

A simple hybrid positioning stage with <1nm resolution

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1. Background

A variety of ultra-precision positioning devices are nowadays effectively in use, complying servomotors, no matter rotary or linear. On the other hand, step motors, or pulse motors, have position holding characteristics in nature and capable to control position without feedback devices. So-called "micro-step drive" is an effective method to extend the positioning resolution of step motors, which controls phase current stepwisely and interpolates the basic step angle. Step motors and drives are relatively compact and cheap. Even though, step motors are still lacking resolution and accuracy, as well as smoothness in motion, for nanometer-order motion control.

One approach is to take those advantages and to compliment those shortages would be utilization of a piezoelectric actuator. Namely, the step motor acts as a coarse actuator driving the stage in a long range, while the piezoelectric actuator as a fine actuator compensates the motion error of the coarse mechanism and interpolates the resolution of the step motor. Simple and cheap mechanical stages with nanometer-order resolution have potential to be applied in many area.

Such hybrid stage systems are already commercialized¹⁾. In some applications, continuous motion control is needed as well as fine positioning. The purpose of this study is to apply a continuous motion control system to the stage mechanism and to evaluate the characteristics with nanometer resolution.

2. Mechanical stage

The hybrid stage used is shown in **Fig. 1**, and its structure is schematically shown in **Fig. 2**. The stage is driven by a step motor via a ball screw of 1mm lead, guided by a pair of crossed roller guides. A PZT actuator is mounted at the other end of the screw, which pushes back the screw, compressing the coupler, and gives slight

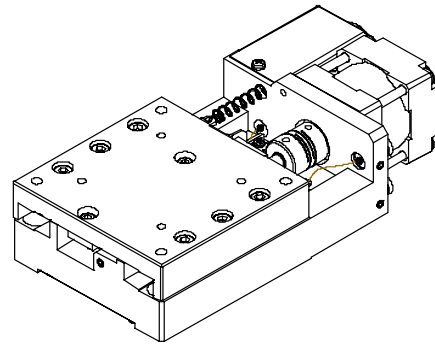


Fig.1 A hybrid mechanical stage

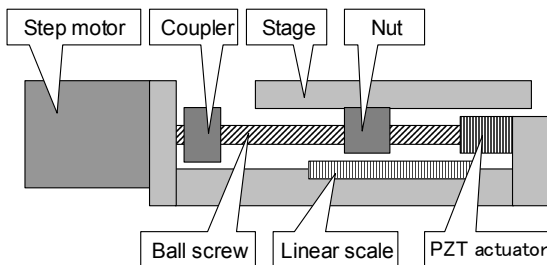


Fig. 2 Schematic diagram of the hybrid stage

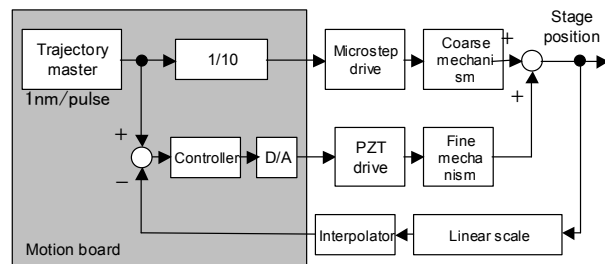


Fig. 3 Schematic diagram of the control system

displacement to the stage. A novel tiny optical linear scale²⁾ is embedded in the stage, which measures the stage displacement with <1nm resolution. The mechanism sizes 60 mm wide and 129 mm long.

3. Control system

The main control scheme shown in Fig. 3 is realized by a DSP-based motion controller, including trajectory generation, pulse distribution, PID controller and analog output for PZT driver. The resolution of command and feedback from the linear scale is set to 1nm. The 5-phase step motor has 0.72 degree of basic stop size. A micro-step driver interpolates the resolution by 200 times, which makes 10nm of coarse positioning resolution. The coarse system is open loop and the fine system is closed-loop. The both displacements of the fine- and coarse system are added mechanically.

Ideally, when the loop gain of the fine system is infinite, the stage displacement would coincide to the command. Actually, the loop gain has a limit due to a compliance at the coupler and the ball nut. This control scheme is a fixed one without any mode change, programmed on a DSP board.

