3B1-1

Proceedings of the 6th JFPS International
Symposium on Fluid Power, TSUKUBA 2005
November 7-10, 2005

DEVELOPMENT OF AN INTELLIEGNT PNEUMATIC-PIEZOELECTRIC HYBRID SERVO POSITIONING SYSTEM WITH HIGH RESPONSE, LARGE STROKE AND NANOMETER ACCURACY

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ABSTRACT

This investigation aims to develop an intelligent hybrid pneumatic-piezoelectric servo positioning system with high response, large stroke and nanometer precision. The rodless pneumatic cylinder serves to position in coarse stroke and the piezoelectric (PZT) actuator compensates fine stroke. Thus, the overall control systems become a dual-input single-output (DISO). Although the rodless pneumatic cylinder has relative higher friction force, it has the advantage of mechanism for multi-axes development. In order to develop an intelligent controller, self-organizing fuzzy sliding mode control theory (SOFSMC) is proposed here for the DISO system. SOFSMC is based on fuzzy sliding mode control (FSMC) combining with self-organizing strategy. Thus, SOFSMC has simple fuzzy rule base and on-line self-organizing ability. Besides, in order to reduce the coupling effects of the DISO system, a decoupling controller is developed. The experimental results clarify that the servo pneumatic-piezoelectric control system can achieve excellent positioning response and accuracy of 20 nm with high response for maximum stroke of 250 mm and multi-step positioning.

KEY WORDS

pneumatic-piezoelectric, positioning control, large stroke and nanometer accuracy and self-organizing fuzzy sliding mode control.

INTRODUCTION

Pneumatic servo positioning control systems have the advantages of high response, easy maintenances and cleanliness. However, the non-linearity of pneumatic systems, such as friction force, restricts the positioning accuracy. Research about the field of pneumatic servo control has been developed since 1954. Control algorithms, such as PID control, state space control and adaptive control of pneumatic servo control system were developed via higher speed microcomputers in 1980s. However, the robustness and the control accuracy of pneumatic cylinders in the past research are still unsatisfactory due to the high non-linearity and the compressibility of compressed air, so that till now pneumatic servo control is still not widely used. Some research [7,8] paid attentions to the influence of non-linearity on pneumatic servo control systems, such as stick-slip effect. The stick-slip effect, which results mainly from friction force of pneumatic cylinders, makes pneumatic cylinders unable to keep steady motion in low velocity conditions. Therefore, the non-linear problems complicate pneumatic servo control so that modern control strategies are essential. Self-tuning adaptive control was used in the position control of pneumatic servo cylinders for adapting control parameters on-line such that the positioning accuracy of 5 μm in no loading conditions was achieved [5]. The additional velocity feedback is inserted in the position control for compensating the influence of friction force. [15].

Because the characteristics of the servo pneumatic driving seriously restrict the positioning accuracy, it can be improved by means of combining with other actuators. Piezoelectric actuators are developed in recent years and already applied in many different fields. One of the application examples is the hard disk reader control system [9]. The piezoelectric actuator works as the second stage positioning combined with an electric motor that operates as the first stage positioning for improving the positioning accuracy of the hard disk driving. The overall system is a dual input single output (DISO) control system. So, the PQ-method was introduced to simply the DISO control system into a single-input single-output (SISO) system, but mathematical models of the two subsystems are necessary for this method. Besides, the piezoelectric actuator, which generates high frequency impact force by open loop control, is combined with the servo pneumatic driving system in order to reduce the friction force effects. The total stroke and the positioning accuracy can reach 2 mm and 1 μm [4]. The research group of Chiang [3,16] has engaged in pneumatic-piezoelectric servo positioning control since 2000 and has some results [3,16]. The pneumatic cylinder with double rod is combined with piezoelectric actuator can achieve 180mm stroke and 0.1 μm that is the minimum resolution of the linear scale used in this paper. From Reference [3,16], the possibility of the nanometer accuracy of the pneumatic-piezoelectric for large stroke could be expected.

This study aims to develop an intelligent hybrid pneumatic-piezoelectric actuator for high response, large stroke of 250 mm and high precision of 20nm positioning control, which includes a pneumatic servo cylinder and a piezoelectric actuator. The servo pneumatic cylinder serves to coarse positioning with high speed and large stroke; the piezoelectric actuator positions in precision range for compensating the influence of friction force and for achieving large stroke, high response and high positioning accuracy at the same time. The overall control systems have complex dual-input single-output (DISO), and coupling interaction exists between the two subsystems. Therefore, a new control strategy of decoupling self-organizing fuzzy sliding mode control (DSOFSMC) is developed in this investigation. Self-organizing fuzzy sliding mode control (SOFSMC) is used for designing the two positioning controller and a decoupling compensator for on-line weighting the two subsystems according to control error and error rate.

