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NANOMETER POSITIONING CONTROL USING NONLINEAR DYNAMICS OF ROLLING GUIDE

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Abstract

Nanometer positioning control with high velocity and long stroke is discussed. A one-axis stage mechanism driven by an AC linear motor and guided by a rolling ball guide has been constructed. Coarse and fine position controls are designed by using nonlinear dynamics of the rolling guide. Switching from coarse positioning to fine positioning is studied.

1. Introduction

Precise position control is a basic and important technology. Ever higher performance is always required. Positioning methods with high precision and long stroke have been designed by using a hybrid coarse and fine mechanical structure [1],[2]. These hybrid mechanisms have two disadvantages: the structure of the mechanism becomes intricate and the size of the mechanism becomes large.

In this paper, nanometer positioning control using a stage mechanism driven an AC linear motor and guided by a rolling ball guide is proposed. Experiments show that dynamics of the guide are different in different displacement regions. We demonstrate that the stage with a single mechanism works both as a long stroke stage with a high velocity and a nanometer positioning stage by changing the control mode.

2. Configuration of the system

The experimental system consists of the following: (1) a one-axis stage mechanism comprised of an AC linear motor, a rolling guide mechanism, and two position sensors, one coarse and one fine, (2) power amplifiers, (3) controllers and (4) a data-processing computer.

Stage mechanism

A contactless direct-drive method and contactless position measurement are adopted in order to eliminate friction force. A diagram of the stage is shown in Fig. 1. The moving table of 5.8 kg is guided by a rolling ball guide mechanism. Moving stroke is 250 mm. The motor windings are located at the center of the base to eliminate moment. The six permanent-magnet pairs are attached to the table to hold the windings between these magnet pairs. The two position sensors are located on the sides of the table: an optical linear scale with 100 nm resolution, 200 mm/s maximum velocity and 250 mm stroke as the coarse long-stroke sensor, and a capacitive gap sensor with 400 μV/nm sensitivity and 50 um range as the fine sensor.

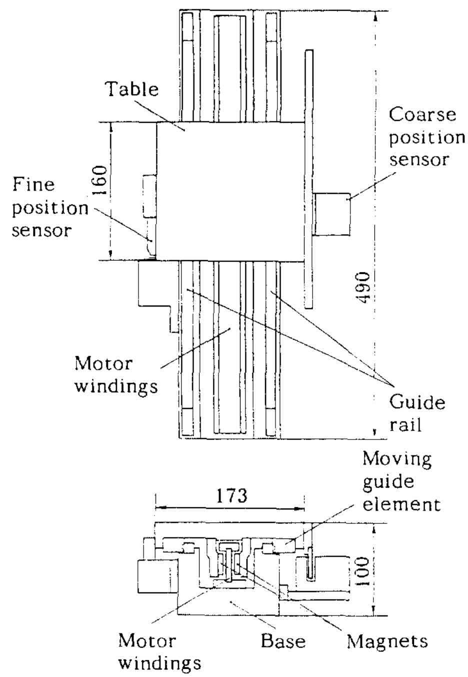

Fig. 1 Diagram of the stage mechanism driven by an AC linear motor and guided by a rolling ball guide.

Motor

A moving-magnet-type synchronous AC linear motor is selected. No iron core or yoke is used

