POSITION CONTROL OF A PNEUMATIC SERVO CYLINDER USING FUZZY-SLIDING SURFACE CONTROLLER

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Abstract

In this paper, both the PID and fuzzy-sliding surface controller are applied to the position control of a proportional-valve-controlled pneumatic rodless cylinder. Because of the highly nonlinear basic equations of pneumatic systems, the modelling of such a pneumatic servo is excluded from this paper. Besides, it is usually quite difficult to obtain a satisfactory position control of a pneumatic rodless cylinder because an apparent dead-zone in the response curve during the starting phase always appears. The dead-zone signifies a serious response delay. One reason for such a response dead-zone is the stick-slip friction and the nonlinear deadband of the proportional valve. In this paper, therefore, the chattering output of sliding mode control is introduced to reduce the effect of stick-slip and the nonlinear fuzzy-logic-controller is employed to control this unmodelled and highly nonlinear system. Accordingly, the fuzzy-sliding surface controller is proposed, which is exactly the combination of the fuzzy-logic-controller with the sliding mode controller. There are two key features of this control scheme. One is the easier implementation of the controller as compared with that of the conventional fuzzy-logic-controller because the number of controller input is reduced by half. The other is the ability to reduce the response dead-zone during the starting phase. Finally, a series of experiments are carried out and the experimental results prove that the fuzzy-sliding surface controller is superior to the conventional PID controller.

Keywords: fuzzy-sliding surface control, pneumatic rodless cylinder, position control, stick-slip

1 Introduction

Nowadays, applications of pneumatic systems may be found almost in the entire engineering field, especially in the field of the process control and automation industries. Some significant features of pneumatic systems are the ready availability of air, the ability to work at high temperature, and the easy maintenance, etc. Conventional position control of a pneumatic cylinder is achieved by using the limit switches and directional control valves. In this paper, however, a pneumatic proportional directional control valve is applied to the feedback position control of a pneumatic rodless cylinder. Such a system is called the pneumatic servocylinder in this paper. Relative to the former open-loop pneumatic control system, the latter closed-loop pneumatic servo possesses the more rapid output response with greater accuracy.

To precisely control the position of the pneumatic servocylinder, an appropriate controller must be designed in advance because the closed-loop system itself raises the issue of stability. In this paper, both the PID and fuzzy-sliding surface controller are applied to the position control of the pneumatic servocylinder. During the past two decades, the fuzzy-logic-controller has been successfully applied in many fluid power servos. It is especially noticeable that the combination of conventional fuzzy-logic-controller with other algorithms, like the sliding mode, neural-network, etc., receives more and more attention in the development of intelligent controller (Chen, 1991), (Hwang, 1994, 1996), (Fung, 1997), (Chen, 2002).

In particular, sliding mode control, also known as variable structure control, having good disturbance rejection property as well as being robust against parameter variations, has been widely accepted as an efficient method for controlling systems in the face of uncertainties. One of interesting features of sliding control is the discontinuous nature of the control action which switches two distinctively different system structures to generate a desired system motion, called sliding mode, on a prescribed sliding surface. However, due to the switching nature in practice it raises the issue of chattering. Chattering is usually undesirable because

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it results in high wear of moving mechanical parts (Chen, 2002). To suppress chattering, various compensation strategies have been proposed. For example, sliding control with time-varying boundary layers (Slotine, 1984), (Hwang, 1996), soft switching strategy sliding control (Chen, 2002), etc. In this paper, however, the nature of chattering is preserved because it is expected to be able to reduce the effect of stick-slip friction inside the proportional valve.

Generally speaking, it is quite laborious to obtain a smooth and satisfactory position control response of a pneumatic rodless cylinder because an apparent dead-zone is inevitable during the starting phase. Such a dead-zone results in a serious response delay. There are two major causes of the dead-zone in the response curve. One is the relatively larger static friction force arising from the seals inside the rodless cylinder. And the other is the stick-slip friction and the nonlinear deadband of the proportional valve. However, it is generally difficult to eliminate the effect of the static friction force inside the rodless cylinder. On the contrary, effects of the nonlinearities of the proportional valve may be reduced by the proposed fuzzy-sliding surface controller.

