Development of compact high precision linear piezoelectric stepping positioner with nanometer accuracy and large travel range

Dongwoo Kang[a)]
Nano-Opto-Mechatronics Laboratory, Department of Mechanical Engineering, KAIST, 373-1 Guseong-Dong, Yuseong-Gu, Daejeon 305-701, Korea

Moon G. Lee
Division of Mechanical Engineering, Ajou University, San 5 Wonchu-Dong, YeongTong-Gu, Suwon 443-749, Korea

Daegab Gweon
Nano-Opto-Mechatronics Laboratory, Department of Mechanical Engineering, KAIST, 373-1 Guseong-Dong, Yuseong-Gu, Daejeon 305-701, Korea

(Received 19 March 2007; accepted 17 June 2007; published online 18 July 2007)

Many application areas such as semiconductor manufacture, precision optics alignment, and microbiological cell manipulation require ultraprecision positioning systems with a high positioning resolution and large motion range. This article describes the development of a compact high precision linear piezoelectric stepping positioner for precision alignment of optical elements. The positioner is designed to have a compact and symmetric structure, high positioning resolution, large motion range, high force density, adequate dynamic range, and power-off hold. The positioner is fabricated according to these specifications and performance evaluation tests are carried out. A resolution of 10 nm, speed of 1 mm/s, push force of 25 N, and stiffness of 10.4 N/μm are attained while maintaining a compact size of $32 \times 42 \times 60\ mm^3$. The required power consumption is 52.33 W. The test results confirm that the developed positioner could be successfully applied to the precision alignment of optical elements. © *2007 American Institute of Physics.*
[DOI: 10.1063/1.2756627]

I. INTRODUCTION

In many cases, the quality in areas such as semiconductor manufacture, precision optics alignment, and microbiological cell manipulation depends on the positioning capability of ultraprecision positioning systems. These applications frequently require a positioning system that can deliver nanometer level resolution while maintaining other positioning characteristics such as large motion range, high force capacity, high speed, quick response, high stiffness, compactness, and wide dynamic range, as well as low power consumption.[1] One example is the x-ray microscope, which can be employed for the imaging of biological, medical, and colloidal samples due to its higher resolution and the natural mechanism that contrasts water with carbon-based substances.[2] To obtain an x-ray microscope image, the optical elements must be aligned very accurately in the designed position[3] and precision alignment stages are required for this work. The present work focuses on the development of a stage suitable for precision optics alignment.

Recently, many kinds of precision positioning systems have been reported. The first is a dual servo system composed of a coarse servo responsible for long range motion and a fine servo responsible for micromotion of high resolution. For the fine servo, the piezoelectric actuator has seen frequent use.[4,5] A piezoelectric actuator possesses many characteristics suitable for ultraprecision positioning, such as theoretically unlimited resolution, large force generation, high stiffness, fast response, low power consumption, and no wear. However, its application area is restricted within micromotion due to its limited displacement. As a coarse servo, several actuators such as a dc motor,[6] ball screw, voice coil motor (VCM)[7] and linear motor[8] can be used. Based on distributing work between two servo systems, the dynamic range and positioning accuracy can be improved. However, because the dual servo type requires secondary position sensing and control, the system is bulky and the control algorithm is complex. Single servo systems, meanwhile, such as hydrostatic leadscrews,[9] electric motors,[9,10] and piezoelectric motors, provide an alternative approach.[11,12] Hydrostatic leadscrews have the capability of nanometer resolution, high stiffness, and large force generation, thereby solving problems related to conventional leadscrews such as stick-slip and lost motion. However, they require high cost and complexity. Electric motors such as a VCM, Brushless DC-type motor, a Halbach-type motor, and so on are capable of nanometer resolution with a simple drive principle. However, because they must supply current successively to maintain position, they may generate significant electrical disturbances. The most promising alternative is piezoelectric linear motors. In the piezoelectric motor, microscopic small motion induced by piezoelectric actuators is transferred to macroscopic linear motion through frictional force. Due to charac-

[a)]Author to whom correspondence should be addressed; FAX: +82-42-869-5225; electronic mail: dwkang@kaist.ac.kr

