A three-axis micropositioner for ultrahigh vacuum use based on the inertial slider principle

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We present a three-dimensional micropositioner using the inertial slider principle which is used to position an optical fiber in an atomic force microscope. It uses only two moving parts as the sideways and vertical motions are realized by either moving a cylinder along its axis or rotating it around its axis and translating the rotation into an approximately vertical motion. The device operates reliably in a baked ultrahigh vacuum system, allows positioning with sub-μm accuracy, and has a forward range of 11.3 mm, a sideways range of 5 mm, and a vertical range of approximately 5 mm. The measured speeds without extra load fall in the range between 1.6 and 3.3 mm/min, in good agreement with the amplitude and curve shape of the applied drive signal. The minimal step size allowing consistent motion is below 25 nm. © *1996 American Institute of Physics.* [S0034-6748(96)01703-5]

I. INTRODUCTION

Positioning with sub-μm accuracy over distances of several mm in ultrahigh vacuum (UHV) is important in many applications. A specific case is vacuum operated microprobe instruments such as scanning tunneling and scanning force microscopes, where the demands on precision, stability, and compact design are particularly high. Conventional mechanical systems are often less suitable for these applications as they tend to be complex, have problems with backlash, and need expensive motion feedthroughs that have to be decoupled to avoid transmission of vibrations. Several solutions requiring only electrical connection are currently used, like vacuum compatible electrical motors,[1] inchworm translators,[2,3] electrostatic sequential clamp systems ("louses"),[4] and inertial sliders.[5–10] Inertial sliders have many inherent advantages for microprobe applications as they allow precise positioning and can be made very compact, especially if piezoelectric shear plates are used as drive elements. They do not require precision machined parts and strict tolerances that can cause jamming, they are reliable, and they use simple drive electronics. The technique also has some inherent drawbacks like low reproducibility over long distances and a relatively low force capability. Inertial sliders are normally operated in the horizontal plane because of problems with asymmetric forces due to gravity if operated vertically. With careful design and optimized drive signals it is, however, also possible to obtain vertical motion.[9,10] The design we present here was developed for three-axis positioning of an optical fiber within μm distance from a cantilever in an UHV scanning force microscope. It is very simple, uses only two moving parts, and operates reliably in a baked UHV system at 8×10^{-11} Torr.

II. DESIGN

Figure 1 shows front and side views of the device, consisting of an aluminum block (37.5×24×10 mm) called the frame that can move in the X direction which supports a ceramic cylinder that carries the probe to be positioned. This cylinder can be rotated as well as moved along its axis using the inertial slider principle.[5] The frame is a normal guided slider with a rail constructed from two parallel rods made from hardened steel mounted with screws in a rectangular groove along one side and a sapphire plate glued in a recess at the opposite side. It is supported by three ruby half-spheres, two in contact with the rail, and the third in contact with the sapphire plate. The half-spheres are glued to piezoelectric shear plates[11] that are electrically connected on their top side and glued to the grounded base plate using conducting epoxy. This design gives a kinematic positioning that will allow well-defined motion along the X direction. The slider body has a 7-mm-deep recess, machined from the top, in the form of a trough with front and backwalls inclined at 35° from the vertical plane while the sidewalls are vertical. Glued to each of the inclined walls is a piezoelectric drive unit of the type shown in Fig. 2. This unit consists of a ceramic plate that supports four piezoelectric shear plates arranged as two sandwiches where the upper and lower plates are poled to move in orthogonal directions with respect to each other. The two upper plates have ruby half-spheres glued to them and the joints between the upper and lower plates are done using conducting epoxy. The ceramic plate has a small recess at one side that allows electrical connections to be made to the bottom side of the lower layer of shear plates. The upper layers of the shear plates have two of their corners cut to allow a common electrical ground connection to be made to both upper and lower plates, minimizing the number of electrical connections and insulating spacers in the design. The shear plates are 8×8×1 mm, the thickness of the ceramic plate is 1 mm, and the diameter of the ruby half-spheres is 4 mm. These drive units are mounted so that a normal from their surface passing through the center of the half-spheres will coincide with a radius of the supported cylinder. In this geometry, the cylinder will align its axis so that it contacts all four support points. As the cylinder is 5 mm shorter than the width of the trough, it can slide 2.5 mm along its axis in each direction measured from its cen-

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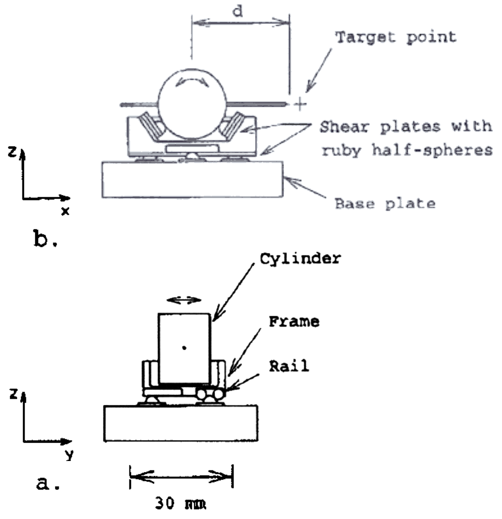

FIG. 1. Front (a) and side (b) views of the micropositioner are shown. The frame and cylinder are shown in cross section. See the text for further details.

tered position. Mounted through a diameter of the cylinder is a tube of length d, measured from the cylinder center, that supports the probe to be positioned.

