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Experimental optimization of power-function-shaped drive pulse for stick-slip piezo actuators

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ABSTRACT

Motion of a stick-slip piezo actuator is generally controlled by the parameters related to its mechanical design and characteristics of the driving pulses applied to piezoceramic shear plates. The goal of the proposed optimization method is to find the driving pulse parameters leading to the fastest and the most reliable actuator operation. In the paper the method is tested on a rotary stick-slip piezo actuating system utilized in an atomic force microscope.

The optimization is based on the measurement of the actuator response to driving pulses of different shapes and repetition frequencies at various load forces. To provide it, a computer controlled testing system generating the driving pulses, and detecting and recording the corresponding angular motion response of the actuator by a position sensitive photo detector (PSPD) in real time has been developed. To better understand and interpret the experimental results, supportive methods based on a simple analytical model and numerical simulations were used as well.

In this way the shapes of the single driving pulses and values of the load force providing the biggest actuator steps were determined. Generally, the maximal steps were achieved for such a combination of the pulse shapes and load forces providing high velocities at the end of the sticking mode of the actuator motion and, at the same time, lower decelerations during the slipping mode.

As for the multiple driving pulses, the pulse shapes and values of repetition frequency ensuring the sticking mode of the actuator motion during the pulse rise time together with the maximum average angular rotor velocity were specified. In this way the effective and stable operation conditions of the actuator were provided.

In principle, the presented method can be applied for the testing and optimization of any linear or angular stick-slip actuator.

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1. Introduction

An impressive development of different precise analytical tools for surface science and nanotechnology research has been made in the last decades. A significant contribution to these results has been also achieved due to a progress in the precise positioning and actuating of samples, probes, and other tool elements. Micro- and nano actuators working with high accuracy and wide range of displacement, their fast response to the control signal, tunable displacement step and simple operation are the main features of the requirements laid upon these systems. Micro- and nano actuators generally utilize piezoceramics as the central part of their design. These piezoelectric actuators can be categorized according to their basic working principles [1] into the stepping inertial (slip-stick) actuators (also called the quasi-static actuators) [2–7] and the ultrasonic motors based on standing or propagating mechanical waves [8–10]. Special designs of actuators are also compatible with ultrahigh vacuum working conditions.

The angular stick-slip actuators rely on a difference in the static and dynamic friction force acting between the rotor and the stator [11], the setup of which works in a stepping mode. Within each step there is a period of the slow deformation of a piezoceramic plate during which the rotor and stator are in the sticking regime, and a period of the fast piezoceramic deformation providing the slipping regime between the rotor and the stator [6]. The deformation of

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piezoceramics is done by driving pulses, typically in a voltage range of 0.2–0.3 kV. This basic stick-slip principle is provided by simple and low cost designs and ensures relatively high-speed motion (∼5 mm/s), long-range displacement and the precise positioning with the accuracy below 5 nm [1]. To provide the fastest and most reliable operation of these actuators, it is crucial to find an adequate setup of optimum parameters such as the voltage, shape and frequency of driving pulses, load force and also materials ensuring appropriate friction coefficients, etc. [6,12,13].

The angular actuator tested in this paper is mounted in an UHV AFM setup and provides the alignment of a laser beam onto a cantilever and position sensitive photo detector (PSPD). To find the optimized parameters of this actuator, a simple testing system has been developed. It detects and records the angular motion of the actuator by PSPD in real time. The optimization is based on the measurement of the actuator response to driving pulses of various parameters being gradually changed by a computer software, at different load forces. To better understand and interpret the experimental results, supportive methods based on a simple analytical model and numerical simulations were used as well. Generally, this approach can be applied for testing and optimizing any linear or angular stick-slip actuator.

The main contribution of this research is the ability to improve the performance of existing actuators without mechanical design changes. The presented approach is based on the systematic changes of driving pulse parameters and their impact to the actuator response. Moreover, we demonstrate that the actuator step size is critically dependent on the instantaneous velocity at the end of the sticking regime.

2. Experimental

2.1. Actuator setup

The actuator, the properties of which were optimized, is a three-axis rotary stick-slip piezo system designed according to [14] and forms a part of an AFM optical detection system (Fig. 1a). Its cross section is shown in Fig. 1b. A couple of these actuators are used in an optical detection system of a cantilever deflection being a part of a home-built UHV STM/AFM unit. The unit provides the alignment of a laser beam with respect to an AFM cantilever and position sensitive photo detector (PSPD). The stator of the actuator is a right-angle 3D corner setup with three pairs of piezoceramic shear plates fixed to each corner wall with a UHV compatible glue (EpoTek H27D). A steel ball of a diameter of 10 mm with a glued mirror on it (EpoTek H27D s) acts as a rotor. An Al-Ni-Co magnet protruding through the corner of the stator is used to control the load force by which the rotor acts upon the plates. Different load forces were chosen by setting specific distances between the magnet and the rotor sphere. The force-distance dependency was calibrated on the disassembled actuator using a scale. The error in determination of load forces in the assembled actuator was estimated smaller than 10%.