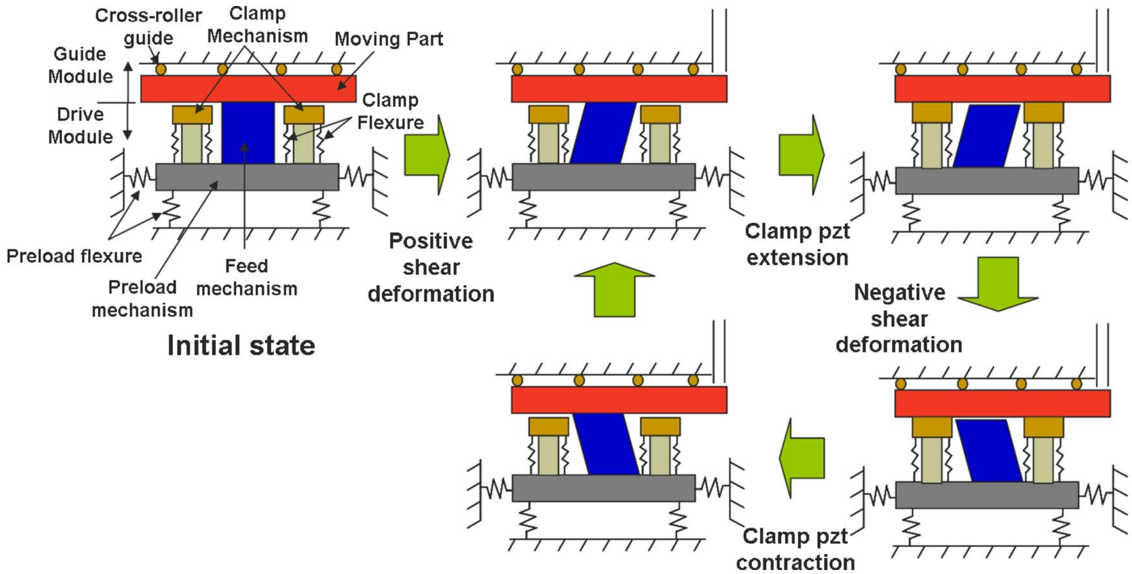

FIG. 1. (Color online) Concept and operation principle of proposed linear piezoelectric stepping positioner.

teristics such as high positioning accuracy, simple structure, high force density, direct drive, high holding forces without power supply, absence of magnetic fields, and wide dynamic range, piezoelectric motors are suitable for many precision applications.

Piezoelectric motors can be roughly divided into two classes.[11,13] The first class is ultrasonic motors that use ultrasonic vibration resulting from the ac characteristics of the piezoelectric actuator. The elliptical motion at the tip of the piezoelectric device is transmitted to a slider through frictional force. Several vibrators were developed to improve efficiency, positioning accuracy, and output force.[11,12,14–18] While ultrasonic motors are capable of fast and continuous motion, they are not suitable for low-speed positioning. Furthermore, they require high power electronics and cannot support large loads. The second class is piezoelectric motor devices that utilize the well known dc characteristics of piezoelectric actuators. These types of motors have the characteristics of relatively large output force, high force density, high stiffness, and accurate motion. However, the maximum speed is lower than a few mm/s in most cases. The inchworm motors[1,19–25] and walking drive[13,26] belong to this class. Inchworm motors usually use two clamp piezoelectric actuators and one feed piezoelectric actuator. These three piezoelectric actuators are controlled so as to generate a microstep for each cycle and the repeated cycles can generate large motion via the accumulation of microsteps. However, their motion is generally discontinuous. For the generation of continuous motion, walking drive motors are driven in a similar manner to the walking motions of animals.

In this article, a piezoelectric motor utilizing the dc characteristics of a piezoelectric actuator for precision optics alignment is employed. Because the objective of this article is the development of a nanometer accuracy optics alignment stage, positioning accuracy and in-position stability are the most important factors. From this point of view, a dc-type piezoelectric motor having high stiffness is the most promising candidate. Furthermore, its high force density is suitable for reducing the size of stage.

II. DEVELOPMENT OF PIEZOELECTRIC LINEAR STEPPING POSITIONER

A. Operation principle

A novel linear piezoelectric stepping positioner mechanism is proposed. This positioner is developed to have high force density and a symmetric and compact structure. The concept and operation principle of the proposed piezoelectric stepping positioner are presented in Fig. 1. It is comprised of two modules, a motion guide module and a piezoelectric drive module. A conventional precision cross-roller guide having high off-axis stiffness is used as the motion guide module. The drive module is composed of one feed mechanism (FM), two clamp mechanisms (CMs), and a preload mechanism (PM). FM uses the shear deformation of the piezoelectric actuator. The micromotion generated by the FM is transferred to the moving part via frictional force at the contact interface of the two modules. The contact state at the interface is controlled by the CMs, which use the extension deformation of the piezoelectric actuator. The moving part is initially contacted with the FM and driven by the FM. If the CMs are extended, the moving part contacts the CMs and the motion of the FM is not transferred to the moving part. Because the CMs are driven by the same signal, the proposed positioner needs only two drive signals, thus making the system simpler and cheaper. The PM used to apply the normal force for friction is designed such that the magnitude of the preload is adjustable. The drive module and motion guide module are always in contact with each other, and thus the drive module is capable of holding the position of the moving part without a power supply.

The proposed piezoelectric stepping positioner is operated via the following sequence. A small motion per each

