Effect of Input Voltage Frequency on Micro-Gripper with Piezoelectric Actuator

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***Abstract*—This paper deals with the study of effect of frequency on a microgripper which uses piezoelectric actuator. In this study different control approaches which are used in piezoelectric microgrippers are investigated and also compared. Then a proper control method for applying in this study is selected. Then with employing the appropriate controller, a micro-manipulation system is implemented, which contains PiezoGripper (microgripper with piezoelectric actuator) and optical sensor for measuring the displacement of microgirpper jaws. Then several input voltages are applied to microgripper with different frequencies and the displacement changes which are influenced by applied frequency are investigated for several closings and openings. At the end of the paper a novel concept is defined to study about deviation of microgripper displacement.**

***Index Terms*—MicroGripper, Piezoelectric, Control methods, Laser Sensor, Microassembly.**

I. Introduction

In recent years, with the increasing effort to minimize the systems and products in industries, the need for micro and nanotechnology has become an important issue. As a consequence, a new scientific challenge in small-scale engineering has been introduced. Micro-scale technologies have been increasing as useful products and applications in electronics, information technology, optics, medicine and biology covering areas such as diagnostics, drug delivery, tissue engineering and minimally invasive surgery [1]. Along with the advances and developments of Micro-Electro-Mechanical Systems (abbreviated as MEMS) gripping and assembling multiple micro-scale parts is becoming a research hotspot [2],[3][4]. Microgrippers are the end-effectors which contact the manipulated objects directly and decide whether the successful assembly has occurred or not, so that microgrippers play a crucial role in micromanipulation and microassembly. A fundamental and important component of all microgrippers is the actuator that supplies the required force to make the device operate as a gripper. Microgrippers are divided into several categories based on the mechanisms employed for their actuation. Different kind of microgrippers with different actuation methods have been used for construction of micromanipulation devices including electro-thermal actuators[5],[6], electrostatic actuators[7],[8], piezoelectric actuators[4][9],[10],[11], electromagnetic actuators[12] and shape memory alloy actuators[13]. Each type of the actuators has some advantages and disadvantages such as:

a) Thermal actuators have small required voltages and large output force. But they cannot be used for biological cells (or) fluid media. Also the movement of jaws is non-linear and is very difficult to control. They also have poor sensitivity[14].

b) Working with electrostatic gripper is very simple. In this type of actuators, high operating voltage is the drawback of the actuator[15] .

c) The problem of gripper with electromagnetic actuator is the big size. Also construction of these grippers is very difficult [16].

d) Piezo-Grippers (piezoelectric microgrippers) have advantages such as: large generated force, stable displacement, high response speed and ease of use. But disadvantage is that their performance is changing due to the changes in temperature [1],[9].

Piezoelectric material is among the most utilized materials and because of its advantages, Piezoelectric is an excellent choice to use as an actuator in microgrippers. Its deformation is proportional to the applied voltage and the movement is reversible for both the positive and negative driving signals. One of the limitations of the piezo-grippers is the inherent hysteresis and creep (Creep is the drift of displacement after each constant step input) which makes the control of micro-gripper much more difficult.

In the industry some of microgrippers are produced for limited gripping, or only for holding the objects, but most of them are produced for unlimited openings and closings. For example using microgrippers in IC assembly manufacturing is a common application. In microgripper area so many researches have been done about design, hysteresis, control, etc. but there are a few studies considering the effect of frequency on microgripper.

The objective of this paper is to investigate the effect of changing input frequency in displacement of microgrippers with the piezoelectric actuator. This goal is achieved by running a microgripper system that includes several components like: a piezoelectric microgripper, optical sensor, laser calibrator, power amplifier, etc. In addition the result of this paper can be used for other piezoelectric applications, with the same piezo-ceramic by considering the effect of gripper's phenomena.

The paper is organized as follows. Section II presents the microgripper structure. Section III describes different control methods and compares them. Experimental setup is presented in Section IV. Finally Section V concludes the paper.

