Nanoaccuracy Position Control of a Pneumatic Cylinder Driven Table*

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The development of ultraprecision positioning technology is urgently required with the incessant demand for higher accuracy in high technology manufacturing. In this study, therefore, a linear pneumatic-driven ultraprecision table is built; and, a velocity compensator is designed to overcome the stick-slip effect of the pneumatic table. The velocity compensation signal is directly added to the conventional PD and Fuzzy controller to control the table, respectively. This method is effective not only to overcome the stick-slip phenomenon of the cylinder but also to improve the positioning accuracy of the pneumatic servo system. The experimental results have shown that the table has the positioning accuracy of 20 nm.

Key Words: Nanometer Positioning, Velocity Compensation, Fuzzy Control, Pneumatic Table

1. Introduction

The pneumatic control systems have been played the important roles in the industrial automation equipments owing to the following advantages—low cost, clean of the working environments, easy in power transfer, and so on⁽¹⁾. The pneumatic system is a highly nonlinear and time variant system because of the compressibility of air, the friction force between the piston and the cylinder, the air mass flow rate through the valve, etc.⁽²⁾ Therefore, the traditionally pneumatic control systems are controlled only to carry out simple on-off position and speed control by using programmable logic controller. The precise positioning control of the pneumatic servo system cannot be reached through on-off logic controller. In recent years, low cost microprocessors and pneumatic components are developed and applied, which make it possible to adopt more complex control strategy and accomplish more sophisticated motion control tasks^{(3)–(10)}. The controllers of the pneumatic position control have been developed for the better accuracy.

Isermann et al.⁽¹¹⁾ used state controller, underlying differential pressure control and adaptive feedforward friction compensation method to control the pneumatic cylinder. Li and Xu⁽¹²⁾ designed a novel pneumatic position system by using an adaptive variable gain control with the pressures, velocity and acceleration feedback techniques. A on-line learning neural network controller was applied to the pneumatic robot position servo system by Heung et al.⁽¹³⁾ Hamiti et al.⁽¹⁴⁾ presented an auto-tuning PI control scheme to achieve precise positioning in the presence of stick-slip friction. For those researches, the designed cost and control complexity are increased, but the precision is still not apparently improved. The general positioning accuracy only can reach to the range from ± 0.1 mm to ± 0.05 mm. Due to the nonlinear behavior of pneumatic system, precise positioning control of a pneumatic cylinder is very difficult. Especially, the friction force and stick slip phenomenon are the greatest influence for the precise positioning.

With the ever-increasing demand for higher accuracy and higher productivity in high technology manufacturing environment, ultraprecision positioning technology is urgently required. In this paper, an ultraprecision pneumatic positioning table is built; and, a velocity compensator is designed to overcome the stick-slip effect of the pneumatic table and

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improve the positioning accuracy. The conventional PD and fuzzy controller with the designed velocity compensation signal are used to control the pneumatic table, respectively.

2. Experimental Setup

Figure 1 shows a photograph of the precision position table. The table consists of a platform, two single rod cylinders and a linear guideway. The positioning platform is pushed by below two air cylinders and moves only along the guideway motion. The positioning table and linear digital scale are fixed to the base plate. The layout of the experimental devices for the precision positioning control system is shown in the Fig. 2. The table is set horizontally and driven by pneumatic cylinder. The stroke of pneumatic cylinder is 100 mm. The 3/5-port proportional control valve which operates at 5 bar is used. It can adjust flow-rate from -700 l/min to 700 l/min with the input voltage (0 to 10 V). When input voltage is half of the nominal voltage, i.e. 5 V, all control edges are closed so that the flow rate is zero. For the position feedback, a linear digital scale with 20 nm resolution is employed. A microcomputer acts as a controller and is used for the experimental data acquisition. The displacement of the platform is measured

Fig. 1 Photograph of the pneumatic precision positioning table

Fig. 2 Layout of the experimental devices

by a linear digital scale and feedback to the computer through the data acquisition and control board. The control input signal is calculated in the microcomputer through the designed software and passed to the 3/5-port proportional control valve by the D/A capability of the data acquisition and the control card. So that the air mass flow rate can be regulated and the pressure difference of the cylinder can be built up to drive the cylinder. Therefore, the platform can move toward the target position.