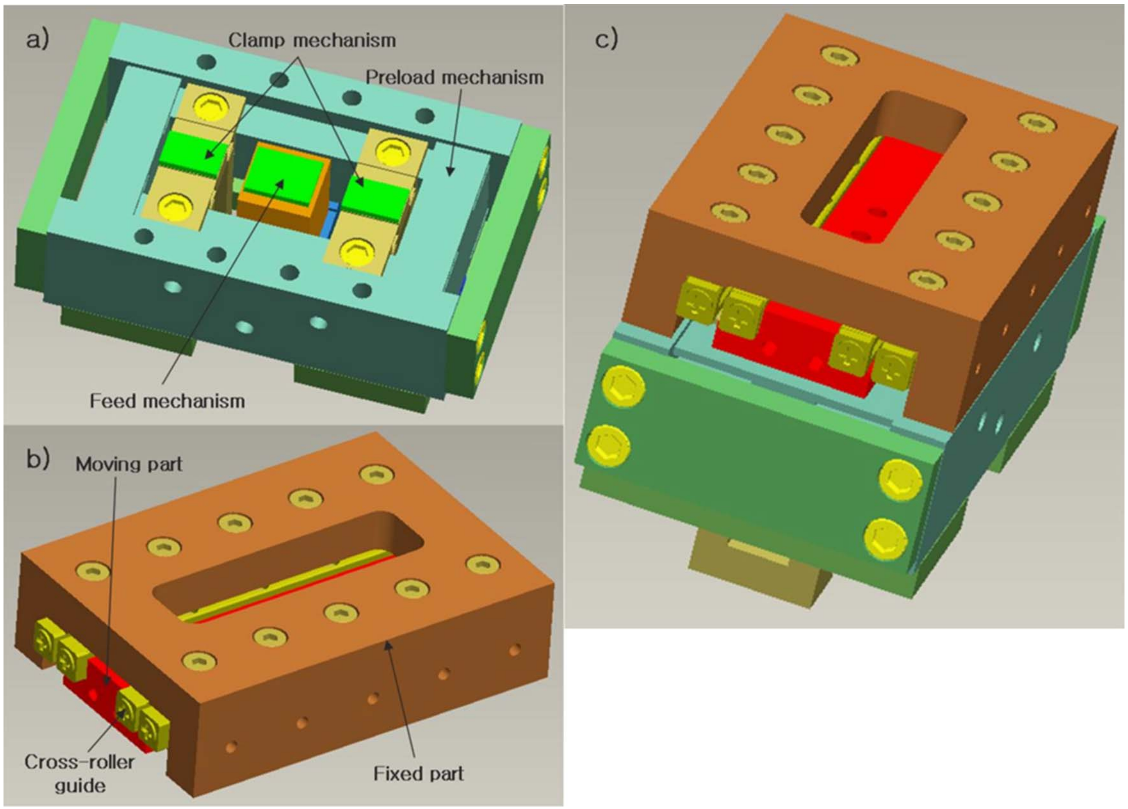

FIG. 2. (Color online) Conceptual design of linear piezoelectric stepping positioner: (a) drive module, (b) guide module, and (c) total system with two modules assembled.

cycle is transferred to the moving part and the repeated cycle can generate large motion.

(1) Initial state
When no power is applied, the moving part is in contact with the FM.
(2) Positive shear deformation of FM
The positive shear deformation of the FM is transferred to the moving part via frictional force and the moving part is moved in the positive direction with the FM.
(3) Extension of CMs
When the CMs are extended, the moving part contacts the CMs and the motion of the FM is no longer transferred to the moving part.
(4) Negative shear deformation of FM
The negative voltage applied to the FM generates negative deformation of the FM. However, this deformation is not transferred to the moving part, because the moving part is in a state of contact with the CMs.
(5) Contraction of CMs
When the voltage applied to the CMs is removed, the CMs contract to their original length and the moving part once again comes into contact with the FM.
(6) Positive shear deformation of FM
The positive shear deformation of the FM is transferred to the moving part via frictional force.

Steps 2–6 make one cycle and the cycle is repeated to obtain large motion. Reverse motion can be obtained by reversing the signal of FM. The speed of the moving part can be controlled by adjusting the shear deformation of one step and the frequency of cyclic operation.

B. Design and fabrication

The concept described above is realized as shown in Fig. 2. The structure is designed symmetrically to have the same characteristics in both positive and negative motion directions. Figure 3 shows the FM. A shear mode piezoelectric actuator, P-141.10 (Physik Instrumente GmbH & Co. KG), is

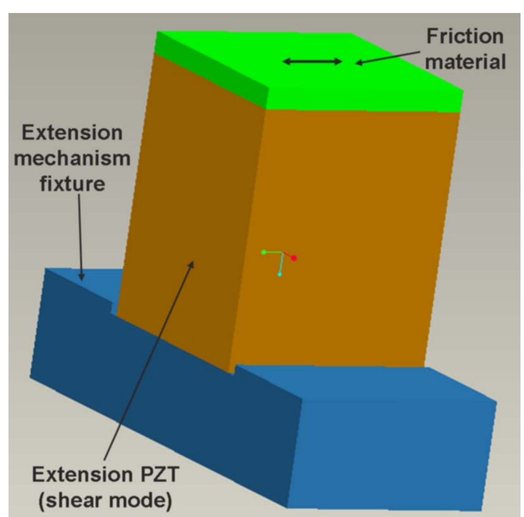

FIG. 3. (Color online) Feed mechanism of linear piezoelectric stepping positioner: a shear mode piezoelectric actuator is used.

