Controller Design for a Pneumatic Actuator System with Proportional Valve

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***Abstract* — With the advantages of simple structure, Pneumatic manipulator is equipped with no pollution, high cost performance in the field of food processing, microelectronics, the production which has been widely used. This paper introduces the control of the system present situation, analyzing the proportional valve in the pneumatic proportional position control system and the characteristics of the rod-less cylinder, to establish the mathematical model of the system, and the study of the characteristics of the system, determine the input signal through the experiment, through the system output signal, based on the method of system identification, the estimated system mathematical model is determined. And based on the mathematical model, PID and the LQR controller is designed to control system, using the offline model, realize the online iteration, getting the most optimal control parameter to realize the optimal control system. Then the experimental results show that this control method makes the system of closed loop characteristics achieves a better characteristic, system stability also has a larger increase at the same time, compared with the traditional proportional control, PID control, the advantages of obtained more satisfactory results, which can provide a reference for the design of the pneumatic mechanism.**

Key words - PID, LQR, Pneumatic Actuator System, Modeling, Controller Design, Control Valve.

I. INTRODUCTION

Pneumatic manipulator with simple structure, no pollution, high cost, etc. in the food processing, microelectronics and other production areas have been widely used. However, due to the disadvantages of low stiffness, strong nonlinearity, time variability and delay of the pneumatic system, it is difficult to achieve the ideal effect, which makes the application in the field of industry limited.

Pneumatic technology is a key technology in the process of realizing the automation of production process, which is based on compressed air as the working medium [1]. After the two World War, due to the rapid progress of science and technology and economic development, it is urgent to improve the level of mechanization and automation of production equipment to improve product quality and production efficiency. Industrial circles in the search for high efficiency, low cost, safe and reliable and has a long service life of the automation components and technology, so pneumatic technology came into being [2]. In recent years, due to the development of modern control theory and microelectronic technology, especially the development of computer technology, electronic technology has been applied in various

fields [3]. At the same time, the performance of the actuator and the control element is very much in the field of pneumatic field. The lubrication and friction characteristics of the cylinder were significantly improved, and the dynamic and static characteristics of the control valve is more excellent, the response speed of the control valve has entered the market, at present, many advanced industrial production departments, such as cars, refrigerators, air conditioners, electrical and electronic components, televisions, watches, bearings and other production lines, a large number of pneumatic device [4].

The basic working principle of pneumatic and hydraulic transmission, working mechanism of the components and the composition of the circuit are similar. However, due to the different working medium, the output power of hydraulic transmission is large, the working process is stable, and it can achieve a wide range of stepless speed regulation and can stop at any position, the output displacement is influenced by the external load and the adjustment precision is high [5]. Widely used in engineering machinery, pressure machine, automobile industry and automation control for a long time. Compared with the hydraulic transmission, although the air pressure of air as the medium, easy to handle, and easy to handle, while the pneumatic device has the advantages of simple structure, strong environment adaptability, low cost, long life, etc., but due to the large air compressor, air pressure transmission is difficult to achieve accurate closed-loop servo control and stepless speed control and other factors, greatly limited the use of pneumatic technology, pneumatic control technology is limited to the environment and some simple switch control [6]. In recent years, the combination of micro electronic technology and pneumatic technology has made new vitality, and the development of the world has paid great attention to the development of the industry [7]. The technology of foreign air is known as the "cheap automation technology". At present, developed industrial countries, all automated processes about 30% with pneumatic system, 90% of packaging machinery, 70% of the casting and welding machine of automatic operation device, 50%, 40% of forging equipment and laundry equipment, 30% of the coal mining machinery, 20% of the textile machine, shoe machine, wood processing and food machinery using gas dynamic system, 43% of the industrial robot is pneumatic transmission.

