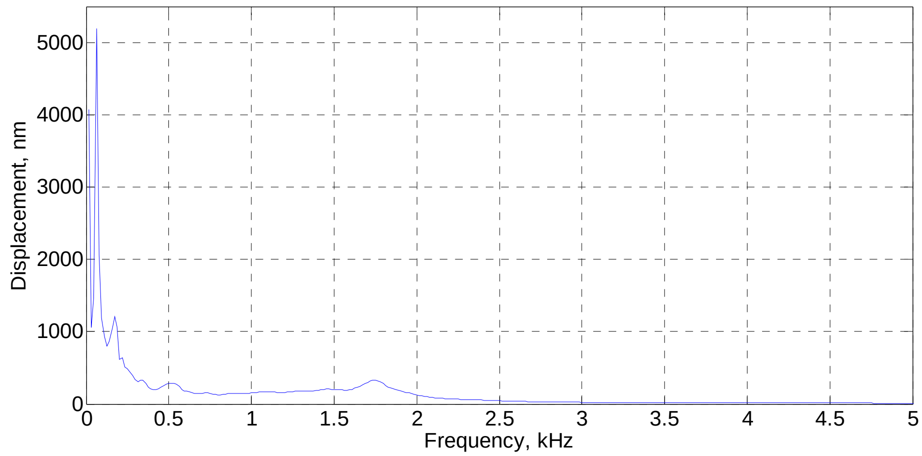


Figure 7. The dependence of the MFC (P1 type) surface's displacement on frequency (voltage -1000÷500 V).

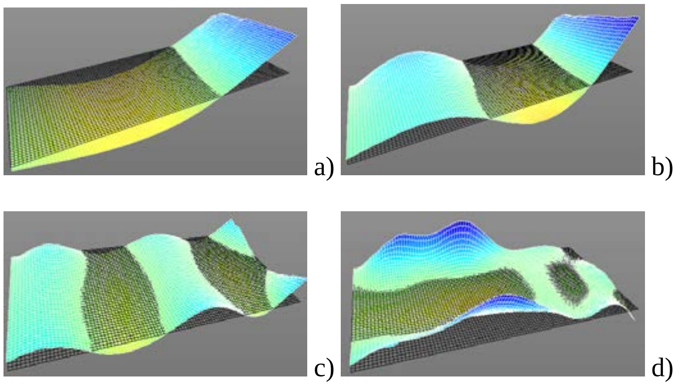


Figure 8. Shapes of the surface of piezoelectric actuator MFC (P1 type): a) frequency 62.5 Hz; b) frequency 171.88 Hz; c) frequency 531.25 Hz; d) 1.75 kHz.

The biggest displacement of the surface of MFC was obtained at the first resonance frequency 62.5 Hz; it is 5190 nm. Temperature was not growing extremely rapidly at this frequency (Fig.9). In 200 s it reached about 40°C and became almost stable. At the second resonance frequency, displacement was almost five times smaller, but temperature was growing more rapidly and reached 56°C. The smallest displacement of the surface of MFC was observed at the third resonance frequency (280 nm), but temperature was growing extremely rapidly. After 80 s it was about 80°C (Fig. 9). At the fourth frequency (1.75 kHz), similar effect was detected. The displacement was quite small, but the temperature was growing rapidly, notwithstanding that it reached only 60°C (Fig. 9).

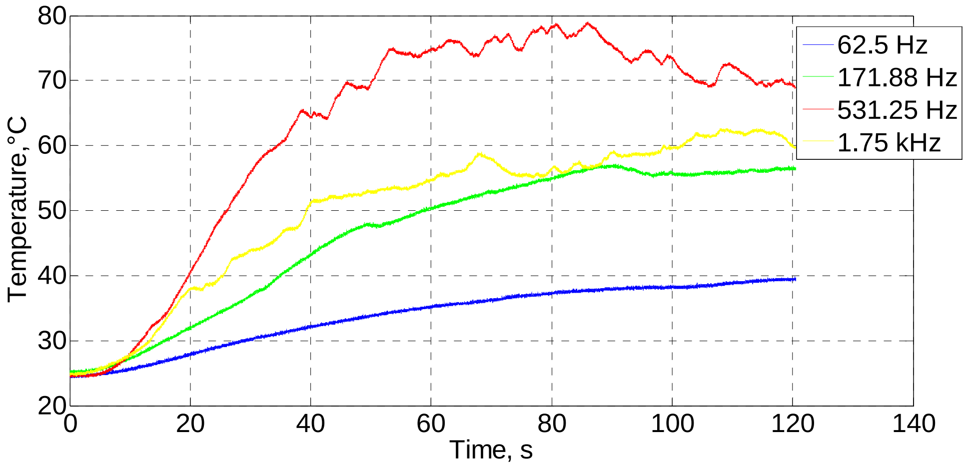


Figure 9. The dependence of the MFC (P1 type) temperature on time (voltage -1000÷500 V).