3. Controller Design

For a servo control system, conventionally, a linearized mathematical model must be built up, and then the modern control theory can be applied to design a suitable controller. In the study, the pneumatic system is a nonlinear and time variant system. It's very difficult to obtain the accurate linear mathematical model. And, the fuzzy control technology is to simulate the mankind's decision process. One doesn't need to get the accurate mathematical model for the controller design. It's the advantage of the controller designed. Therefore, the fuzzy control is applied and implemented in a computer to control the pneumatic control system. Figure 3 shows the block diagram of the control system. In the paper, a velocity compensator is designed according to the error and velocity. Many kinds of controllers can be applied to the designed velocity compensator. Besides the fuzzy controller, a conventional PD controller with velocity compensator is applied to control the system. The detailed algorithm of the controller and velocity compensator is shown in the following paragraph:

3.1 Fuzzy control

The structure of the fuzzy control includes four parts: fuzzification inference, knowledge base, decision logic and defuzzification⁽¹⁵⁾⁻⁽¹⁷⁾. In the article, Mamdani control rules and maximum-minimum algorithm are applied, and the "center of the gravity" method is used to defuzzify and to get the accurate control signal. The variables E , CE and U are chosen to be the two inputs and one output of the controller, respectively. The error (E) and the change of error (CE) are defined by

$$E(k) = (r(k) - y(k)) * Ge, \quad (3)$$

$$CE(k) = de(k) * Gce = (e(k) - e(k-1)) * Gce, \quad (4)$$

Fig. 3 Block diagram of the control system

Table 1 Fuzzy control rules

$\begin{matrix} E \\ \backslash \\ CE \\ U \end{matrix}$	N	ZE	P
N	N	N	ZE
ZE	N	ZE	P
P	ZE	P	P

Fig. 4 Membership functions for fuzzy control

where Ge and Gce are the scaling factors of error and change of error. The output signal ($u_f(k)$) from the microcomputer is defined as:

$$u_f(k) = U(k) * Gu, \quad (5)$$

where $U(k)$ and Gu denote the controller output and the scaling factor of the controller output. In the paper, the triangular membership function is applied to define the fuzzy sets of the inputs and the output, as Fig. 4 illustrated. Three linguistic fuzzy sets are applied for the input and output variables. The control rules are illustrated in Table 1. The "max-min" and "center of gravity" methods are adopted for fuzzy inference logic and defuzzification algorithm.

3.2 PD control

The model of the pneumatic servo control system is identified and similar to the type-one system⁽¹⁸⁾. The steady state error for type-one system with the step input is zero. So, the integrator hasn't been used to design a PID controller in the paper. An error $e(k)$ is defined between the desired value $r(k)$ and position output $y(k)$ of control system.

$$e(k) = r(k) - y(k). \quad (1)$$

The PD control algorithm used in this study can be written as

$$u_f(k) = Kp * e(k) + Kd * (e(k) - e(k-1)) / T_s, \quad (2)$$

where Kp is the proportional gain, Kd is the derivative gain, and T_s is the sampling time.

3.3 Friction force of pneumatic cylinder

The relationship between the friction force and the cylinder velocity is shown in Fig. 5. The variables F_{max} and V_c represent the maximum static friction force and the critical velocity which the cylinder occurred the stick-slip phenomenon, respectively. A

Fig. 5 Pneumatic cylinder characteristic of friction force vs. velocity

Fig. 6 Stick-slip phenomenon of the pneumatic cylinder at the low speed range

region of the low velocity is defined as $-V_c < V < V_c$. Outside this region, the friction force is an arbitrary function of velocity. In the low velocity range, the friction force cannot be measured and it may cause the stick-slip phenomenon of the cylinder, which was shown in Fig. 6. The stick-slip causes great difficulties for precision position control of a pneumatic cylinder. The static friction forces are unevenly distributed along the cylinder. In the paper, the static friction forces distribution with the piston position and the direction of its movement are also measured and illustrated in Fig. 7.

3.4 Characteristic curve of the servo valve

The characteristic curve of the servo valve is shown in Fig. 8. A dead-zone is in the neighborhood of the zero point as the operating range of the input electrical signal is from a to $-b$ voltage.

3.5 Velocity compensator design

The velocity compensation signal, which approximates full-wave rectification signal, is designed according to characteristic curve of the valve and the relationship between the friction force and the velocity to reduce the effects of friction force during the fine-tuning process. The algorithm of the compensation signal is defined as follow:

Fig. 7 Static friction force at different position of cylinder

Fig. 8 Characteristic curve of the servo valve

$$u_v(k) = u_A(k) + u_B(k), \quad (6)$$

where $u_A(k)$ is an offset of compensation signal and $u_B(k)$ is the velocity compensation signal.

