Research on characteristics of integrated type hydraulic transformer's control angle[①]

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Abstract

In order to realize remote control of hydraulic transformers and improve the control precision of the pressure ratio, an integrated type electric hydraulic servo hydraulic transformer is proposed in this paper, a mathematical model is built and simulation of electro-hydraulic servo integrated hydraulic transformer's control angle is carried out, the principle prototype of the transformer is designed and manufactured, and experimental study is carried out on the experimental bench. The experimental results verify the correctness of the mathematical model. The results show that electro hydraulic servo control can improve the accuracy and dynamic response speed of control angle, which provides a reference for the further research of the hydraulic transformers.

Key words: electro-hydraulic servo, hydraulic transformer, control angle, simulation, experimental

0 Introduction

With more and more serious environmental pollution, energy saving and emission reduction technology has become a hot research topic. A hydraulic common pressure rail system is an efficient hydraulic transmission system[1], in which the power source is composed of a high pressure oil rail and a low pressure oil rail, and various executive components are connected to the pressure network in parallel, loads obtains power according to their own needs from the power system. The system fully realizes power supply on demand without throttling loss, therefore, it has high efficiency and broad application prospects. In the hydraulic pressure common rail system when the actuator is a hydraulic cylinder, because the hydraulic cylinder's area is fixed in the process of working, the control of the load can only be controlled by the hydraulic valve, thus throttling loss affects the transmission efficiency of hydraulic common pressure rail system. In order to solve this problem, a hydraulic transformer, a kind of hydraulic component, is developed[2].

Hydraulic transformer can be categorized into tandem type and integrated type according to the structural form. The tandem type is that the hydraulic pump and hydraulic motor are connected directly in series through a spindle, having large volume and weight, slow dynamic response, which limits its application. The integrated hydraulic transformer is formed by processing three valve grooves evenly distributed on the valve plate, first proposed by the Holland Innas company and Noax company[3]. With the characteristics of compact structure, small volume, high efficiency, and fast dynamic response, the integrated type has broad application prospects and become a hot spot of research.

According to the features of the integrated hydraulic transformer, Achten, et al. studied the hydraulic transformer's valve plate and hydraulic transformer application[4]. Rotation of valve plate caused reduced flow area to generate throttling loss. Transformation factor range of hydraulic transformer is limited due to the small rotation angle of the valve plate. Yang and Xu studied integrated manual hydraulic transformer and its application[5,6], an integrated hydraulic transformer's principle prototype was designed based on A2F hydraulic motor. In order to avoid throttling loss, the rear end cover of the hydraulic transformer's valve plate was designed. The application of hydraulic transformer in the hydraulic elevator, shield equipment,

drilling machine cutter on the system were studied. The results show that the cutter power system transmission efficiency can be increased by 4.9% [7]. The research of integrated electronic control hydraulic transformer was carried out by Jiang, et al. [8-10], in which electronic control type hydraulic transformer was developed, the remote control of the transformation ratio was realized and the servo motor could directly drive valve disc rotation and a continuous adjustment of the range of $0 \sim 2$ could be achieved to broaden the scope of the transformer ratio. Zhang, et al. analyzed and studied the hybrid excavator system with hydraulic transformer[11].

Many countries in the world have studied the application of hydraulic transformers, Vael conducted the hydraulic hybrid cars based on hydraulic transformer[12], and test results showed that in the medium car fuel consumption was decreased by 50%, CO_2 emissions was decreased by $82g/km$, much lower than the European emission standards in 2012. In 2014, the United States Caterpillar Inc. applied the hydraulic transformer excavator boom energy recovery system patents[13]. Lee studied the trajectory tracking performance of hydraulic transformer control hydraulic cylinder[14]. Its experimental study has not yet been carried out because the hydraulic transformer's principle prototype has not been manufactured. In 2015, Danzl, et al. applied for a non-road vehicles hydraulic power system of the invention patent, with the hydraulic transformer to control the power, the power matching of engine could be better[15].

Control angle of hydraulic transformer determines the control performance of hydraulic transformer directly. This paper simulates and experiments on the control performance of hydraulic transformer's control angle, which has laid a foundation for the research of the integrated hydraulic transformer.

1 Mathematical model of control angle

The integrated electro hydraulic servo hydraulic transformer is composed of a hydraulic swing motor and a servo valve. The structure of integrated electro hydraulic servo of the hydraulic transformer is shown in Fig. 1.

