Investigation of Heating Problem in a Langevin Piezoelectric Actuator

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Abstract

Langevin piezoelectric actuators have large dielectric and mechanical losses. Most of these losses are converted into accumulating internal heat that increases the temperature of the actuator. Heating problem of Langevin piezoelectric actuator is analyzed in the paper. Investigated actuator consists of a half wavelength Langevin transducer and a half wavelength waveguide. Numerical modeling was carried out to find the dependence of the actuator's temperature and heat flux rate from ratio between cross-section area of the transducer and waveguide while vibration amplitudes of the specific transducer point remain the same. Distribution of the temperature along the actuator was measured when the different diameters of the waveguide are used. Results of numerical modeling and measurement are compared and discussed.

Key words: Langevin piezoelectric actuator, heating, dielectric, mechanical losses

1. Introduction

Piezoelectric Langevin type actuators are used in variuos industrial systems such as micromanipulation and positioning devices, ultrasonic welding and cutting machines and etc [1], [2]. In many cases actuators operate under elevated temperature where mechanical, dielectric and piezoelectric losses play major role in the heat generation [3]. High temperature could lead to a degradation of piezoelectric material properties and indicates a low efficiency and short working life of the actuator [4]. Working temperature of the piezoelectric Langevin actuator can be reduced by increasing the heat dissipation rate in the structure. Self-heating of the actuator also can be reduced by separating piezoceramic elements and moving them symmetrically from the node of vibrations [5]. Heating flow rate and temperature distribution problem in piezoelectric Langevin actuator is analyzed in this paper. Numerical modeling and experimental study were carried out to find the dependence of the temperature of Langevin type actuator on the position of the piezoceramic elements. Results of numerical and experimental studies are discussed.

2. Energy losses of Langevin Actuator

Piezoelectric actuators transform the alternating electric energy into mechanical vibration of the structure by converse piezoelectric effect. Energy losses happen due to internal characteristics of the materials and are dissipated as heat. Generally, three types of the losses can be defined for piezoelectric actuator: dielectric, piezoelectric, and mechanical losses [3, 6]. Dielectric loss is caused by the hysteresis between the electric field and electric displacement. Piezoelectric loss is the electromechanical hysteresis between the mechanical strain and electric field. Mechanical loss includes the internal elastic loss due hysteresis between the strain and stress. All aforementioned losses generally are described as complex constants of the material properties matrices [6]:

$$\begin{aligned} \hat{\mathrm{C}} &= \mathrm{C}\left(1-\mathrm{i}/\mathrm{Q}\right) \\ \hat{\mathrm{d}} &= \mathrm{d}\left(1-\mathrm{i}\gamma\right) \\ \hat{\varepsilon} &= \varepsilon\left(1-\mathrm{i}\delta\right) \end{aligned} \tag{1}$$

where C, d, ε are matrices of elasticity, piezoelectric coefficients, and permittivity respectively; Q, γ, δ are quality factor, piezoelectric and dielectric loss angles respectively. The energy loss density during one period of vibrations can be deduced to be [3]:

$$\mathrm{W} = -\int_{\mathrm{T}} \mathrm{D}\,\mathrm{dE} - \int_{\mathrm{T}} \mathrm{s}\,\mathrm{dT} \tag{2}$$

where s, T, D, and E are the matrices of strain, stress, electric displacement, and electric field respectively. Power density obtained by dielectric losses of the vibrating actuator can be calculated using as follows [7]:

$$\mathrm{P_d} = \frac{\omega \mathrm{E}^2 \varepsilon\, \delta}{2} \tag{3}$$

Power density obtained by mechanical losses:

$$\mathrm{P_m} = \frac{\omega\ \mu \mathrm{Re}\left(\mathrm{s}\,\overline{\mathrm{C}\ \mathrm{s}}\right)}{2} \tag{4}$$

3. Numerical Modeling and Results

Heating problem of piezoelectric actuator consisting of half wavelength Langevin transducer and half wavelength waveguide was analyzed (Fig.1). Three waveguides with same length but different diameters: 5, 10 and 15 mm were investigated. Two different configurations of Langevin transducers were analyzed. Piezoceramic rings were combined and located at the node of longitudinal vibrations in the first case. Piezoceramic rings were separated and moved symmetrically from the node in the second case. An additional metal block was inserted between separated piezoceramic so that total length of the transducer remained the same. All investigated actuators operate at the first resonance frequency of longitudinal vibrations. PZT-8 piezoceramic rings are used as active part of actuator and steel 40X13 are used as passive parts of the actuator.

