New Inchworm type Actuator with I/Q heterodyne Interferometer Feedback for a Long Stroke Precision Stage

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ABSTRACT

The precision stage is an essential device for optic fiber assembly systems, micro machines and semiconductor equipments. A new piezoelectric inchworm type actuator is proposed to implement an actuator-integrated long-stroke linear stage. An in-and-quadrature phase (I/Q) heterodyne interferometer is developed as a feedback sensor of a servo system, and a synchronized counting method is proposed. The proposed measurement system can measure the accurate position of fast moving object with robustness to external sensing noise from actuator vibration. The developed servo stage will be applied to optic fiber device assembly system.

Key Words : Inchworm actuator, I/Q heterodyne interferometer

1. Introduction

The precision linear stage is an essential device in the fields of micro assembly system and bio technology. As an actuator for the precision stage, a piezoelectric actuator is preferred to a conventional electro-magnetic actuator because it has good linear characteristics, fast response time, and small size. But its displacement is too small to be used for a long stroke stage, only a few hundred micrometers at most. So, various methods to extend its stroke have been introduced.[1] Inchworm type actuator, which is one of them, has merits that it has strong force and good stiffness, but demerit that it moves slowly, with a speed of a few millimeters per second.[2] The speed of actuator is an important factor which determines the productivity. Some improved inchworm type actuators have been proposed by Zhang[3], Ni[4] and Frank[5]. The accuracy, speed, output force and stroke are important performance factors of a precision stage. Here, a new inchworm type actuator is proposed, which can be operated with relatively high speed, nanometer level accuracy and enough output force to implement a long-stroke servo stage for a fiber optic device assembly system. To make stage frame more compact, the developed actuator is integrated into a stage body. As a precise position sensor, an interferometer is good solution for a long range measurement, and some measurement methods were published.[6,7] A new measurement device using I/Q He-Ne heterodyne interferometer is also proposed, and a servo system integrated with the proposed actuator and I/Q heterodyne interferometer is implemented. The characteristics of the proposed actuator and measurement system are evaluated with a commercial laser interferometer.

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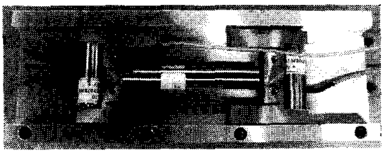
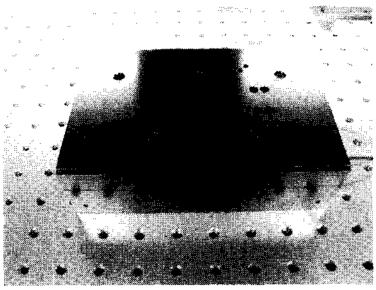
2. Proposed Inchworm Motor

2.1 Design of a new inchworm type actuator

The motions of inchworm motor consist of clamping motions and extraction/contraction motions. Figure 1 shows the developed inchworm actuator and stage in which the actuator is integrated.



(a) The developed actuator



(b) Stage in which developed actuator is integrated

Fig. 1 The developed actuator and stage

It has two clamping parts on the left and right side of actuator body, and one extraction/contraction part in the middle of the actuator. The principle of the moving the stage to the right is as follows. First, the piezo actuator for clamping at the left is activated, and piezo actuator for extracting in the middle of the actuator extends to push the stage to the right. When the actuator is extracted to its maximum length, the right clamp actuator is activated, the left clamp actuator is deactivated, and the extraction/contraction actuator is deactivated. So the actuator returns to the initial length. Long stroke can be accomplished by repeating the action of the above sequence, and high resolution can be attained by the accurate displacement of the extraction/contraction motion. By reversing the sequence, actuator moves to the left.

Motions of inchworm actuator consist of the series of discrete N motions, and then speed of inchworm actuator S is given as equation (1).

$$S = \frac{\sum_{i}^{N} d_i}{\sum_{j}^{N} t_j} \quad (1)$$

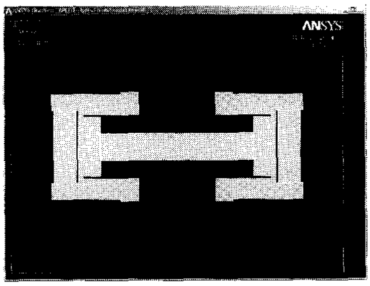
d_i : travel of i-th motion (zero for clamping motion)

t_j : time required to complete j-th motion

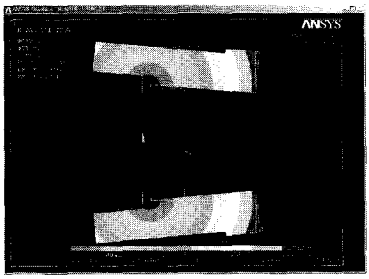
So, design rule to increase the speed of actuator is as follows.