4. Results

4.1 Response of the sole coarse system

Fig. 4 and Fig. 5 show responses of the bare coarse system, with the fine system disabled, for 10 nm pulses issued at every second. The following features are recognized:

- 1) Overshoot of 7 to 15 nm arises at the step jerk, and it takes about 100 ms to settle.
- 2) Step size is not constant, changing sinusoidally with period of 500 nm. The amplitude of the deviation from ideal step size reaches to +/- 60 nm. A period contains a stationary region equivalently of 70nm where no displacement is generated (marked by "S"). The period of 500 nm corresponds to a quarter of basic step size of the motor, 2 μm.
- 3) Another stepwise deviation of about 20 to 50 nm occurs by a period of 2 μm (marked by arrows). This

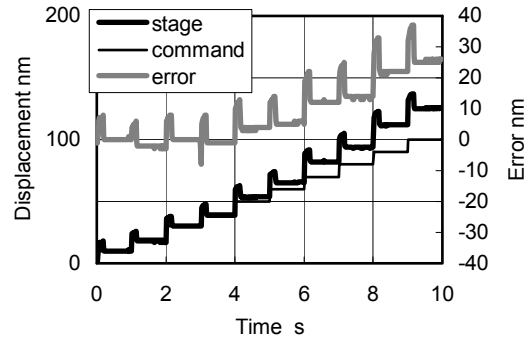
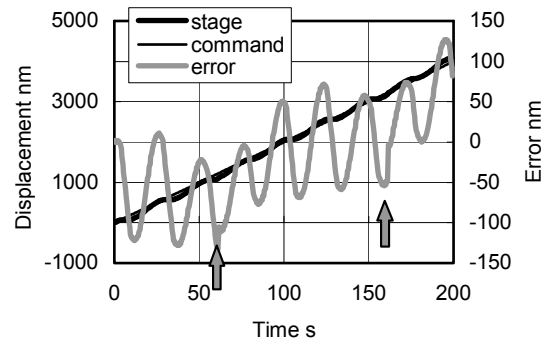
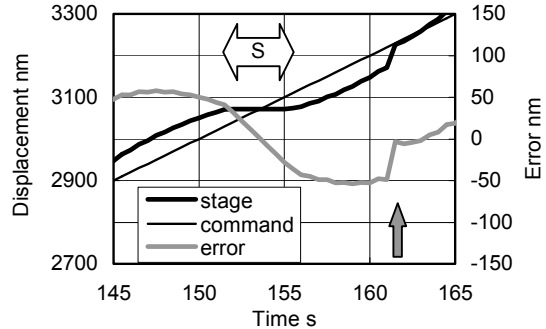


Fig. 4 Response of the sole coarse system

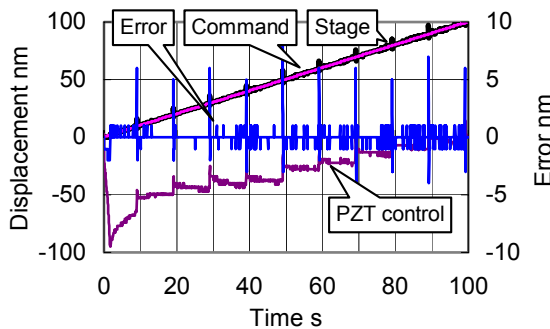


(a) Overview

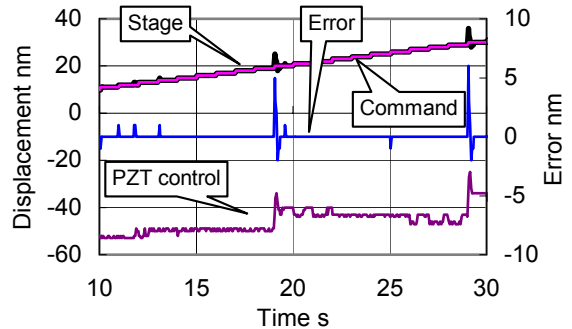


(b) Magnified

Fig. 5 Periodic deviation of coarse system



(a) Overview



(b) Magnified

Fig. 6 Response of hybrid system (1nm step, 1nm/s)

periodic deviation is out of phase with the deviation of 500 nm period.

4.2 Responses of the hybrid system

(1) At low and medium speed

Responses of the fine-coarse system were measured, giving various command step size and step rate, measuring stage displacement, following error and PZT control signal.

