A COMPACT, COMPOUND ACTUATOR FOR THE MOLECULAR MEASURING MACHINE

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INTRODUCTION

At the National Institute of Standards and Technology, we are developing a large-range, metrology-grade scanning probe microscope (SPM), which we call the Molecular Measuring Machine (M^3). M^3 is uniquely designed to make point-to-point, two-dimensional measurements within a 50 mm by 50 mm measurement area with nanometer-level uncertainties.[1] The instrument uses Michelson interferometers to measure the displacements of the SPM probe relative to the test artifact. Motion in the three orthogonal axes is provided by stacked coarse and fine motion stages that are guided by slide ways and flexure constraints, and driven by piezoceramic linear stepping motors and direct piezoceramic actuators, respectively. The instrument operates in a high vacuum environment, includes multiple stages of vibration isolation, and has temperature control with near millidegree stability at 20 °C.

The machine core is a copper sphere with orthogonal vee and inverted-vee slideways for the upper and lower carriages, which provide the Y and X coarse motion, respectively. The Z-axis motion assembly is suspended from the upper carriage. The design of the Z assembly is particularly challenging because of various competing constraints, especially a limited available volume of only 25 mm in height and 35 mm in diameter, and the need for repeatable motion, and high-resolution position sensors. The coarse-motion stage generates long range motion for the controlled approach of the probe tip to the surface. The fine-motion stage generates guided high-speed motion for servo tracking of the sample height.

In the 20 years since the development of the SPM, many compact actuator designs have been reported. Most of the early designs used piezoelectric steppers as the sample approach element and a piezoelectric tube scanner as the fine motion element. More recently, stage designs have been reported that include metrology capabilities afforded by displacement sensors and motion guides. In exchange, some of the compactness was generally lost. Here, we describe the design, performance, and calibration of a compact, compound Z-motor assembly.

DESIGN

The Z-motor is composed of two motion stages operating in a 25 mm internal diameter stainless steel housing cylinder. The coarse-motion stage is an inchworm-like piezoceramic stepping actuator with a potentiometer-type coarse-motion position sensor. The fine-motion stage is a flexure-guided, piezoceramic-driven actuator with a linear differential capacitance fine-motion position sensor.

Coarse-motion Stage

A cut-away view of the coarse-motion stage is shown in *Figure 1*. The coarse-motion inchworm motor is driven by three multi-stacked piezoelectric ceramic actuators, which are upper brake, pusher, and lower brake. Four-layer stacks are used for the upper and lower brakes, and a six-layer stack for the pusher. Using stacks increases the stroke of the pusher actuator and the radial force of the brakes. The piezoelectric ceramic material for the brakes and pusher is PZT-5H and the thickness of each layer is 0.51 mm. The transverse mode, d_{31}, is used for the brakes and the longitudinal mode,

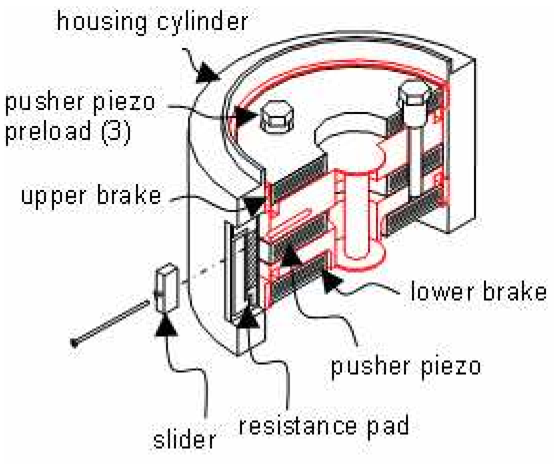

Figure 1. Cut-away view of the Z-motor coarse-motion stage.