1) Increase the travel length through one cycle.
2) Decrease the time required to complete each motion.
3) Decrease the number of steps to be required to complete one cycle.

Fig. 2 shows the mechanical analysis of actuator body. Each clamping actuator has displacement amplification mechanism which increases the displacement about three times. It fixes actuator firmly to the base frame. The maximum displacement of the extraction/contraction actuator is up to 45 micrometers.



(a) Actuator body



(b) Clamping part

Fig. 2 Mechanical analysis of actuator body

Table 1 shows performance comparison between the developed actuator and a commercial inchworm actuator (Expo's IW-800).

2.2 State machine-based controller

A state machine for the developed inchworm actuator is shown in Figure 3, and the block diagram of a controller for the proposed inchworm motor is shown in Figure 4. The 'speed curve generator' block in Figure 4 has a role to generate the speed curve, according to the speed setting. The 'clamping logic' block is the state machine which has role to change the clamping state, and 'PID controller' block, which is activated only in the control phase of Figure 3, generates control output according to the PID control rule as equation (2). A PID controller is known to be robust to the hysteresis and drift of piezo electric actuator.[8,9]

$$V = K_p \cdot (Pcom - P) + K_I \cdot \int (Pcom - P) \qquad (2)$$

V : Output voltage

K_P, K_I: Proportional, Integral gain

P_{com} : Position command

P : Current position

The controller has hysteresis region at the end of linear region as shown in Figure 5, in order to prevent the repetition of forward-backward clamping motion by small disturbance at the moment of clamping action.

Table 1 Performance comparison of the proposed inchworm actuator and a commercial inchworm actuator (experimental results)

Resolution	
Developed actuator	50 nm, with interferometer
Commercial actuator	500 nm, with encoder
Maximum Speed (Unloaded)	
Developed actuator	10.2 mm/s
Commercial actuator	1.5 mm/s
Output force	
Developed actuator	10 N
Commercial actuator	10 N
Stroke	
Developed actuator	100 mm
Commercial actuator	50 mm

Commercial actuator : IW-800 (Expo)

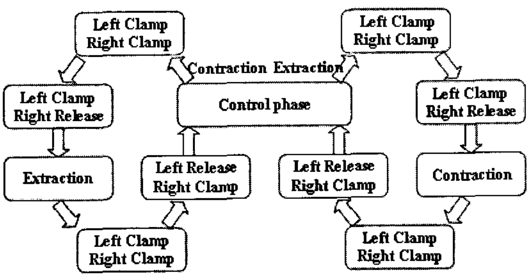


Fig.3 A state machine for clamping logic

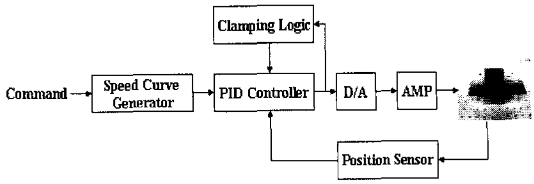


Fig. 4 A block diagram of the controller

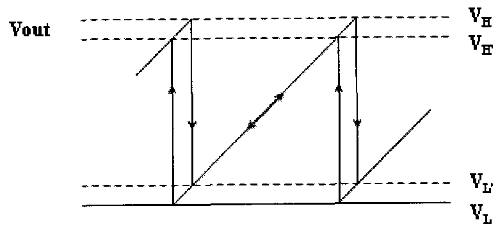
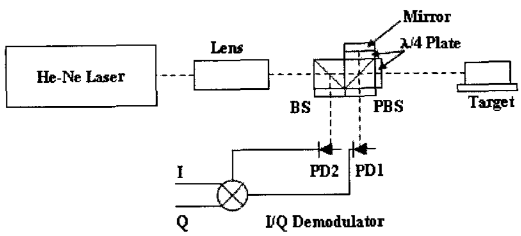


Fig. 5 Controller output

3. Measurement system for a fast moving stage

3.1 He-Ne Heterodyne interferometer using I/Q demodulator

The block diagram of the measurement system proposed by Cho[10], co-worker of this research, is shown in Fig. 6. It uses a He-Ne laser which has dual frequency and dual polarization.



BS : Beam Splitter

PBS: Polarization Beam Splitter

PD : Wide bandwidth photodiode

Fig. 6 Block diagram for measurement system

The reflected beam at BS (Beam Splitter) is reference beam and the reflected beam with λ/2 phase shift at PBS (Polarization Beam Splitter) is signal beam. Each beam is detected by photodiode, and wideband I/Q demodulator converts detected signals to in-and-quadrature signals. Phase of these signals, ΔΦ, is detected by A/D conversion of a wideband I/Q-demodulator output signals, and phase difference can be obtained as equation (3).

$$\Delta\Phi = \tan^{-1}(\frac{V_Q}{V_I}) \quad (3)$$

Fig. 7 shows the spectrum of this phase signal, and S/N ratio is about 39dB, and it indicates that it can measure with 1 nano meter resolution even if noise exists.