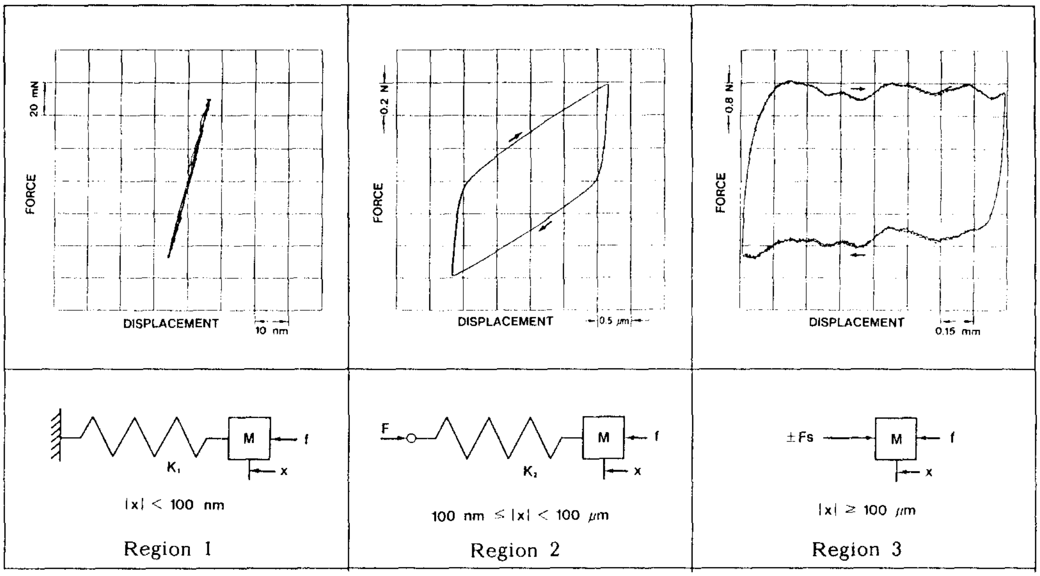

Fig. 2 Measured force-to-displacement relationships and dynamic models of the stage for three different displacement regions.

in order to minimize the time constant and force ripple of the motor. The bandwidth of the current control and the force resolution of the motor were 10 kHz and better than 1 mN respectively.

3. Nonlinear micro-dynamics of the rolling guide

Measured force-to-displacement relationships and dynamic models of the stage are shown in Fig. 2. The dynamic characteristics of the guide are different in different displacement regions:

Region 1: In a displacement of less than 100 nm, the force is proportional to the displacement which means that the guide bearing acts as a linear spring;

Region 2: In a displacement between 100 nm and 100 μm, the guide bearing acts as a nonlinear spring;

Region 3: In a displacement over 100 μm, the force saturates and normal rolling takes place.

The dynamic model of the stage in region 1 is expressed as a simple mass-spring system, where x= position of the table, f= motor force, M= mass of the table and K1= spring constant. In this system, fine displacement can be directly controlled by changing the motor force. The natural frequency of this system was about 200 Hz. The dynamic model of the stage in region 3 is a simple mass system acting under

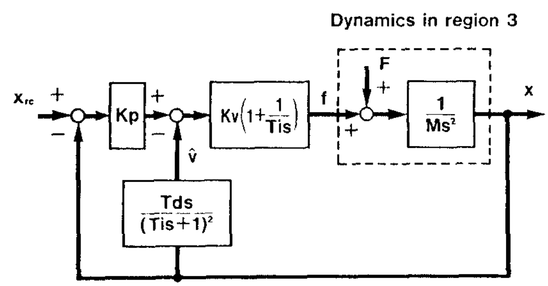

Fig. 3 Block diagram of coarse position control.

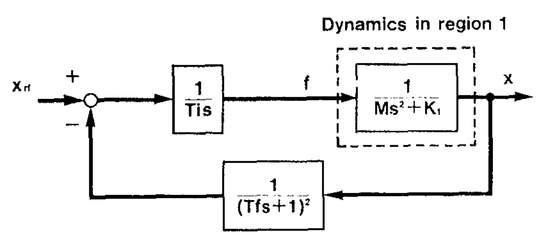

Fig. 4 Block diagram of fine position control.

motor force and Coulomb friction Fs.

The spring characteristic in region 1 is suitable for fine positioning. The normal rolling characteristic in region 3 is suitable for long-stroke coarse positioning.

4. Control design

Coarse position control

Coarse positioning is carried out by using the normal rolling characteristic of the guide in region 3. The coarse position control is designed as a combination of a proportional position control and a proportional-integral velocity control as shown in Fig. 3. The dynamics of the stage are shown within the dotted line. The velocity is obtained from the coarse position signal using a frequency-to-voltage converter. The friction force F is compensated by the integral control.