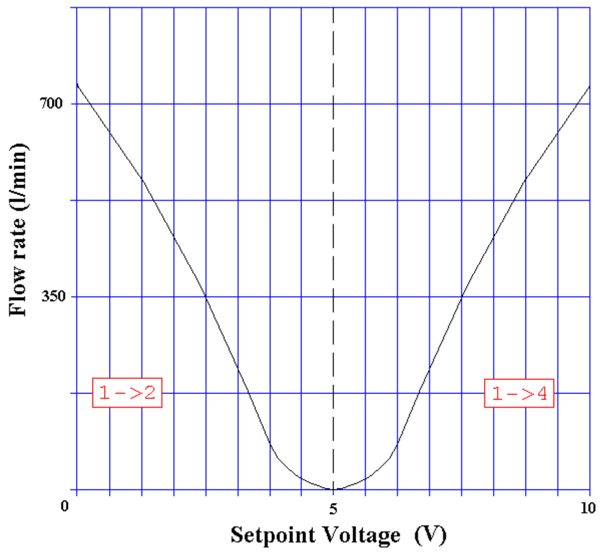

Fig.1: *Static performance of the chosen pneumatic proportional valve*

The stick-slip friction between the spool and valve body inside the proportional valve may give rise to the unsatisfactory position control response (Merritt, 1967). In this paper, therefore, the sliding mode controller is introduced. The basic idea is to take advantage of its chattering output. The chattering output of the sliding mode controller is basically a signal with high frequency but small amplitude, which is very similar to the dither signal used in hydraulic servo systems. Besides, Fig. 1 shows the static performance of the chosen pneumatic proportional valve, in which a strong variation in the flow gain around the 5 V zone is quite obvious. This is a big problem in the position control of the cylinder and is assumed to be the nonlinearity of deadband because of the similarity. Thus, in addition to the sliding mode controller, the nonlinear fuzzy-logic-controller is also introduced to control this unmodelled and highly nonlinear pneumatic system. Consequently, we propose the fuzzy-sliding surface controller, which is exactly the combination of the fuzzy-logic-controller with the sliding mode controller. The conventional fuzzy two-input control is usually good for most applications. However, the proposed fuzzy-sliding surface controller needs only one input signal, which signifies easier implementation of the controller and less computational time required. In the following, the test bench of the pneumatic servocylinder is firstly outlined.

2 Test Bench of the Pneumatic Servo Cylinder

Figure 2 shows the pneumatic circuit of the test device. The schematic layout of the test bench is shown in Fig. 3. A proportional pneumatic directional control valve (Festo, MPYE-5-1/8) is employed to control the position of a pneumatic rodless cylinder (Festo, DGP-25-120). The piston diameter and the stroke of the pneumatic rodless cylinder are 25 mm and 120 mm, respectively. To sense and feedback the actual position of the cylinder, a linear position transducer (potentiometer) is attached to the output plate of the cylinder. Besides, a filter-regulator-lubricator unit is located at the test bench to condition and regulate air from the main supply line. In this paper, the supply air pressure is regulated to be 6 bar. In addition, all the control and data-acquisition tasks are integrated in a PC-based software controller. The block diagram of the control system is shown in Fig. 4.