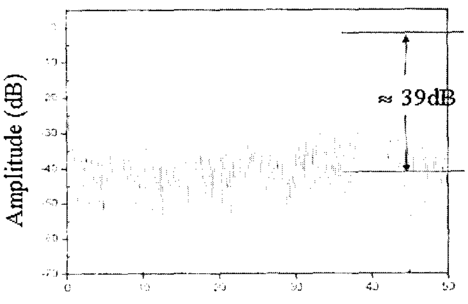


Fig. 7 Spectrum analysis with 2 phase signals which are located at 20 and 40 Hz

3.2 New measurement technique

The inchworm actuator clamps the stage frame at the moment of clamping motion, and it brings some vibration on the stage body and mirror. Figure 8 shows vibration measured on the stage body with an accelerometer, and rapid change of position brings the phase ambiguity with conventional A/D conversion method unless sampling frequency is very high.

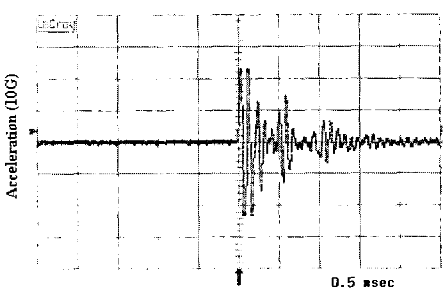


Fig. 8 Vibration measured on stage body

To implement a robust sensor system, a new synchronized counting method was devised. An interface circuit is shown in Fig. 9. 90° phase different logic-level signal is inputted to a counter as proposed by Yim[11], except digitized wideband I/Q signal is used instead of low pass filtered signal. In addition, quadruple phase counter is used, and the counter latch signal and A/D conversion ignition signal are synchronized. Because of asynchrony of counter reading and A/D conversion, Yim used dual mode, fine resolution mode with A/D conversion at low speed and coarse resolution mode with pulse counting at high speed. But the cutoff speed was very low, a few millimeters per second, so it brought discontinuity of measurement accuracy. To reduce the effect of asynchrony, a synchronized counter latch is used. The start signal triggers the latch in the middle of trace time of the A/D conversion.

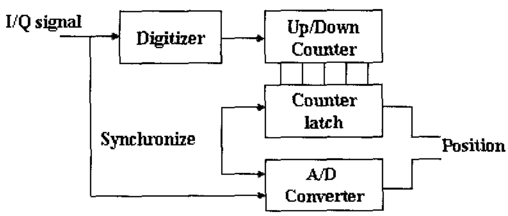


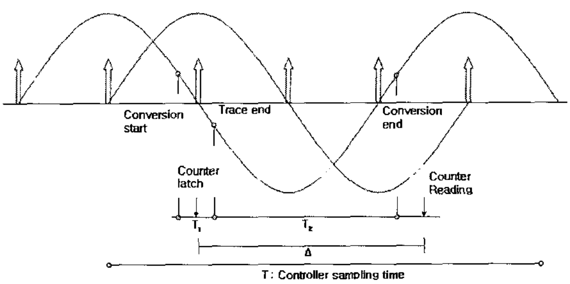
Fig. 9 Block diagram for measurement system interface circuit

Then, the position is obtained by equation (4).

$$position = (\frac{latched\ \ count}{4} + \frac{\Delta\Phi}{2\pi}) \times \frac{\lambda}{2} \quad (4)$$

λ: wave length

A typical A/D conversion process is shown in Figure 10,



T_1 : trace time T_2: conversion time

T : controller sampling time

Δ : asynchronous time

Fig. 10 Time chart for an I/Q signal and A/D Conversion

With above timing chart, the mean measurement error is shown in Figure 11 where knee point is about 20mm/s with our circuitry.

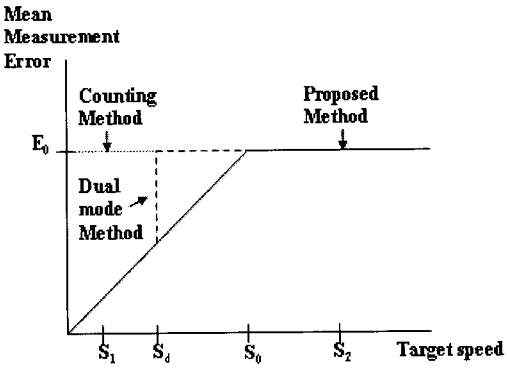


Fig. 11 Mean measurement error with respect to target speed

Each point is given as:

$$E_0 = \frac{\lambda}{16}$$

mean measurement error of the pulse counting method,

$$S_0 = \frac{\lambda}{16T_2}$$

approximate maximum target speed where the proposed method is preferable,

$$S_1 = \frac{\lambda}{4T}$$

cutoff speed at which ambiguity occurs with the A/D conversion method,

$$S_2 = \frac{\lambda}{8T_1}$$

cutoff speed at which ambiguity occurs with the proposed method, and

$$S_d = \frac{\lambda}{4\Delta}$$

cutoff speed of the dual mode method
where, Δ is time between asynchronous counter reading and A/D converter reading

