

# Evaluation of a compact 1nm resolution servo stage with hybrid control scheme

Yuichi Okazaki  
Nat'l Institute of Advanced Science and Technology  
Ibaraki 305-8564, Japan  
okazaki-u1@aist.go.jp

Soji Ichikawa  
Sigma Tech Co. Ltd.  
Saitama 357-0035, Japan  
info-s@sigma-tech.co.jp

Jiro Otsuka  
Shizuoka Institute of Science and Technology  
Shizuoka 437-8555, Japan  
otsuka@me.sist.ac.jp

## 1. Background

Precision positioning stages are nowadays commonly required and utilized in the area of , for example, assembling devices, manufacturing equipments and instrumentation. In some applications, the stages should follow a continuous trajectory, rather than point-to point positioning. The control resolution required will be down to nanometer region. The stages may well be compact and even cost-effective. For those needs, a mechanical stage having a simple structure has been developed and evaluated preliminary [1]. The stage has a dual actuation system, i.e. rotary step motor as a coarse actuator, and a piezoelectric actuator as a fine actuator. So-called "microstep drive" is an effective method to extend the positioning resolution of step motors, which interpolates the basic step angle by changing phase currents. The piezoelectric actuator compensates for the remaining error motion of the coarse mechanism. The motion of the stage is detected by an embedded linear encoder with one nanometer resolution. The control scheme functions so that the stage follows the continuously changing reference with high resolution.

In the former report, the motion accuracy of the system was measured and analyzed. Although the quasi-static following error was one nanometer level, the error was increasing rapidly as the stage velocity increases. The error was categorized into three types. However, the reasons for the most errors were not clarified.

We have newly made analysis of the following error, and have made modification in mechanical configuration and electronics. Tests were performed over a wide velocity range, and the tracking performance was revealed to be much improved.

## 2. Mechanical stage

The hybrid mechanical stage used is illustrated 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 displacement to the stage. A novel tiny optical linear encoder [2] is embedded in the stage, which measures the stage displacement with 1nm resolution after 2000-time interpolation. The mechanism sizes 60 mm wide and 129

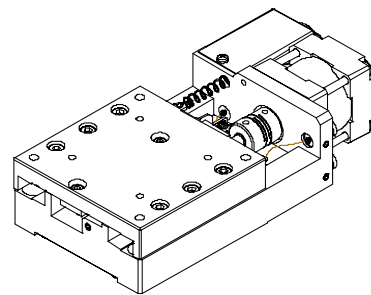


Fig.1 The hybrid mechanical stage

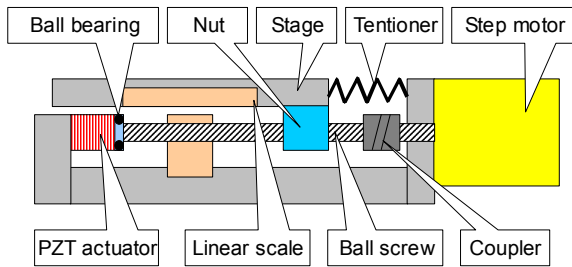


Fig. 2 Schematic diagram of the hybrid stage

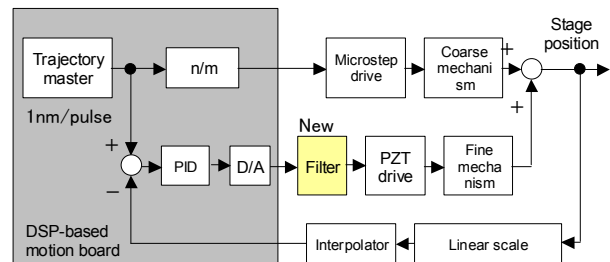


Fig. 3 Schematic diagram of the control system

mm long.

### 3. Control system

The main control scheme shown in **Fig. 3** is realized by a DSP-based motion controller (National Instruments NI-7344), including trajectory generation, pulse distribution, PID controller and analog output for PZT driver. The resolution of command and feedback from the linear encoder is set to 1nm. The 5-phase step motor has 0.72 degree of basic step size. A microstep driver interpolates the resolution. The coarse system is an open loop and the fine system is a 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. In reality, the loop gain has a limit due to compliance at the coupler and the ball nut. This control scheme is a fixed one without any mode change, programmed on the DSP board.