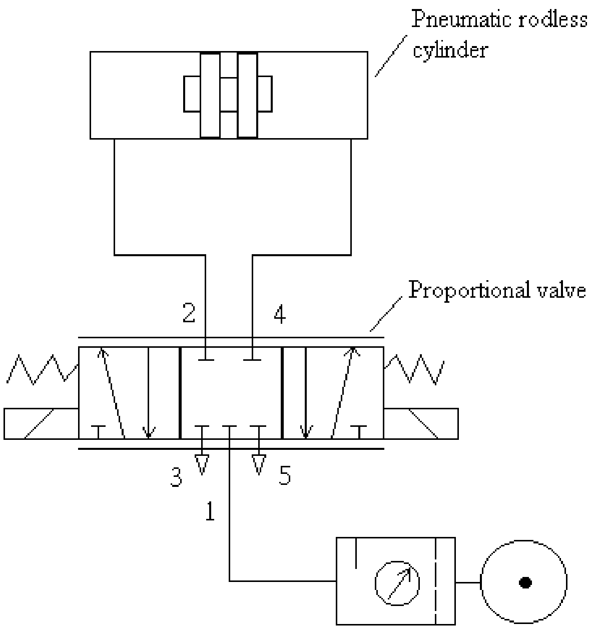

Fig. 2: *The pneumatic circuit of the test device*

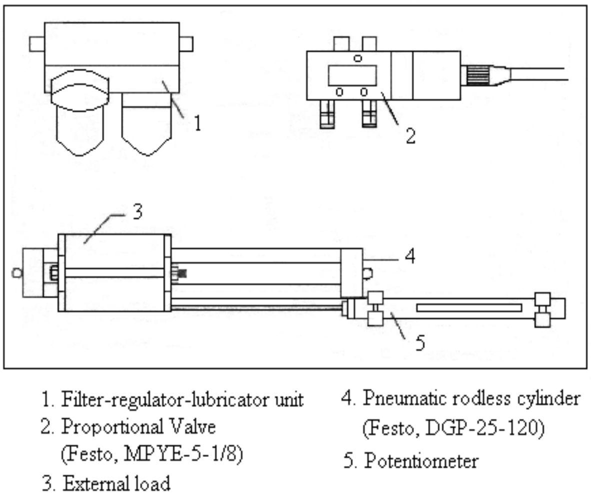

Fig. 3: *The schematic layout of the test bench*

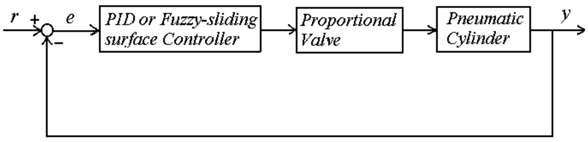

Fig. 4: *The block diagram of the control system*

3 Experimental Results using the Conventional PID-Controller

The continuous-time, or analog PID-controller can be expressed as:

$$u(t) = K_{\text{P}} \left\{ e(t) + \frac{1}{T_{\text{I}}} \int_0^t e(\tau)\, d\tau + T_{\text{D}} \frac{de(t)}{dt} \right\} \quad (1)$$

Equation 1 can be transformed into the discrete-time formulations

$$u(k) = u(k-1) + \Delta u(k), \quad (2)$$

$$\Delta u(k) = K_{\text{P}}\left[e(k) - e(k-1)\right] + K_{\text{I}} e(k)$$

$$+ K_D\left[e(k) - 2e(k-1) + e(k-2)\right], \quad (3)$$

where

$u(k)$: actuating signal,
$\Delta u(k)$: actuating signal change,
$e(k)$: error signal,
$e(k\text{-}1)$: error signal at previous $(k\text{-}1)_{\text{th}}$ instant of sampling,
$e(k\text{-}2)$: error signal at previous $(k\text{-}2)_{\text{th}}$ instant of sampling,
K_{P}: gain of the proportional controller,
K_{I}: gain of the integral controller,
K_{D}: gain of the derivative controller.

The suggested gains for the PID-controller can be determined by Ziegler-Nichols method (Ziegler, 1942), which is described briefly as follows. First, the gain of a simple P-controller is slowly increased until the system response is marginally stable. If this proportional gain is denoted by K_{CP} and the period of the sustained oscillation is found to be T_{C}, thus the suggested gains for the PID-controller can be derived.

$$K_{\text{P}} = 0.6\, K_{\text{CP}}, \quad (4)$$

$$K_{\text{I}} = K_{\text{P}} / 0.5\, T_{\text{C}}, \quad (5)$$

$$K_{\text{D}} = 0.125\, K_{\text{P}} T_{\text{C}}. \quad (6)$$

Basically, Eq. 4 to 6 give a set of suggested gains for the PID-controller. After fine adjustments, however, the optimal gains are found and summarized in Table 1.

