High-Precision Position Control Utilizing the Combined Piezo-VCM Actuator

Yung-Tien Liu*, Rong-Fong Fung*, and Jiunn-Chau Wang**,
* Department of Mechanical and Automation Engineering
National Kaohsiung First University of Science and Technology
University Road, Yenchau, Kaohsiung 824, Taiwan
** Department of Electrical Engineering
Kao-Yuan Institute of Technology

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Abstract

This paper reports about a novel high-precision positioning actuator composed of a piezoelectric element (PZT) and a voice-coil motor (VCM). The novel actuator is applicable to the fields of manufacturing, assembling, examining, and aligning works for the miniaturized components of high-tech industry. It shows that the long-range positioning table could be actuated continuously by the integral variable structure controller for the VCM, and nanometer positioning capability by the impact force controller for the piezoelectric element. Hence, it could behave as a high-precision actuator with the long-range and nanometer positioning capability. It will be widely applied to the precision industry.

Keywords: Voice-Coil Motor, Piezoelectric Element, Integral Variable Structure Controller, Impact Force, Precision Positioning

1. Introduction

In recent years, the merchandised products in the growing fields of photoelectric, information, or semiconductor related industry, such as optical scanner, copying machine, hard disk, etc., are becoming more and more compact. It is difficult to image that a variety of complex components could be assembled internally in their small and good-looking cases of the compact products. These components with precise dimensions are necessary to be positioned or examined accurately during their assembly processes. In high-precision industry, the piezoelectric actuator (PZT) is widely used for the position control because that the PZT has the characteristics of good performance in controlling precise motion, high-frequency response, high conversion efficiency between electrical energy and mechanical energy, miniature size, and small thermal expansion during actuation. The positioning accuracy can possibly attain as high as 1~10 nanometers, but the total displacement of a PZT has only a few microns. To overcome this main disadvantage, a number of efforts have been made in the practical applications [1~5]. In reference [5], the author had reported the combined piezo-VCM actuator that features 10 nm actuating ability and large travel range based on fundamental experiments. In this paper, for examining the automatic positioning ability utilizing the combined piezo-VCM actuator, a positioning device is configured and a dual-controller is implemented for the hybrid actuators.

This paper is organized as follows: Firstly, the components of positioning device and its driving process will be described, and an analysis model will be established based on the configured device. In the next, a variable structure controller with integral compensations (IVSC) is constructed for controlling the long operation rang of VCM, and an impact force controller is derived for
obtaining nanometer positioning ability by PZT. Finally, the performance of the positioning device will be examined experimentally.

2. Physical System and Dynamic Modeling

2.1 Configuration of Dual-Stage Actuator

Figure 1 shows the photograph of the experimental setup with the actuation on the horizontal plane. The experimental configuration can be divided into two main parts: one is the driven part of the sliding table $M$ which is mounted upon the V-groove base, and the other is the actuating part which is mainly composed of a piezoelectric element and a voice-coil motor. Both sides of the piezoelectric element are glued separately to the moving shaft of the VCM and the hammer. The hammer is used for the actuation of the sliding table, and it is delivered to keep in contact with the sliding table by the electromagnetic force of VCM. Under the contact condition, an impact force is generated by the rapid deformation of the piezoelectric actuator, and is then transmitted to the sliding stage through the hammer by means of contact force. As a result of the actuation of the PZT, the sliding stage will move forward precisely; and the VCM will continuously keep the contact condition for long range of operation. The detail actuating process is explained in the next section.

2.2 Actuating Process

Figure 2 depicts the detail driving process for the positioning stage along one direction of actuation on the horizontal plane. The driving process is described as follows:

(a) In the initial state, there is a gap between the target object and the hammer. Practically, this gap should be smaller than the stroke of VCM.

(b) In the extrude state, the moving shaft of the VCM is push forward by applying a constant current to the VCM which produces an electromagnetic force. As a result, the hammer will move forward and keep the contact with the sliding table.

(c) In the rapid expansion state, a pulse voltage waveform is applied to the piezoelectric element. Due to the rapid deformation of the piezoelectric actuator, an impulsive force will be generated and then transmitted to the sliding stage through the hammer in the form of contact force. If the contact force is larger than the static frictional force of the target object, the sliding stage will start to move by a small distance.

(d) In the contract state, the hammer is forced to rebound right after the actuation for the piezoelectric actuator, and the PZT contracts to its initial length. Though this will result in a gap existing between the hammer and the sliding table, the thrust of the VCM can finally keep the contact condition again. In this state, the sliding table is ready for another actuations. By repeating the steps of (c) and (d), the sliding table can be actuated continuously with a long distance.

