601. Piezoelectric Actuator for High Resolution Linear Displacement Systems

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Abstract. This work presents a piezoelectric actuator which is designed to improve resolution for micrometer screws or motorized actuators such as actuators with stepper motors. Several modifications of piezoelectric actuator were implemented for closed-loop and open-loop applications. For closed-loop applications strain gages are used to obtain a feedback signal. As a result a resolution of displacement measurement up to 18 nm is achieved.

Keywords: piezoelectric actuator, strain gage feedback, high resolution

Introduction

Piezoelectric actuators are widely used in various arias of science and industry, which requires actuators with nanometer or sub-nanometer resolution in the range from micrometer to several hundreds of micrometers: for positioning tools in mechanical engineering, active vibration damping, generation of ultrasonic or sonic vibrations, to position masks, wafers or magnetic heads in microelectronics, AFM probe manipulation, for fluid applications designing pumps, injectors, droplet generators, for optic applications to position mirrors or lenses, focusing, aligning fibers, for scanners, interferometers, modulators, shutters, for energy harvesting (electrical power generation from mechanical energy).

Some applications do not require very high accuracy and do not need feedback from the actuator since a displacement of an actuator is defined from applied voltage. Therefore the main advantage of open-loop systems is significantly reduced price, and more simple control algorithms compared with closed-loop systems. For example, one of such applications would be optic fiber alignment. However, piezoelectric actuators cannot be directly applied in positioning applications as they exhibit a significant amount of nonlinearity - hysteresis, and creep - and these factors reduce accuracy of a system.

There was performed some research work in order to reduce hysteresis and creep of open-loop systems by driving piezoelectric actuator using charge input, or method which involves a capacitor insertion in series with a piezoelectric actuator, which is driven using a voltage input [1].

Another method to cancel out nonlinearity is to use feedforward or feedback scheme applying one of piezoelectric actuators hysteresis model: Prandtl-Ishlinskii [2], Preisach [3], modified Rayleigh [4], Bouc-Wen [5] or Duhem [6].

There are generally three types of sensors used for closed-loop-based piezoelectric actuator applications: capacitive, optical, and strain gage. Optical sensors can achieve high resolution and at the same time maintain long measurement ranges. For example Zygo interferometers can achieve 0.3 nm resolution and even more [7]. Optical encoders with advanced signal processing and interpolation can achieve 10 nm [8].

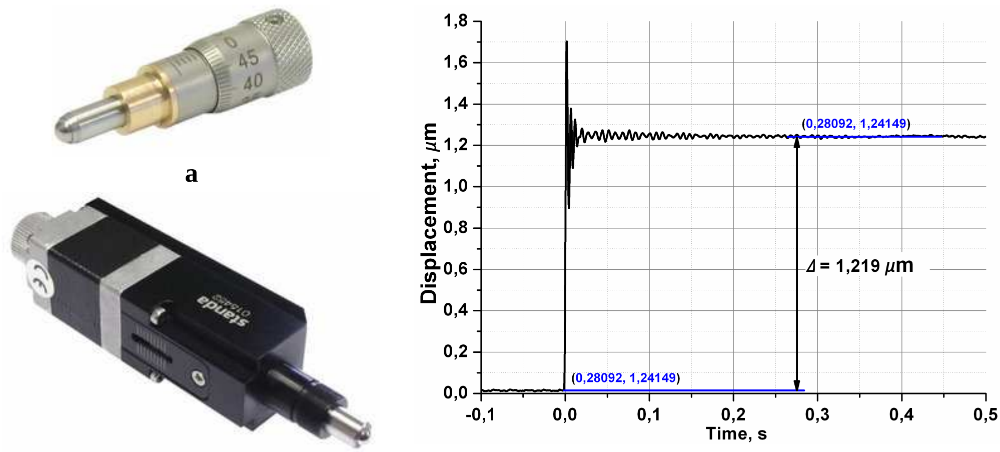
Capacitive sensors are often used in accurate and high resolution requiring systems since they are able to measure displacements with sub-nanometer resolution. Usually capacitive sensors which have high resolution do not have long measurement ranges. Therefore encoder-like or comb-like capacitive displacement sensors are used to increase measurement range [9, 10].

All of the aforementioned displacement systems and sensors show very good performance, but they are relatively complex and costly solutions. Therefore strain gages are used, because their implementation is fairly easy, signal processing electronics is simpler and they are not expensive.

This study reports on design of piezoelectric actuator for high resolution linear displacement systems. Several modifications of piezoelectric actuators for open-loop and closed-loop applications are considered.

Design Consideration

Proposed actuator was designed with the intention to improve the resolution of micrometer screws or motorized actuators (Fig. 1, a, b). The casing of piezoelectric actuator was designed according to chosen motorized actuator (Standa 8CMA06-13) tip which is 6 mm in diameter (Fig. 1, b), but it is not difficult to manufacture the casing according to tip of different size.



a

b

c

Fig. 1. Micrometer – a; motorized actuator – b; measured motorized actuator resolution – c.