Fig. 6 shows the response for a 1nm step train command given at every second. At every step edge the fine system is activated to interpolate the resolution. The deviation is less than 1 nm quasi-statically, but at the every step edge, spike following error arises as overshoot and following undershoot. These are due to the limited bandwidth of the fine system.

Fig. 7 (a) is for a similar condition, while pulse rate is ten times higher. The settling time is measured again as 100 ms, which corresponds to the transient error of the coarse system. This following error is here to be called "FE-A". Another following error is seen, which is due to the stationary region of the coarse system response described in the previous section, and is not compensated perfectly. This following error is here called "FE-B".

Fig. 7 (b) is in such case that command step size is 10 nm. The following observation is made:

- 1) Undershoot of the following error-A is greater than the case at low speed.
- 2) Amplitude of FE-A changes sinusoidally with period of 500 nm. FE-B occurs where FE-A is minimized.
- 3) PZT control as command to fine system also changes periodically, but not sinusoidally.
- 4) Another pulsive following error arises when displacement jump occurs at every 2 μm . This is here "following error-C (FE-C)".

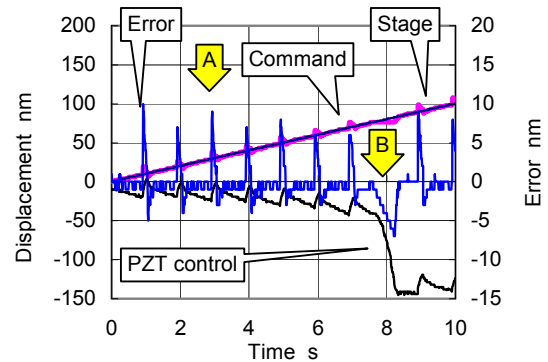
Observing responses under other conditions, velocity and step size were found affecting the degree of the following errors: In **Fig. 7 (c)** peak values of FE-B and FE-C are increased, as well as width of FE-B.

Peek change of each following errors are plotted as function of velocity and step size, in **Fig. 8**, where "A+" and "A-" denote positive and negative maximum peek of FE-A respectively, and "B" and "C" stand for maxima of following error B and C respectively. The results is summarized as follows:

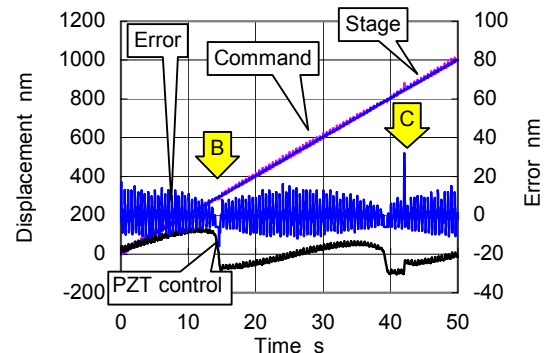
- 1) FE-A+ nor FE-A- does not change very much.
- 2) FE-B bursts when step size exceeds 10 nm.
- 3) FE-C bursts as step size or velocity increases.

(2) At high speed

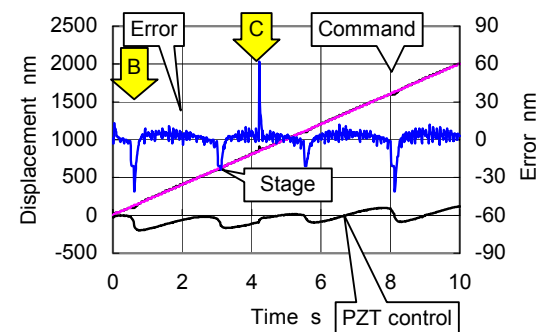
As command velocity is raised into high velocity region, following errors-B and-C increase. Peak value and width of the FE-B burst to be dominant factors of following errors. Also, the periodic deviation of step size of the coarse system with 500 nm period appears as waviness in the following errors (Fig. 7(c)). This phenomena is due to the fine system does not compensate the error of the coarse system effectively in higher speed region.



(a) 1 nm step, 10 nm/s



(b) 10 nm step, 20 nm/s



(c) 20 nm step, 200 nm/s

Fig. 7 Response of hybrid system

(3) Effects of integral loop gain

The following characteristics of the fine system is influenced by its servo loop gain. Proportional gain Kp is set as stable limit. Integral gain Ki has some margin to be increased.