TEST RIG LAYOUT

The new high precision pneumatic-piezoelectric hybrid positioning control system developed in this paper contains a pneumatic servo system and a piezoelectric servo system, as shown in Fig. 1. Table 1 specifies the main components.

Table 1 Specification of the test rig

Components	Specifications
Rodless cylinder	Diameter 25mm Stroke 317mm
PZT actuator	Stroke 90 μm Freq. 15kHz Voltage 0~150 V
PZT amplifier	Input : 0~5V Gain: 30
ADDA card	12bit D/A D/I, D/O
Servo valve	5/3, input: 0~10v
Linear scale	Range: 450mm Accuracy 20nm
Counter card	3x 24-bits counters 1.0MHz Input Rate
Compressor	5HP、0.38KW

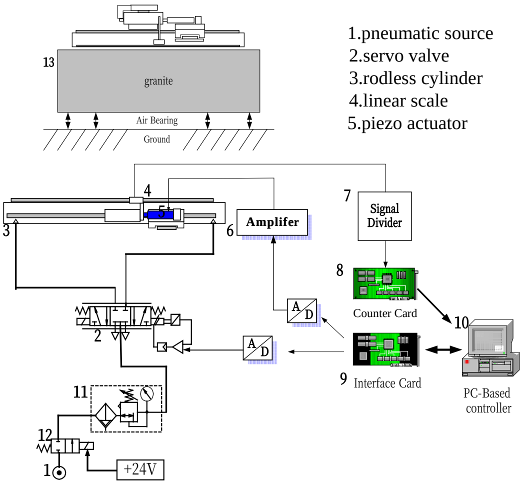

Figure 1 Test rig of pneumatic-piezoelectric hybrid positioning system

The pneumatic servo system mainly consists of a pneumatic source, a servo valve and a double acting rodless cylinder. In order to improve the positioning accuracy of the pneumatic cylinder, a piezoelectric actuator with a stroke of 90 μm is mounted on the pneumatic cylinder via an adaptor. Hence, the pneumatic cylinder and the piezoelectric actuator drive the loading mass simultaneously. In addition, a linear encoder with the resolution of 20nm is necessary for measuring the overall position, which is the sum displacement of the pneumatic cylinder and the piezoelectric actuator. The measuring signals of the linear encoder are fed back to the control computer via a decoder and a digital I/O converter. The control signals of the pneumatic servo valve and the piezoelectric actuator are given from the control PC with the sampling time of 1 ms via D/A converters and enlarged by a servo amplifier and a piezoelectric amplifier respectively.

Therefore, the overall control systems have dual-input single-output, which is shown in Fig. 2 to illustrate the complex block diagram of the overall control system. The servo pneumatic cylinder serves to coarse positioning with high speed and large stroke and the piezoelectric actuator positions in fine stroke for compensating the influence of friction force. The position control of the two control systems, namely pneumatic servo system and piezoelectric servo system, performs at the same time. Therefore, the integrated overall system can achieve large stroke, high response and high positioning accuracy simultaneously.

DECOUPLING SELF-ORGANIZING FUZZY SLIDING MODE CONTROL

In this study, decoupling self-organizing fuzzy sliding mode control (DSOFSMC) is developed for solving the DISO control problem, decreasing the fuzzy rule numbers and on-line self-organizing the fuzzy rules. DSOFSMC contains, self-organizing fuzzy sliding mode control (SOFSMC) and decoupling controller. Figure 3 schematically depicts the control block diagram of the SOFSMC.

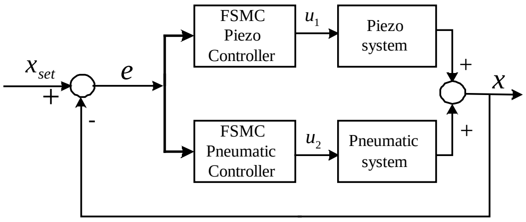

Figure 2 Block diagram of decoupling dual-input single-output (DISO) system for pneumatic-piezoelectric hybrid positioning control system