Table 1: The optimal gains for the PID-controller

Gain	20 mm	40 mm	50 mm
K_P	0.033	0.023	0.021
K_I	0.0001	0.0001	0.0001
K_D	0.0003	0.0001	0.0001

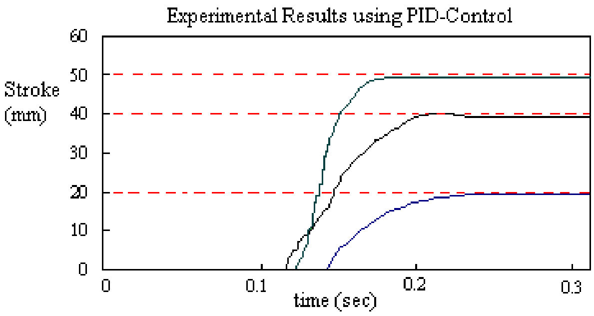

Fig. 5: *Experimental position control responses of the pneumatic servocylinder using PID-controller*

Figure 5 shows the experimental position control responses of the pneumatic servocylinder to three different stroke settings. Obviously, the responses are non-smooth and unsatisfactory because of the noticeable dead-zone during the starting phase. As stated previously, such a dead-zone arises mainly from the large static friction of the rodless cylinder and the stick-slip friction plus nonlinear deadband inside the proportional valve. To suppress the response dead-zone, the gain of the proportional controller, K_{P}, may be increased. However, higher gain may also produce a much larger overshoot that is normally not acceptable. In the following section, therefore, we propose and describe the fuzzy-sliding surface controller, which is proved to be the better solution to surmount all the nonlinearities.

4 Theory and Design of Fuzzy-sliding Surface Controller

The combination of fuzzy-logic-controller with sliding mode controller results in the fuzzy-sliding surface controller, which possesses the advantages of less number of input signal needed and the ability to control nonlinear systems more effectively. Figure 6 shows the schematic block diagram of the fuzzy-sliding surface controller. The error signal, $e(k)$, and the error signal change, $\Delta e(k)$, are denoted by x_1 and x_2 respectively, that is

$$x_1 = e(k) = r - y, \tag{7}$$

$$x_2 = \Delta e(k) = e(k) - e(k\text{-}1), \tag{8}$$

where

r: command input, y : actual position of the cylinder.

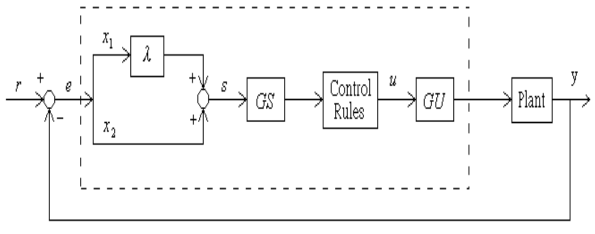

Fig. 6: *Schematic block diagram of the fuzzy-sliding surface controller*

Unlike the conventional controller, there are four procedures involved in the implementation of a fuzzy-sliding surface controller, fuzzification of the input, fuzzy inference based on the knowledge, the defuzzification of the rule-based control signal and the determination of the scaling factors.

(a) Fuzzification

Instead of two input signals fed into the conventional fuzzy-logic-controller, the fuzzy-sliding surface controller need only one input signal, s, which is the combination of the parameters x_1 and x_2.

$$s = \lambda x_1 + x_2. \tag{9}$$

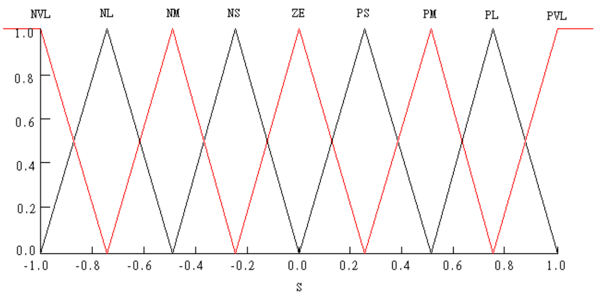

Fig. 7: *Triangular fuzzy membership function for the input signal*

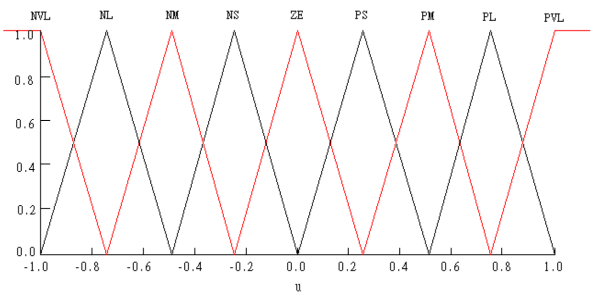

Fig. 8: *Triangular fuzzy membership function for the output signal*

Figure 7 shows the triangular fuzzy membership function for the input signal to determine the degree of input. On the other hand, the input signal, s, also represents the switching function of the sliding mode controller. Similarly, Fig. 8 shows the triangular fuzzy membership function for the output signal, u, of the fuzzy-sliding surface controller.