II. Structure of Microgripper

In this section, microgripper structure will be introduced briefly. Fundamental parts of a typical microgripper that have been used in industries and researches are a micro-actuator, micro-displacement transmission mechanism (μDTM) and a pair of gripping jaws[17]. The output displacement of a microgripper with piezoelectric actuator usually is amplified with μDTM before transferring to jaws. One of the popular mechanisms that uses μDTM is compliant mechanism[18]. This mechanism consists of flexure parts, which are connected to each other directly by single-axis flexure hinges. Also in recent studies some researchers have used leaf-type flexure hinges to realize the compliant mechanisms for micro-grippers[19]. But in the leaf-type, accuracy of position and ability to repeat are worse than previous case because of large deviation from rotation center during rotation. Another concern about microgrippers is their jaws movement. Up to now, most of the microgrippers open and close their jaws by their jaws' rotation. If the gripping jaws move in parallel, the gripping task could be completed more easily and reliably. Fig. 1 illustrates a two-jaw parallel microgripper. This type of actuator is based on a double bimorph structure and it is made of PZT (lead zirconate titanate) ceramic. Because of its kinematics each finger has motion on Y axis and Z axis. Also Fig.2 shows the cross-section of a piezoelectric actuator. In this case each gripper fingers are driven by five electrodes, ground and four signals that create four degrees of freedom (DOF) by combination of these signals.

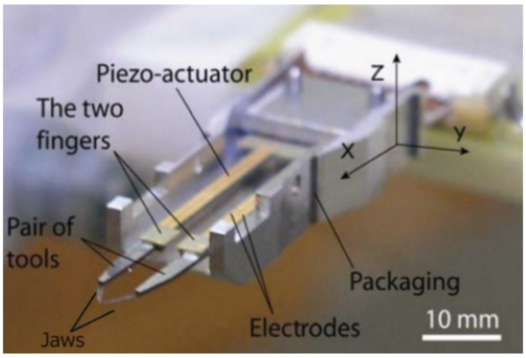

Fig. 1. Structure of a typical Micro-gripper [20].

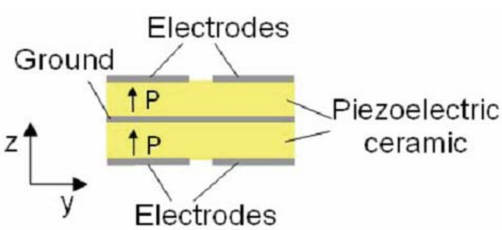

Fig. 2. Cross-Section of a Piezoelectric actuator[3].

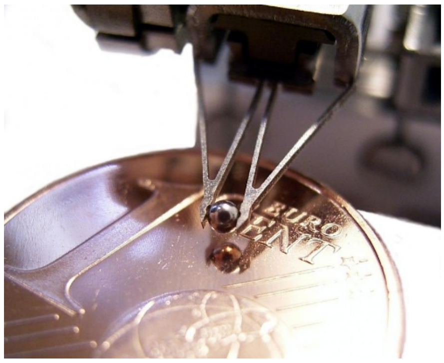

Fig. 3. SG-06-EX microgripper with piezoelectric actuator[25]

III. Controller For Microgripper

In order to gripping, holding and moving the object correctly and without damage, it is necessary to detect and control the gripper jaws' position and also the force between jaws and the object. One of the most important issues in using microgripper is selecting a reasonable controller to decrease undesirable phenomena like hysteresis or creep. There are several researches about different types of controllers in order to drive the microgripper with piezoelectric actuator. These controllers consider two types of outputs for a microgripper, Position and Force. Most studies consider the position; some of the recent ones consider both position and force. There are several methods to measure and detect the position of microgripper jaws which measuring by laser sensor is one of the popular methods used in [21],[22]. The control of force is more difficult because it requires the integration of very small sensors, hence some researchers [22],[23] have estimated the force, also several used a force sensor that is attached to one gripper jaw to measure the force. For example, the capacitive types of force sensors have been used in [24] or the strain gauges have been used to measure the force in [17]. This paper considers the position and the objective is to find an acceptable control system which focuses on displacement. The SG-06-EX microgripper which has been made by SmarAct[25] is used in this paper (Fig.3). The paper describes hysteresis effect in piezoelectric materials and controlling methods as follows.