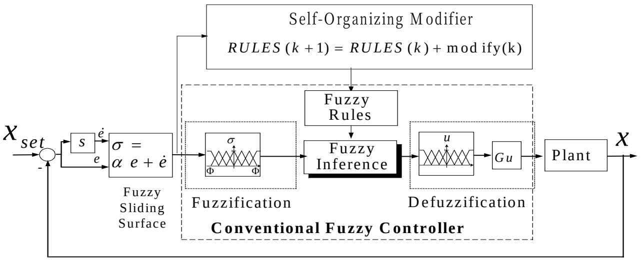

Figure 3 Self-organizing fuzzy sliding mode control

Self-organizing fuzzy sliding mode control

Consider the state vector of a second order system as

$$\mathbf{x} = [x, \dot{x}]^T \tag{1}$$

The tracking error of the state vector is defined as

$$\mathbf{e} = \mathbf{x_d} - \mathbf{x} = [e, ec]^T = [x_d - x, xc_d - xc]^T \tag{2}$$

where x_d and xc_d indicate the desired output and the desired output change rate. The fuzzy sliding surface is described as

$$\sigma = (ec + \alpha \cdot e) = ZERO \tag{3}$$

where α is a positive constant. The fuzzy sliding surface $\sigma = ZERO$ is a straight line with slope α in the phase plane, as shown in Fig. 3(a). The sliding surface can be divided into 7 sections by the membership function set of $M(\tilde{\sigma}) = \{NB, NM, NS, ZR, PS, PM, PB\}$. The membership function set for the control input u is defined as $M(\tilde{u}) = \{NB, NM, NS, ZR, PS, PM, PB\}$. Therefore, the fuzzy sliding mode control can reduce the fuzzy rules into 7 rules via the fuzzy sliding surface σ, shown in Fig. 3. The Mamdani method is used in the fuzzy inference and the centroid method is used for defuzzification.

The self-organizing modifier of the SOFSMC is designed by self-organizing fuzzy control theory for on-line adapting the fuzzy rules according to the variations of working points and external disturbance. The detailed derivation of the self-organizing modifier is shown in [17].

the i^{th} rule can be modified by the modifying value Δu through an exciting intensity w_i

$$\begin{aligned} u_i(nT+T) &= u_i(nT) + w_i \cdot \Delta u \\ &= u_i(nT) + w_i \frac{\gamma_s}{M_s} \sigma(nT) \qquad , \quad i = 1, \cdots 7 \end{aligned} \tag{4}$$

where the exciting intensity w_i is the grade of

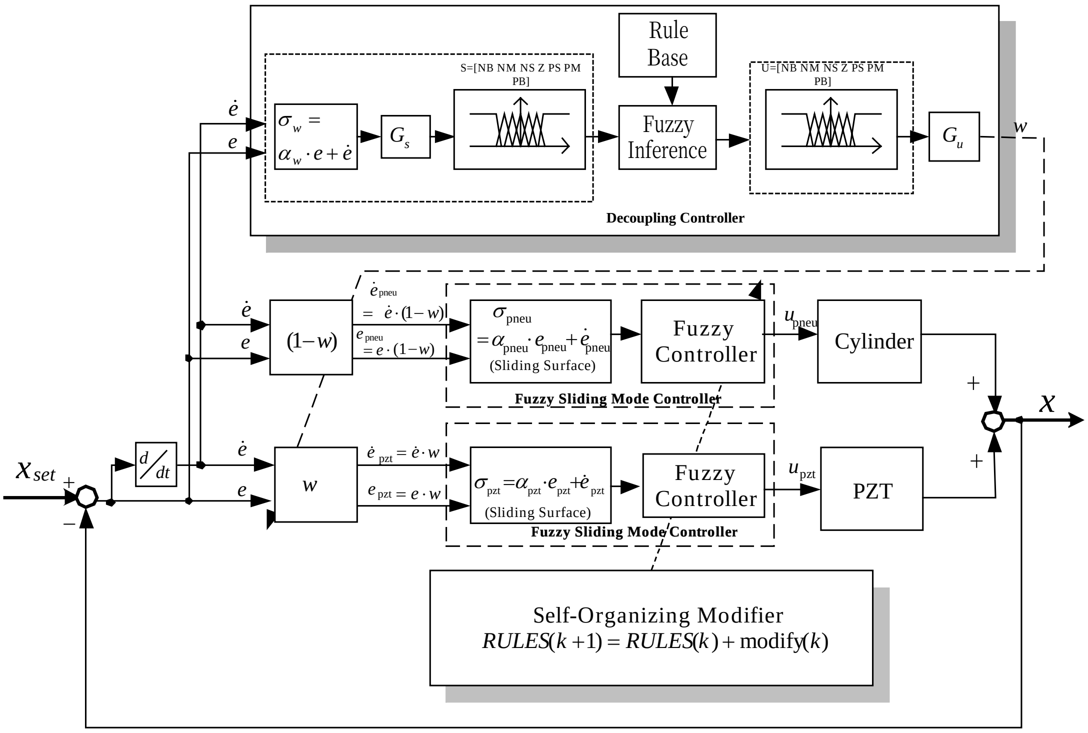

Figure 4 Decoupling self-organizing fuzzy sliding-mode control

membership. According to the normalized fuzzy sliding surface $\tilde{\sigma}$, two rules, the i^{th} and $(i+1)^{\text{th}}$ rules, are excited and modified at the same time. Therefore, the fuzzy rules of the SOFSMC can be described as

$$\text{RULES}_i(nT+T) = \text{RULES}_i(nT) + w_i \frac{\gamma_s}{M_s}\sigma(nT) \qquad (5)$$