The servo amplifier is used for amplifying the control signal, in which the input is the voltage signal, the output is the current signal, and the output current of the servo amplifier is simplified as linear relationship.

$$i = K_a u \tag{1}$$

where u is the amplifier input control voltage (V), i is the amplifier output current (A), and K_a is the gain of amplifier (A/V).
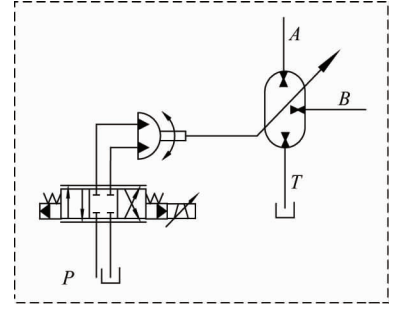

Fig. 1   Integrated electro hydraulic servo hydraulic transformer

The electro-hydraulic servo valve is an electro-hydraulic converter and power amplifying element, where the electrical signal is converted into small hydraulic power, and a key component of electro-hydraulic servo control integrated hydraulic transformer, while the servo valve is seen as two order oscillation, when the transfer function is

$$G_{sv}(s) = \frac{Q_0(s)}{I(s)} = \frac{K_{sv}}{\dfrac{s^2}{\omega_{sv}^2} + \dfrac{2\xi_{sv}}{\omega_{sv}}s + 1} \tag{2}$$

where ω_{sv} is equivalent to undamped natural frequency of electro hydraulic servo valve (rad/s), K_{sv} is no-load flow gain of electro hydraulic servo valve ($m^3/s \cdot A$), ξ_{sv} is equivalent to the damping ratio of electro hydraulic servo valve.

The linear flow equation of the valve port of the servo valve is

$$Q_L = K_q x_v - K_c P_L \tag{3}$$

where K_q is the electro-hydraulic servo valve port flow gain, x_v is the spool displacement of the servo valve, Q_L is the electro-hydraulic servo motor load flow, K_c is the flow of the valve port flow pressure coefficient, and P_L is the load side pressure.

The Laplace transform of Eq. (3) is obtained:

$$Q_L(s) = K_q X_v(s) - K_c P_L(s) \tag{4}$$

Flow continuity equation of oscillating hydraulic motor is

$$Q_L = D_m \frac{d\theta_c}{dt} + C_{tm} P_L + \frac{V_t}{4\beta_e} \frac{dP_L}{dt} \tag{5}$$

where θ_c is the control angle of hydraulic transformer, C_{tm} is the total leakage coefficient of swing hydraulic motor, D_m is the swing displacement of hydraulic motor, V_m is the total volume of swing hydraulic motor, servo valve chamber and connecting pipe, β_e is the effective volume elastic modulus of working fluid.

The Laplace transform of Eq. (5) is obtained as

$$Q_L(s) = D_m \Theta_c(s)s + C_{tm} P_L(s) + \frac{V_m}{4\beta_e} P_L(s)s \tag{6}$$

Neglecting the mass of the oil in the chamber of the hydraulic motor, the torque equation of the main shaft of the hydraulic transformer is obtained:

$$D_m P_L = J_m \frac{d^2\theta_c}{dt^2} + B_m \frac{d\theta_c}{dt} + G\theta_c + T_{Lm} \qquad (7)$$

where J_m is the total inertia on the motor shaft, B_m is the viscous damping coefficient, G is the spring stiff-ness of load, T_{Lm} is the external load torque on the motor shaft.

The Laplace transform of Eq. (7) is obtained:

$$D_m P_L(s) = J_m s^2 \Theta_c(s) + B_m s\Theta_c(s) + G\Theta_c(s) + T_{Lm} \qquad (8)$$

The transfer function of the control angle of hydraulic transformer is obtained:

$$\Theta_c(s) = \frac{\frac{K_q}{D_m}X_v(s) - \frac{K_{ce}}{D_m^2}\left(1 + \frac{V_m}{4\beta_e K_{ce}}s\right)T_{Lm}(s)}{\frac{J_m V_m}{4\beta_e D_m^2}s^3 + \left(\frac{J_m K_{ce}}{D_m^2} + \frac{B_m V_m}{4\beta_e D_m^2}\right)s^2 + \left(1 + \frac{B_m K_{ce}}{D_m^2} + \frac{GV_m}{4\beta_e D_m^2}\right)s + \frac{GK_{ce}}{D_m^2}} \qquad (9)$$