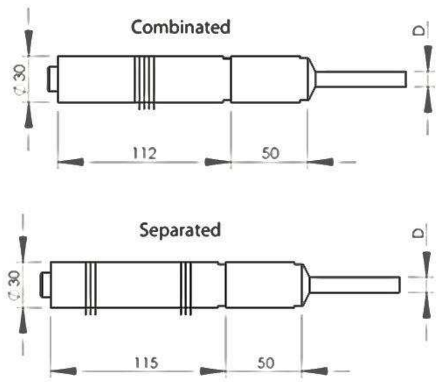

Fig. 1: Principle schemes of piezoelectric Langevin type actuator

A finite element model using Comsol Multiphysics has been developed to analyze the heat flow rate and temperature distribution along the actuator. Vibration amplitudes of the end point of Langevin transducer was set to 1 μm in all simulated models, while excitation voltage differs from 200V till 300 V. Steady state and transient thermal analysis were carried out by evaluating dielectric, piezoelectric and mechanical losses. No mechanical boundary conditions were applied while convection heat transfer boundary conditions were used for all external areas of the actuator. The ambient temperature was set to 22°C. Distribution of the temperature along the actuator with combined and separated piezoceramic rings is shown in Fig. 2 and Fig. 3 when different diameters of the Langevin transducer are used. It can be noticed that temperature starts rapidly to increase at the position, where waveguide is mounted and largest temperature is located in the end of waveguide in all cases. Also it can be

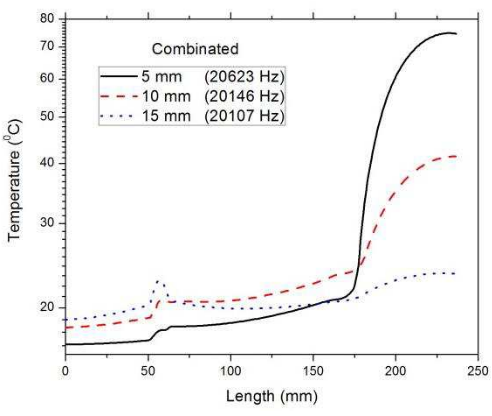

Fig. 2: The distribution of temperature along actuator with combined piezoceramic rings when different waveguide diameters are used

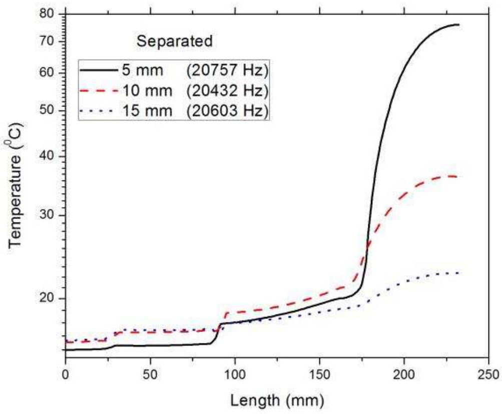

Fig. 3: The distribution of temperature along actuator with separated piezoceramic rings when different waveguide diameters are used

indicated that temperature of the of the waveguide decreases when diameter increases. It can be explained because waveguide with larger diameter has smaller mechanical stresses and larger surface area of the heat being transferred. It also can be seen that temperature of the Langevin transducer is smaller. Power dissipation density of Langevin actuator with the different diameters of the waveguide is presented in Fig. 4. Different lines indicate power dissipation density of different parts of the acutator. It can be seen that power dissipation density is much smaller when separated ceramic is used. Power dissipation density of the metal parts in all cases is similar because during simulation the same vibration amplitude values of the transducer were excited.