d_{33}, is used for extending the pusher. Three screws, equally spaced around the motor at 120° increments, clamp the brake bodies against the pusher and provide the preload for the pusher piezo. The upper and lower brakes are wrapped with friction pads. The pads are made of beryllium copper and cut with 12 shoes on the circumferential surface to allow easy expansion. The outer diameters of the brake pads are carefully diamond turned and hand matched to fit the inner diameter of the precision-ground housing cylinder. The fit must be close enough that friction will keep the motor slug from sliding down even when the power is off, yet loose enough that the dragging friction force with a brake released can be overcome by the clamping force of the other brake and the force and stroke of the pusher piezoceramic stack. The static friction force is measured to be over 50 N, enough to prevent a substantial mass from sliding along the vertical direction under gravitational loading.

The coarse-motion potentiometer-type position sensor is integrated into the Z-motor assembly. A cermet resistance pad is fixed in a rectangular window in the housing cylinder, and a slider having a spring-loaded electrical contact is connected to the motor slug. As the coarse-motion stage is actuated, the slider moves over the resistance pad and the contact position changes. The relative resistance ratio represents the position of the coarse-motion actuator relative to the stationary housing cylinder. To minimize the effects of variations in contact resistance between the sensor and the measuring electronics, we measure the relative potential difference instead of the relative resistance in actual operation.

Fine-motion Stage

As a consequence of the limited space available for the Z-motion assembly, the fine-motion stage actuator is embedded within the coarse-motion actuator. A cut-away view is shown in *Figure 2*. The actuators are three cofired rectangular piezoelectric ceramics with the dimensions of 2 mm x 3 mm x 8 mm. Under no-load conditions, according to the manufacturers specifications, a maximum stoke of 9.1 μm should be achieved when the maximum drive voltage of 150 V is applied. The motion of the actuators is transmitted to the probe through a flexure-guided decoupling mechanism in order to minimize the lateral motion in X and Y direction. The mechanism chain includes a drive plate with flexure hinges, a decoupling ball-between-two-flat, and a center shaft that is guided by two diaphragm flexures. The drive plate is fixed on the Z-motor using the same three threaded rods that provide the preload to the pusher piezo actuator. At the center of the plate is an adjustment screw to provide the preload to the diaphragms. Because the anchored points of the drive plate and the contact points between the actuators and the drive plate are not aligned, the motion range at the center of a simple drive plate was found to be smaller than the motion of the actuators, i.e., motion was lost. Instead, flexure hinges and slots are cut into the drive plate using electrical discharge machining (EDM) in order to build a mechanism for amplifying the displacement at the center of the plate. Precipitation-hardening stainless steel is

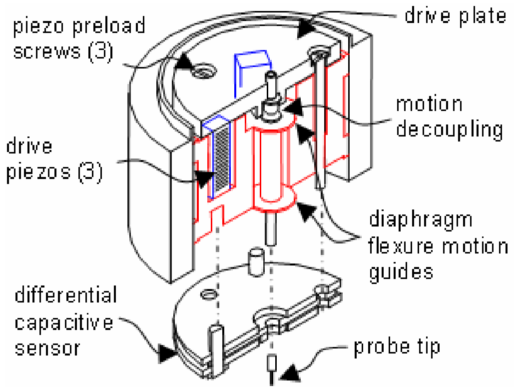

Figure 2. Cut-away view of the Z-motor fine-motion stage.

selected for the drive plate for its high yield strength and good fatigue properties. The diaphragms that guide the shaft motion are EDM-machined into the same piece as the friction pads of the upper and lower brakes. The thickness of the diaphragms is 0.25 mm. The stiffness of the diaphragms in tandem is about 1.98 N/μm.

The fine-motion position sensor is a linear differential capacitance gage which has three sections and has the ability to measure the displacement and tilt of the fine-motion output. The design detail is shown in *Figure 3*. The capacitance gage is composed of inner and outer capacitance plates, and a differential capacitance plate, with differential screws for adjusting the gaps. The inner and outer capacitance plates are mounted on the coarse-motion stage. The differential plate is fixed to the center shaft and moves with the fine-motion stage. The relative position of the inner and outer plate assembly is adjusted by the three differential screws. The thickness of spacers between the inner and outer capacitance plates determines their separation, and thereby the measurement range of this capacitance gage. Currently, the measurement range is about 30 μm.

