A vertical piezoelectric inertial slider

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Abstract

We have developed a linear translation device using piezoelectric-induced slip-stick motion. Reproducible single steps of about 30 Å, as well as continuous stepping with an overall translation speed of 0.25 mm/s, are routinely realized. The notable feature of this device is that this performance is achieved in the vertical orientation with the translator moving against gravity. This remarkable result is made possible using cycloidal functions instead of sawtooth signals to activate the motion. We have realized a very simple translator which can be used in any orientation with a displacement onset voltage of 15 V. The instrument was successfully tested in the temperature range from 1.6 to 300 K. Since no mechanical connections are required, this design is well suited for many applications, including scanning tunneling microscopy.

Reference

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A vertical piezoelectric inertial slider

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We have developed a linear translation device using piezoelectric-induced slip-stick motion. Reproducible single steps of about 30 Å, as well as continuous stepping with an overall translation speed of 0.25 mm/s, are routinely realized. The notable feature of this device is that this performance is achieved in the vertical orientation with the translator moving against gravity. This remarkable result is made possible using cycloidal functions instead of sawtooth signals to activate the motion. We have realized a very simple translator which can be used in any orientation with a displacement onset voltage of 15 V. The instrument was successfully tested in the temperature range from 1.6 to 300 K. Since no mechanical connections are required, this design is well suited for many applications, including scanning tunneling microscopy.

INTRODUCTION

Building a new scanning tunneling microscope (STM) for low temperature applications led us to develop a novel linear translation device to approach the sample to the tip probe. This new system had to be able to move a sample vertically (against gravity) over several millimeters in a very controlled manner. In the literature,[1] a wide variety of translation systems for STM have been proposed. They can be divided into mechanical devices where micrometric screws activate the motion, and inchworm and slipstick mechanisms where the piezoelectric effect is the source of the motion.

The basic idea of inertial slip-stick motion has been described by Pohl.[2] Some applications have been presented by Niedermann *et al.*[3] and Lyding *et al.*[4] From our experience, this type of motion allows the smallest reproducible steps; however, it is the most difficult to make work reliably. The vertical translator we present is based on a design first proposed by Lyding *et al.*[4] Their concept and design allow linear motion within 7° of the horizontal whereas our device functions equally well at any orientation including the vertical one.

I. DESIGN

A piezoelectric tube[5] forms the motor of this vertical translation device [Fig. 1(a)] but any expanding piezoelectric would also be adequate. Two parallel rails are glued to one end of the tube. These rails are optically polished sapphire rods (diameter 2 mm, length 20 mm). The wagon shown in Fig. 1(b) is made of two stainless-steel anvils clamped together onto the rails with a spring. This fixation system enables the adjustment of the friction force between the wagon and the rails which is a critical parameter. The wagon weighs $m = 3.75$ g and a spring with constant $k = 100$ N/m is suitable to provide the friction force $F_r = \mu_s F_n$. Here $\mu_s = 0.15$ is the static friction coefficient for stainless steel on sapphire, and $F_n = k\tau\eta$, where τ is the screw pitch and η is the number of screw turns. The grooves which affix the wagon to the rails have to be carefully machined to obtain regular motion. On each anvil one groove is V-shaped and one has a rectangular profile resulting in self-lateral positioning of the wagon without mechanical play. This gives very reproducible positioning while stepping back and forth. The vertical position of one anvil is fixed with respect to the other by the design of the screw tightening the clamping spring. All assembling is done using UHV and low temperature compatible glues.

For the purpose of development, the voltage signals are computer generated and output via a Data Translation DT2801 digital to analog converter, amplified by a factor of 15 to ± 150 V with a fast high voltage operational amplifier[6] and applied to the piezoelectric tube.

II. OPERATION

Applying the appropriate waveform to the piezoelectric was found crucial for the proper operation of the translation device, besides a very smooth surface state of the sliding parts. In the past, slip-stick motion has been activated with sawtooth signals. However, in our setup sawtooth voltages, even filtered, failed to move the translator against gravity; in the best case it kept its position or else it moved downwards. This observation for the vertical orientation can be understood from the following simple arguments. We consider the motion along a vertical axis z [Fig. 1(a)]. In order to make the wagon slide upwards with respect to the rails, these have to be moved downwards with an acceleration $a_s^u < 0$ given by

$$-\mu_s F_n/m - g > a_s^u. \tag{1}$$

The wagon will slide downwards if the rails are moved upwards with an acceleration $a_s^d > 0$ satisfying

$$\mu_s F_n/m - g < a_s^d. \tag{2}$$

Thus, different accelerations are needed depending on the desired direction of motion. For controlled stepping, only condition (1) or (2) should become satisfied during each cycle of the voltage signal; if they both become satisfied, each step will contain contributions in the two opposite directions leading to erratic motion. A sawtooth voltage signal leads to very high accelerations of opposite amplitude at the turning points during each cycle, limited only by the finite response of the electronics and the piezoelectric element. Since condi-