With the demand of industrial production automation, it can only be reliably located at the two mechanical position and its movement speed by the single set of one-way throttle valve single set of pneumatic system, has been unable to meet many of the automatic control requirements [8]. The electric servo system can be very convenient to realize stepless speed regulation and stepless speed regulation. It can meet the requirements of the flexible production of the automation equipment, which makes it more and more attention and application [9]. The first pneumatic servo valve was developed successfully in the hydraulic pressure drive and Control Research Institute of R.W Aachen Industrial University of West Germany in 1979, and the development of pneumatic servo control was greatly promoted by the W.Backe. Many university research institute, the company focused on the pneumatic servo included in the project, and there are new results on display [10]. At the beginning of 80 "s, T.Eun et al designed a new type of pneumatic servo mechanism, and studied the stability and precision of the mechanism. Italy's C.Belforate et al the locomotive brake technology is introduced into the pneumatic mechanism, design a brake device realizes positioning of the cylinder at the target position, the positioning accuracy is about 0.3mm.

In this paper, the control of the system is introduced, and the characteristics of the proportional valve and the non rod cylinder are analyzed, and the characteristics of the system are studied. Through the experiment to determine the input signal, the output signal is obtained by the system, and the system identification method is based on the system identification. Based on this model, the design of PID and LQR controller is used to control the system. The model is used to realize the optimal control of the system. Experimental results can provide reference for the design of the pneumatic mechanism.

II. Pneumatic Actuator System

A. *The basic model for the pneumatic actuator system*

In recent years, due to the rapid development of modern control technology and the rapid development of micro computers, the development and application of pneumatic servo technology have created conditions. The development of pneumatic position control, mainly in several aspects: control mode, continuous control instead of quasi continuous control and brake position control; valve structure, the structure of simple pneumatic proportional valve to replace the structure of complex pneumatic servo valve, and the characteristics of the flow characteristics and flow characteristics, the use of computer control: structure design, the use of mechanical and electrical combination. And rely on electric proportion control technology, pneumatic device in control precision has been a qualitative leap, electric stretch ratio / servo control system application will be pneumatic technology development direction and the tendency.

The pneumatic servo system is consist of the controller, the electrical pneumatic control components, pneumatic actuator, sensor and interface circuit in general. The controller is such as a computer, single chip computer or programmable controller, etc. [11]. Electro pneumatic control components includes electro pneumatic servo valve, electro pneumatic proportional valve and electro pneumatic valve. Pneumatic actuators are commonly used in the cylinder, rotating cylinder, gas, gas, motor, etc.. Sensor generally refers to the position sensor, pressure sensor or speed sensor. Interface circuit between the controller and the control element, the interface between the controller and the sensor. The basic model for the pneumatic actuator system is shwn in Fig. (1).

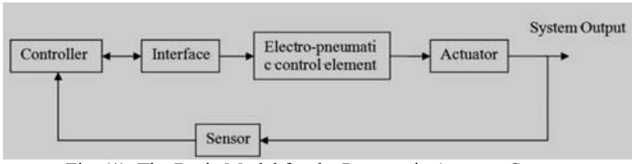

Fig. (1). The Basic Model for the Pneumatic Actuator System

B. *Hardware implementation*

In this research, the working principle of the pneumatic proportional pressure servo control system is shown in Fig. (2). As the whole system of the controlled object, the FESTO pneumatic proportional directional valve is used as the control valve of the whole system. Based on the use of data collection module Advantech PCL728 , the control system is connected with the bending the air inlet of the cylinder pressure sensor voltage signal real-time acquisition, through the operation of the PID control algorithm. Finally, through Advantech PCL728 module of data outputting control signals output pneumatic proportional directional control valve, proportional directional control valve controls access to the bending of the cylinder flow, tune into bending cylinder pressure to reach the target pressure, so as to control the bending of the cylinder stroke to set the goal of metal tube bending angle.