According to Eq. (9), the transfer function block diagram of electro-hydraulic servo integrated hydraulic transformer's control angle is shown in Fig. 2.
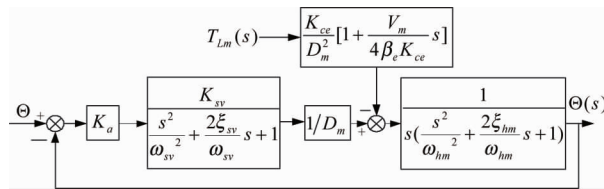

Fig. 2   Transfer function block diagram of control angle of hydraulic transformer

2   Simulation research of control angle

According to the transfer function of the hydraulic transformer's control angle, the simulation is carried out in Matlab. The Bode diagram of hydraulic transformer's control angle is shown in Fig. 3.
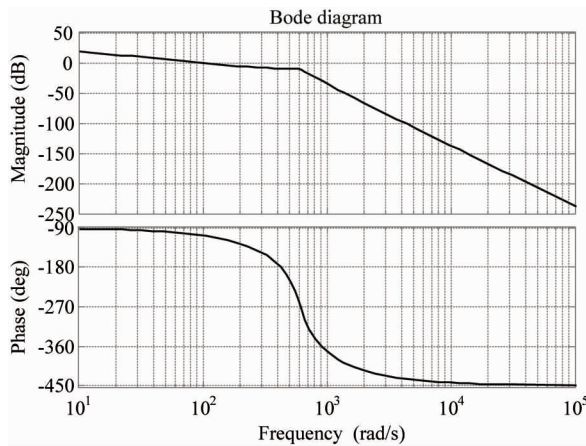

Fig. 3   Bode diagram of hydraulic transformer's control angle

Fig. 3 shows that magnitude margin control angle of hydraulic transformer is 9.6dB, phase margin is 74°, the bandwidth of the control system is 94rad/s. The step simulation curves of hydraulic transformer's angle are shown in Fig. 4 and Fig. 5, in which 1 is for a given signal, 2 is for tracking signal. The Fig. 4 shows that when the amplitude is 50°, the adjusting time is 0.15s, the overshoot is 8%. The Fig. 5 shows that when the amplitude is 100°, the adjusting time is 0.4s, the overshoot is 5%. The control angle of integrated type hydraulic transformer has fast dynamic response and small steady state error. The power density of integrated type hydraulic transformer is higher than that of servo motor.
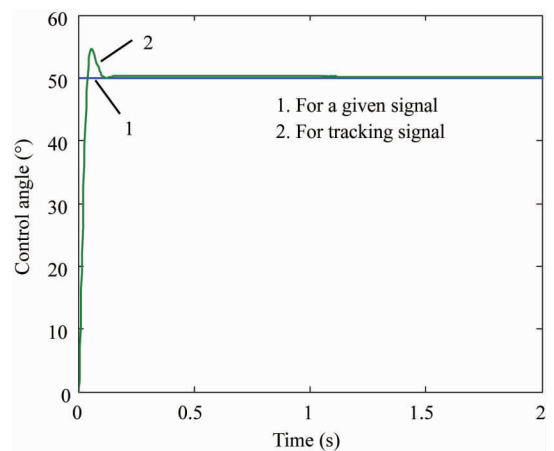

Fig. 4   Hydraulic transformer's control angle step response curve (amplitude 50°)

The slope response simulation curve of hydraulic transformer's control angle is shown in Fig. 6 and Fig. 7, 1 for a given signal, 2 for tracking signal. When the slope of ramp signal is 80°/s, the control angle of hydraulic transformer can be tracked well.