### 4. Reposes and system modification

#### 4.1 Following errors of the former system

As reported in the former report [1], by means of the dual actuation function, the periodic positioning error and the insufficient resolution of the coarse system were effectively compensated by the fine positioning system. The typical response charts are shown in **fig. 4**. In the original system, the interpolation ration of microstepping was 200 times, which makes 10 nm of coarse positioning resolution. The quasi-static following error could be suppressed almost within one nanometer. Dynamically, the following error of the closed-loop system could be categorized into three types as follows:

FE-A: At every step edge where the fine system is activated, spike following error arises as overshoot and following undershoot (marked as “A”). 5-10nm

FE-B: At every 500 nm, the following error increases (marked as “B”). 5-50nm

FE-C: At every 2 $\mu$ m, spike following error arises (marked as “C”), independently from FE-B timing. 30-80nm

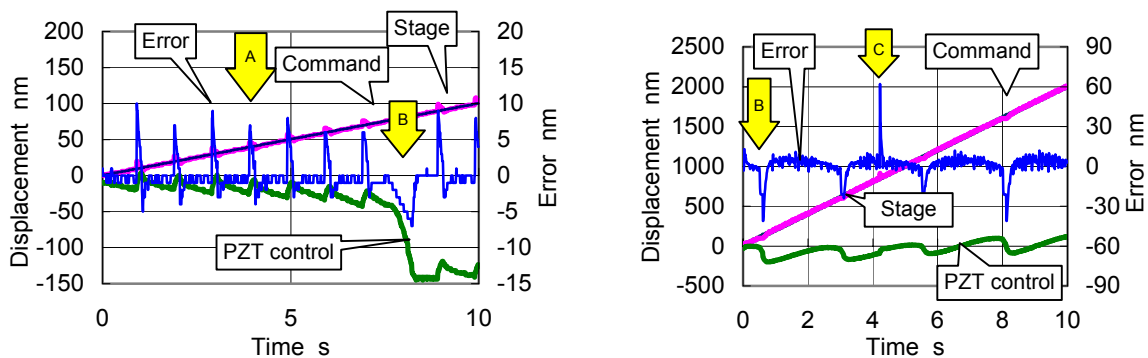
As command velocity is raised into high velocity region, FE-B and FE-C increase. Peak value and width of the FE-B burst to be dominant factors of following errors. Also, the periodic deviation of step size of the coarse system with 500 nm period appears as waviness in the following errors (**Fig. 4 (b)**). These phenomena is due to the fine system which does not compensate the error of the coarse system effectively in higher speed region.

#### 4.2 Modifications and results

(1) Higher interpolation ratio of the microstepping driver: Formerly the microstepping ratio was 200 times, which corresponds to 10 nm as resolution of the coarse system. The ration has been gradually elevated as 400 times for 5nm, 600 times for 10/3 nm, and 800 times for 2.5 nm. The step size of the coarse system and resulting shock movement have been reduced. As the result, the following error A (FE-A) diminished.

(2) Modification of the linear encoder electronics: The source of the following error-B was revealed to be malfunction of the analog electronics for the encoder signal processing, ceasing the pulse generation periodically. By renewal of the circuit, the following error-B has disappeared.

(3) Additional analog filter to the fine system: Because the loop transfer function of the fine system (PZT compensation system) includes a mechanical resonance, the achievable loop gain was limited. By inserting an



(a) 1nm step, 10 nm/s

(b) 20 nm step, 200 nm/s

Fig. 4 Response of the former hybrid system

analog notch filter into the loop to cancel the resonance (Fig. 5), the achievable gain parameters have been much elevated, maintaining stability. ( $K_p/K_d/K_i=7/2/50$  to  $50/20/100$ ). As the result, the dynamic compensation functionality by the fine system has been elevated, and following error has been suppressed

### 4.3 Evaluation of the tracking characteristics over a wide velocity range including direction

The former report describes that tracking performance of the system was evaluated in a low velocity range up to 500nm/s, and that the errors burst as the velocity increased. Tracking characteristics have been newly evaluated in a wide velocity range. Supposing a circular motion with an X-Y stage, sinusoidal motions have been also tested. The tracking performance has been evaluated as a root-mean-square (RMS) value of the following errors.