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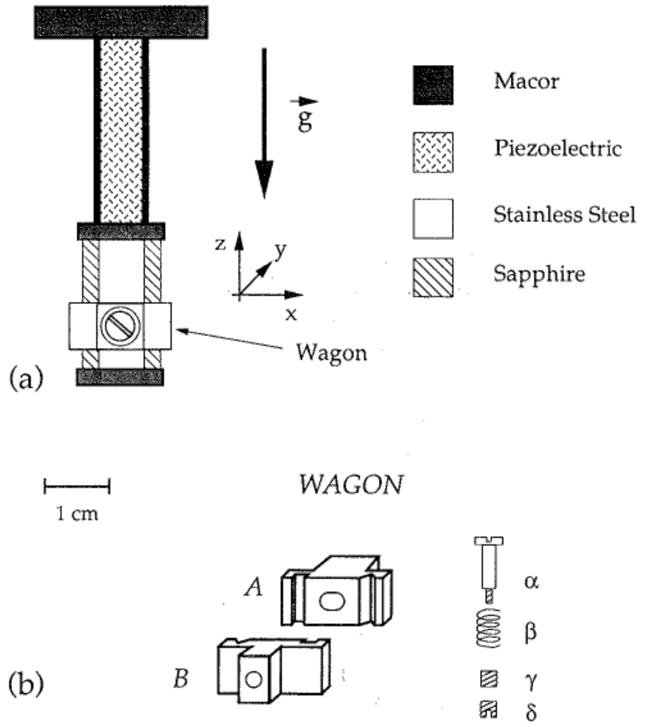

FIG. 1. The vertical translation device with a detailed view of the wagon. The screw (α) and spring (β) fit into anvil A, whereas the counterpiece (γ) and the blocking screw (δ) are screwed into anvil B.

tion (2) is more readily satisfied than condition (1) for equal magnitudes of a_s^d and a_s^u it is likely that a sawtooth voltage will fail to move the wagon against gravity. One way to control the acceleration is to apply voltage signals with a quadratic time dependence. The cycloid is a possible function leading to sufficiently high acceleration in one direction while it remains very low in the opposite direction. The waveforms we used to successfully make the wagon move up and down are shown in Fig. 2. The voltage amplitude versus time $a(t)$ output from the computer to the high voltage amplifier is calculated using

$$a^2(t) + (t - T/2)^2 = (A/15)^2$$

for each cycle. With the configuration drawn in Fig. 1 (a), this signal will make the wagon move upwards provided the

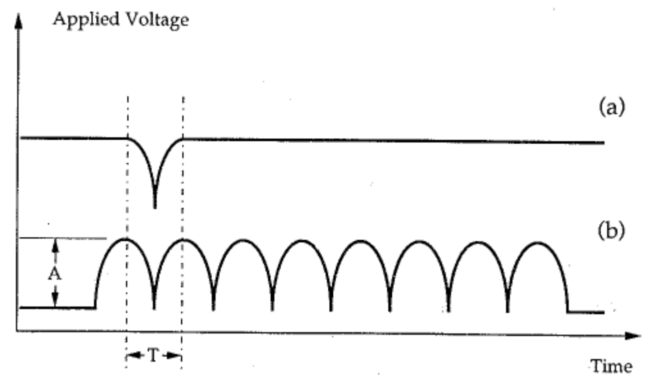

FIG. 2. Cycloidal functions required to move the wagon upwards: (a) single step; (b) continuous stepping.

positive voltage elongates the piezoelectric tube. Downward motion is obtained by inverting the polarity of these signals. Typical amplitude and frequency are $A = 30$ V and $f = 800$ Hz with a sensitivity of the piezoelectric element of 110 Å/V. In the present setup, the maximum frequency of the D/A converter is 23 kHz which puts a limit to the definition of the waveforms (in particular at the high acceleration sections). This may be the cause of the observed lowest motion onset voltage of 15 V. It should be possible to go below this value using smoother, hardware generated signals.