Fig. 9 is comparing the system following error with regular $Ki=50$ and when increased up to 400. As Ki is increased, the following error-B and periodical undulation of following errors were suppressed, while step size as 50 nm, velocity as $2.5\mu\text{m/s}$. But when the command velocity was decreased back to 100 nm/s keeping $Ki=400$, another type of following error like oscillation was observed, which differs from transient error seen in previous measurements. Amplitude of the following error is not greater than ever, but the oscillation remains in low velocity region and even under stationary condition. That indicates that higher integral gain is effective only in higher velocity region.

5. Conclusion

Dynamic servo tracking characteristics has been evaluated of a simple hybrid mechanical positioning stage system comprising a pulse motor and a PZT actuator. Fixed control scheme and parameters were applied with 1 nm system resolution. Results are summarized as follows:

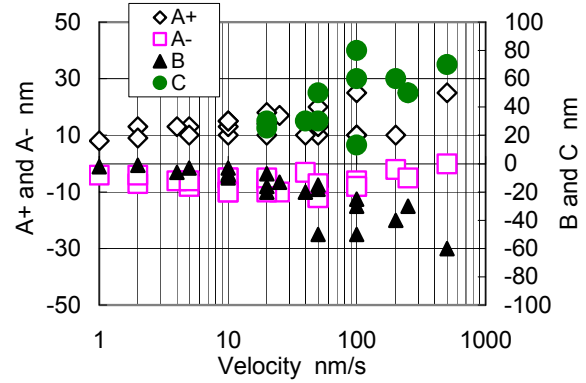
- 1) Quasi-static positioning error is less than 1 nm.
- 2) In dynamic motion control, some transient following errors reside, and they fail smoothness of the motion.
- 3) The limited resolution and variation in step size are effectively compensated by the fine motion system.
- 4) Stepwise and periodic large deviation of the coarse system is not compensated. This imperfection increases as velocity or step size increases.
- 5) It is effective to increase the integral closed loop gain of the fine system for suppressing following error in higher velocity region, while high integral gain introduces instability in low speed region.

6. Acknowledgement

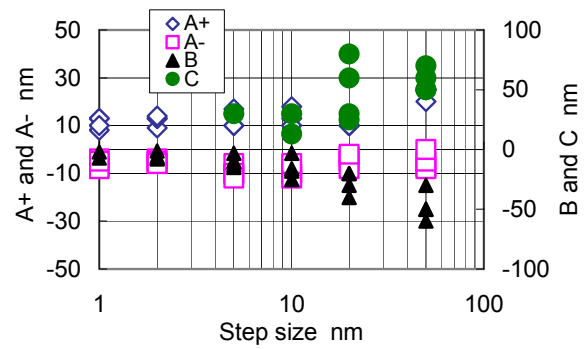
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References

- 1) www.sigma-tech.co.jp/products/
- 2) Japanese patent, No. 3198019

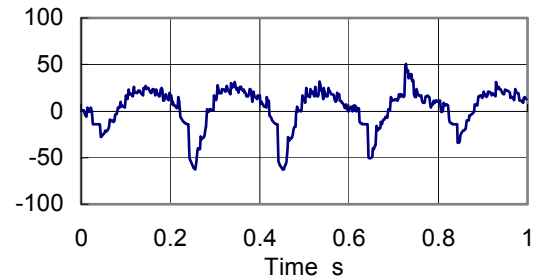


(a) By command velocity

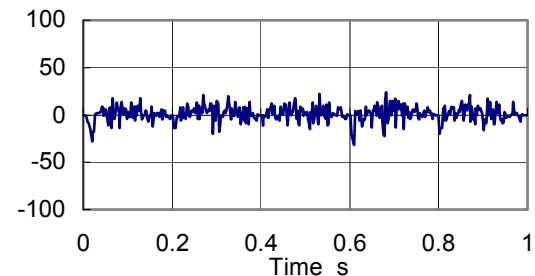


(b) By step size

Fig. 8 Deviation change



(a) $V=2500\text{nm/s}$, $Ki=50$



(b) $V=2500\text{nm/s}$, $Ki=400$

Fig. 9 Effect of integral gain Ki (50nm step)