The hysteresis multipath looping behavior in piezoelectric material is highly nonlinear so that control of piezoelectric actuators with high accuracy is difficult. The maximum hysteretic error is typically about 15% in fixed position, which is not an acceptable error in high-precision systems[26]. For instance, [27] has displayed effect of dynamic interaction between hysteresis loop and frequency, where the hysteretic loop becomes larger as the driving frequency increases (Fig.4). Also, the result of changing the hysteresis loops caused by several closings and openings of the micro-gripper jaws has been shown in Fig.5.

Recent researches in hysteresis modeling, control and compensation can be categorized in following groups: 1) electric charge control; 2) closed-loop displacement control; and 3) linear control with feedforward inverse hysteresis model. In piezoelectric materials, the relation between deformation of piezocremic and applied voltage has

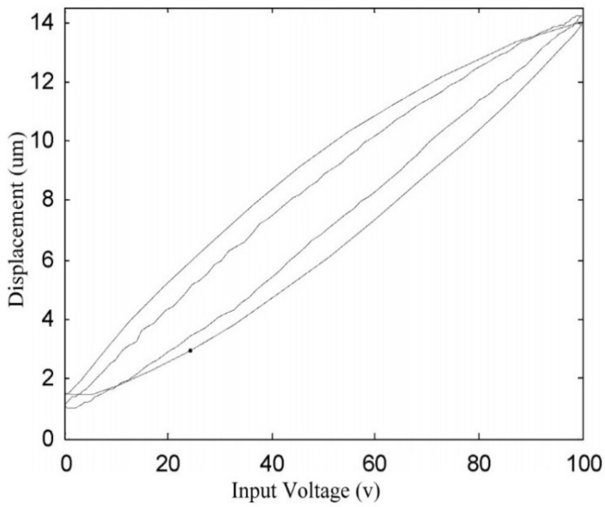

Fig. 4. Hysteresis of piezoelectric actuator at two different frequencies[27]

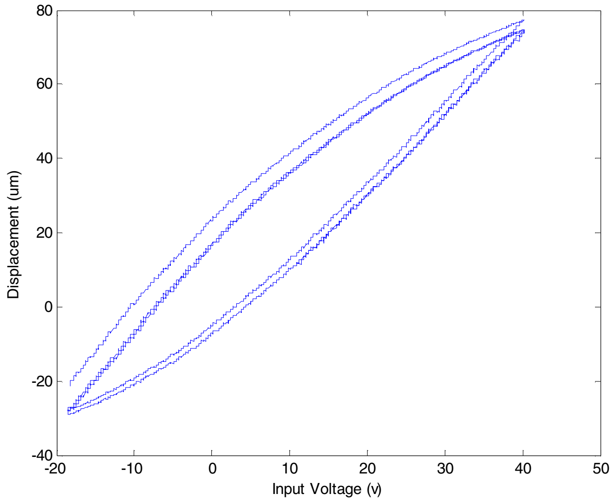

Fig. 5. Measured response of a piezoelectric actuator at three openings and closings at the same driving frequency. The hysteretic loop becomes different at each opening and closing

remarkably more hysteresis than that between deformation and the induced charge, which is the fact that first category uses [30]. This method has drawbacks; it requires specialized equipment for measurement and amplification of induced charge that causes reduction of the responsiveness of the actuator. Most applications in industry use second category based on using laser sensors, strain gauges or capacitive sensors as the feedback sensors. The third category works based on mathematical models that show the hysteretic behavior to implement an inverse feedforward controller based on the inverse hysteresis model to linearize the actuator's response[27]. Some of these models are as follows: The Maxwell's slip model[29], the Duhem model[30], polynomial approximation [26]and the Preisach model [31],[32]. These models are most well-known and widely used in both closed-loop and open-loop systems. [33] has proposed $H\infty$ controller, but it is difficult to obtain a fast system response. A flexible hinge of the piezoelectric hysteresis model has been defined in [34] which is simple and easier to control, but closed-loop control is not achieved. A hybrid PID control algorithm based on Dahl model with feedforward compensation control for hysteresis has been proposed in [35]. A PID controller has been investigated In [36]. Also, a robust PID controller by using interval arithmetic and related tools in order to ensure the specified performances has been designed in [21].

Each of different control modeling approaches has some advantages for a specific application and disadvantages for another. Being easily obtainable and fast response of the system have been considered as criterion in this paper, so that a simple PID controller with displacement feedback has been used to control the microgripper because of its straightforward, convenient and simple usage and also fast response.