It is important to mention that cooling of this actuator was not analysed, since it is cooled on the same time as heated. Temperature was growing at the first two resonance frequencies, but displacement was the biggest in these cases too. It is useful to work at the first or the second resonance frequency, if it is necessary to get big displacement in any kind of devices.

The analysis of piezoelectric actuators shows that it is useful to work at the first resonance frequency and to reduce the excitation voltage if there is a need to get smaller displacement. Working in these operational conditions makes possible stabilization of thermal characteristics.

CONCLUSIONS

The article analyses and presents the dependence of the displacement of two piezoelectric actuators of different structures on frequency. In both cases, the biggest displacement of the surface was obtained at the first resonance frequency. In addition, the article delivers the experimental analysis of temperature properties of piezoelectric actuators. It identifies that maximum excitation voltage at the first resonance frequency generates the biggest displacement of the surface of piezoelectric actuators, and the temperature remains below 40 °C in all cases what is not dangerous to piezoceramics and might be used in various devices. However working at other frequencies, the displacement is smaller, but the temperature rapidly reaches limits that are dangerous to piezoceramics.

ACKNOWLEDGMENTS

This work was supported by the FP7 Marie Curie IAPP project “STADYWICO” (FP7-PEOPLEIAPP2009, Grant Agreement No. 251309).

REFERENCES

1. O. Bilgen, Y. Wang, D. J. Inman, Electromechanical comparison of cantilevered beams with multifunctional piezoceramic devices, Mechanical Systems and Signal Processing 27 (2012) 763-777.
2. Y. Roh, C. Moon, Design and fabrication of an ultrasonic speaker with thickness mode piezoceramic transducers, Sensors and Actuators A: Physical 99 (3) (2002) 321-326.
3. C.C. Ma, H. Y. Lin, Experimental measurements on transverse vibration characteristics of piezoceramic rectangular plates by optical methods, Journal of Sound and Vibration 286 (3) (2005) 587-600.
4. K. T. Ooi, Simulation of a piezo-compressor, Thermal Engineering 24(4) (2004) 549-562.
5. I. P. Lipscomb, P.M. Weaver, J. Swingler, J.W. McBride,The effect of relative humidity, temperature and electrical field on leakage currents in piezo-ceramic actuators under dc bias. Sensors and Actuators A: Physical 151(2) (2009) 179-186.
6. K. S. Kwon, Methods for detecting air bubble in piezo inkjet dispensers, Sensors and Actuators A: Physical 153 (1) (2009) 50-56.
7. H. K. Suh, S. W. Park, C. S. Lee, Effect of piez-driven injection system on the macroscopic and microscopic atomization characteristics of diesel fuel spray, Fuel 86 (17–18) (2007) 2833-2845.
8. F. Aono, K. Kawano, M. Kuwayama, Y. Takehara, K. Kato, O. Kato, In vitro and in vivo developmental ability of the embryo derived from pronuclear microinjection using Piezo-micromanipulator in cattle, Fertility and Sterility 92 (3) (2009) S63.
9. Q. S. Nguyen, H. C. Park, D. Byun, Thrust Analysis of a Fish Robot Actuated by Piezoceramic Composite Actuators, Journal of Bionic Engineering 8 (2) (2011) 158-164.
10. S. Yang, J. Cho, S. Lee, K. Park, J. Kim, Y. Huh, E. S. Yoon, H. S. Shin, Feedback controlled piezo-motor microdrive for accurate electrode positioning in chronic single unit recording in behaving mice, Journal of Neuroscience Methods 195 (2) (2011) 117-127.
11. W. Hu, X. Tan, K. Rajan, $BiFeO_3$–$PbZrO_3$–$PbTiO_3$ ternary system for high Curie temperature piezoceramics, Journal of the European Ceramic Society 31 (5) (2011) 801-807.
12. J. C. Kim, J. T. Chung, D. J. Lee, Y. K. Kim, J. W. Kim, S. W. Hwang, B. K. Ju, S. K. Yun, H. W. Park, Development of temperature feedback control system for piezo-actuated display package, Sensors and Actuators A: Physical 151 (2) (2009) 213-219.
13. F. Heidary, M. R. Eslami, Piezo-control of forced vibrations of a thermoelastic composite plate, Composite Structures 74 (1) (2006) 99-105.