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Design and Research of Hydraulic Expansion Control System for Reducing Pipe

Haoya Hu[1, *]

[1] Tianjin Key Laboratory of High Speed Cutting and Precision Processing, Tianjin, 300222, China
[*] Corresponding author: Haoya Hu (Email: 756075210@qq.com)

Abstract: In the aerospace industry's part forming processes, there is a pursuit of structural integration and lightweighting to reduce material and energy waste. Consequently, hydraulic expansion (hydroforming) has been widely applied, commonly utilized during the manufacturing processes. This paper focuses on the production of stepped aluminum tubes using hydraulic expansion technology and mainly studies the control techniques of hydraulic expansion for stepped tubes.

Keywords: Adapter bonnet, Hydro-bugling, Numerical simulation analysis.

1. Introduction

With the development of sectors such as aviation, aerospace, and automotive, the hydraulic expansion technology for lightweight and integrated tube structures has become a research hotspot both domestically and internationally [1, 2]. Currently, it is widely applied across various fields. Due to the advantages of hydraulic expansion processes, such as effective forming, fewer operations, material savings, and low cost, it is typically used in forming parts from tubular materials. The hydraulic control system is one of the critical components in the hydraulic expansion process. When the hydraulic control system operates in open-loop or semi-open-loop control, issues such as slow response speed and large displacement control errors may arise. A PID controller can be utilized to correct the errors present in the system [3].

2. Control Requirements for the Hydraulic System

This paper achieves the forming of the target stepped tube through the hydraulic expansion process. Based on the project requirements, the hydraulic expansion experiment process, and the failure modes of the parts, the requirements for the hydraulic control system are determined as follows [4]:

(1) Provide clamping force for the hydraulic expansion experiment;

(2) At the beginning of the experiment, complete the high-speed fluid filling process;

(3) During the experiment, accomplish real-time control of the internal pressure within the tube cavity;

(4) During the experiment, achieve real-time control of the displacement of the push cylinder pistons on both sides;

The hydraulic system designed in this paper mainly controls displacement, with a required displacement control precision of 0.1 mm.

3. Establishment of the Mathematical Model for the Hydraulic Control System

3.1. Development of the Mathematical Model

In this chapter, by analyzing the structure of the control system, a flowchart for the position control system is drawn, as shown in Figure 1. Subsequently, mathematical models for each component of the system are established. By applying Laplace transforms to the developed system's mathematical model, the system's transfer function is obtained. Finally, based on the established mathematical model of the hydraulic system, a corresponding Simulink model is constructed in Matlab for further research and analysis.

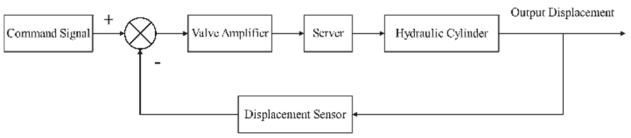


Figure 1. Hydraulic position control system flow diagram

3.2. Valve Amplifiers

In the hydraulic control system, valve amplifiers serve as both energy conversion elements and power amplification components. They are capable of converting an input voltage signal into an output current signal, and can also amplify the input signal according to a certain ratio before outputting it. The output signal is transmitted to the valve [5], which can be considered a proportional link. The transfer function is as follows:

$$G_R(s) = K_a \tag{1}$$

where K_a is the gain of the valve amplifier.

3.3. Displacement Sensors

The input of a displacement sensor is displacement, and its output is voltage. Within the measurement range of the displacement sensor, its input and output are proportional. Therefore, the transfer function of the displacement sensor can be regarded as a proportional link, and the transfer function is shown as Equation (2):

$$G_f(s) = K_f \tag{2}$$

where K_f is the feedback coefficient of the displacement sensor.

3.4. Servo Valves

In order not to make the servo valve a limiting factor for the system's bandwidth, electro-hydraulic servo valves with a higher natural frequency are generally chosen. Since the natural frequency of the system's electro-hydraulic servo valve is much higher than that of the hydraulic cylinder, the transfer function of the servo valve in this system can be considered a proportional link, as shown in Equation (3):

$$G_{sv}(s) = \frac{Q(s)}{I(s)} = K_{sv} \tag{3}$$

where K_{SV} is the gain of the servo valve.

3.5. Hydraulic Cylinders

The mathematical model of the asymmetric valve-controlled hydraulic cylinder is derived by writing the flow equation for the servo valve's orifice, the flow continuity equation for the hydraulic cylinder, and the force balance equation for the hydraulic cylinder. The general schematic diagram of a valve-controlled asymmetric cylinder is shown in Figure 2. The servo valve is connected to the hydraulic cylinder through piping. To facilitate the establishment of a mathematical model, some non-critical influencing factors are disregarded [6]. Prior to conducting the research, the following assumptions are made:

(1) The connecting pipes between the valve and the hydraulic cylinder are symmetrical, short, and wide; pressure losses in the pipes, the influence of fluid mass, and the dynamic characteristics of the pipes can be neglected.