The one-pulse (100 nm) step response of the coarse position control is shown in Fig. 5. The position followed the reference and no backlash was observed. A maximum velocity of 200 mm/s was achieved in this control as shown in Fig. 6. This value was limited by the maximum measuring velocity of the coarse position sensor.

Fine position control

Fine positioning is carried out by using the spring characteristic of the guide in region 1. The fine position control is designed as a simple integral control with a cascaded second -order lag filter for stabilization as shown in Fig. 4. The dynamics in region 1 are shown within the dotted line. The oscillatory characteristic of the control object is actively damped by this control. This control is relatively insensitive for high frequency sensor noise. It is also advantageous that no velocity signal is used.

The one-nanometer step response is shown in Fig. 7. The position precisely followed the reference and no backlash was observed. The bandwidth of the fine control was higher than 100 Hz.

5. Switching from coarse to fine positioning

It is found that the dynamic transition from region 3 to 2 and then to 1 easily takes place when the deformation of the guide bearing is released by decreasing the motor force. Using this phenomenon, a long stroke and fine positioning can be obtained by the following sequence:

(1) Carry out long and coarse positioning from the starting point to a reference position;

(2) Release the deformation of the guide by decreasing the motor force just before the coarse positioning is completed;

(3) This release causes a dynamic region transition from region 3 to 2 then to 1;

(4) Turn off the control and set the motor

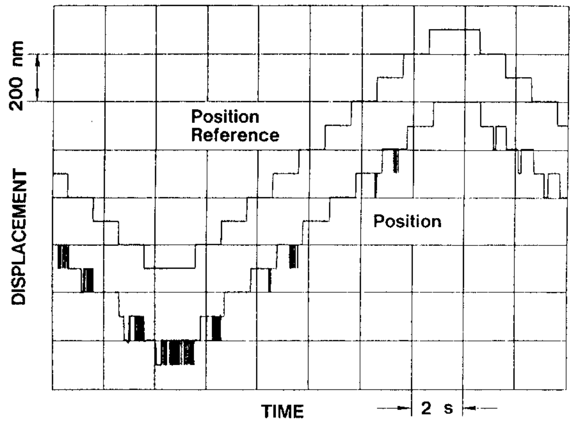

Fig. 5 One-pulse (100 nm) step response of the coarse position control.

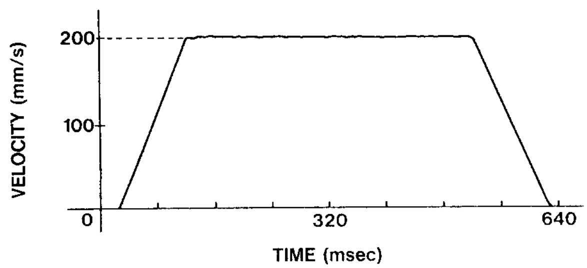

Fig. 6 Maximum velocity response of the coarse position control.

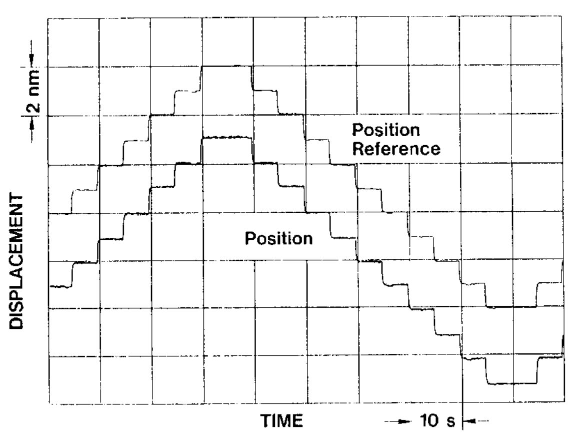

Fig. 7 One-nanometer step response of the fine position control.