III. PERFORMANCES

This vertical translation device showed excellent characteristics which even go beyond our expectations. Single steps as small as 30 Å up and down have been achieved. The step size increases linearly as a function of voltage amplitude applied to the piezoelectric with saturation onset at 0.23 μm/step against gravity for $A = 128$ V applied to the piezoelectric at room temperature. However, the stepping is most efficiently controlled by selecting the maximum acceleration at the turning point of the waveform. We achieved an upwards speed of 0.25 mm/s, which is calculated from the time the wagon needs to run over a distance of 1 mm. This distance was measured using a 200× magnifying telescope. All these results are obtained in air at room temperature. No lubrication is required with our setup and efficient stepping is obtained in all cases by cleaning the grooves and the rails with alcohol before using the translator. Similar impressive performances regarding the reproducibility and the size of the steps have been measured in He gas at liquid nitrogen temperature and in liquid helium down to 1.6 K. In all these conditions we could make the wagon climb over the full range (11 mm) of the sapphire rails. In Fig. 3 we show sequences of single steps against gravity in air at room temperature [(a) and (c)] and in He gas at 77 K [(b) and (d)]. These steps are monitored by bringing a tip into tunneling with the wagon. This tip is connected to a second piezoelectric tube and the curves are taken with a feedback loop regulating the tip/wagon separation during stepping like in stan-

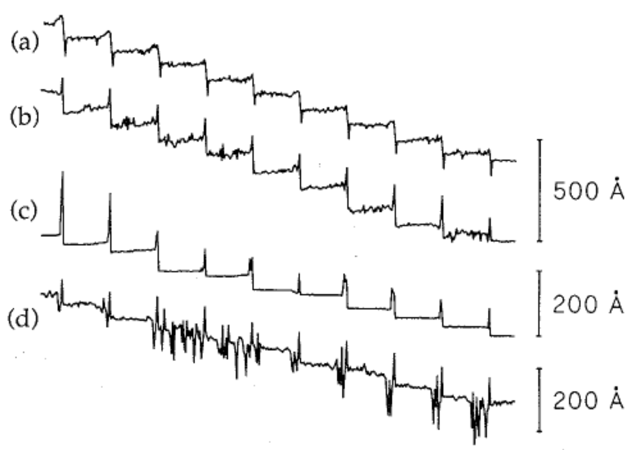

FIG. 3. Tunneling probe recording of single steps against gravity: (a) in air at room temperature, $A = 33.5$ V, $f = 800$ Hz; (b) in He gas at 77 K, $A = 37.1$ V, $f = 800$ Hz; (c) in air at room temperature, $A = 15$ V, $f = 5.5$ kHz; (d) in He gas at 77 K, $A = 35.6$ V, $f = 800$ Hz ($f = 1/T$).

dard STM topographic imaging. The tip is not scanning the surface so each line is a trace of the wagon's height as a function of time when single steps as shown in Fig. 2(a) are performed at a rate of one per second. The spikes at the step edges are not the real glitch motion of the wagon. They are due to capacitive coupling between the current probe wire and the piezoelectric moving the rails. The same spikes are observed if we move the wagon while it is out of tunneling range with the tip probe. The scales on Fig. 3 are calculated from the piezoelectric coefficient of the tube holding the tunneling probe at room temperature since we have not yet calibrated our tube at low temperature. According to published data,[7] the piezoelectric coefficient for PZT ceramic is reduced by a factor of 2–3 if cooled from room temperature down to 77 K. Therefore, the actual smallest step size is about 2–3 times smaller compared to the value taken directly from Figs. 3(b) and 3(d). A selection of the smallest reproducible single steps we have measured so far is shown in Figs. 3(c) and 3(d). The wagon starts to move upwards with only 15 V applied to the piezoelectric holding the rails. A small load of 5 *g* did not prevent the wagon from moving upwards. We believe the specific waveforms used to be the reason for these excellent characteristics and low onset voltage.

We have shown that slip-stick-type motion is capable of moving small objects against gravity in a very controlled way. This is made possible using cycloidal functions instead of the sawtooth signals traditionally used for slip-stick motion. We believe the performances of existing inertial translators could be improved using this type of signal also for horizontal motion. The concept we have presented is quite general and the design itself can be easily miniaturized leading to a very stable instrument in the case of STM. In principle, this translation device can be run in UHV, in liquids, magnetic fields, weightlessness, and many other environments. A low temperature STM exploiting the extraordinary capabilities of this type of translator to move a sample by angstrom-sized steps against gravity as well as quickly over large distances will be presented in a forthcoming publication.[8]

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