For some applications it is sufficient to use piezoelectric actuator without feedback, and for some it is necessary to have it. The feedback is implemented using metal-foil resistance strain gages bonded on a multilayer piezoelectric stack PICMA P-885.31 (Physic Instrumente Monolithic Multilayer Actuator) (Fig. 2). Technical data of multilayer piezoceramic stack is shown in Table 1.

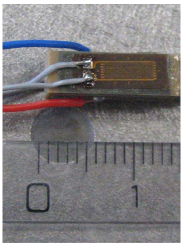


Fig. 2 Strain gage bonded on piezoelectric actuator.

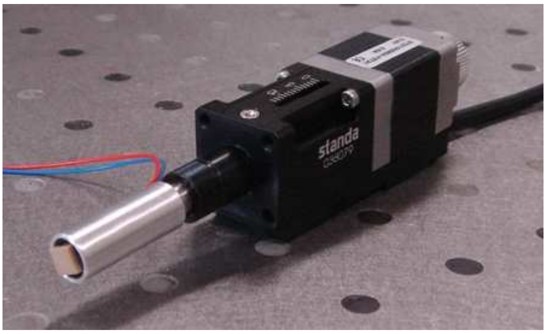


Fig. 3. Piezoelectric actuator mounted on motorized actuator

Table 1. Technical data of multilayer piezoceramic PICMA P-885.31.

Dimensions , mm	5x5x13,5
Nominal displacement at 100 V, mm	11 ±20%
Maximal displacement at 120 V, mm	13 ±20%
Blocking force at 120 V, N	870
Stiffness, N/□m	67
Electrical Capacitance, mF	1,1 ±20%
Resonant frequency, kHz	90 ±20%

Strain gage temperature compensation

The main parameter of the strain gauge is its sensitivity to strain referred to as gage factor and denoted as G_f . It is defined mathematically as follows:

$$G_f = \frac{\Delta R/R}{\Delta L/L} = \frac{\Delta R/R}{\varepsilon}, \tag{1}$$

where ε is strain, L - initial length of an object, ΔL - object elongation, R - strain gage resistivity, ΔR - elongation initiated resistance change.

In ideal case, we would like that a resistance of the strain gauge would change only in response to applied strain. However, it depends on temperature as well. This temperature-induced resistance change, called apparent strain, is the most serious source of error. It depends on strain caused due to the difference in thermal expansion coefficients between the gage and the piezoceramics, and due to temperature dependence of the electrical resistivity of strain gage material. The apparent strain can be expressed as [11]:

$$\varepsilon_{app} = \left(\frac{\beta}{G_f} + \left(\alpha_o - \alpha_g \right) \right) \cdot \Delta T \ , \tag{2}$$

where β is temperature coefficient of resistance of strain gage element, G_f - gage factor of strain gage, α_o , α_g - respectively thermal expansion coefficient of the object material (in our case piezoceramics) and strain gage material, ΔT - temperature change from initial reference temperature.

There are two methods of apparent strain compensation. One approach is based on application of self-temperature-compensation gages (SELCOM gages). The temperature coefficient of resistance of strain gage is controlled by thermal treatment during the manufacturing process. It is obvious from equation (1) that if $\beta = G_f \cdot \left(\alpha_g - \alpha_o \right)$ there will be no thermal-induced apparent strain, but SELCOM gages can be used only for specific materials, for which they are intended to.

Another method of apparent strain compensation for strain gages involves dummy strain gage bonded in a transversal direction on the same object or different object of the same material at the same ambient temperature as the first one.

As literature indicates strain gages can tolerate power densities from 1.5 mW/mm^2 to 16 mW/mm^2 depending on object material and required accuracy. The maximum excitation voltage can be evaluated according to the following equation [12]:

$$E_{Ex} = 2\sqrt{\rho \cdot L_g \cdot W_g \cdot R_g}\ , \qquad (3)$$

where ρ is power density, L_g - strain gage grid length , W_g - strain gage grid width, R_g - strain gage resistivity. Therefore, to increase excitation voltage while maintaining the same measurement accuracy, resistivity or dimensions of strain gage should be increased.

Since we use Wheatstone bridge with two active strain gages connected to opposite arms of the bridge an output of the bridge would be:

$$E_{Out} = \frac{G_f \cdot \varepsilon}{2} \cdot E_{Ex}\ , \qquad (4)$$

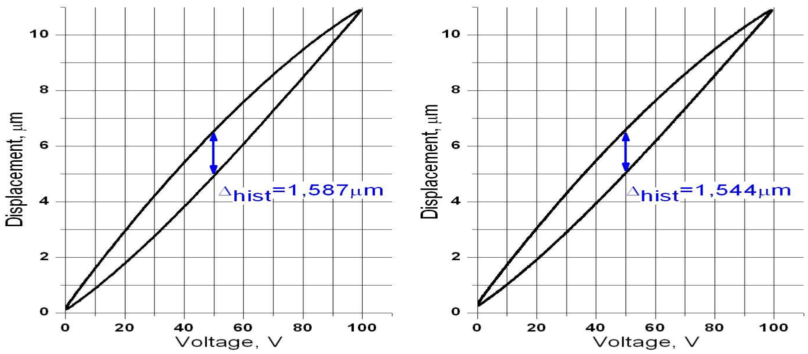
where G_f is gage factor, ε - strain, E_{Ex} - excitation voltage.