(e) As a result of the impact actuations, the sliding stage can reach a final expected position. The positioning process ends with the retraction of the moving shaft of the VCM.

2.3 The Physical Model

Referring to the experimental schematic diagram shown in Fig. 1, the theoretical model can be expressed as shown in Fig. 3. As mentioned above, the positioning device is mainly composed of the actuating part and the driven part. The corresponding analysis model is also divided into two parts for easily understanding. In this section, we formulate the actuating part as a 2-DOF mass-spring-damper mechanical system, which includes two masses, one piezoelectric element, and one voice-coil
motor; and the driven part of the sliding table is subjected to two external forces. The analysis model of the positioning device is therefore expressed as follows,

\[
\begin{align*}
\begin{cases}
(m_2\ddot{\xi}_2) &= -c_2(\dot{\xi}_2 - \dot{\xi}_1) + k_2(\xi_2 - \xi_1) - F_p + F_v, \\
(m_1\ddot{\xi}_1) &= -c_1(\dot{\xi}_2 - \dot{\xi}_1) + k_1(\xi_2 - \xi_1) + F_p - F_v, \\
M\ddot{X} &= F_v - F_p \quad (F_i > F_p, \geq 0)
\end{cases}
\end{align*}
\]

where \(m_2, m_1, \) and \(M\) respectively represent the masses of the hammer, the moving shift of VCM and the sliding table, and their corresponding displacements are expressed as \(\xi_2, \xi_1\) and \(X\). The damping coefficients of the piezoelectric element and the Back EMF (BEMF) of the VCM are expressed as \(c_i\) and \(c_1\), respectively, and the stiffness coefficient of the piezoelectric element is symbolized as \(k_i\). There are four external forces acting on the system: (1) the thrust force, \(F_v\), caused by the electromagnetic force of the VCM, (2) the impact force, \(F_p\), generated by the actuation of the piezoelectric element, (3) the contact force \([6]\), \(F_c\), occurred during the collision between the hammer and the sliding table, and (4) the nonlinear frictional force \([7]\), \(F_f\), existing between the sliding surfaces.

3. Control Strategy

In this section, we design a controller for the dual-stage actuator composed of a piezoelectric element and a VCM. The block diagram of the controller is shown in Fig. 4. The design of the controller can be separated into the two steps: (1) In the first step, we construct a variable structure control with integral compensations (IVSC) \([8]\) for long operation range of a VCM. In the beginning of the control procedure, IVSC is used to position the sliding table with a rough accuracy and speed up its response. Once the position of sliding table reaches to a final value with steady-state error of \(\varepsilon (\mu m)\), the control mode is switched to a constant thrust control of the VCM, and an impact force controller is then used to carry out the final high-precision positioning control by means of the piezoelectric element. (2) The impact force of piezoelectric element is generated by applying a pulse voltage waveform to the PZT, and it is transmitted to the sliding table through the hammer by the form of contact force. The design strategy of a VSC controller with integral compensations involves: (1) the design of an appropriate control function \(U\) to guarantee the existence of a sliding mode, (2) the determination of a switching function \(\sigma(X)\) and an integral control gain \(K_i\) for obtaining good control performance, and (3) the elimination of chattering phenomenon.

Let the control input function \(U\) has the form of

\[U = s_wU_I + (1 - s_w)U_T,\]

where \(U_I\) is the IVSC, \(U_T\) is the constant thrust control, and

\[s_w = \begin{cases} 1 & \text{if } r - X_j \geq \varepsilon \\ 0 & \text{if } r - X_j < \varepsilon \end{cases},\]

in which, \(\varepsilon\) is the steady-state position error.

4. Experimental Results

Figure 5 shows the measured displacement of sliding table, and the input voltages of the VCM as well as the PZT with respect to the time axis. The displacement command was given as 2.5 mm at time 0.2 s. As a result of the actuations of VCM and PZT, it can be seen that the sliding table behaves continuous movement thought two types of voltage waveforms were separately applied to the VCM and the PZT. In the first stage, the sliding table actuated by the VCM moved from the reference origin to the position of 2.49 mm in 0.51 s with the positioning accuracy of 10 \(\mu m\). In the second stage, the sliding table actuated by the PZT moved from the position of 2.49 mm to
the target position of 2.49999 mm in 0.9 s with the positioning accuracy of 10 nm. The total control time was 1.6 s. According to the result, the performance of the positioning device utilizing the combined piezo-VCM was effectively demonstrated based on the derived controller.

5. Conclusion
This paper reported the automatic positioning performance of a precision positioning device utilizing the combined piezo-VCM actuator based on the derived controller. According to the experiment result, it is shown that the proposed positioning device featuring 10 nm order of positioning ability and large-operation range has attractive practical applications in the field of precision industry.

6. Reference