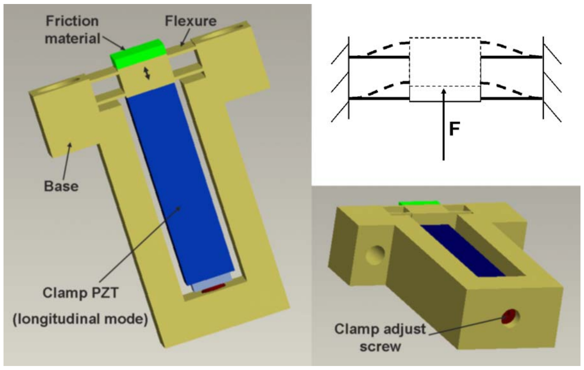

FIG. 4. (Color online) Clamp mechanism composed of a longitudinal mode piezoelectric actuator and a flexure.

used as the feed actuator and it drives the moving part directly without any special apparatus. Shear deformation can be obtained by applying the electric field perpendicularly to the poling direction, while longitudinal deformation is generated by an electric field parallel with the poling direction. The FM is related to the moving speed as given in the following equation:

$$v = d_{1\ \mathrm{step}} \times f_d, \tag{1}$$

where v is the speed of the positioner, $d_{1\mathrm{step}}$ is the displacement per cycle, and f_d is the drive frequency. Because the maximum value of $d_{1\mathrm{step}}$ is 10 μm, the maximum stroke of the selected feed piezoelectric actuator, a drive frequency of 100 Hz can produce a speed of 1 mm/s. As the drive frequency is increased, the speed is increased. However, increased speed results in greater power consumption and increase of cost. Therefore, the positioner is designed to have a maximum speed of 1 mm/s and the drive frequency is set to 150 Hz, considering the discrepancy in the stroke of a real feed piezoelectric actuator and the safety margin.

Figure 4 shows a CM composed of a longitudinal mode piezoelectric actuator and a flexure. The flexure guides the motion of the piezoelectric actuator and prevents the piezoelectric actuator from failing by shear force or the bending moment generated by an external load. However, the flexure reduces the stroke of the piezoelectric actuator. The actual stroke of the flexure guided piezoelectric actuator is expressed by the following equation:

$$l = \frac{k_p}{k_p + k_s} l_p, \tag{2}$$

where k_p is the stiffness of the piezoelectric actuator, k_s is the stiffness of the flexure, and l_p is the stroke of the piezoelectric actuator. Therefore, the flexure must be designed to be flexible enough along the longitudinal direction of the clamp piezoelectric actuator so that the stroke of the clamp actuator can be generated efficiently. The stroke must be larger than the sum of the roughness of the contact surface and the lost motion caused by the ductility of the contact surface and other uncertainties in order to obtain stable change of the contact state at the interface. In addition, its resonant frequency must be much higher than the drive frequency in order to avoid resonance at the maximum speed and the maximum stress generated by the deformation of the flexure must be maintained below the yield stress of the flexure material.

In order to satisfy the above requirements, a finite element microscopy (FEM) simulation (Pro/Engineer and Pro/Mechanica Software) was conducted. An AE0505D16 (NEC TOKIN Corp.) was selected as the clamp piezoelectric actuator and the clamp flexure were designed to have a stiffness of 2.04 N/μm, a resonant frequency of 6.57 kHz, a maximum displacement of 16.7 μm, and a maximum stress of 114 MPa. The flexure is made of Al 7075-T6. A clamp adjust screw is used for adjusting the height against the FM and controlling the contact condition efficiently.

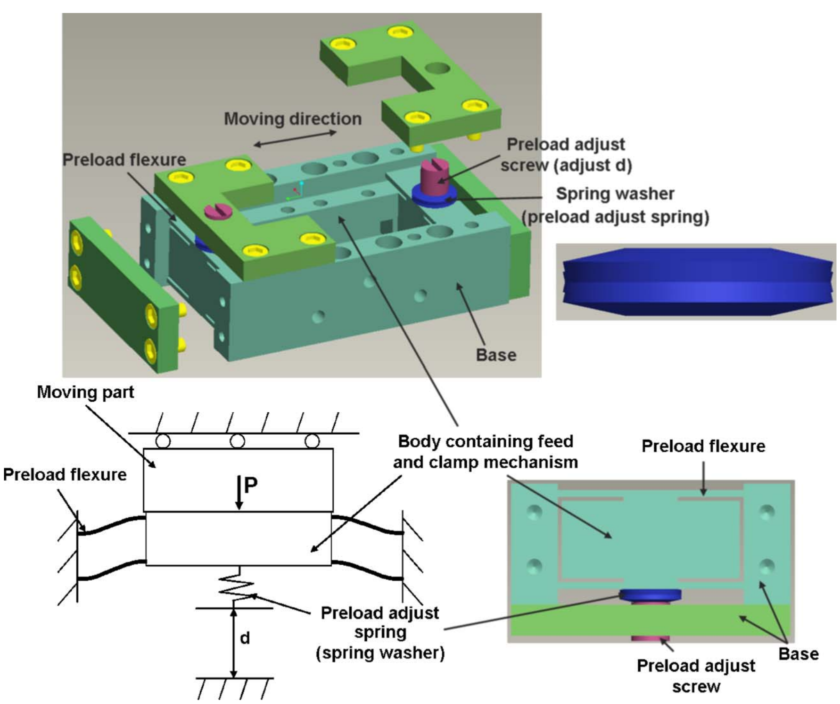

FIG. 5. (Color online) Proposed adjustable preload mechanism: As d is changed, the preload can be adjusted.