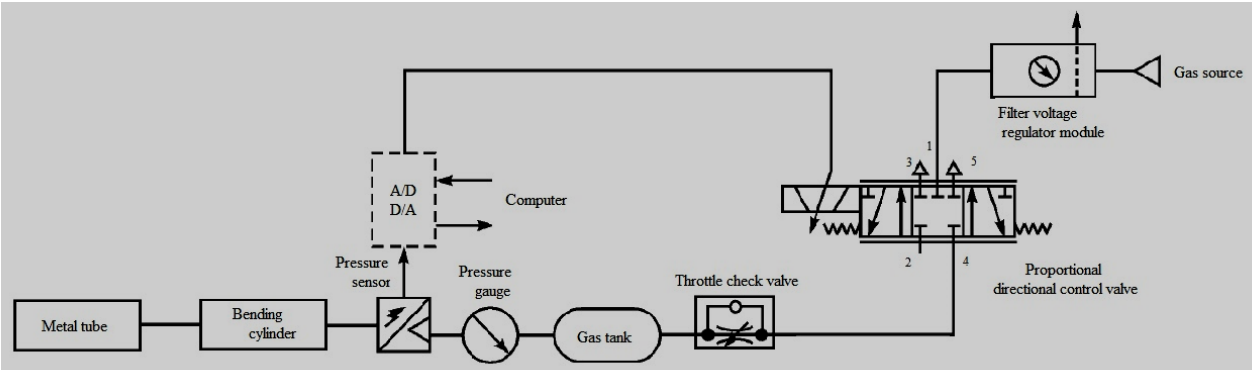

Fig. (2). The Working Principle of the Pneumatic Proportional Pressure Servo Control System

C. Software implementation

In this research, MATLAB system identification toolbox is adopted to analyze the system model. System identification toolbox is a graphical user interface, which is mainly used for estimation and analysis of linear and nonlinear models. Based on the user defined input and output, it can be constructed by the mathematical model of the dynamic system. So as to predict the output of the model based on the estimation. The user can use the frequency domain or time domain input and output data to establish the discrete time and continuous time transfer function and process model and state space model. The Identification Toolbox provides the maximum likelihood, predictive error minimization (PEM), subspace system identification, and other identification methods. The user can realize the model to predict or forecast the response of the system and Simulink simulation.

D. The basic mathematical model of pneumatic proportional pressure system

Fig. (2) shows that the mathematical model of the pneumatic proportional pressure control system is mainly composed of two parts, the mathematical model of the proportional directional valve and the bending cylinder.

The mathematical model of the valve controlled cylinder is formed by the combination of the two parts. In order to simplify the derivation process, the following assumptions are mde:

A. The working medium is an ideal gas.

B. The supply pressure and temperature are constant.

C. The gas in the cylinder is a homogeneous gas.

D. There are no gas leak in the cylinder.

Based on the assumption that the transfer function of the proportional directional valve is shown, the current negative feedback amplifier is usually used to avoid the influence of the characteristics of the amplifier.

$$\frac{X(s)}{U(s)} = \frac{1/K}{\frac{s^2}{\omega_0^2} + \frac{2\xi_0}{\omega_0} + 1} \tag{1}$$

$X(s)$ is the shift of the valve core displacement; $U(s)$ is the input voltage of the proportional valve. K is the sensor gain; ω_0 is proportional to the natural frequency of the valve; ξ_0 is proportional to the damping ratio of the valve.

The open loop transfer function of the bending cylinder system is obtained according to the force balance equation of the bending cylinder.

$$\frac{Y(s)}{U(s)} = \frac{b_1 s + b_0}{s(a_3 s^3 + a_2 s^2 + a_1 s + a_0)} \tag{2}$$

$Y(s)$ is the laplace transform of the output displacement of the cylinder, and the $X(s)$ is the displacement of the valve core.

The mathematical model of the pneumatic proportional pressure system is obtained by integrating the proportional directional valve and the mathematical model of the bending cylinder system. By the equation (1) and (2), the transfer function of the pneumatic proportional pressure system is shown in equation (3):

$$G_s = \frac{k_n}{s(\frac{s^2}{\omega_n^2} + \frac{2\xi_n}{\omega_n} s + 1)} \tag{3}$$

k_n is the speed of the system, the k_n is the natural frequency of the system; the ξ_n is the damping ratio of the system.

