Development and Assessment of a Novel Hydraulic Displacement Amplifier for Piezo-Actuated Large Stroke Precision Positioning

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Abstract—In recent years, piezo-actuated micro/nano positioning stages emerge as a significant tool in the nanotechnology. However, the shortcomings of small positioning stroke and hysteresis of piezoelectric actuators have constrained their further development and applications. In this paper, a novel piezo-actuated hydraulic displacement amplifier (PHDA) based on Pascal’s law and area differential principle is first proposed aiming to solve the contradictions among positioning stroke, positioning resolution and mechanism dimension in piezo-actuated micro/nano positioning stages. After a series of optimal designs, the proposed PHDA mechanism is fabricated and experimentally tested. In this study, a piezoelectric (PZT) actuator P-840.20 with open-loop travel of 30 µm is employed, the experimental results indicate that the displacement amplification ratio can reach up to 34.6, thus the maximum output displacement can achieve up to around 1.02 mm. Both theoretical derivation and prototype test results testify the well performance of the proposed mechanism. This new amplifier can be widely extended to practical precision manipulation applications in case of large motion range required.

I. INTRODUCTION

In recent years, along with the rapid development in micro/nano scales technology, flexure-based micro/nano positioning stages have played a significant role in high precision positioning applications due to their advantages such as no trouble of backlash, no friction, no cumulative errors, no repeatable motion, and easy to fabricate. The broad applications can be found in the field of atomic force microscope (AFM) [1], nanoelectronics [2], and biology micromanipulation [3]. In these kinds of micro/nano positioning instruments, PZTs are widely employed because of their advantages including large blocking force, ultra-high resolution, high stiffness and rapid response characteristics.

Due to these advantages, many micro/nano electromechanical systems adopt these stages in a robust, automated, and reliable manner. Unfortunately, most of the proposed piezo-actuated micro/nano positioning stages are constrained by the small output displacement of the PZTs, which has become a bottleneck issue restricting the further applications of these devices [4]. Generally, the proposed compliant micro/nano positioning stages have the motion stroke of less than 500 µm. For most applications in terms of biological cell manipulation, biomedical surgery and micro-fluidic chip technology, a large motion range more than 1 mm is usually required.

To meet with these requirements, many methods have been proposed and applied in the past few years, which can be classified into two categories. The first type is based on some mechanical displacement amplifiers, which are the most popular devices to amplify the stroke of the PZTs. The common adopted displacement amplifiers are lever mechanisms [5], Scott-Russell mechanism [6], pantograph mechanisms [7], and bridge-type amplification mechanisms [8]. In these mechanisms, the lever displacement amplifiers (LDAs) have been widely employed due to its simple mechanism structure. According to our experiences, however, the lever amplification ratio will always be smaller than the theoretical value which is caused by the lever arm bending and the connection flexure stretching. The second type is based on some large-stroke drivers. In the processing of literature review, it is found that magnetic levitation drivers [9] and voice coil motors (VCMs) [10] are popularly adopted. As far as the large-stroke driving mechanisms, VCMs are most widely selected to drive the micro/nano positioning stages for the virtues of millimeter-level output displacement and low cost. However, the VCMs have lower blocking force and lower displacement resolution compared with the PZTs. Therefore, to facilitate a mechanism with VCMs actuation, the compliant positioning stage should be designed with low-enough stiffness, which will reduce the mechanism bandwidth and positioning precision. In consequence, the contradictions among positioning stroke, positioning resolution, and mechanism dimension have become the bottleneck issues which may limit the applications and development of the micro/nano positioning stages.

To effectively solve these problems, a novel hydraulic displacement amplifier based on area differential principle is proposed for the mechanism design of compliant micro/nano positioning stages. In this displacement amplification device, the input piston is directly connected to a PZT output tip, and the output piston is directly connected to the compliant positioning mechanism, the output displacement of the PZT actuator will be amplified due to the differential area of hydraulic cylinder, then the amplified displacement will be delivered to the compliant positioning stages. For this device, the amplification ratio is determined by the ratio of the two piston diameters, which can be specified according to the practical applications. To the best knowledge of the authors, this research is the first attempt at extending hydraulic displacement amplification device to the mechanism design and...
actuation of piezo-actuated compliant micro/nano positioning stages.

Finally, by means of a series of mechanism optimal designs, a prototype is fabricated and tested. A PZT (P-840.20 from PI, Inc.) with open travel stroke of 30 µm is employed in this research. The command signal and the output displacement signal are acquired and recorded by the dSPACE system, the amplification ratio can reach up to 34.6, thus the output displacement of the PHDA can achieve up to 1.02 mm, which confirms the effectiveness of the proposed device.