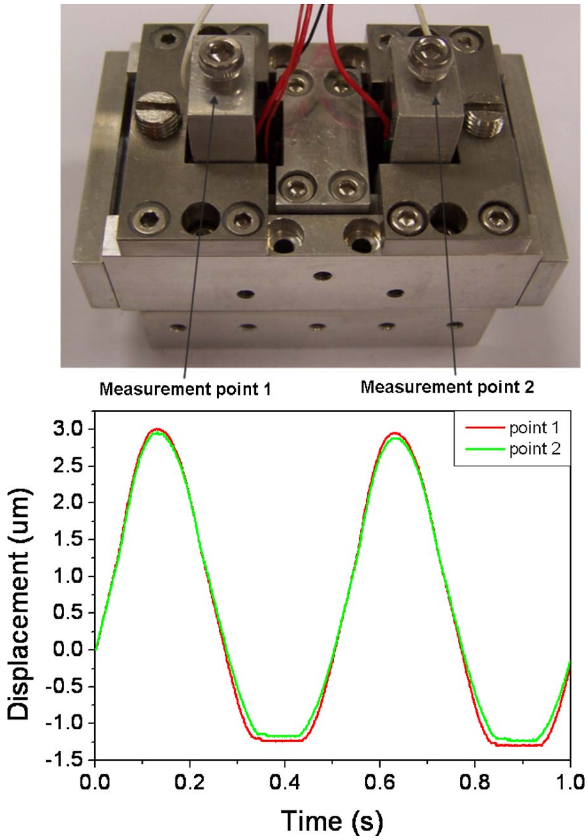

FIG. 6. (Color online) Adjustment of the developed piezoelectric stepping positioner: gaps of FM and CM against the moving part are adjusted so that only FM can be contacted with the moving part.

The PM to adjust the frictional force at the contact interface is presented in Fig. 5. The frictional force can be changed by adjusting the normal force at the contact interface. For this purpose, a Belleville disk spring and an adjust screw are used. There are also constraints over the resonant frequency and the maximum stress such as the clamp flexure. The stroke must be larger than the tolerance of the gap between the two modules at the contact interface. In addition, the preload flexure must be designed to have a large off-axis stiffness except in the preload direction, because the load is supported through this mechanism. The preload flexure was

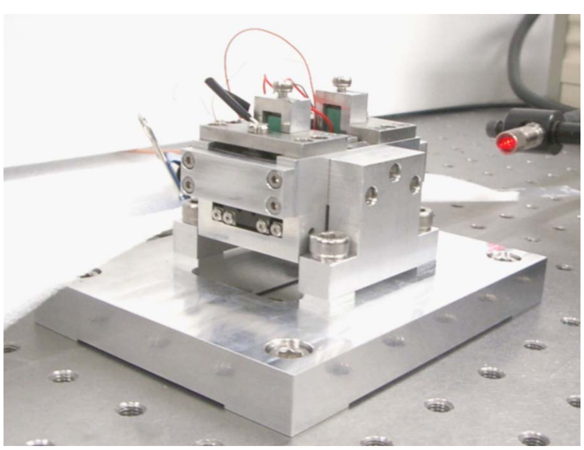

FIG. 7. (Color online) Experimental setup for performance evaluation of developed piezoelectric stepping positioner.

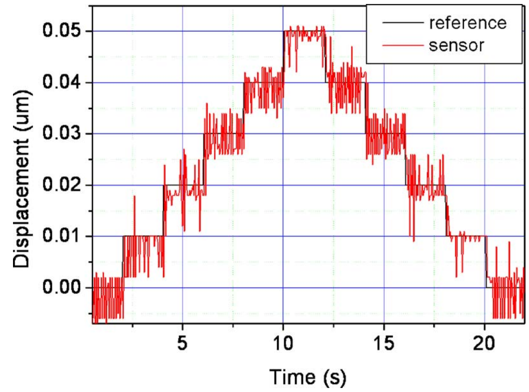

FIG. 8. (Color online) 10 nm step control.

designed through a FEM simulation and it has a preload direction stiffness of 4.95 N/μm, a resonant frequency of 1.57 kHz, and a maximum stress of 180 MPa at a deformation of 50 μm. The maximum preload is calculated by the following equation:

$$P_{\max} = 2F_{ds,\max} - k_{s,p} d_g, \tag{3}$$

where $F_{ds,\max}$ is the force of the disk spring at maximum deflection, which is limited to 75% in order to avoid sharply increasing the force and stress characteristics, $k_{s,p}$ is the stiffness of the preload flexure, and d_g is the maximum tolerance of the gap between the two modules. $F_{ds,\max}$ is given in the datasheet of Ref. 27 and the maximum allowable d_g is as-

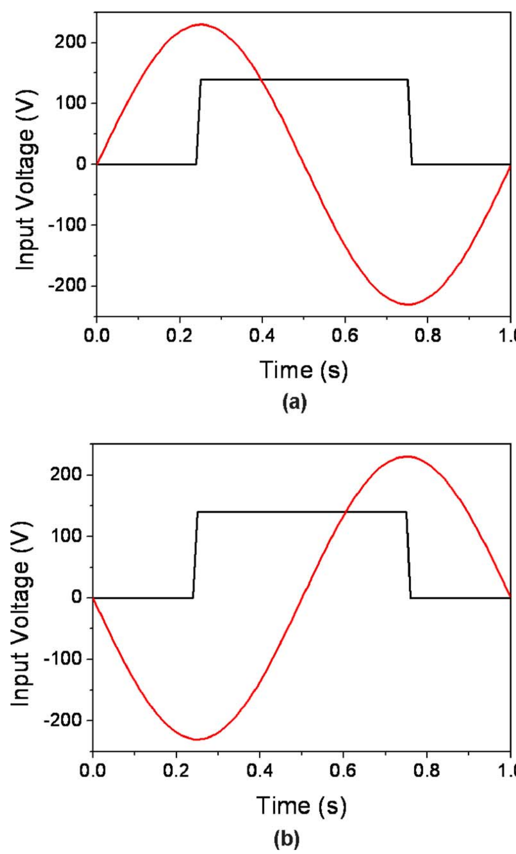

FIG. 9. (Color online) Wave form graph for large motion test: (a) wave form for forward direction movement and (b) wave form for backward direction movement.