4. Experiments

An experimental servo system consists of the developed linear stage, I/Q heterodyne interferometer as a position sensor, and a commercial interferometer as shown in Figure 12. The commercial interferometer, which was used for performance evaluation, had resolution of 9.8 nm, and sampling time of the controller was 50 micro seconds.

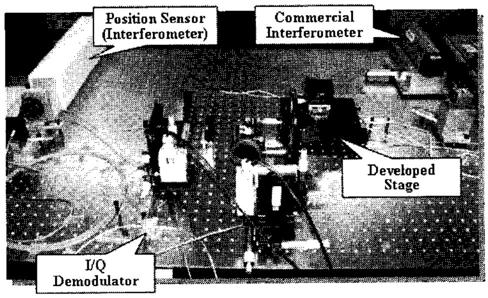


Fig. 12 Experimental servo system

Fig. 13 shows a measured position of objects, which are moving with 10 mm/s and 20 mm/s speed. With the conventional A/D conversion method and 50 micro seconds sampling, the position of object which moves only up to 3.3 mm/s can be measured. Either the proposed method or the dual mode method could measure the position up to a few meters per second without phase ambiguity[11].

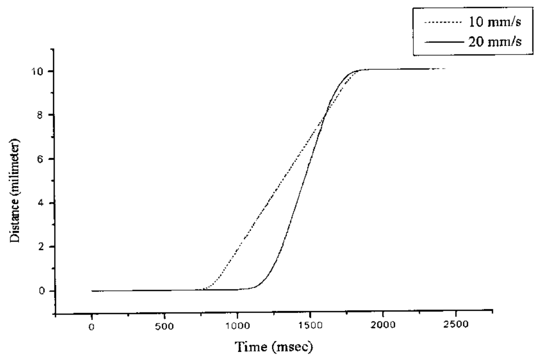


Fig. 13 Position measurement of fast moving object (With I/Q interferometer)

Fig. 14 shows an experimental result of 50 nanometer-step position control with I/Q heterodyne interferometer feedback, and it shows the accuracy of servo system is within 50 nanometers. Figure 15 shows an experimental result of long-stroke position control, which carries with clamping motions, and it shows that there is no accumulation of positional error due to the phase ambiguity which comes from actuator vibration at the moments of the clamping motions.

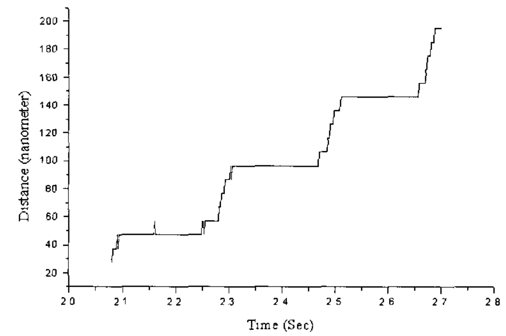


Fig. 14 Short-stroke position control (With commercial interferometer)

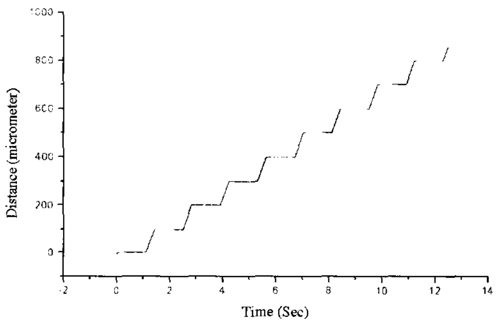


Fig. 15 Long-stroke position control (With commercial interferometer)

5. Conclusions

New inchworm type precision actuator which moved with nano-meter level positional accuracy and high speed was devised. Devised actuator was integrated into a stage, so it was easy to make the stage frame more compact. Developed actuator moved up to 10mm/s and produced 10N as output force. To measure the position with inexpensive circuitry and with less computational burden, and to overcome the phase ambiguity problem, a synchronized counting method with I/Q heterodyne interferometer was proposed. Servo system, which is implemented with I/Q heterodyne interferometer and state machine-based PID controller, showed accurate positioning. Developed servo stage will be applied to an optical device assembly system.

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