PERFORMANCE

The performances of the coarse-motion and fine-motion stages have been tested and their position sensors have been calibrated. The coarse-motion actuator is capable of translating at speeds of up to 35 μm/s over a 3 mm range, with overshoot-free steps ranging from 1 μm to 2 μm. The clamp and unclamp voltage input to two brakes is set at ± 400 V. The voltage sweep magnitude to the pusher can be adjusted to vary the step size. When the maximum voltage applied to the pusher is varied from ± 400 V to ± 100 V, for the up-step, the step length that is generated ranges from 1.50 μm to 0.03 μm; for the down-step, the step length ranges from 1.96 μm to 0.47 μm (*Figure 4* and *Figure 5*). There is a significant directional dependence to the step size. We believe that this difference may be caused by a difference of the friction force between the two brakes combined with the relative compliance of the pusher motion in compression versus tension. Gravity was ruled out as a cause by testing inverted operation. To generate uniform-size steps in both directions that do not overshoot in the direction of the sample, we are using ± 300 V input to the pusher for the up-step and ± 200 V input for the down-step. To check the multi-step performance and the speed, the coarse-motion actuator is tested with various slew rates. When the input voltage to the pushers is ± 400 V and the slew rate is at the maximum of 9 600 V/s, which is limited by the performance of the high voltage amplifiers, the maximum speed of up-motion and down-motion can reach at 22.0 μm/s and 35.8 μm/s, respectively. For the coarse-motion position sensor, the sensitivity is about 0.177 (V/V)/mm and the cycle to cycle repeatability is better than 3 μm.

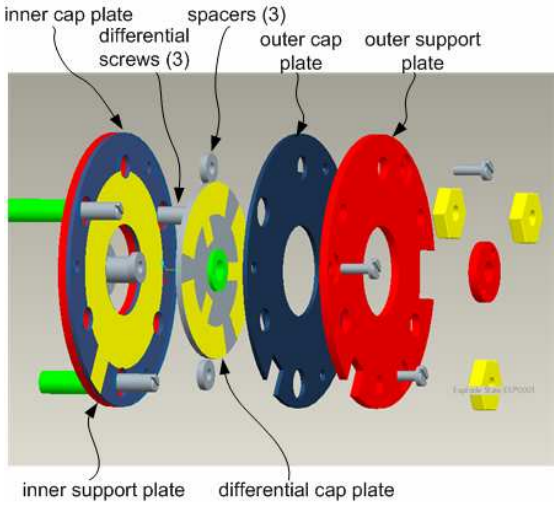

Figure 3. Exploded assembly drawing of the differential capacitance gage — the fine-motion position sensor.

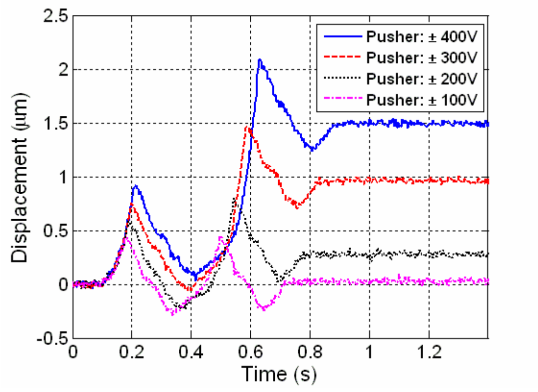

Figure 4. Up-steps with various input voltages to the pusher.