(2) The internal leakage and external leakage of the hydraulic cylinder are both laminar flows.

(3) The pressure is equal at all points within each working chamber of the hydraulic cylinder.

(4) The bulk modulus of elasticity of the hydraulic fluid and the fluid itself are constants.

(5) The non-linear effects of the valve are not considered.

(6) The valve is an ideal zero-lap four-way valve, with clearance leakage ignored.

(7) The system's supply pressure is maintained constant, and the return pressure is zero.

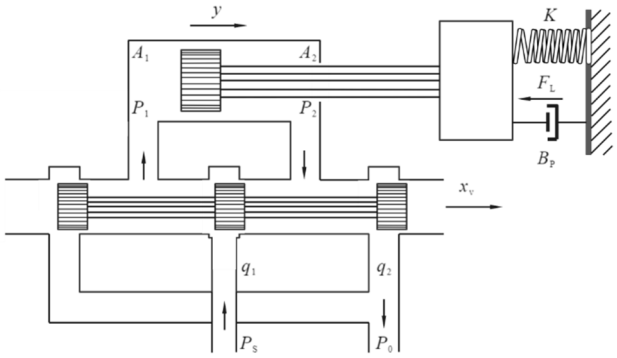


Figure 2. Valve controlled asymmetrical cylinder

In order to thoroughly analyze the dynamic performance of the hydraulic servo control system, it is necessary to perform the Laplace transform on the control equations of the system and calculate its transfer function. The following results can be obtained:

$$Q_L = K_q X_v - K_c P_L$$

$$Q_L = A_p S X_p + C_{tp} P_L + \frac{V_t}{4\beta_e} S P_L$$

$$A_p P_L = m_t S^2 X_p + B_p S X_p + K X_p + F_L$$

With an externally applied arbitrary load, the transfer function can be derived with valve displacement as the input and hydraulic cylinder displacement as the output:

$$\varphi_1(s) = \frac{x_{p1}(s)}{x_v(s)} = \frac{\frac{K_q}{A_p}}{\frac{m_t V_t}{4\beta_e A_p^2} s^3 + (\frac{m_t K_{ce}}{A_p^2} + \frac{B_p V_t}{4\beta_e A_p^2}) s^2 + (1 + \frac{B_p K_{ce}}{A_p^2} + \frac{K V_t}{4\beta_e A_p^2}) s + \frac{K K_{ce}}{A_p^2}}$$

4. Establishment of the Hydraulic Control System Simulink Model

In this paper, a control strategy model is developed within the MATLAB/Simulink environment [7]. The Simulink Control Design toolbox in Matlab is utilized to complete the simulation. Based on the transfer function derived above, the Simulink simulation model of the system is constructed in MATLAB/Simulink software, as shown in Figure 3:

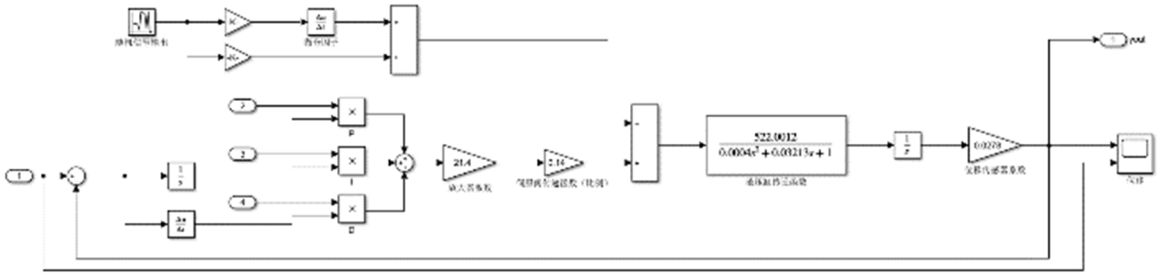


Figure 3. Simulink model of electro-hydraulic position servo system

The Simulink simulation model of the system includes six components: a PID controller, an amplifier, a servo valve, a hydraulic cylinder, a displacement sensor, and an external load force. The computer inputs the displacement signal of the ram during the axial feed process into a self-constructed PID controller, which then enters the amplifier stage for signal amplification. The output current signal flows into the servo valve stage, where the valve begins to move to control the

flow of hydraulic oil. After reducing the external load signal, it flows into the hydraulic cylinder. The hydraulic cylinder outputs the cylinder displacement signal based on the valve displacement, and finally, the oscilloscope displays the hydraulic cylinder displacement signal. A closed-loop control is formed with the displacement sensor.

5. Conclusions

Firstly, the electro-hydraulic servo control system block diagram is drawn, and mathematical models are established one by one according to the working process of the closed-loop position control system. Then, mathematical models for the valve amplifier, displacement sensor, servo valve, and valve-controlled asymmetric cylinder are established and the transfer function is obtained by performing Laplace transforms on the established system mathematical models. Finally, based on the system's transfer function, a position control transfer function simulation model is constructed using Matulab/Simulink software.

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