III. RESULTS AND DISCUSSION

Activating the shear plates moving in the Y direction will move the cylinder along its axis until it hits the wall of the trough, while activating the plates moving along the tangent of the cylinder will rotate it, moving the tip of the tube vertically along a circle of radius d. The device will thus produce ideal linear motions in the X and Y directions, while the vertical Z direction will be approximated by a motion along a circle with radius d which normally will cause no problems for movements of a few mm. The range in X and Y is directly related to the size of the device and is 11.3 and 5 mm in our case. If an extended X range is needed, the shear plates can be mounted on the frame, giving unlimited range. The Z range is depending on the tube length d and is restricted downwards by the point where the tube hits the frame. For larger movements in Z, the deviation from an ideal linear motion could cause problems so we estimate a practical Z range of approximately 5 mm for a device of our size. A typical application of this positioner would be to align a probe like a fiber or an electrode in a vacuum system while observing the target point with a microscope through a window, using a joystick for control.

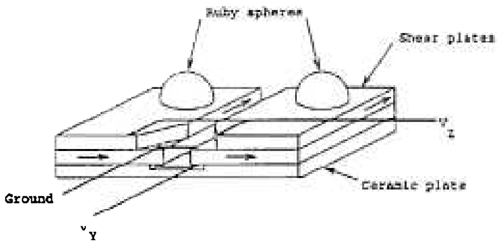

FIG. 2. One of the two drive units on which the cylinder rests is shown. Poling directions of the shear plates are indicated with arrows. V_Y and V_Z refer to the voltages causing the probe to move in the respective directions. All joints are done using one component UHV compatible epoxy (Epotek H35-175MPV where electrical contact is required and Vacseal in other locations).

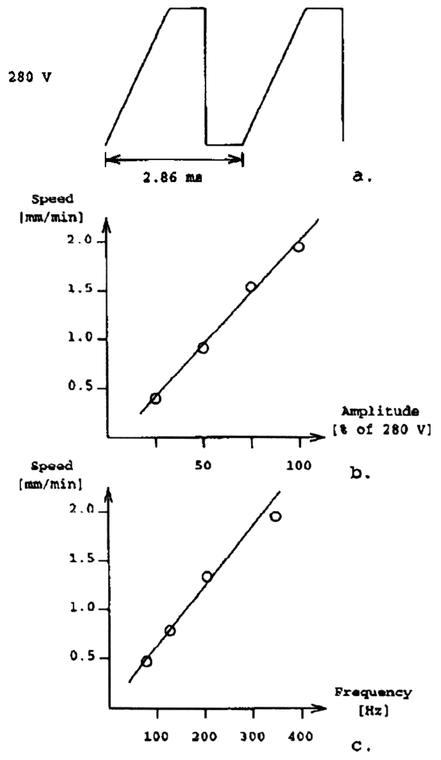

FIG. 3. The upper panel (a) shows the curve shape of the drive signal without extra delays. The frequency is changed by increasing the delays before or after the ramp, keeping the slope constant. The two lower panels show the speed of the X motion: (b) as a function of amplitude at a constant frequency of 350 Hz, (c) as a function of frequency at a constant amplitude of 280 V.

To generate the drive signal for the shear plates we use a computer with a 12 bit digital-to-analog converter connected to an integrated HV amplifier, making it easy to adjust the curve shape. We use a sawtooth voltage with variable amplitude and variable delays before and after the linear ramp, see Fig. 3(a). At maximum speed we drive the plates with 280 V at 350 Hz using a 0.75 ms delay before and after the ramp. The two lower panels in the figure show the speed of the X motion as a function of ramp amplitude (b) and step frequency (c). In both cases the variations are fairly linear. The linear behavior with voltage amplitude for speeds down to 0.5 mm/min indicates that the minimal step size is well below 25 nm (slow fine positioning with arbitrary resolution, limited only by voltage noise, can of course be performed without stepping). The piezoelectric material has a d_{15} coefficient of 400×10^{-12} m/V (Ref. 11) giving a theoretical step

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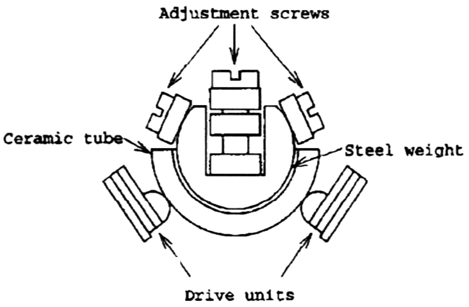

FIG. 4. The figure shows a modified version of the rotating part of the positioner that allows changing the center of gravity by screw adjustments.

length D of 112 nm ($D=d_{15}\times V$, where V is drive amplitude) for our normal drive voltage, in good agreement with the value of 104 nm measured with the interferometer in our force microscope. The speeds we measure without load (except spring forces from the contacting wires) for the motion in X and Y and the peripheral rotation of the cylinder lie in the range between 1.6 and 3.3 mm/min which is in relatively good agreement with the speed calculated by multiplying the step frequency with the measured step length which gives 2.2 mm/min. A perfect correlation is not to be expected as the duration of the riding phase and the sliding phase in an inertial slider will never coincide exactly with the wave form applied. In practice the speeds are strongly dependent on the external forces from connected wires, optical fibers, etc. A simple way to offset static forces that disturb the rotation of the cylinder is to use an arrangement that allows a continuous adjustment of its center of gravity. In our latest version, we use a ceramic tube which is cut along its axis and that has an attached stainless steel weight with screws that are used for balancing, see Fig. 4. This geometry has the additional advantage that it gives a better view of the target area than using a compact cylinder.

ACKNOWLEDGMENTS

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