Design and Simulation of the Controller for Pneumatic Self-Balancing Hoist System

Liang Yang¹,², Peng Yin¹, Rong Yin²

¹ School of Mechanical and Automotive Engineering, South China University of Technology, Guangzhou 510640, China
² R&D Department, Guangzhou Hyetone Electromechanical Equipment Co., Ltd., Guangzhou 510407, China

Corresponding author’s e-mail address: 18814113085@163.com (Peng Yin), leonyounggod@msn.com (Liang Yang).

Abstract. The design of the controller of the pneumatic hoist system is the most important step in the whole work process. The quality of the design of the controller is directly related to the realization of the system. This paper elaborates the detailed design of the system in a few steps. Firstly, a set of optimal control parameters $k_p^*$, $k_i^*$, and $k_d^*$ are selected. Then the fuzzy self-tuning PID controller is designed for the valve-controlled cylinder system. Finally, the response characteristic simulation of the fuzzy self-tuning PID controller is designed based on Matlab/Simulink platform. From the result and analysis, it can be seen from the simulation results that through the adjustment of the fuzzy self-tuning PID controller, the system adjustment time $t_a$ are within 0.8s, and the steady-state error rate is controlled within 3%.

1. Introduction

The pneumatic self-balancing hoist system allows the operator to easily carry out various handling, assembly and special positioning tasks and is widely used in industrial fields such as home appliance manufacturing, automobile assembly, and weapon production [1]. It plays an important role in improving production efficiency and improving the working environment. At present, the pneumatic self-balancing hoist system independently developed in most of the country has the disadvantages of low positioning accuracy, poor operation stability, small suspension stroke and complicated pneumatic routes. Therefore, it is necessary to develop a pneumatic hoist system that can be widely used in the production of heavy objects lifting, material handling and full suspension.

The controller design of the pneumatic self-balancing hoist system is one of the important steps of the whole system [2]. The quality of the controller design is directly related to the realization of the system function. The system mathematical model is based on the basic theorems of fluid mechanics, pneumatic transmission, dynamics, etc., and applies mathematical forms to quantitatively describe the static and dynamic relationships between various parameters in the physical model system. In the control system, accurate mathematical models play a very important role in analysing component and system characteristics and design control strategies [3].

2. Design strategy

Using the appropriate control strategy is a key part of the entire control system. The quality of the control strategy is directly related to the operation of the entire system. The pneumatic system is
complex because of its non-linear characteristics. Hence the pneumatic hoist control system is much more complicated than other types of servo control systems such as hydraulics.

2.1. PID Controller Design

PID control is one of the earliest developed control strategies [4]. Because of its simple algorithm, good robustness and high reliability, it is widely used in process control and motion control. When the structure and parameters of the controlled object cannot be completely mastered, When the precise mathematical model is not available, it is most convenient to apply PID control technology [5]. The PID controller is a linear controller. The principle is as follows: The deviation is calculated according to the given value \( r(t) \) and the output \( c(t) \), which is expressed as follows [6]:

\[
e(t) = r(t) - c(t)
\]

(1)

By linearly combining the differential, integral, and proportional deviations to form a control quantity, and thus effectively controlling the object, the control law can be expressed by the following equation:

\[
u(t) = k_p e(t) + \frac{1}{k_i} \int_0^t e(t) \, dt + k_d \frac{d(e(t))}{dt}
\]

(2)

In the above formula, \( k_d \) represents the differential time constant, \( k_i \) represents the integral time constant, and \( k_p \) represents the proportional coefficient. These three parameters determine the controller performance. Therefore, the core of the design of the PID controller is to determine 3 parameters for controls. According to the mathematical model of the valve-controlled cylinder deduced in the previous section, a system simulation model based on PID control is established, as shown in Figure 1.

Figure 1. PID control simulation block diagram.

The response characteristics of the output signal to the input signal are simulated under the same mass load, and the optimal control parameters are selected according to the simulation results. Wherein, the input voltage of the electric proportional valve is an input signal, and the pneumatic pressure value in the cylinder is an output signal. In order to ensure the validity of the control parameter selection, three sets of simulations are performed on the PID control system. The input signal settings under different loads are shown in Table 1.