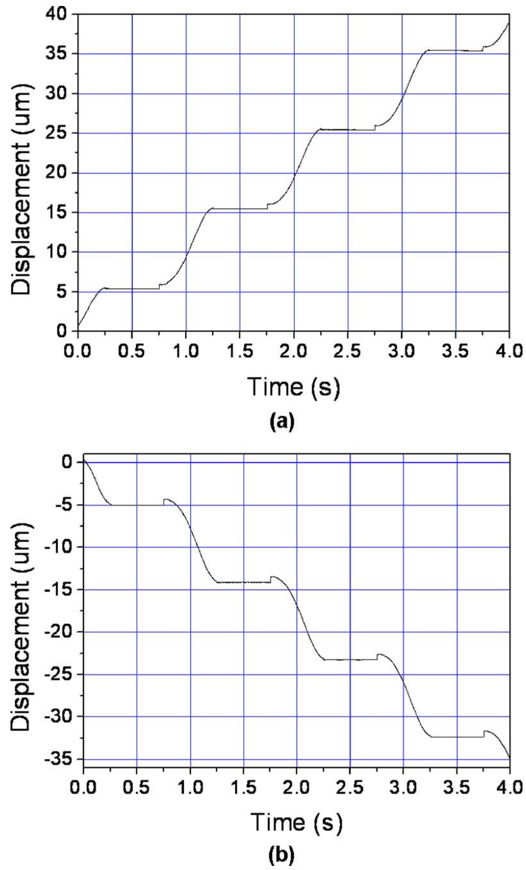

FIG. 10. (Color online) Measured piezoelectric stepping movement driven at 1 Hz frequency: (a) forward direction and (b) backward direction.

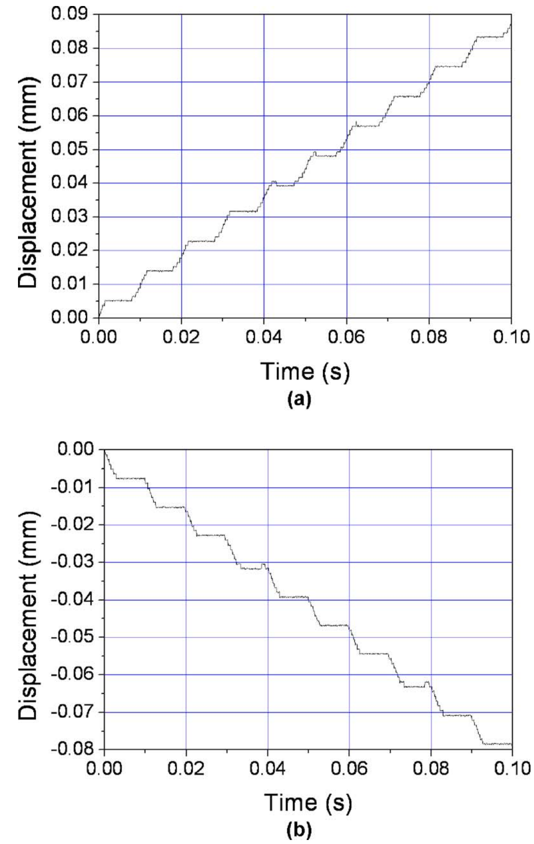

FIG. 11. (Color online) Measured piezoelectric stepping movement driven at 100 Hz frequency: (a) forward direction and (b) backward direction.

sumed as 100 μm. The maximum preload of 141 N is obtained with a disk spring having an outer diameter of 8 mm, an inner diameter of 4.2 mm, and a thickness of 0.4 mm.

According to the design results, the piezoelectric linear stepping positioner is fabricated. The frictional surfaces between the two modules are composed of hard anodized Al 7075-T6 and SUS 316 and they are grinded such that the roughness is below 1 μm.

For the proper operation of the developed piezoelectric stepping positioner, gaps of FM and CM against the moving part are adjusted so that only FM can be contacted with the moving part. To verify this contact condition, two CMs are excited by sine wave and the motion of the fixed parts of CMs is monitored by a laser Doppler vibro-meter (LDV) (Polytec. OFV 501, OFV 3001). If CM is in contact with the moving part, each fixed part moves with the excitation signal. Otherwise, the fixed parts remain stationary. Therefore, the gaps are adjusted so that the motion of two fixed parts shows the same sine shape whose lower part is clipped. The gap adjust screw of CM is used for this purpose. From this method, the reproducible adjustment becomes possible and the results are presented in Fig. 6.

III. PERFORMANCE EVALUATION

The experimental setup for the test of the fabricated positioner is shown in Fig. 7. Position is measured by a LDV and the interface with a PC is embodied by an analog-to-digital/digital-to-analog (AD/DA) board (National instrument, PCI-6733). There are two amplifiers, a PZD 350-1 (TREK Corp.) for the feed piezoelectric actuator and an ENV 400 (Piezojena Corp.) for the clamp piezoelectric actuator.