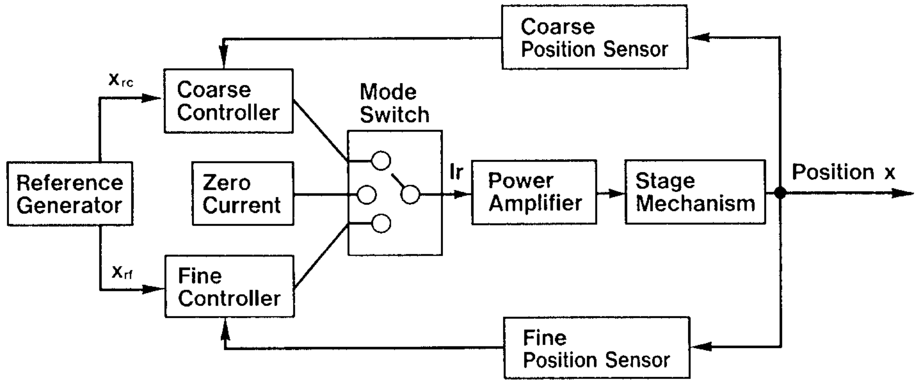

Fig. 8 Block diagram of the overall control system.

force to zero;

(5) Lastly, activate the fine position control and adjust the coarse positioning error.

A block diagram of the overall control system is shown in Fig. 8. One of the three control modes -- the coarse control, fine control and zero current mode -- is selected by the mode switch.

A long stroke and fine positioning response is shown in Fig. 9. The positioning distance was 50 mm and the maximum velocity was 50 mm/s. The deformation of the guide bearing which was 23 µm was released. After that, the control was cut off in order to settle the stage dynamics into region 1. Finally, the fine position control was activated to correct the coarse positioning error as shown in Fig. 10.

6. Conclusion

A nanometer position control system was constructed using a single-stage mechanism driven by an AC linear motor and guided by a rolling guide mechanism. Nonlinear micro-dynamics of the guide were examined. By using the micro-dynamics of the rolling guide, nanometer positioning of better than 1 nm resolution, 200 mm/s maximum velocity and 250 mm stroke was achieved.

Reference

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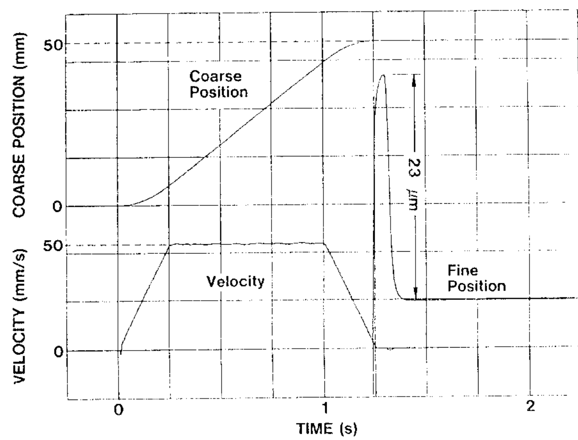

Fig. 9 Positioning response of 50 mm distance and 1 nm precision.

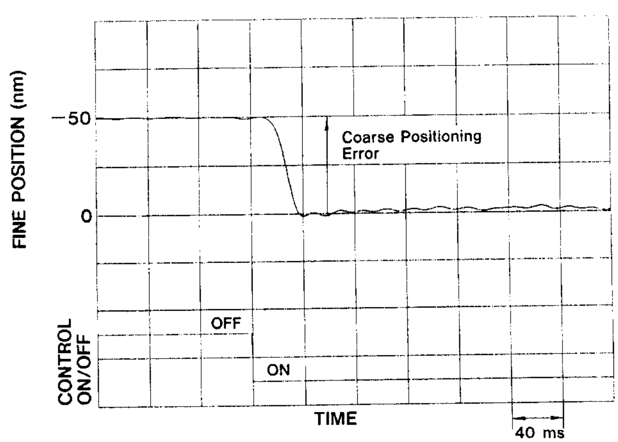

Fig. 10 Fine positioning response to correct the coarse positioning error which was 50 nm.