The fine-motion actuator is capable of translating the probe over a range of 6 μm with the

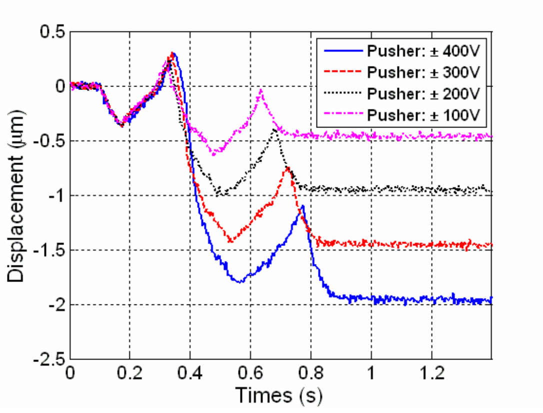

Figure 5. Down-steps with various input voltages to the pusher.

specially-designed drive plate. The flexure-hinged cantilever beams on the drive plate can amplify by 40 % the displacement from the piezo actuator to the center of the drive plate, compared with the previous simple drive plate without flexure structures. The fine-motion position sensor is a highly sensitive and linear differential capacitance sensor. This differential capacitance sensor has five terminals with three sections and is capable of measuring both the displacement and the tilt. Three capacitance AC bridges are used to measure each section of the differential capacitance gage. The signal to noise ratio for the demodulated signal, operating at 10 kHz oscillator frequency, can reach 1:69 000 when the unshielded AC bridge is tested with an update rate at 13.8 kHz and oscillator amplitude set at ± 10 V.[2] Because the design has three electrodes on the active plate of the differential capacitance, the sensing area cannot be surrounded by a general guard ring. Even without the guard ring to minimize the fringe effects, the linearity of this capacitance gage is still better than 0.4 %. The current noise of the capacitance gage is about 0.5 nm (1σ), tested in air with a 0.2 °C room temperature fluctuation. The capacitance gage is calibrated using a laser interferometer and autocollimators. The displacement and rotations in the X/Y/Z axes are measured. The AC bridge output versus the displacement in the Z direction is shown in *Figure 6*. For a 10 µm calibration excursion of the fine motion stage, the pitch (θ_y) and roll (θ_x) are about 15 arc-seconds and 5 arcseconds respectively, while the yaw (θ_z) is less than 0.5 arcseconds and can be ignored. By the Moore-Penrose matrix inverse method[3], the linear least-squares solution of the parameters of the model that relates the three capacitance gage sections to the displacement in Z and the rotation about X and Y are calculated and shown in the following equations.

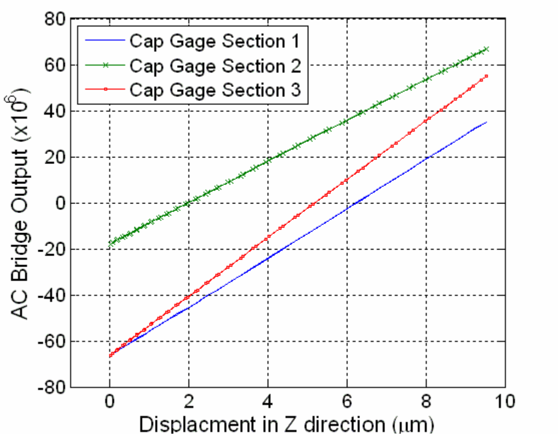

Figure 6. Capacitance AC bridge output versus the Z displacement.

$$\begin{bmatrix} Z \\ \theta_x \\ \theta_y \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ 1 \end{bmatrix} =$$

$$\begin{bmatrix} 0.0259 & 0.0043 & 0.0549 & 5.3394 \\ -0.1894 & 0.2238 & 0.0454 & -5.2978 \\ 0.1726 & 0.0718 & -0.0672 & 7.6997 \end{bmatrix} \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ 1 \end{bmatrix}$$

The Z-motor actuator assembly is still under development. Its design and performance will be optimized further to help decrease the uncertainty of M^3 when the Z-motor is assembled into M^3 in the future.

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