To increase the output of a bridge for certain gage factor and strain the excitation voltage must be increased. The recommended power density for accurate strain gage measurements is from 77.5 µW/mm^2 to 0.31 mW/mm^2, when a strain gage is bonded on a different material than copper or aluminum and substrate thickness is less then strain gage length.

We reasonably selected slightly higher power density, ρ=0.49 mW/mm^2, to increase strain gage sensitivity and therefore the excitation voltage was $E_{Ex}=3$ V. Two active strain gages were connected to opposite arms of the Wheatstone bridge. Dummy strain gages were bonded on the same piezoceramic material but on a different stack. Considering that the piezoelectric actuator is operating in a static and quasi-static mode and the current flowing through the strain gages is low, we can make an assumption that the temperatures of the active and dummy strain gages are the same. Therefore, the thermal compensation is accomplished.

Results and analysis

Experimental research was performed in order to evaluate the influence of the casing and strain gages bonding on a piezoceramic stack to the actuators hysteresis. No reasonable influence was observed from the measurement results (Fig. 4).



a b

Fig. 4. Hysteresis of piezoceramic stack without casing – a, with casing and strain gages - b

The structural schematic for the measurement of piezoelectric actuator resolution is depicted in Fig. 5. The signal from the arbitrary waveform generator (Agilent 33220A) is supplied to the linear amplifier (Piezosystems EPA-104), from the amplifier signal is transmitted to the piezoelectric actuator. Displacement of piezoelectric actuator due to applied voltage change is measured with laser Doppler vibrometer (Polytec fiber interferometer OFV-512 and vibrometer controller OFV-5000) and with strain gages connected to Wheatstone bridge. The instrumental amplifier is used to amplify measurement signal from Wheatstone bridge.

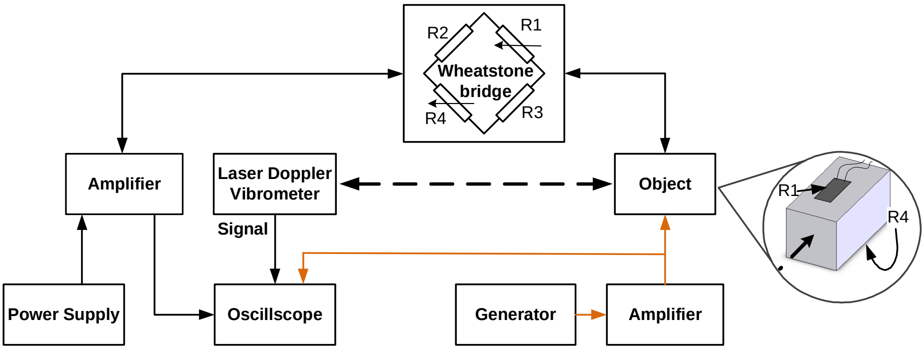


Fig. 5. Structural schematic for the resolution measurement of piezoceramic actuator

The measurement result of strain gage signal change due to voltage change supplied to piezoelectric actuator is presented in Fig. 6. For the voltage change of 240 mV the strain gage signal changes 2.2 mV it corresponds to 18 nm.

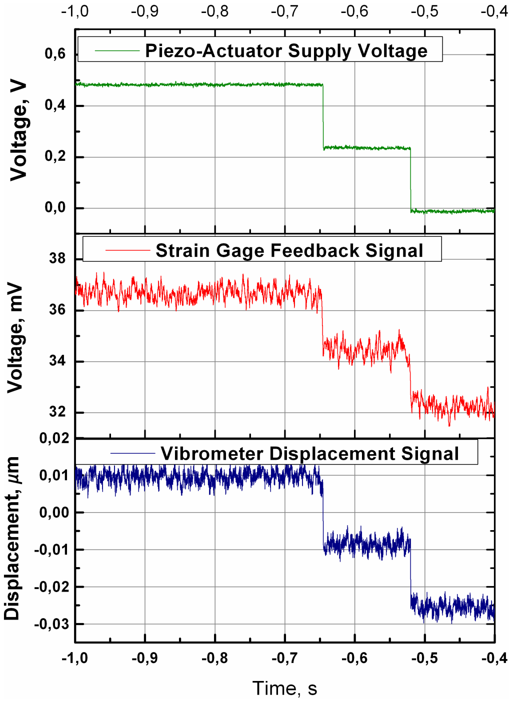


Fig. 6. Strain gage measurement signal corresponding to the displacement of the piezoelectric actuator

Conclusions

Several modifications of piezoelectric actuators for close-loop and open-loop applications were designed and investigated. Proposed actuators are intended for implementation in high-resolution linear displacement systems. A feedback measurement resolution up to 18 nm is achieved using strain gages for displacement measurement. The operating range of actuators is 10.8 μm with the operating voltage of 100 V.

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