III. CONTROLLER DESIGN OF PNEUMATIC ACTUATOR SYSTEM

PID controller is a linear regulator. The controling output is formed by the difference between the given signal $p(t)$ and actual output value $y(t)$ with the function of the ratio of proportion (P) integral (I) and differential (D) by linear combination of control. The control object is controlled. Among them, the proportion of the control system is proportional to the deviation signal $e(t)$. Once produced, the regulator immediately is produced control to reduce the deviation. Integral part is mainly used to eliminate static error, improving the system of no difference. The integral function is determined by the integral time constant T_i, the T_i is bigger, the integral function is weaker, and vice versa. Differential function is treated that the variation trend can reflect the deviation signal (change rate), and can introduce an effective early correction signal in the system, so as to speed up the system's movement speed and reduce the adjustment time.

A mathematical description of the PID controller as below:

$$I(t)=K_P\left[E(t)+\frac{1}{T_i}\int_0^t E(\tau)d\tau+T_D\frac{dE(t)}{dt}\right] \tag{4}$$

where, before the summation of disturbance $D(t)$, $I(t)$ is the input data of the control system. And the error signal $E(t)$ is defined by the following equation.

$$E(t)=p(t)-y(t) \tag{5}$$

In addition, $p(t)$ is the current input signal of the system. Base on the negative feedback of the output signal, the PID controller can be modified to change the coefficients of proportional, integral and derivative gain in order to reduce the feedback error and get the better controlling for the system.

For linear systems, the integral of the two functions of state variables and control variables is used as the performance index. The optimal control problem of the two time performance index of the linear system is called the two time. Its optimal solution can be written as a unified analytical expression. And it can be derived from a simple state linear feedback control law, which is easy to calculate and implement. LQR (quadratic regulator linear) is a linear system with two times[12] The object is a linear system which is given by the state space form in the modern control theory, and the objective function is the two function of the object state and the control input. LQR theory is one of the most mature state space design methods in modern control theory. , the optimal control law of LQR can be obtained by the state feedback, which is easy to constitute the closed-loop optimal control [13]. And the application of Matlab provides the conditions for the simulation of LQR, and provides the convenience for us to realize the stable, accurate and fast control target.

Using the linear two time optimal controller for the control system design and calibration the biggest advantage is not necessary according to the performance of the closed-loop pole position, just need to find the appropriate state variables and control variables based on the response curve of the system. Because the controller is an error indicator J optimal controller, the performance of the system is also the optimal J index.

Many modern control theories have been studied as a research object. Many papers introduce the PID control system based on output feedback, but the control effect is not satisfactory, the main reason is the high order and multi variable of the system. In this research, the LQR optimal regulator is adopted based on the state space design method, and the robust stability and the speed of the system is better.

However, the traditional theory for the system controlling is based on both the input-output relationship and the transfer function. In the configuration of LQR, the state-space models for the LQR process control are derived as follows:

$$\dot{x}(t)=Ax(t)+BI(t) \tag{6}$$

$$y(t)=Cx(t)+DI(t) \tag{7}$$

$$I(t)=-Kx(t)+u(t) \tag{8}$$

$$\dot{x}(t)=(A-BK)x(t)+Bu(t)=A_Px(t)+Bu(t) \tag{9}$$

Generally, the optimal LQR is often defined as the following equation and determined by the controller transfer-matrix $M(s)$ that minimizes.

$$H_{LQR}=\int_0^\infty w'(t)Qw(t)+\lambda I'(t)RI(t)dt \tag{10}$$

Among the above equation, Q is known as $n\times n$ symmetric positive-definite matrix, where R is a $m\times m$ matrix which is a symmetric positive-definite. And λ is a positive constant. Parameters R and Q are selected to weignt the step signal to the system and optimize the cost function respectively. In the LQR controller design, it is assumed that $R=1$ and $Q=M^TM$.

The key to design a linear two time optimal controller is to select the weighting matrix R and Q. Generally, the greater the Q is selected, the shorter the time required for the system to reach the steady state. But also reducing the R, the system can achieve the desired time of the steady state. Of course, the actual system is required to allow.

In order to reduce the steady state error of the system output, Nr is added after the reference input. State vector is multiplied by the feedback vector. K is adopted to reduce the system feedback error after the addition of constant gain. Nr can be decided by realizing the function which is defined by the users. Eventually, the performances of PID and LQR controllers are compared for analysis purposes.