II. COMMON DISPLACEMENT AMPLIFIERS

With the considerations of the balance among motion stroke, positioning resolution, and mechanism dimension, how to design a piezo-actuated compliant micro/nano positioning stage with a large stroke has become a focus for the scholars [11–13]. Therefore, in this section, several common displacement amplification mechanisms will be presented and discussed in order to make comparisons.

A. Lever Mechanism

A lever is a straight object placed on a point or pivot. It can be used as a simple method of lifting a heavy object. The force placed on one end of the lever will be transferred to lift the payload. With the comparison to the other common amplification mechanisms, the lever mechanism has a simpler structure, herewith lever mechanisms have been the most widely used displacement amplifiers.

In order to clearly make a demonstration, a lever schematic diagram is presented as shown in Fig. 1. Adding the lever displacement amplifiers to the micro/nano positioning mechanisms is an effective way, however, there is always a displacement loss effect, which causes the actual lever amplification ratio to be always smaller than the theoretical value, the reason may be caused by the combination of lever arm bending and connecting flexure stretching. This defect will greatly reduce the performance of the positioning mechanism. In order to suppress this effect, some modeling studies have been carried out in detail and a conclusion has been made in our former research [5, 14]. In practice, some more detailed analytical modelings should be conducted to enhance the amplification ratio of the lever displacement amplifier.

B. Scott-Russell Mechanism

In the past few years, there are numbers of researchers focused on the study of Scott-Russell mechanism [6], which can be described as four bar mechanism as shown in Fig. 2. In this mechanism, the force is generated by the flexure hinges C and O. The magnitude of preload is obtained by two aspects: the first one is the equivalent stiffness of the flexure positioning mechanism; the second one is the initial preload displacement in the assembly process. Based on the Hooke’s law, the larger the flexure positioning mechanism is compressed, the bigger the piezoelectric actuator is subjected to preload. On the other hand, the high stiffness of the flexure hinges and large preload force will accordingly reduce the motion range of the flexure-based Scott-Russell mechanism. The reason is that piezoelectric actuator has finite stiffness and the actual output displacement is always less than the nominal output displacement under the preload condition. Therefore, the mechanical design of the flexure hinge is significant for the flexure Scott-Russell mechanism. If circular flexure hinge as shown in Fig. 3 is employed in the mechanism design, the equivalent linear stiffness $K_{sr}$ can be derived as follows:

$$K_{sr} \approx \frac{1}{2l_{AB}^2} K_{M, a_z} = \frac{Eb}{9\pi r^3 t^{2.5}} l_{AB}^2, \quad t \ll r$$

(1)

where $l_{AB}$ denotes the length between the point A and B, $K_{M, a_z}$ denotes the stiffness of circular flexure hinge around $Z$-axis. $E$ denotes the Youngs modulus, $b$, $t$, and $r$ denote the thickness, minimum thickness, and circle radius of circular flexure hinge, respectively. The reduction of displacement...
of the piezoelectric actuator due to the flexure-based Scott-Russell mechanism can be calculated as follows:

\[ D_{pr} = \frac{K_{sr}}{K_{sr} + K_{pzt}} (D_{pn} + D_{pre}) \]  

(2)

where \( D_{pr} \) is the reduction displacement of the piezoelectric actuator, \( K_{pzt} \) is the stiffness of the piezoelectric actuator, \( D_{pn} \) is the nominal displacement of the piezoelectric actuator, and \( D_{pre} \) is the initial displacement under the preload force. Thus, how to reduce the displacement loss due to the preload effect should be considered in the process of mechanism design and assembly. In this mechanism, according to the theory of mechanics, the driving force will simultaneously generate force and bending moment at the locations of flexure hinges, which will make the flexures generate stretching and bending deformation, thus the motion precision will be reduced accordingly.

C. Pantograph Mechanism

As shown in Fig. 4, a pantograph displacement amplification mechanism is a mechanical linkage connected in a manner based on parallelograms so that the movement of input point, in tracing an image, produces identical movements in an output point. If a trajectory is traced by the input point \( D_i \), an identical, enlarged, or miniaturized copy will be generated by the output point \( D_o \). Because of their effectiveness at translating motion in a controlled fashion, pantographs mechanisms are used as a type of motion guide for large and small objects [7].

D. Bridge-Type Amplification Mechanisms

The schematic diagram of a traditional bridge-type displacement amplification mechanism is displayed in Fig. 5. If we exert an input voltage to the PZT actuator, an extending motion will be generated, which will drive the bridge-type amplifier mechanism to produce a high precision motion along the vertical direction. With the comparisons to the other common displacement amplifiers, a bridge-type amplifier has the virtues of large amplification ratio and compact dimension, which has been widely employed for micro/nano scale applications.

