

# Control method for pushpull type piezo-driven linear motion stage with smooth motion, long travel range and high resolution

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## Abstract

This paper presents new control methods to reduce vibration errors, which occur in clamping operation. Firstly, optimal clamping force is adjusted experimentally. Secondly, optimal control parameters of PID control are determined using a genetic algorithm. The new parameters are compared with ones from the conventional method. Finally, a power supply procedure for feed and clamp actuators is proposed and tested to reduce interference between push-pull feed motion. The proposed methods improve the vibration errors significantly.

**Key words:** Piezoelectric actuator, Smooth motion, Nanometer, Inchworm, PI control, Genetic Algorithms.

## Introduction

Development of precision measurement/ control technology in the Precision Engineering has made an ultra-precision positioning whose displacement resolution is 0.1 nm since 1990s [1]. Relative uncertainty to quantitatively show density between resolution and stroke range is expressed to ratio of resolution and stroke range. Nowadays, an attained uncertainty level in the Precision Engineering exists in the range of  $10^{-3}$  and  $10^{-6}$ . It is real condition that Precision Engineering of the  $10^{-9}$  uncertainty (BUPE: Billionth Uncertainty Precision Engineering) is urgently required [2]. Therefore, it is required the stage that has a high resolution and long stroke range. In order to realize this requirement, many types of control methods have been introduced so far. For example, friction drive, ball screw, dual servo type and inchworm type are representative. Inchworm type is ultra feed device that overcome the limited displacement in combination with fine displacement of PZT and motion apparatus. This type is controlled by electrostatic clutch mechanism to improve motion controllability and force transmission. This paper has developed a pushpull type linear motion stage that is composed of two clamp and two feed actuators. The newly developed stage provides continuous motion, but vibration error still exists during clamping and feeding operations [3]-[6].

This paper presents new control methods to reduce the vibration error. At first, the optimal control parameters of PID control are determined through the Genetic Algorithm, and compared with the conventional method. Secondly, the optimal clamping force is applied that affects strongly on the residual vibration. The suggested methods improved the vibration error significantly.

## Pushpull type motion stage

Existing inchworm stage that is composed of one feed piezo actuator and two clamp actuators is not continuous but stepwise.

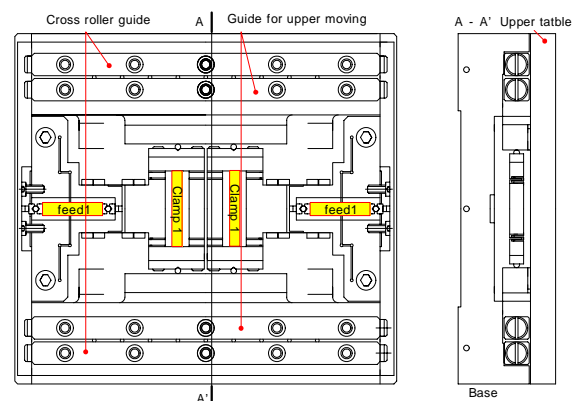


Fig. 1 Inner side of inchworm stage

In order to overcome, authors have developed a pushpull type linear motion stage that is composed of two clamp and two feed actuators. The inner side of pushpull stage is indicated in Fig. 1.

### Principle of stage motion

The two clamp piezo actuators (clamp1, clamp2) are linked with the outer two feed piezo actuators (feed1, feed2) with lateral symmetrical fashion. Each piezo actuator is fixed on the base. The moving part is clamped on the clamp piezo actuators, and actuated by the feed piezo actuators along the guide. The operation procedure includes simultaneous extending and shrinking of the two feed piezo actuators in opposite polarities in cooperation with clamping and unclamping action of the clamp piezo actuators. The pushpull stage is actuated by motion of 6 steps in 1 cycle. The cyclic repetition enables the moving table to move long stroke range with smooth and continuous fashion, theoretically.

The principle of stage driving is indicated in Fig. 2. **Step 1:** Clamp 1 and Clamp 2 PZTs are clamped, and Feed 1 and Feed 2 keep half elongation. **Step 2:** Clamp 1 unclamps and the moving table is moved by shrink of Feed 2. **Step 3:** Feed 1 shrinks immediately and Feed 2 continues to shrink. **Step 4:** Clamp 1 clamps the moving table, and Feed 1 extends. The Clamp 2 unclamps. **Step 5:** Feed 2 extends immediately. **Step 6:** Clamp 2 clamps, and the moving table is moved by extension of Feed 1 and shrink of Feed 2.

At here, extension of Feed 1 and shrink of Feed 2 provides Push and Pull motions, respectively. Through these repeated motions, the stage moves continuously [7].