Decoupling controller

In order to solve the structure coupling interference, the decoupling controller designed by SOFSMC is merged. The output of the decoupling controller can be considered as weighting functions for the two subsystems in the DISO system.

Controller design for DISO using DSOFSMC

Figure 4 shows the control strategies to solve the DISO system using DSOFSMC. The overall systems contain the pneumatic controller, the piezoelectric controller and the decoupling controller that are designed using SOFSMC.

EXPERIMENTAL RESULTS

Figure 5 shows the test results of the positioning control with 250 mm stroke in the pneumatic-piezoelectric positioning system using SOFSMC and DSOFSMC respectively. Figures 5A describes the control performance of SOFSMC and Figs.5B show that of DSOFSMC. The step response of the positioning control, control input of pneumatic system, control input of piezoelectric system and the error zooming are shown respectively. The steady state error of the SOFSMC can reach about 0.1μm with high frequency vibrations. Through the compensation of the decoupling controller, the steady state error of the DSOFSMC is smooth and he settling time (e<0.5μm) is 3.695 sec and the steady state error can reach 20nm, as shown in Fig.5B(c).

The rising time in the test rig is limited by the transformation speed of the counter card. If the counter card with higher speed and support of real-time demand is used, the rising time can be improved significantly.

CONCLUSIONS

A novel large stroke and high precision pneumatic-piezoelectric hybrid positioning control system is well developed and verified experimentally in this study, which contains a pneumatic servo cylinder serving for high speed, large stroke positioning and a piezoelectric actuator positioning in fine stroke. The two controllers work in parallel and the two position outputs are added in cascade. Such complex dual-input single-output systems are solved by the DSOFSMC both for the pneumatic cylinder positioning control system and the piezoelectric positioning control system as well as the decoupling controller. The DSOFSMC developed in this paper incorporates fuzzy sliding mode

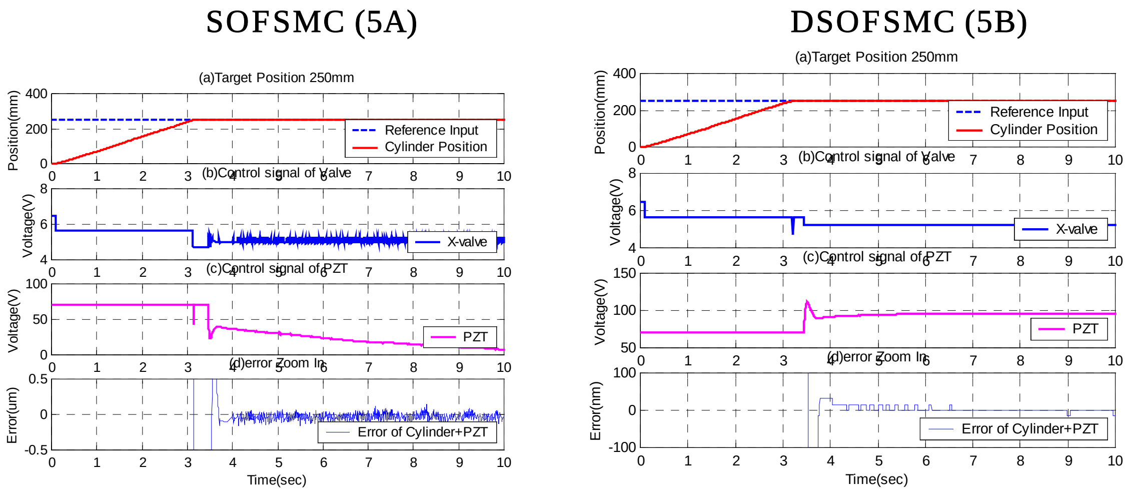

Figure 5 Experimental comparison of pneumatic-piezoelectric positioning control with SOFSMC and DSOFSMC (a) step response of 250 mm, (b) pneumatic control input, (c) PZT control input, (d) error zoom.

control, self-organizing modifier and decoupling controller. The test results show that the developed pneumatic-piezoelectric positioning control system can achieve 20nm accuracy for 250 mm with high response.

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