IV. Experimental Setup and Result

A. Microgripper

As mentioned before, in this paper a SG-06-EX microgripper is used. This device is suitable for both micro and macroscopic applications. Unlike most other microgrippers, this one can hold the object even if there isn't any power supply. Basic data for this microgripper is listed in Table.1.

Table 1.Microgripper Specifications.

Gripper opening	1 mm and smaller or larger
Gripping force	Min 0.3 N
Weight	2 g
Voltage	-20 to 120 V
Frequency	Up to 18.5 kHz
Capacitance	25 to 35 nF
Gripping time	100 ms
Resolution	Nanometers

B. Experimental Setup

Fig.6 displays the experimental parts used in this research and are briefly introduced in the following part.

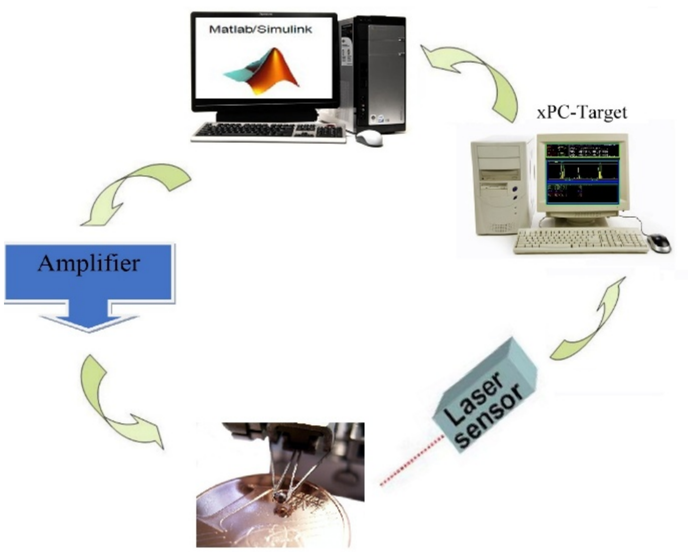

Fig. 6. Schematic of Experimental Setup.

A SIMULINK model has been designed at first step. As mentioned in Table.1, the piezoelectric actuator requires high voltage to provide deflection. Therefore, the main PC is connected to a power amplifier (after D/A). Input voltage for microgripper is changed in different frequencies and different amplitudes. Negative voltages (up to -20) could be applied to a SmartAct microgripper. Therefore, this study supplies negative voltage to investigate the effect of input. Microgripper displacement has been measured along y-axis by employing a 0.01 um resolution laser sensor. The output of the laser sensor is available in real time in X-PC Target (xPC Target is an additional product based on RTW architecture framework provided and issued by MathWorks, and can easily convert an Intel80X86/Pentium computer or PC compatible computer into a real-time system to achieve fast prototype development and hardware-in-loop test of control system or DSP system. It also supports multi-type I/O card (including ISA and PCI)) [37]. Also output of the laser sensor is used as feedback signal for the controller. The laser should be adjusted and calibrated according to the microgripper position for getting the displacement in the best way, which has been done by a driver shown in Fig.7. Also, Fig.8 illustrates the micro-gripper when the laser sensor detects the displacement.

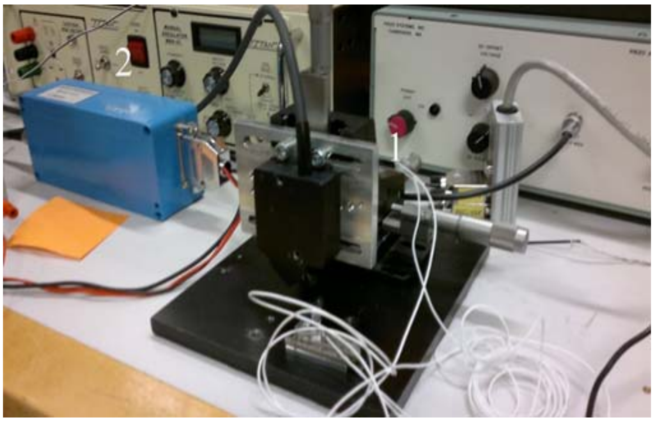

Fig. 7. Laser Sensor setup,1.laser sensor. 2. Laser sensor driver and calibrator.