The first experiment is a resolution test of the developed positioner. For this, the feed piezoelectric actuator is controlled without applying voltage to the clamp piezoelectric actuators. The proportional integral derivative (PID) control law is used and the results in the case of 10 nm step control are shown in Fig. 8.

A large motion test based on piezoelectric stepping movement is also performed. Proper wave forms must be applied to each piezoelectric actuator according to the operation sequence. Figure 9 shows the wave form graph for forward and backward drives. The feed piezoelectric actuator is driven by a 460 $V_{p\text{-}p}$ sine wave and the clamp piezoelectric actuator is driven by a 140 $V_{p\text{-}p}$ square wave. The no-load

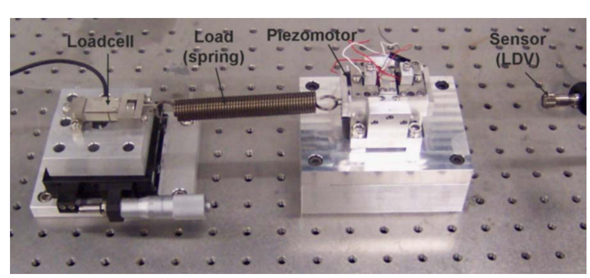

FIG. 12. (Color online) Experimental setup for test of load and stiffness characteristics.

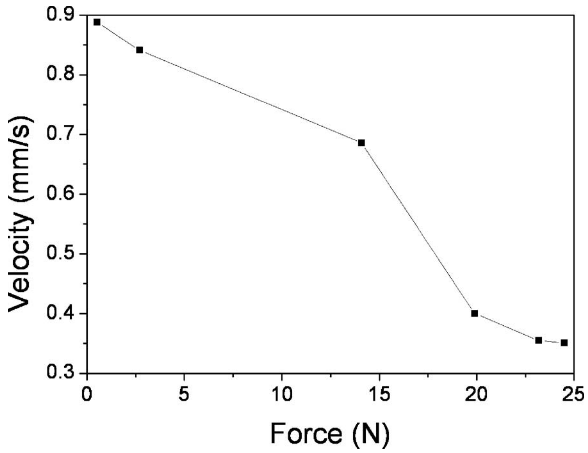

FIG. 13. Load-speed characteristics of the developed piezoelectric stepping positioner.

motion test results at drive frequencies of 1 and 100 Hz are presented in Figs. 10 and 11. A speed of approximately 1.1 mm/s is attained at a drive frequency of 150 Hz. At the moment of contact condition change, a slight glitch is observed. However, the glith is repeatable and can be compensated algorithmically.

The power consumption of the positioner can be calculated for this movement. The piezoelectric motor can work by transferring the electric power given at the piezoelectric actuators to mechanical power of the moving part. Given that the piezoelectric actuators are regarded as a capacitance load, the required electric power of the piezoelectric actuator can be calculated by the following equation:

$$P = VI = VC\frac{dV}{dt}, \tag{4a}$$

$$P_{f,\max} = 2\pi f_d C_f V_f^2, \tag{4b}$$

$$P_{c,\max} = C_c V_c^2 / t_{r,c}, \tag{4c}$$

where P is the power consumption of the piezoelectric actuator, V is the voltage applied at the piezoelectric actuator, C is the capacitance of the piezoelectric actuator, $P_{f,\max}$ is the maximum power consumption of the feed actuator, C_f is the capacitance of the feed actuator, V_f is the maximum voltage

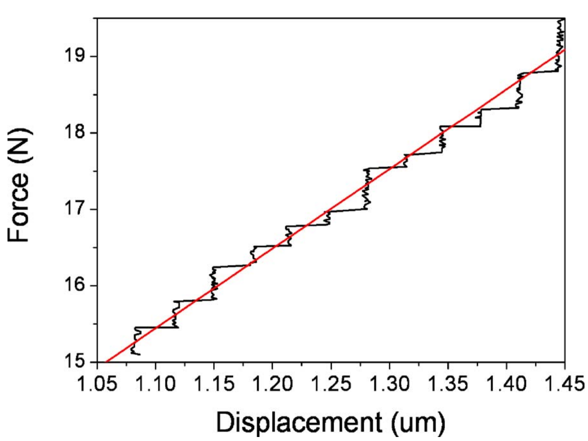

FIG. 14. (Color online) Load-displacement characteristics of the developed piezoelectric stepping positioner.

TABLE I. Performance evaluation of the developed piezoelectric stepping positioner.

Characteristics	Value
Drive frequency	150 Hz
Resolution	10 nm
Speed	1.1 mm/s
Travel	30 mm
Push force	25 N
Power consumption	52.33 W
Stiffness	10.4 N/μm
Size	$32 \times 42 \times 60$ mm^3

of the feed actuator, $P_{c,\max}$ is the maximum power of the clamp actuator, C_c is the capacitance of the clamp actuator, V_c is the maximum voltage of the clamp actuator, and $t_{r,c}$ is the required rise time for the clamp actuator. $t_{r,c}$ is set to a sixth of the period of the drive signal. The required power for the operation at 150 Hz is 2.94 W for the feed actuator and 49.39 W for the clamp actuator.