(b) Inference

The inference process consists of nine rules driven by the linguistic values of the input signal, s. There are:

- If s is very large-positive, then u is very large-positive.
- If s is large-positive, then u is large-positive.
- If s is medium-positive, then u is medium-positive.
- If s is small-positive, then u is small-positive.
- If s is zero, then u is zero.
- If s is small-negative, then u is small-negative.
- If s is medium-negative, then u is medium-negative.
- If s is large-negative, then u is large-negative.
- If s is very large-negative, then u is very large-negative.

(10)

It is obvious that the control rules for a fuzzy-sliding surface controller are one dimensional IF-THEN statements rather than the look-up table consisting of two dimensional control rules for a conventional fuzzy-logic controller. Consequently, less computational time is required.

(c) Defuzzification

The defuzzification is to transform control signal into exact control output. In the defuzzification, the method of center of gravity is used.

$$u = \frac{\sum_{i=1}^{n} W_i B_i}{\sum_{i=1}^{n} W_i} \tag{11}$$

where

u: output of the fuzzy-sliding surface controller,
W_i: the degree of firing of the i_{th} rule,
B_i: the centroid of the consequent fuzzy subset of the i_{th} rule.

(d) Determination of scaling factors, *GS* and *GU*

Before the input signal, s, is fed into the fuzzy-sliding surface controller, it has to be multiplied by the scaling factor, *GS*, so that the product is normalized in the interval [-1, 1]. Similarly, the output signal of the fuzzy-sliding surface controller, u, is multiplied by the scaling factor, *GU*, to meet the actual operating voltage range, 0-10 V, of the proportional valve. It is worth mentioning that the values of the factors, *GS* and *GU*, affect the system response greatly.

5 Experimental Results using the Fuzzy-sliding Surface Controller and Discussions

There are three unknown parameters involved in the design of the fuzzy-sliding surface controller, the parameter λ, the scaling factors *GS* and *GU*. In general, larger value of λ results in a faster but more oscillatory response. After some try-and-errors, the best switching function is found to be

$$s = 3x_1 + x_2 = 3e(k) + \Delta e(k) \qquad (12)$$

From the control rules (10), it is noticeable that the output, *u*, is always positive if the input, *s*, is greater than zero. Similarly, a negative input generates only a negative output. During the phase of sliding mode on the sliding surface, sustained switching between positive s ($s > 0$) and negative s ($s < 0$) results in the chattering output. Since the sampling time of the controller is set to be 5 ms, the maximal frequency of the output chattering may be 200 Hz, which agrees well with the frequency of the usual dither signal.

As mentioned previously, the values of the scaling factors, *GS* and *GU*, affect greatly the system response. On the other hand, the fuzzy-sliding controller is basically a PD-controller. The design of the scaling factors is similar to the design of a PD-controller. Accordingly, after some real-time adjustments, the best values for the scaling factors are determined and shown in Table 2. Similar to Fig. 5, experimental results of the position control of the pneumatic servocylinder using the fuzzy-sliding surface controller are shown in Fig. 9. In addition, Fig. 10-12 show the comparisons of the position control responses using the two different control algorithms. Obviously, smaller response dead-zone in the control curves is obtained by using the nonlinear fuzzy-sliding surface controller. Some quantitative comparisons of the control performance are summarized in Table 3, in which the delay time is defined as the time required to reach 50% of the final value. Apparently, the delay time by using the nonlinear fuzzy-sliding surface controller is much shorter than that by using the linear PID-controller because the response dead-zone is reduced as shown in Fig. 10-12 and Table 3. This further proves that using the linear approach cannot properly compensate the stick-slip friction and nonlinear deadband of the proportional valve.