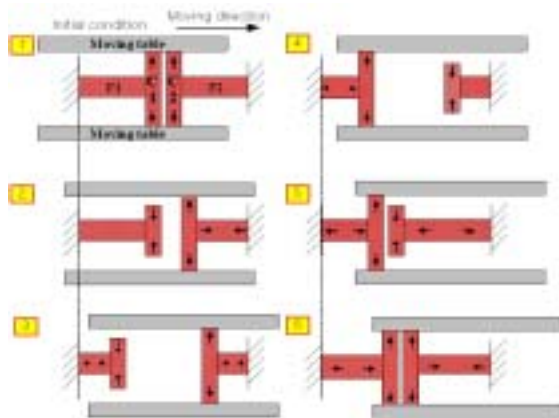


Fig. 2 Principle of Pushpull drive

### Optimal PID parameters

The population is typically chosen over 30, sometimes over 1000. The lower boundary of a

population size that guarantees with 95% probability, that allele loss does not occur in the first generation, is 10[8]-[10]. Crossover rates should be kept high, generally between 0.7 and 0.9, since recombination produces highly fitted chromosomes that are different from their parents, yet retain some of their parents' characteristic. A high probability of mutation rate may increase population diversity, but will decrease average population fitness, hence typical mutation rates range from 0.01 to 0.05[11]-[13].

The procedure of the control loop indicated in Fig. 3 is as follow:

**Step 1:** Initial population about each gain  $K_p$ ,  $K_i$ , and  $K_d$  is provided randomly. At here  $y(t)$ ,  $M_{ps}$ , and  $T_s$  represent input, overshoot, and settling time respectively.  $r$  and  $y$  mean reference input and output of plant respectively.

**Step 2:** The gotten population is given to the system, and  $y(t)$ ,  $M_{ps}$ , and  $T_{sy}$  are received. And then the response is calculated by the system reference.

**Step 3:** New population of string about PID gains is given and converted into decimal number.

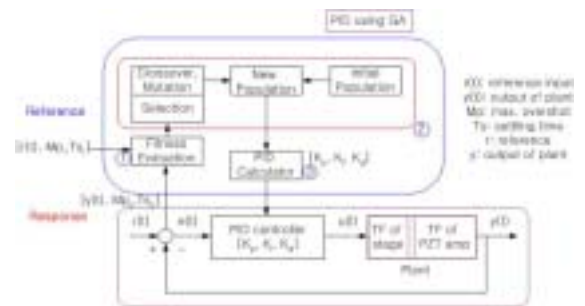


Fig. 3 PID control loop for Genetic algorithm

This cycle is repeated as much as generation number. Plant is given by the transfer functions of stage and PZT amp that are obtained from experiment. The transfer functions of stage and

$$G_{sig} = \frac{1.3}{1.3s^2 + 247s + 3.9 \times 10^6} \quad \text{and}$$

$$G_{amp} = \frac{7.5}{0.88 \times 10^{-3}s + 1}$$

Using this Genetic Algorithm, it could be determined the PID parameters such as  $K_p=0.15$ ,  $K_i=100$ , and  $K_d=0$ . Fig. 4 shows the comparison between the new results and the existing one.

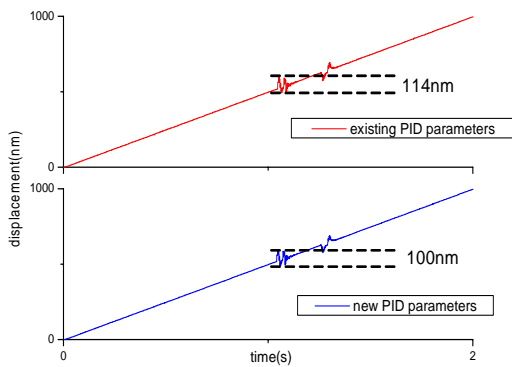


Fig. 4 Comparison results between existing and calculated PID gains

From the result, it could be reduced clamping vibration from 114nm to 100nm using PID parameters got from genetic algorithm.

### Optimal clamping voltage

Clamping actuations are considered as major existing sources in the pushpull operations. Fig. 5 shows a clamping mechanism design. Clamping is achieved by PZT extension through the ball contact.

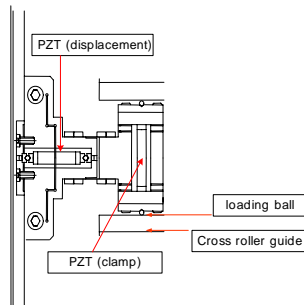


Fig. 5 Clamping mechanism design

The optimal clamping force not only provides rigidity appropriately but minimizes vibration excitation. To investigate the optimal input voltage of PZT, the resonant frequency of the displacement according to the clamp voltage was observed. As shown in the Fig. 6, sweep sign signal is provided to the Feed 1 PZT via function generator while the clamping voltage to the clamping 1 PZT. The signal was changed from 0.1 Hz to 1000 Hz for 15 sec with amplitude of 5V for each clamp voltage, which was changed from 40V to 150V. The displacement of stage was measured by the laser interferometer during those operations.