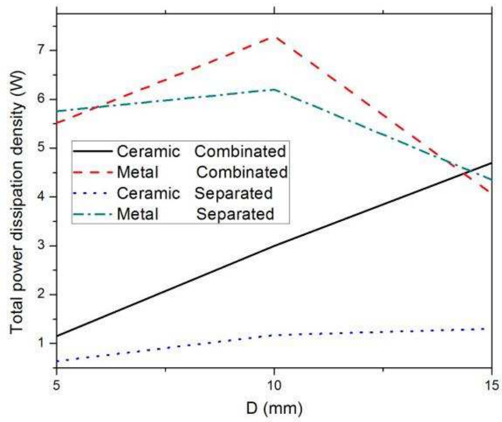

Fig. 4: Power dissipated density of Langevin actuator versus diameter of the waveguide

4. Experimental Study

Three prototype actuators with different diameters 5, 10, and 15 mm were fabricated for experimental study and special setup for the experiments was made (Fig. 5). The aim of experiment was to verify results of numerical modeling by measuring temperature distribution on the surface of the Langevin actuator. FLIR thermal imaging infrared camera was used for measurement. Image of the actuator made by aforementioned camera is shown in Fig. 6 and present visual temperature distribution along the Langevin actuator. More detailed results of the temperature measurement are given in Fig. 7 and Fig. 8.

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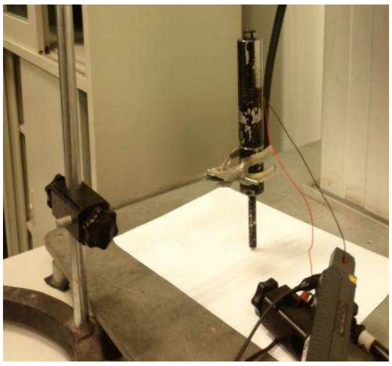

Fig. 5: Langevin actuator prototype and experiment setup

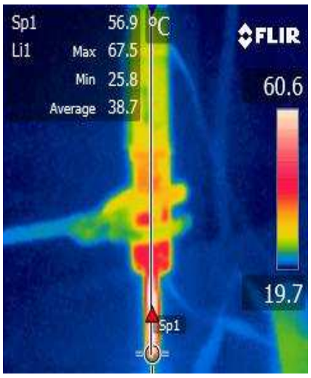

Fig. 6: Measured temperature of the prototype Langevin actuators

It can be noticed that distribution of the temperature on surface of the transducer is in principle the same as were obtained during the numerical simulation. The difference between calculated and measured values differs because it was complex problem to develop isothermal holder of the actuator and keep stable ambient temperature in the laboratory.

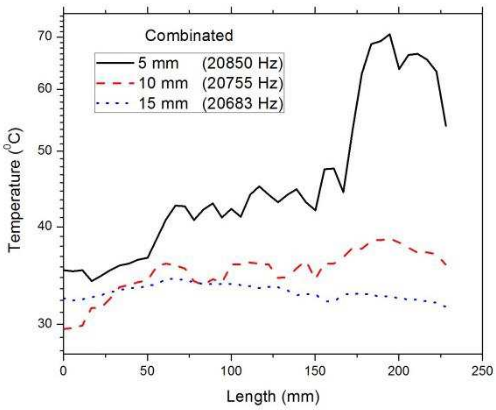

Fig. 7: The distribution of measured temperature along actuator with combined piezoceramic rings when different waveguide diameters are used

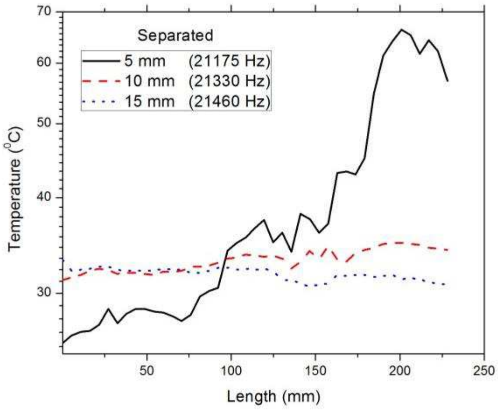

Fig. 8: The distribution of measured temperature along actuator with separated piezoceramic rings when different waveguide diameters are used

5. Conclusions

Results of the numerical modeling and experimental study of Langevin transducer show that the heat generation of the transducer can be reduced by separating piezoceramic elements and adding additional metal block between them without loss in vibration amplitudes of the contact. Power dissipation rate of the piezoceramic element decreases when they are separated and symmetrically moved out of the node of vibrations. Power dissipation rate due to mechanical losses are 5-10 time large compare to dielectric losses of this type of Langevin actuator.

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