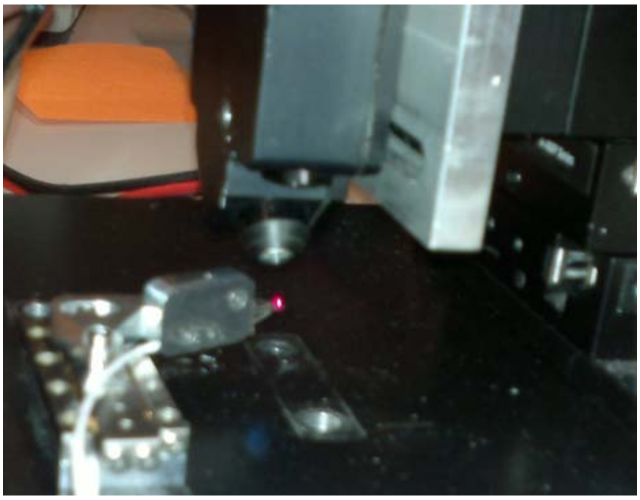

Fig. 8. Micorgripper under laser sensor measurment.

C. Results

The objective of this section is analysis of effect of changing the frequency in the behavior of Piezogripper. To achieve this goal, experiment is done as follows: first, a DC input voltage is applied to the microgripper and the maximum displacement of microgripper jaws is measured. (The hysteresis and creep do not have effect in this displacement due to first and only one changing of microgrippers jaws). Then, a small step signal is applied to piezogripper frequently with increasing amplitude periodically until reaches the mentioned DC voltage (e.g. in Fig.9). This scenario runs 38 times for the specific amplitude with frequencies from 5 Hz to 18 KHz and each time maximum displacement for each frequency is measured. The test runs for numerous amplitudes; however this paper only shows two of them for summarization. Fig.10 and Fig.11 illustrate the results of effect of frequency in changing displacements of microgripper jaws. In these figures, expected maximum displacement is reached when the input voltage equals the mentioned DC voltage. The reason that changing displacement occurs by changing the frequency of input voltage is classified into two main types: one is the effect of inherent piezoelectric material phenomena in changing the frequency. The other reason is microgripper effect.

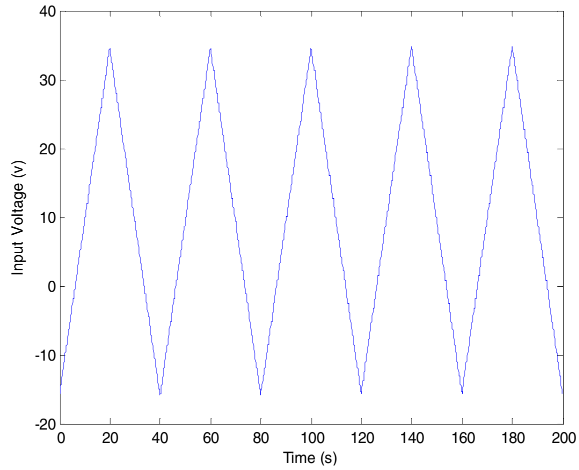

Fig. 9. Example of Microgripper's Input Voltage.

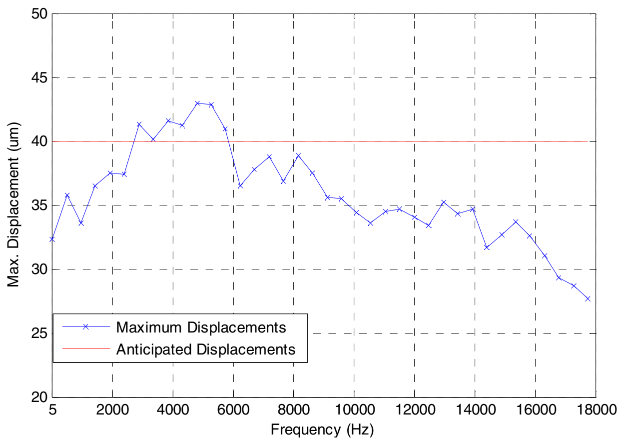

Fig. 10. Maximum Displacements of Microgripper jaws in Different Frequencies. (Maximum Input voltage in this case is 25V)