Table 1. Input voltage values under different loads.

| No. | M/kg | u/V  |
|-----|------|------|
| 1   | 25   | 1.09 |
| 2   | 75   | 3.27 |
| 3   | 125  | 5.46 |

Through a large number of simulation analysis, a set of PID parameters is obtained: when \( k_p \) is 1.43, \( k_i \) is 0, and \( k_d \) is 0.04, the response of the system to the input signal is ideal, the introduction of the PID controller significantly improves the dynamic response performance of the system, reduces the number of system oscillations, shortens the rise time, and reduces the steady-state error. The simulation results also show that the response time of the system is close to 3s after the introduction of
PID controller. It is difficult to improve the response speed by adjusting the three control parameters $k_p$, $k_i$, and $k_d$. Therefore, it is necessary to design a more suitable control strategy to improve the performance of the system.

2.2. Fuzzy Control Principle
Fuzzy Control is an intelligent control method based on fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning [7]. It mimics human fuzzy reasoning and decision-making process [8]. The method firstly classifies the operator or the experience into fuzzy rules, then fuzzes the signal from the sensor, and uses the fuzzy signal as the input of the fuzzy rule to complete the fuzzy reasoning[9]. The resulting output after inference is added to the actuator. The basic principle block diagram of fuzzy control is shown in Figure 2.

![Figure 2. Block diagram of fuzzy control.](image)

3. Fuzzy-PID controller simulation
The Simulink software package in Matlab software can be used to realize the establishment and dynamic simulation of PID control system, fuzzy control system and Fuzzy-PID control system [10]. When designing the fuzzy controller, it includes the determination of fuzzy input and output, the determination of membership function, the setting of the range of input and output, the establishment of fuzzy rule base and the method of defuzzification [11].

3.1. Building a system simulation block diagram
According to Figure 3, composing the PID controller, fuzzy controller and Fuzzy-PID controller in Matlab/Simulink, the results are shown in Figure 3 to Figure 6. Figure 3 is a block diagram of the PID controller model. In the block diagram, $k_{p0}$, $k_{i0}$, and $k_{d0}$ are preset values of the Fuzzy-PID controller. Figure 4 shows the fuzzy controller model. Figure 3 and Figure 4 are packaged and connect to get the simulation block diagram of fuzzy PID control, as shown in Figure 5. The model of Figure 5 is packaged and combined with Figure 3 to obtain the simulation model of the fuzzy self-tuning PID control system of the pneumatic hoist system, as shown in Figure 6.

![Figure 3. PID controller simulation block diagram.](image)

![Figure 4. Fuzzy controller simulation block diagram.](image)
3.2. Simulation and result analysis

![Figure 5](image5.png) Fuzzy PID controller simulation block diagram.  

![Figure 6](image6.png) Simulation model of fuzzy self-tuning PID control system for pneumatic hoist system.

The system parameters and simulation parameters are taken in Table 2, and the optimal parameters obtained by the PID controller simulation process are used as pre-tuning parameters of the fuzzy adaptive PID controller. The simulation results are shown in Figure 7, Figure 8, and Figure 9.

Referring to Figures 4, 5, and 6, it can be seen from Figures 7, 8, and 9 that the response speed of the Fuzzy-PID control system is significantly higher than that of the PID control system. Relatively small, and the simulation curve of the Fuzzy-PID control system agrees well with the set curve, and the adjustment time $t_s$ is in the range of 0.5~0.8 s, which also explains the correctness of the controller design. The figure also shows the under each load. The response curve has an error rate of 0~3%, which is difficult to eliminate by adjusting the controller parameters. The possible reasons for the analysis are as follows: In the dynamics module of the valve-controlled cylinder model, the damping coefficient $C_s$ data is derived from the third chapter cylinder friction characteristics. The fitting results of the experimental study, in this experiment, neglected the subtle influence of the cylinder pressure on the damping coefficient, resulting in a small $C_s$ setting. During the simulation process, after the system reaches a steady state, the gas volume $\frac{dv}{dt}$ change A in the cylinder is too large. According to the equation (2), the steady state value of the cylinder pressure is small.