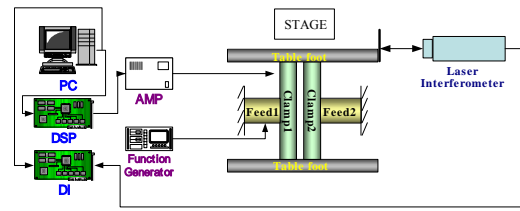


Fig. 6 Schematic of experimental equipment

Using the displacement measurements, it could be obtained the corresponded resonant frequency of each clamping voltage. And then relationship between this natural frequency and real vibration error was compared when the clamping voltage is changed. Fig. 7 illustrates about the relationship.

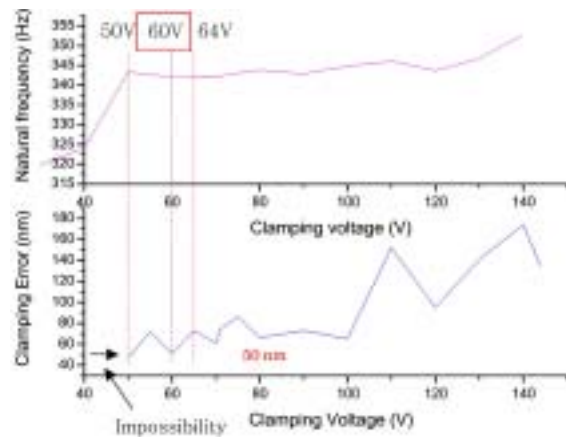


Fig. 7 Natural frequency and measured real error about each clamping voltage

As indicated in Fig. 7, the resonant frequency almost converged over 50V.

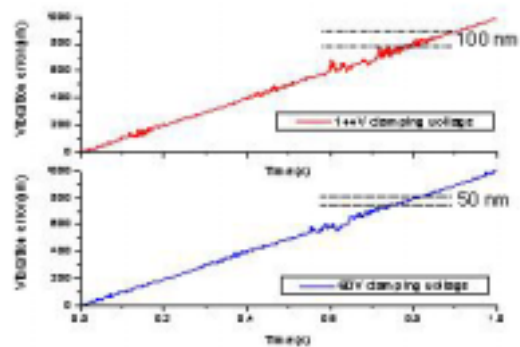


Fig. 8 Comparison of vibration error due to clamping voltage

It indicates that 50V is enough for the clamping rigidity to provide the feed actuation of the stage. On the consideration of stable clamping, the optimal voltage was applied 60V for this stage.

As a result, the vibration error was reduced from 100nm to 50nm by applying the optimal

clamp voltage. The results are compared in Fig. 8.

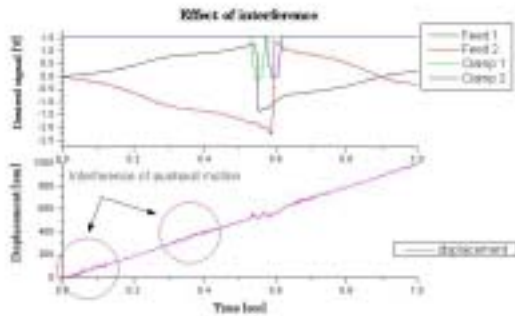


Fig. 9 Existing driving signal

As indicated in Fig. 9, existing signal has the interference during pushpull motion. In order to overcome this problem, this paper presents new driving signal which remove the interference of pushpull motion.

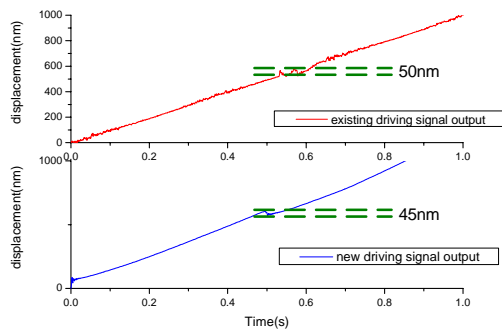


Fig. 10 Results about existing and new driving signal

Fig.10 shows the results of each driving signal. Through the comparison of each result, it is verified to the superiority of new driving signal.

## Conclusion

In order to reduce clamping vibration, this paper presents new control methods. At first, the optimal control parameters of PID control are determined through the Genetic Algorithm, and compared with the conventional method. Secondly, the optimal clamp voltage was determined by examining the rigidity of feed stage. Finally, the interference during pushpull motion is removed using the new driving signal. Consequently, the vibration error was decreased to 45nm.

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