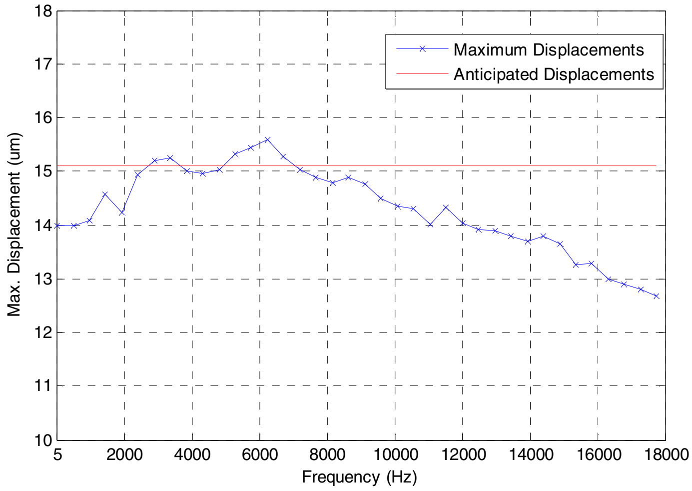

Fig. 11. Maximum Displacements of Microgripper jaws in Different Frequencies. (Maximum Input voltage in this case is 10V).

The first type happens because of piezoelectric ceramic behavior which is the main reason of this changing displacement are: Hysteresis, creep and the required time to achieve to maximum displacement in piezoelectric ceramic. Hysteresis and the required time are two main reasons. Hysteresis and creep are clear and the required time means that piezoceramic cannot achieve to maximum displacement in high frequencies. Because when a voltage is applied to a piezoceramic, the displacement does not happen immediately. That means to achieve to the maximum displacement of the piezoceramic a short time is required. Also, the second type happens due to microgripper structure which is coupling motion. Coupling motion creates unwanted motions on one axis when the other one is actuated, which complicates the manipulation of micro-object.

As it can be seen in Figs.10 and 11 the maximum displacement change which has been influenced by changing frequency, has increased by increasing the input voltage. To obtain a realizable factor for comparing the deviation of microgripper displacement in different frequencies, this paper has used D concept which is defined as follows (1):

$$D = \frac{A - B}{A} \times 100 \tag{1}$$

Where D is deviation of microgripper's displacement influenced by frequency, A is anticipated voltage value; B is the average of maximum displacements of microgripper at different frequencies.

For the first test (Fig.10) D equals to 10.67 % and for the second one (Fig.11) is 5.78 %. Also Fig.12 shows the deviation of microgripper at different input voltages.

V. Conclusion

Different control approaches that is used in piezoelectric microgrippers are investigated and compared in this paper. Then with employing the appropriate controller, a micro-manipulation system is implemented, which contains several components like microgripper with piezoelectric actuator and

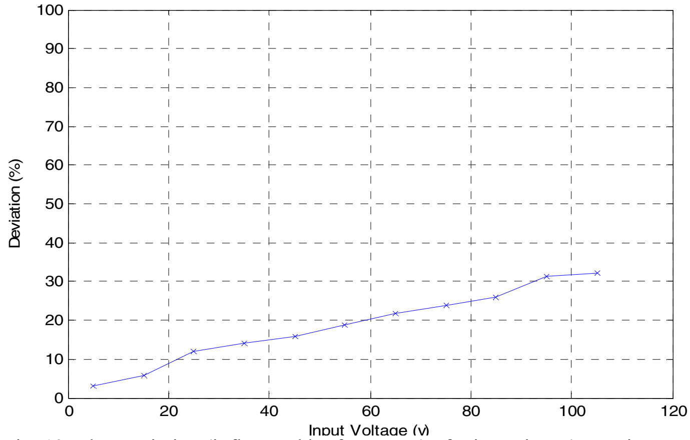

Fig. 12. The Deviation (influenced by frequency) of microgripper's maximum displacement from desired displacement (based on DC input) in different input voltages

optical sensor. Then several input voltages are applied to a microgripper with different frequencies and the displacement changes which are influenced by applied frequency are investigated for several closings and openings. At the end of the paper a novel concept is defined to study about deviation of microgripper displacement.

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