For further observation, the bottom of the simulation curve is enlarged, as shown in Figure 10. It can be seen from the figure that the system response curve has a delay at the initial moment, and theoretically, the gas source and cylinder pressure difference is the largest at the initial moment, and the gas mass flow rate, the maximum pressure rises the fastest. The reason for the analysis is as follows: the initial pressure of the cylinder is set to the atmospheric pressure $P_a$ (relative pressure value is 0), and the gas passes through the air pipe from the gas source to the gas pipe. During this time, the air pressure of the cylinder is almost It does not change, so the response curve has a delay and the delay time is close to 0.15 s.

![Figure 7](image7.png) Response curve under 25 kg load.  

![Figure 8](image8.png) Response curve under 75 kg load.

**Table 2.** Pre-setting parameters table.

| Pre-setting parameters | Values |
|------------------------|--------|
| $k_p^*$                | 1.43   |
| $k_i^*$                | 0.06   |
| $k_d^*$                | 0.04   |


4. Conclusion
Based on the Matlab/Simulink simulation, the mathematical model of the valve-controlled cylinder system is firstly established based on the flow equation, pressure equation and dynamic equation of the cylinder. Secondly, the PID controller is designed for the valve-controlled cylinder system. Through the simulation on the Matlab/Simulink platform, the dynamic response performance of the system is greatly improved by the introduction of the PID controller. The fuzzy self-tuning PID controller is designed again for the valve-controlled cylinder system. The optimal control parameters $k_p^*$, $k_i^*$, and $k_d^*$ obtained by PID control are used as pre-setting values. At the same time, the controller design is detailed and calculated. Finally, based on the Matlab/Simulink software, the response characteristics, simulation and result analysis of the fuzzy controller of the designed fuzzy self-tuning PID controller can be seen from the simulation results. Through the adjustment of the fuzzy self-tuning PID controller, the system adjustment time $t_s$ is within 0.8 s, stable. The state error rate is controlled within 3%.

5. References
[1] Zaguroli Jr J 2008 Electric motor driven traversing balancer hoist. Google Patents
[2] Liu, X., Zhao, R. & Zhao, Z. J, 2012, Automatic lifting system design and application of large load powered support test rig. Journal of Coal Science and Engineering (China), Volume 18, Issue 4, pp 428–431
[3] Ching-Han Chen, Chien-Chun Wang, Yi Tun Wang, and Po Tung Wang, 2017. Fuzzy Logic Controller Design for Intelligent Robots. Mathematical Problems in Engineering, pp 12
[4] Yao X, Su X and Tian L 2009 International Workshop on Intelligent Systems and Applications, 2009), vol. Series: IEEE pp 1-5
[5] Hassan A A and Domzalski D B 2002 Jet actuators for aerodynamic surfaces. Google Patents
[6] Chao, C.-T.; Sutarna, N.; Chiou, J.-S.; Wang, C.-J. An Optimal Fuzzy PID Controller Design Based on Conventional PID Control and Nonlinear Factors. Appl. Sci. Vol. 9, Iss: 6. pp 1224
[7] Ching-Han Chen, Chien-Chun Wang, Yi Tun Wang, and Po Tung Wang, 2017. “Fuzzy Logic Controller Design for Intelligent Robots,” Mathematical Problems in Engineering, vol. 2017
[8] Alexander M. Veprik, Sergey V. Riabzev, and Nachman Pundak, 2004. Dynamically counterbalanced pneumatically driven expander of a split Stirling cryogenic cooler, Infrared Technology and Applications XXX
[9] Y. J. Zhang et al., 2011. Research on Four Type-2 Fuzzy Reasoning Models, Advanced Materials Research, Vols. 204-210, pp. 406-411
[10] Soyguder S, Karakose M and Alli H 2009 Design and simulation of self-tuning PID-type fuzzy adaptive control for an expert HVAC system Expert systems with applications 36 4566-73
[11] Cheng X C, Jiang X W and Cheng Z X Applied Mechanics and Materials, 2014), vol. Series 457): Trans Tech Publ) pp 1503-6

Acknowledgements
This paper is supported by Guangzhou Scientific and Technological Projects (NO.201802010067).