Fig. 6 shows a typical response of the modified hybrid control system as a constant velocity motion test, and a trend of the following error as a function of the velocity. In a low velocity range up to 500 nm/s, the following error remains within several nanometers. As the motion velocity exceeds the limit, the error bursts, where the compensation action by the PZT fine mechanism does not function perfectly, because of its limited bandwidth.

In Fig. 7, similar results of sinusoidal motion tests are shown. In a low velocity range, i.e. small amplitude or long period, the tracking is almost on the same level as the constant velocity motion tests. The error increases as the velocity, which is proportional to amplitude over period, increases. Different from the constant velocity test, the following error increases when the moving direction turns. In a high velocity region, the lost motion of the coarse system exceeded the capacity of the fine system, so that the compensatory operation was disabled.

### 4.4 Lost motion of the coarse system

The lost motion of the coarse system, namely the difference of the actual displacement from command, should be compensated by the PZT fine mechanism. When the lost motion exceeds the capacity of the fine system in the sense of working travel and bandwidth, large following error is generated. The rotation angle of the step motor is determined by the mechanical balance of the hold torque, which is controlled by phase currents, and mechanical load including mechanical compliance, preload, nonlinear spring characteristics and friction force. The rotation angle is in turn transferred to the stage displacement via nonlinear transfer characteristics of the mechanism. The lost motion is mainly caused by; 1) interpolation error of the microstepping, 2) torque ripple of the motor, and 3) sticking friction force by the load, appearing at the direction turn. The lost motion has been measured as shown in Fig. 8. The amount of the lost motion and capacity of the fine system are both

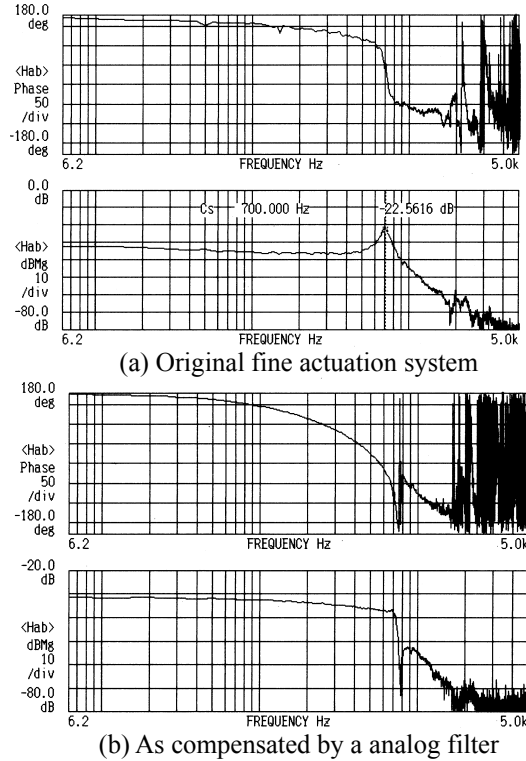
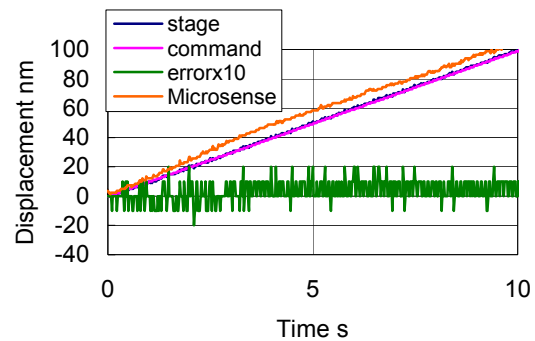
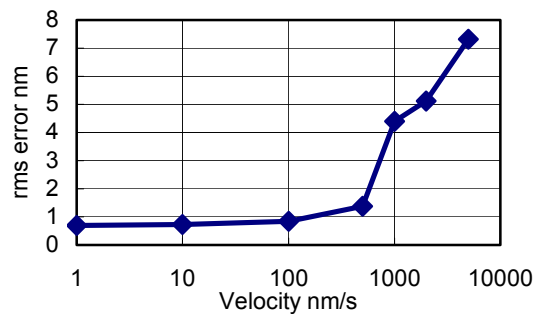


Fig. 5 Transfer function of the fine actuation system



(a) Time chart (10nm/s)



(b) RMS following error  
Fig.6 Constant velocity motion tests of the modified system

dominating the limitation of the hybrid control system. In Fig. 8, deviation of the lost motion can be seen, as two types of waviness, i.e. those of 20- $\mu\text{m}$  period and 2- $\mu\text{m}$  period. The former period corresponds to signal pitch of the linear encoder and one fifth of the ball screw lead. The latter period corresponds to the basic step angle of the motor. Further investigation will be needed to locate the error sources.