However, this mechanism has the flaw that its lateral stiffness is low. Herewith, the amplification ratio of this amplifier is always not large enough, if we want to improve the output stroke, a larger and more complex mechanism will be generated, which will constrain its further applications. In order to improve the positioning performance, some advanced and effective displacement amplification devices should be investigated and applied.

III. HYDRAULIC DISPLACEMENT AMPLIFIER OPTIMAL DESIGN

Based on above analysis, a type of novel PHDA based on Pascal’s law and area differential principle is proposed for designing large stroke micro/nano positioning stage. As shown in Fig. 6(a-b), a PZT is carried by a cylindrical metal holder, and one end is immobilized by a screw, while the other end is connected to the input piston. Then, the input piston and output piston will be connected through a hydraulic cylinder. The other end of output piston will be connected to the interface of the compliant micro/nano positioning mechanism. As shown in Fig. 6(c), in order to improve the mechanism response speed and motion repeatability, a small spring is added to the gap. With the PZT driving the input piston directly, the fluid in the cylinder will be compressed quickly. According to the Pascal’s law, the generated pressure will be uniformly transferred to anywhere of the closed hydraulic cylinder. Then, the output piston will be driven to output a amplified smooth motion. Finally, this smooth motion will be transferred to the connected interface to drive the connected compliant micro/nano positioning stage to output a large stroke precision motion. According to the equivalent volume principle, the following relationship can be obtained:

\[ \frac{\pi}{4} A_i D_i^2 L_i = \frac{\pi}{4} A_o D_o^2 L_o \]  

(3)

where \( D_i \) and \( D_o \) denote the diameter of input piston and output piston, respectively. \( L_i \) and \( L_o \) denote the motion displacement of input piston and output piston, respectively. Then, the displacement amplification ratio of the PHDA mechanism can be derived as follows:

\[ A = \frac{L_o}{L_i} = \frac{D_i^2}{D_o^2} \]  

(4)

where \( A \) denotes the displacement amplification ratio. It is observed that the amplification ratio is determined by the quadratic ratio of these two piston diameters, which can be specified conveniently to fulfill the practical requirements in different levels. Besides, although the resolution of the output displacement will be inevitably reduced due to the
A PZT with ultra-high resolution can be considered to adopt, which will make the compliant mechanism output a high precision motion with large motion range. In this design, the ratio of the diameter of input piston and output piston is specified to 8, here with $A = 64$. If a high resolution PZT with a large stroke of 180 µm is employed in this design, the maximum output displacement can achieve up to 11.52 mm in theory.

Therefore, with the comparisons to the common displacement amplifiers, the proposed PHDA has the major virtues including ultra-large amplification ratio, compact structure, high resolution, large output force, low cost, and easy to assembly. According to our former study, the output motion resolution of the traditional displacement amplifier will be reduced accordingly, in order to improve the positioning precision, some PZT actuators with higher resolution should be adopted. Thus, the mechanism stroke will be greatly affected due to the PZT actuator property (higher resolution, smaller motion travel). In this study, this side-effect is small, since the amplification ratio of the PHDA mechanism is big, meanwhile the amplification ratio can be specified according to the practical requirements. Moreover, there is another advantage of the PHDA that the mechanism dimension will be reduced. For a traditional displacement amplifier, if we want to greatly enhance the amplification ratio, the mechanism size of the amplifier must be larger, thus it will make positioning stage become too larger, which will greatly reduce the mechanism bandwidth. In this design, the utilization of the PHDA mechanism will not magnify the stage dimension, conversely, it will reduce the size of the positioning stage since the amplification ratio is mainly related to the diameter ratio of the input piston and the output piston. Thus, the dimension of positioning stage can be reduced since the output force of the PHDA mechanism is large enough to drive the high stiffness mechanism to output a motion. A prototype is fabricated and a series of tests are carried out to validate the performance of the proposed PHDA in the next section.

IV. Prototype Fabrication and Experimental Study

In this section, a PHDA prototype is fabricated and an experimental system is built up. Afterwards, a series of open-loop tests are implemented to assess the performance of the developed PHDA mechanism.