IV. COMPUTATIONAL RESULTS AND DISCUSSION

A. Model estimation for the system

The experiment data is input to the system identification toolbox in Matlab for various data processing, model estimation, and model analysis tasks. Input signal is created by the equation (11). The signal is taken into use to the system in order to find the differences between the estimated output signal and the actual signal from the black system. The results are illustrated with the input and output signals with the duration of 50 seconds in Fig. (**3**).

$$y(t) = 35\left[0.56\left(\cos(\pi t)\right) + 1.13\cos\left(0.3\pi t + 2.5\cos(2\pi t)\right)\right] \quad (11)$$

Based on the estimated results, the ARX model is chose as the simulation structure for the control system. In order to ensure the best estimations for the system the controllers are designed. As shown in Table I, by varying the coefficients, offset value and time interval are tried to find the best solver and performance for the system.

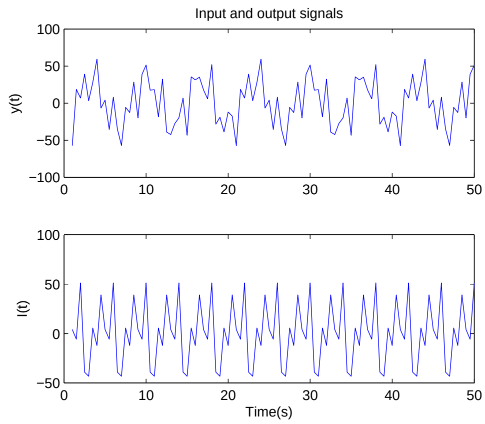

Fig. (3). Input and Output Signals

TABLE I. PERCENT OF BEST FIT BY VARYING OFFSET VALUES AND TIME INTERVAL

Offset Value	$T_s = 0.01$	$T_s = 0.02$	$T_s = 0.03$
-0.090000	90.32	87.60	91.30
-0.105000	83.42	82.42	80.10
-0.100000	91.43	87.53	87.03
-0.091500	91.65	86.15	88.01
-0.090350	91.65	88.04	88.04
-0.090475	92.05	87.73	88.02

T_s is the sampling time.

Due to the best fit percentage is above 90%, the results are acceptable and reasonable. The sampling rate must be large enough so that the analog signal can be reconstructed from the sample with sufficient accuracy. In order to avoid losing any information, the interval must be small enough.

B. Controller design

ARX331 model is adopted to simulate the output response by designing the PID and LQR controllers. Bilinear transformation and zero order hold methods are used to achieve the discrete time model into the continuous time model. The transfer functions are transformed into continuous time model after the conversion of Bilinear transformation and zero order hold are stated in (8) and (9) respectively.

$$G_{BT}(s) = \frac{1.113s^3 + 235.5s^2 - 424.1s + 18560}{s^3 - 1759s^2 + 35674s - 101298} \quad (12)$$

$$G_{ZOH}(s) = \frac{0.4541s^3 + 15650s^2 - 24565s + 1710201}{s^4 + 72.33s^3 + 101100s^2 + 2779780s - 8113490} \quad (13)$$

Based on the parameters of K_P, K_I and K_D in Table II, PID controller is designed to measure the performace of the system. Square wave signal is input to the system for the designing and testing for different PID controller designs.

TABLE II. PARAMETERS OF K_P, K_I AND K_D

Controller type	Continuous time model ($K_C = 12.655, T_C = 0.6$)			Discrete time model ($K_C = 6.4523, T_C = 1.78$)		
	K_P	K_I	K_D	K_P	K_I	K_D
P	6.113	-	-	2.339	-	-
PI	5.236	10.29	-	2.196	3.135	-
PID	7.285	22.16	0.50	3.103	2.983	0.72

From Fig. (4) and Fig. (5), it can be observed that the set time is 0.75 seconds, and the rise time is 0.5 seconds, percentage overshoot is 4.2%. In addition, the steady state error is 2.2%. Fig. (5), sine wave signal is used to test the estimated model in the system. Obviously, the output response is 55.4 degrees phase compared with the input.