For the $u_A(k)$ signal, it is designed to compensate the dead-zone of the valve according to characteristic curve of the valve. It is decided as Eq. (7)

$$u_A(k) = \begin{cases} a, & \text{if } e(k) > 0 \\ -b, & \text{if } e(k) < 0, \end{cases} \quad (7)$$

For the $u_B(k)$ signal, the velocity compensation signal is designed to overcome the stick-slip at low speeds motion process. The signal $u_B(k)$ is expressed as Eq. (8).

$$u_B(k) = \begin{cases} (u_{\max} - V(k) \times (u_{\max} - u_{\min}) / V_c) \\ \quad \times |\sin(\omega k T_s)|, & \text{if } V(k) > 0 \\ (-u_{\max} - V(k) \times (u_{\max} - u_{\min}) / V_c) \\ \quad \times |\sin(\omega k T_s)|, & \text{if } V(k) < 0, \end{cases} \quad (8)$$

where $u_{\max}$ and $u_{\min}$ are the control voltage, which are sent to servo valve when the cylinder overcome the maximum static friction force (as Fig. 8 illustrates) and the cylinder velocity is V_c , respectively. And, the value of ω is decided according to the natural frequency of the system.

Fig. 9 Relationship between amplitude and velocity

The amplitude of the signal $u_B(k)$ is designed according to the relationship between the friction force and velocity. The relationship between amplitude and velocity is shown in Fig. 9. When the cylinder is at stop state and the error is not uniform zero, the compensation signal in Eq. (8) is designed to overcome the maximum static friction force by using the maximum amplitude of the signal $u_B(k)$. After overcoming the maximum static friction force, the amplitude is reduced instantaneously according to the velocity. Therefore, the stick-slip phenomenon can be improved and the pneumatic cylinder is maintained between move and stop instantaneously.

4. Experimental Results

The air supply pressure is set to be 5 bar, the sampling time is chosen to be 20 ms. The stroke of pneumatic cylinder is 100 mm. The resolution of the linear digital scale is 20 nm. According to the paragraphs 3.5 velocity compensator design method, the compensation signal is directly added to the conventional PD and Fuzzy control signal, respectively. The control parameter values of Kp and Kd are obtained to be 0.15 and 0.01, respectively. The scaling factors of fuzzy controller are decided according to the experience and the reasonable mapping range into the membership function. The scaling factors Ge , Gce and Gu are chosen to be 0.8, 1 and 1.2, respectively. The various experimental results are shown below.

4.1 Step input

For centimeter step displacements, Fig. 10 shows the time responses of the pneumatic table position control using PD controller and velocity compensation signal with the different step input. Figure 11 shows the time responses of the pneumatic table position control using fuzzy controller and velocity compensation signal. Generally, the transient responses of PD and fuzzy controller are different, but in the study Fig. 10 and Fig. 11 have shown that the experimental results are almost the same for both of the PD controller and fuzzy controller in the pneumatic control

Fig. 10 Time responses of the pneumatic table position control using PD controller and compensation signal under the different commands

Fig. 11 Time responses of the pneumatic table position control using fuzzy controller and compensation signal under the different commands

system, because both of the transient responses are constrained by the limit of response speed of the linear digital scale, which maximum traveling speed is 15 mm/s. Therefore, the control signals of both controllers are relative saturated and the same at the beginning responses. Until the output position approaches the desired command, both controllers have the control function at the stage and the velocity compensation signal plays an important role for the control system.

4.2 Step input under loading

For the study of carrying loading, Fig. 12 shows the time responses of the pneumatic table position control using fuzzy controller and compensation signal under carrying 5 kg and 10 kg, respectively. The

Fig. 12 Time responses of the pneumatic table position control under carrying 5 kg and 10 kg loading, respectively

Fig. 13 Multi-step responses of the pneumatic table with 1 m step displacement under carrying 5 kg and 10 kg loading, respectively

table can still reach the positioning accuracy of 20 nm under carrying different loading. But, the time which the table accomplishes the nanometer position is slower for the heavier loading, because the heavier loading has the larger friction force.

4.3 Small multi-step input

In the experiment, the multi-step responses of the fine position control with a small displacement under carrying different loading were studied. The experiments are executed by using the conventional fuzzy control with the designed compensation signal. Figure 13 shows the multi-step responses of the pneumatic table with 1 μ m step displacement under carrying 5 kg and 10 kg, respectively. All steady state errors are still within ± 20 nm range.

5. Conclusions

Through the above experimental results, the

several advantages of the pneumatic table and controller can be described in the following:

(1) In the paper, the designed velocity compensation signal is very important, which is combined with the conventional PD controller and simple fuzzy controller. Due to the characteristic of the system sensor, the control effects of the pneumatic table are nearly the same and successful. The positioning accuracy of the pneumatic servo has great breakthrough; also, it can reach the nanometer order (20 nm) by using the proposed compensation technique.

(2) The cost of the designed pneumatic table is lower than the other nanometer positioning actuators such as piezoelectric actuator, ultrasonic motor, etc.; and, the table can be controlled in large operation range from centimeter step displacement to nanometer step displacement.

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