A. Prototype Fabrication

An overview of the experimental setup and the details of the designed PHDA prototype are graphically demonstrated in Fig. 7 and Fig. 9. The PHDA prototype is fabricated by the CNC (computerized numerical control) processing technology from a piece of AL6061-T651 material with a high yield strength, which can be used to reduce the output motion error arising from the mechanism deformations.
Besides, the employed flexure-based compliant positioning mechanism is fabricated through the WEDM (wire electro-discharge machining) process from a piece of AL7075-T651 material, which has a higher elasticity, yield strength and lighter mass than the common steel or aluminum material. In the process of mechanism fabrication, the wire walking technology is selected to improve the machining accuracy. In order to reduce the “amplification ratio loss” effect arising from the entrained air in the hydraulic cylinder, the hydraulic fluid is injected by a hypodermic needle.

B. Experimental Setup

The experimental system is shown in Fig. 7 and Fig. 9, among which a PZT (model P-840.20 with open-loop travel of 30 \( \mu \text{m} \), from PI, Inc.) is selected in this study. In order to obtain the output displacement of the compliant mechanism driven by the PHDA mechanism or single PZT actuator, a laser displacement sensor (model LTC-050-10-SA, from MTI Instruments, Inc.) is employed in this system. A dSPACE-1005 rapid prototyping system (from dSPACE GmbH) equipped with 16-bit DS2001 A/D and DS2102 D/A modular boards with the sampling frequency of 2 KHz are employed to generate the command signal and collect the displacement signal. The output voltage signals of the dSPACE system (0-10 V) are amplified by a three-channel amplifier (E-503 from PI, Inc.) which generates an output voltage signal (0-100 V) to drive the PZT actuators. Besides, an up-right microscope system (BX51WI, Olympus) with a monochrome camera (from TIS, Inc.) is utilized for visual tracking. To avoid the trouble of vibrations, the experimental prototype and the microscope system are mounted on high performance vibration isolation tables (from Newport, Inc. and Thorlabs, Inc.).

C. Open-Loop Experimental Test

To assess the practical displacement amplification performance of the fabricated PHDA prototype, a series of open-loop tests are conducted in this section.

Firstly, the comparison tests are carried out to determine the actual displacement amplification ratio of the fabricated prototype. As shown in Fig. 7, a kind of linear ramp signal with a low-slope (0.5) ranging from 0 to 100 V is applied to the PHDA mechanism and single PZT actuator, respectively. Then, the input voltage and output displacement data are all collected and plotted in Fig. 8. As shown in Fig. 8(a), the results indicate that the relationship between the input voltage and the output displacement is linear with a constant slope 0.295, among which the maximum output displacement is around 29.5 \( \mu \text{m} \). As shown in Fig. 8(b), when the PHDA mechanism is employed, the relationship between the input voltage and the output displacement is nearly linear with a slope 10.2, among which the maximum output displacement is around 1020 \( \mu \text{m} \). It reveals that the amplification ratio achieves up to 34.6, which validates the effectiveness of the proposed PHDA mechanism.

Secondly, with the considerations of further applications in biological micromanipulation, the visual tracking experiment...
is preliminary carried out in this study. As shown in Fig. 9, the prototype system is mounted on the microscopy antivibration stage, a 4x objective is employed for micropipette motion observations. Herewith, a linear ramp signal with a low-slope (0.3) ranging from 0 to 100 V is applied to PHDA mechanism, and then the motion trajectory of the micropipette is captured and displayed in Fig. 10(a-e), and the image of a standard micrometer (10 μm/scale) under the 10x objective is demonstrated in Fig. 10(f). It can be observed that the micropipette can smoothly move from the left side to the right side, and then the motion travel can be determined as around 1000 μm, which is identical to former results measured by laser sensors. All the results confirm that the proposed PHDA mechanism has a large displacement amplification ratio and can output a large stroke and high precision motion.

Even so, the displacement amplification ratio of the prototype is much lower than the expected designed value. The reason mainly comes from the manufacture errors and the quality of the employed hydraulic oil, which will be carefully considered in our further work.

V. CONCLUSIONS

In this paper, a novel hydraulic displacement amplification device is proposed towards designing large-stroke compliant micro/nano positioning stages. It aims to provide a new amplification mechanism to effectively balance the indexes of motion stroke, positioning resolution, and mechanism dimension in the field of micro/nano technology. Firstly, some traditional displacement amplifiers are introduced and discussed. Thereafter, the optimal design of a hydraulic displacement amplifier with the discussions on the mechanism advantages are conducted. Afterwards, a amplifier prototype is fabricated and some open-loop experiments in terms of actual amplification ratio determination, accuracy analysis and error analysis have been carried out in detail. It indicates that the proposed hydraulic displacement amplification device has an ideal property for large-stroke micro/nano positioning, meanwhile it can be extended to the other precision manipulation fields when a large stroke is required.

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REFERENCES