Table 2: The best values of the scaling factors

Scaling factor	20 mm	40 mm	50 mm
GS	0.0071	0.0035	0.0028
GU	2.17	2.52	2.67

Table 3: Some quantitative comparisons of the control performance

	20 mm		40 mm		50 mm	
	Delay time (sec)	Steady-State error (mm)	Delay time (sec)	Steady-State error (mm)	Delay time (sec)	Steady-State error (mm)
PID Control	0.163	0.847	0.149	0.781	0.138	0.717
Fuzzy-sliding Control	0.128	0.148	0.121	0.094	0.105	0.069

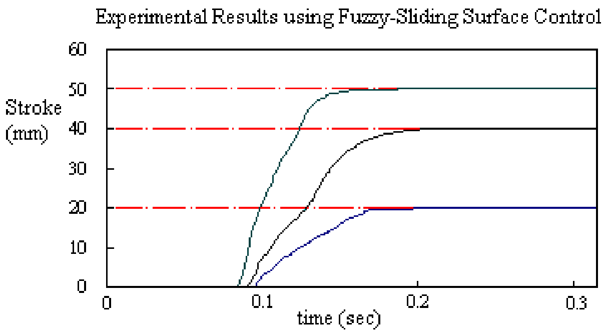

Fig. 9: *Experimental results of the position control of the pneumatic servocylinder using the fuzzy-sliding surface controller*

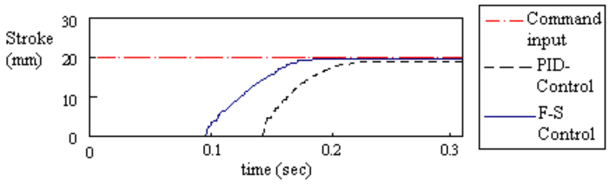

Fig. 10: *Control responses using PID and fuzzy-sliding surface control (command input: 20 mm)*

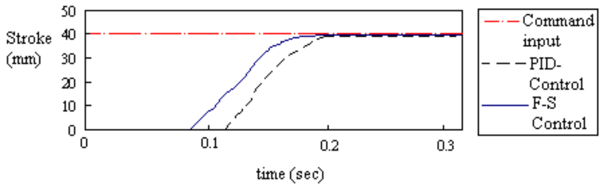

Fig. 11: *Control responses using PID and fuzzy-sliding surface control (command input: 40 mm)*

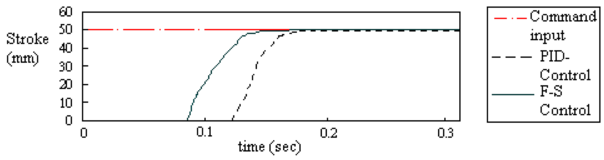

Fig. 12: *Control responses using PID and fuzzy-sliding surface control (command input: 50 mm)*

6 Conclusion

In this paper, we have successfully developed a fuzzy-sliding surface controller and applied this controller to the position control of a pneumatic servocylinder. Although the fuzzy-sliding controller is basically a PD-controller, one major difference between the linear PID- and nonlinear fuzzy-sliding controller is the dither-like chattering signal provided by the latter controller. Consequently, it is possible to obtain better control results by using the fuzzy-sliding controller. Experimental results have also shown that the fuzzy-sliding surface controller is superior to the conventional PID controller. In addition, four conclusions may be drawn from this research.

The proposed fuzzy-sliding surface controller possesses both the advantages of fuzzy-logic-controller and sliding mode controller.

The fuzzy-logic-controller provides a nonlinear approach, which is suitable to the control of the unmodelled and highly nonlinear pneumatic servo.

The generally undesirable chattering output of the sliding mode controller, on the contrary, contributes to overcome the stick-slip friction inside the proportional valve.

The response dead-zone in the position control curve is successfully reduced by using the proposed fuzzy-sliding surface controller.