With the PI controller for positioning control, additional loads with different weights are added to the system.

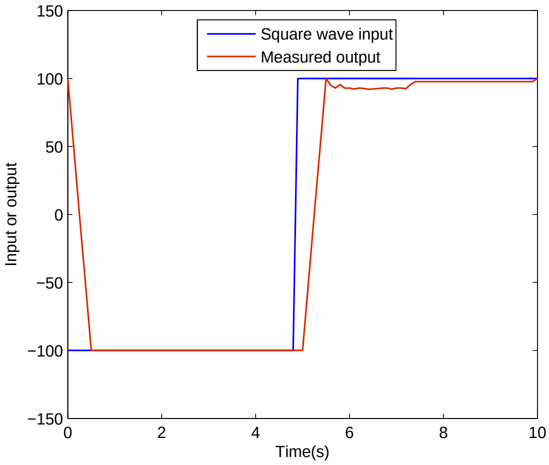

Fig. (4). PI Controller Online Testing with the Square Wave Input

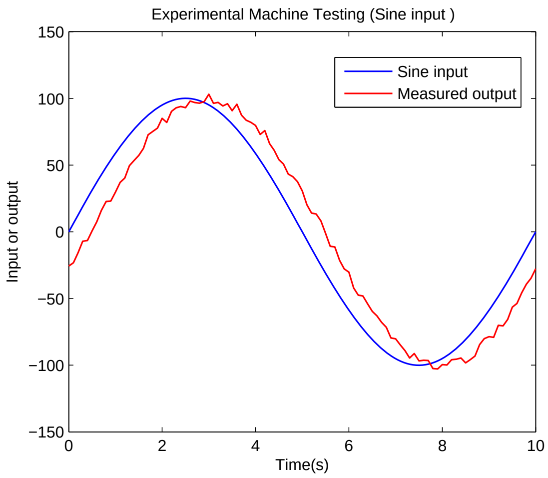

Fig. (5). PI controller Online Testing with the Sine Wave Input

In order to compare the difference of the performance between the PID controller and LQR controller, all the related parameters are stated as follows. The comparison between LQR and PID Controller is shown in Fig. (6). Both LQR and PID Controller can be applied controlling for position of the pneumatic actuator in the experiment system. Table III shows the difference and the different performance of two different controller by the simulation.

$$\begin{cases} K = [2.4463, 0.6687, 0.4123, 2.7989] \\ Nr = 1.0732 \end{cases} \tag{14}$$

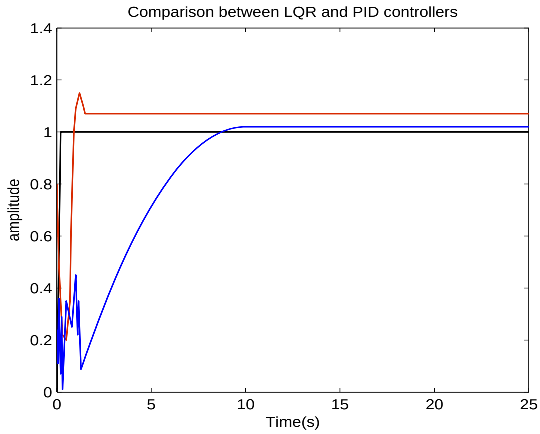

Fig. (6). Comparison between LQR and PID Controller

TABLE III. DIFFERENCE BETWEEN LQR AND PID CONTROLLERS

	LQR Controller	PID Controller
Rise time (s)	5.35	1.14
Settling time (s)	5.86	1.38
Steady state error (s)	0	6.15
Overshoot (%)	0	3.92

V. CONCLUSION

The experimental results show that this control method makes the system of closed loop characteristics achieves a better characteristic, system stability also has a larger increase at the same time, compared with the traditional proportional control, PID control, the advantages of obtained more satisfactory results, which can provide a reference for the design of the pneumatic mechanism. The research content of this paper lays the foundation for the future research, and points out the direction and provides the means for the future research.

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