### 5. Conclusion

On the developed simple hybrid mechanical positioning stage system comprising a step motor and a PZT actuator, some modifications in electronics have been made. Dynamic servo tracking characteristics has been evaluated over wide velocity range, and the following error has been proved being much reduced compared to the former system. In order to extend the velocity range where the system functions properly, the following task should be done:

- 1) Minimizing the lost motion of the coarse system.
- 2) Expansion of the range of the fine system to compensate the error motion of the coarse system, both in displacement and bandwidth.

Furthermore, to assure the motion control accuracy, the following items would be needed.

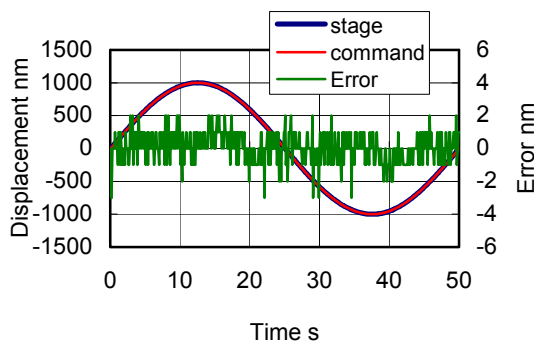
- 3) Accuracy assurance of the embedded linear encoder
- 4) Evaluation of the error motion of the stage and resulted offset error
- 5) Minimizing the heat generation from the step motor and effective compensation.

### 6. Acknowledgement

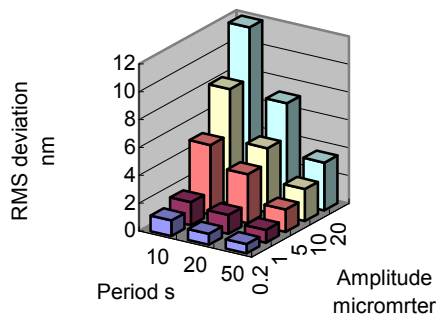
This study has been performed as a part of a Japanese national program, "Regional Consortium Research Development in FY 2001" supported by Ministry of Economy, Trade and Industry, and following research program by the Organization for Hamamatsu Technopolis.

### References

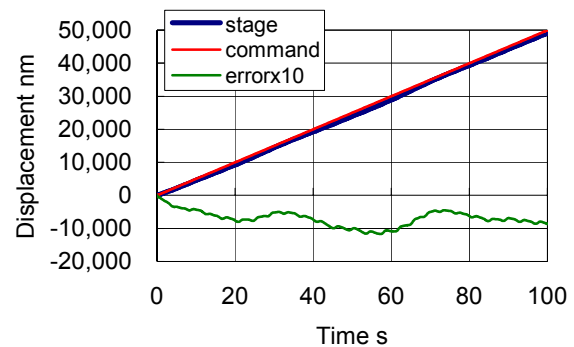
- [1] Okazaki, Otsuka, Ichikawa: A simple hybrid positioning stage with <math><1\text{nm}</math> resolution, Proc. ASPE 2003 Annual Meeting (2993) p.p.235-238
- [2] Japanese patent, No. 3198019



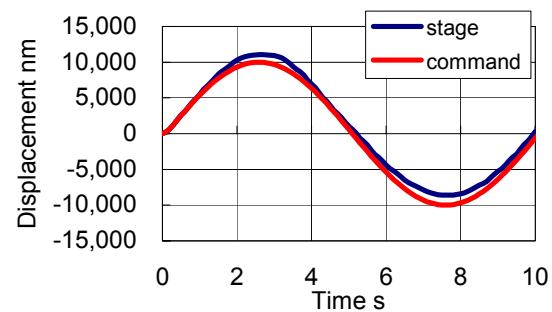
(a) Time chart (1 $\mu\text{m}$ , 50 s)



(b) RMS following error



(a) Constant velocity motion (500 nm/s)



(b) Sinusoidal motion

Fig. 7 Sinusoidal motion tests of the modified system

Fig. 8 Typical lost motion behavior of the coarse system