Acknowledgment

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Nomenclature

B_i	The centroid of the consequent fuzzy subset of the ith rule	[-]
$e(k)$	Error signal	[mm]
$e(k\text{-}1)$	Error signal at previous (k-1)th instant of smapling	[mm]
$e(k\text{-}2)$	Error signal at previous (k-2)th instant of sampling	[mm]
GS	Scaling factor	[-]
GU	Scaling factor	[-]
K_P	Gain of the proportional Controller	[V/mm]
K_{CP}	Proportional gain for marginal Stability	[V/mm]
K_I	Gain of the integral controller	[V/smm]
K_D	Gain of the derivative controller	[Vs/mm]
r	Command input	[mm]
s	Input signal of the fuzzy-sliding surface controller	[-]
T_C	Period of the oscillation for marginal stability	[s]
u	Output of the fuzzy-sliding surface controller	[V]
$u(k)$	Actuating signal	[V]
$\Delta u(k)$	Actuating signal change	[V]
W_i	The degree of firing of the ith rule	[-]
y	Actual position of the Cylinder	[mm]
$\Delta e(k)$	Error signal change	[mm]

References

Backé, W. 1993. *Steuerungs- und Schaltungstechnik II*, Umdruck zur Vorlesung. RWTH Aachen, Germany.

Chen, H. M., **Su, J. P.** and **Renn, J. C.** 2002. A novel sliding mode control of an electrohydraulic position servo system. *IEICE Transactions on Fundamentals*, Vol. E85-A, No. 8, pp. 1928-1936.

Chen, P. C. and **Shih, M. C.** 1991. An experimental Study on the position control of a hydraulic cylinder using a fuzzy login controller. *JSME Int. J. Series C*, Vol. 34, No. 8, pp. 481-489.

Chern, T. L. and **Wu, Y. C.** 1991. Design of Integral Variable Structure Controller and Application to Electro-hydraulic Velocity Control. *IEE Proc. –D*, Vol. 138, pp. 439-444.

Diong, B. M. 1997. A sliding mode control approach to the benchmark problem for nonlinear control design. *Proc. IECON'97*, Vol. 1, pp. 68-72.

Fung, R. F., **Wang, Y. C.**, **Yang, R. T.** and **Huang, H. H.** 1997. A variable structure control with proportional and integral compensations for electrohydraulic position servo control system. *Mechatronics*, Vol. 7, pp. 67-81.

Ha, Q. P., **Nquygn, H. Q.**, **Rye, D. C.** and **Durrant-Whyte, H. F.** 1998. Sliding mode control with fuzzy tuning for an electrohydraulic position servo system. *IEEE Conf. Knowledge-Base Intelligent Electronic System*, Australia, pp. 141-148.

Hung, J. Y., **Gao, W.** and **Hung, J. C.** 1993. Variable Structure Control: A Survey. *IEEE, Trans. on Industrial Electronics*, Vol. 40, No. 1, pp. 45-55.

Hwang, C.-L. 1996. Sliding mode control using time-varying switching gain and boundary layer for electrohydraulic position and differential pressure control. *IEE Proc. Control Theory Applications*, Vol. 143, pp. 325-332.

Hwang, C.-L. and **Lan, C. H.** 1994. The position control of electrohydraulic servomechanism via a novel variable structure control. *Mechatronics*, Vol. 4, pp. 369-391.

Kim, S. W. and **Lee, J. J.** 1995. Design of a Fuzzy Controller with Fuzzy Sliding Surface. *Fuzzy Sets & Systems*, Vol. 71, No. 3.

Merritt, H. E. 1967. *Hydraulic Control Systems*. John Wiley and Sons Inc., New York.

Murrenhoff, H. 1999. *Grundlagen der Fluidtechnik Teil 2: Pneumatik*, Umdruck zur Vorlesung. RWTH Aachen, Germany.

Palm, R. 1992. Sliding Mode Fuzzy Control. *IEEE, International Conference on Fuzzy Systems*, pp. 519-526.

Slotine, J.-J. E. and **Li, W.** 1984. Sliding Controller Design for Nonlinear System. *Int. J. Control*, Vol. 40, pp. 421-434.

Su, W. C. and **Kuo, C. Y.** 2000. Variable Structure Control of a Rodless Pneumatic Servoactuator with Discontinuous Sliding Surface. *Proceeding of the American Control Conference*, pp.1617-1621.

Ziegler, J. G. and **Nichols, N. B.** 1942. Optimum Settings for Automatic Controllers. *Trans. ASME*, 64, pp. 759-768.

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