Finally, the force and stiffness characteristics of the proposed piezoelectric stepping positioner are measured. Spring force is exerted as the external load is measured by the load cell, i.e., a CSBA-10LS (CASKOREA Co. Ltd.), as shown in Fig. 12. In general, piezoelectric motors display drooping torque-speed characteristics, i.e., the speed decreases as the load increases. Similar phenomena are observed in the developed piezoelectric positioner, as shown in Fig. 13. The maximum load that the positioner can drive is measured to be about 25 N, at which point the velocity is decreased to 0.1 mm/s. Figure 14 shows the load-displacement characteristics of the developed piezoelectric stepping positioner. The slope implies the stiffness of the positioner and is calculated to be 10.4 N/μm. The evaluation results of the positioner are summarized in Table I.

IV. DISCUSSIONS

A novel high precision linear piezoelectric stepping positioner for the purpose of precision optics alignment was proposed and designed to have a compact and symmetric structure, high positioning resolution, large motion range, high force density, adequate dynamic range, and power-off hold. The positioner was fabricated according to the design specifications and performance evaluation tests were carried out. A resolution of 10 nm, speed of 1.1 mm/s, push force of 25 N, and stiffness of 10 N/μm were obtained while maintaining a compact size of $32 \times 42 \times 60$ mm^3. The required power consumption was 52.33 W. The above test results confirm that the developed positioner could be successfully applied to the precision alignment of optical elements.

Acknowledgment

This work was supported by ITEP Grant No. 10006942 under the auspices of the Korea Ministry of Commerce, Industry, and Energy.

[1] P. E. Tenzer and R. Ben Mrad, IEEE/ASME Trans. Mechatron. **9**, 427 (2004).

[2] J. Kirz, C. Jacobsen, and M. Howells, Q. Rev. Biophys. **28**, 33 (1995).
[3] D. Kang *et al.*, Jpn. J. Appl. Phys., Part 1 **46**, 394 (2006).
[4] M. Taniguchi, M. Ikeda, A. Inagaki, and R. Funatsu, Int. J. Jpn. Soc. Precis. Eng. **26**, 35 (1992).
[5] J. W. Ryu, D.-G. Gweon, and K. S. Moon, Precis. Eng. **21**, 18 (1997).
[6] Y. Okazaki, S. Asano, and T. Goto, Int. J. Jpn. Soc. Precis. Eng. **27n**, 172 (1993).
[7] D. W. Kang, K. H. Kim, J. H. Jeong, and D. G. Gweon, *Joint International Symposium on Optical Memory and Optical Data Storage/ Technical Digest*, IEEE, p. 51 (2002)..
[8] W. Guo, S. Weerasppriya, I. B. Goh, O. H. Li, C. Bi, K. T. Chaing, and T. S. Low, IEEE Trans. Magn. **34**, 450 (1998).
[9] A. H. Slocum, *Precision Machine Design* (Prentice-Hall, Englewood Cliffs, NJ, 1992).
[10] Q. Lee Sung, Ph.d. thesis, KAIST, 2001.
[11] K. Uchino, *Piezoelectric Actuators and Ultrasonic Motors* (Kluwer, Dordrecht, 1996).
[12] T. Hemsel and J. Wallaschek, Ultrasonics **38**, 37 (2000).
[13] Y. Egashira *et al.*, Jpn. J. Appl. Phys., Part 1 **41**, 5858 (2002).
[14] S. Ueha and Y. Tomikawa, *Ultrasonic Motors, Theory and Applications* (Oxford University Press, New York, 1993).
[15] T. Sashida and T. Kenjo, *An Introduction to Ultrasonic Motors* (Oxford University Press, New York, 1993).
[16] M. K. Kurosawa, O. Kodaira, Y. Tsuchitoi, and T. Higuchi, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **45**, 1188 (1998).
[17] C.-H. Yun, T. Ishii, K. Nakamura, S. Ueha, and K. Akashi, Jpn. J. Appl. Phys., Part 1 **40**, 3773 (2001).
[18] T. Muneishi and Y. Tomikawa, Jpn. J. Appl. Phys., Part 1 **43**, 5858 (2004).
[19] Y. Li, M. Guo, Z. Zhou, and M. Hu, Precis. Eng. **26**, 7 (2002).
[20] B. Zhang and Z. Zhu, IEEE/ASME Trans. Mechatron. **2**, 22 (1997).
[21] N. Shimizu, T. Kimura, T. Nakamura, and I. Umebu, J. Vac. Sci. Technol. A **8**, 333 (1990).
[22] P. Gao, H. Tan, and Z. Yuan, Meas. Sci. Technol. **11**, N15 (2000).
[23] T. Galante, J. Frank, J. Bernard, W. Chen, G. A. Lesieutre, and G. H. Koopmann, Proc. SPIE **3329**, 756 (1998).
[24] G. Powers, J. Fasick, and Q. Xu, Smart Materials Bulletin, June, 7 (2002).
[25] G. Powers, Q. Xu, T. Guidarelli, and J. Smith, Proc. SPIE **5762**, 287 (2005).
[26] E. Shamoto and T. Moriwaki, Precis. Eng. **20**, 85 (1997).
[27] http://www.bellevillesprings.com