2.2. Measurement setup

All the experiments for the optimization of the actuator operation were carried out with a measurement setup consisting of three basic parts as follows: an optical detection system, electronic system and control software.

The optical detection system is used to measure the angular displacement of an actuator and is identical with that one mentioned above (Fig. 1a) and to which the actuator is part. To modify such a system primarily developed for the detection of cantilever deflections in an AFM setup to this purpose, the cantilever has just to be replaced by a mirror.

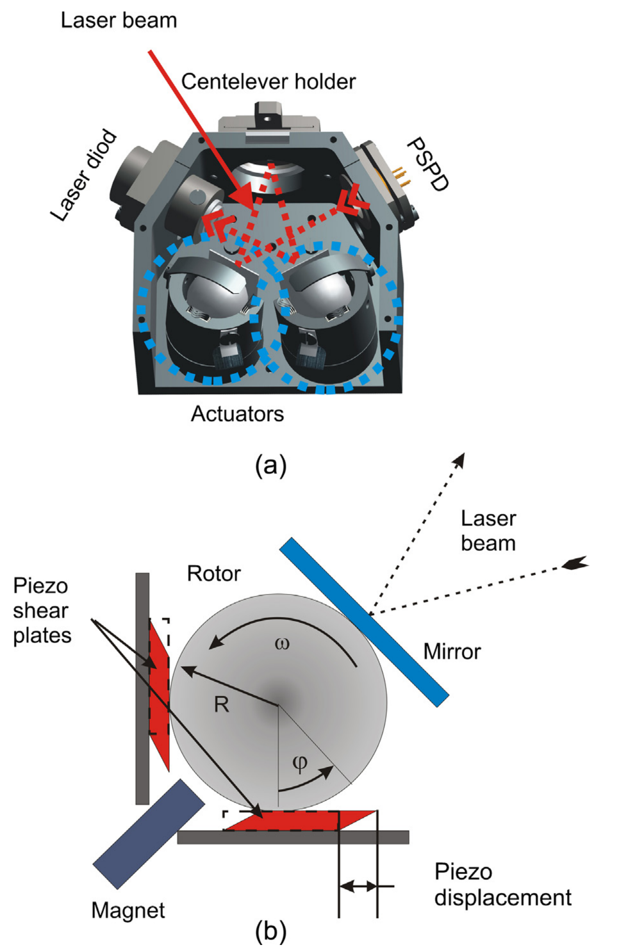

Fig. 1. A view of the optical detection system with a couple of the actuators used for the alignment of the laser beam with respect to the AFM cantilever and PSPD (a). Cross section of the three-axis rotary stick-slip actuator with the legend (b). For testing the actuator response the cantilever was replaced by a mirror.

In such a modified detection unit the laser beam generated by a laser diode with a collimating lens is reflected by mirrors to the PSPD. If the actuator is in motion, the laser spot is proportionally moving over the PSPD and the corresponding signal is used to monitor the displacement. The advantages of this technique can be listed as follows: almost no additional load to the actuator (a small mirror can be used), high resolution (time development of a piezo-shear displacement during one single step can be observed – see Fig. 7), and non-contact remote measurements (e.g. through a view port of a vacuum chamber).

The central part of the electronic system is a data acquisition computer card (DAQ). This card (NI-6221 PCI) was used to generate the driving signal (800 kS/s DAC) and to measure displacements at low time-resolution (250 kS/s multiplexed ADC), i.e. in multiple pulse experiments (Fig. 2). A digital registration oscilloscope (2 GS/s) was utilized for the simultaneous measurement of actuator response and driving signal at high time-resolution (single pulse experiments). The driving pulses processed by a D/A converter are led through a high voltage amplifier to piezoceramic shear plates. The high voltage amplifier [6] operating in the voltage range 0–1000 V consists of a low noise and low voltage op-amp driving high voltage MOSFET transistors to achieve the required amplification. The PSPD is a four segment photodiode. Two differential amplifiers provide output analogue signals giving information on the coordinates of the laser spot. These signals are consequently digitalized by the DAQ or the oscilloscope.

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