When the slope of ramp signal is $100°/s$, the lag time of hydraulic transformer´s control angle is 0.15s, the error of control angle do not continue to expand.
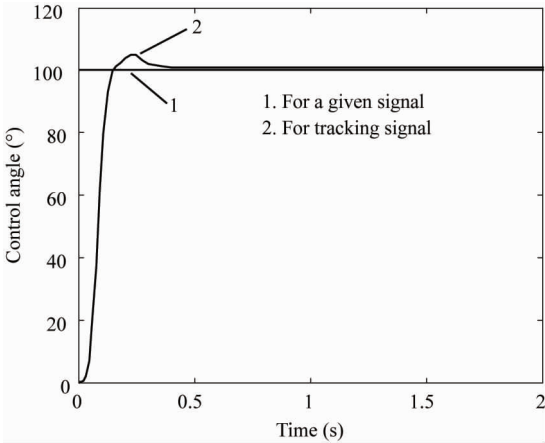

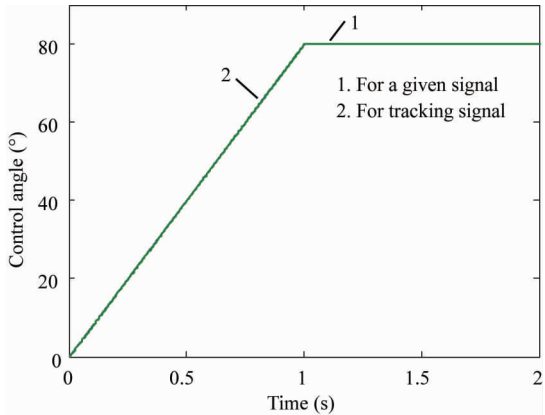**Fig. 5** Hydraulic transformer's control angle step response curve(amplitude $100°$)

Fig. 6 Slope response curve of hydraulic transformer's control angle(slope $80°/s$)
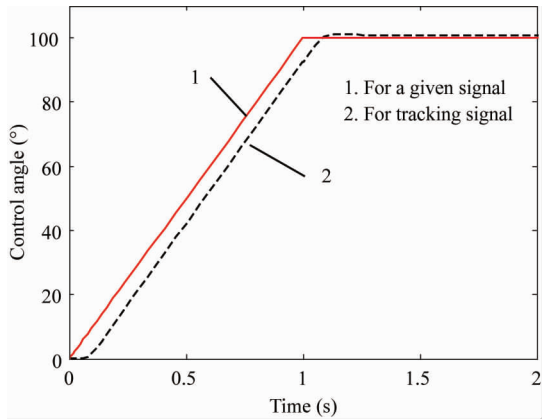

Fig. 7 Slope response curve of hydraulic transformer's control angle(slope $100°/s$)

3 Experimental study

In order to carry on the research of the integrated electro hydraulic servo hydraulic transformer, a princi-

ple prototype of the integrated hydraulic transformer is designed and built. The experiment platform is built, and the system of the experiment table is shown in Fig. 8.
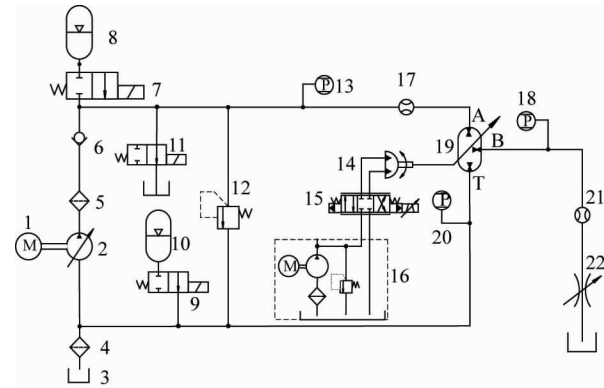
1- motor 2- constant pressure variable pump 3- tank 4, 5- oil filter 6-check valve 7, 9, 11-accumulator safety valve 13, 12- 18, 20- pressure sensor 14-swing hydraulic motor 15-servo valve 16- electro-hydraulic servo oil source 19- hydraulic transformer 22- throttle valve 17, 21- flow sensor
Fig. 8 Integrated hydraulic transformer test bench

The control program is written based on C + + language, and the experimental study was carried out used PID control strategy. The step response curve of electro-hydraulic servo hydraulic transformer's control angle is shown in Fig. 9 and Fig. 10. Fig. 9 shows that the adjusted time is 0.4s, steady state error is 2%, overshoot is 10%, when the amplitude is $10°$. Fig. 10 shows that the adjusted time is 0.7s, steady state error is 0.5%, overshoot is 5%, when the amplitude is $50°$. The time lag of the control angle's step response is about 0.1s, which is caused by inertia of integrated type hydraulic transformer. Steady-state error of hydraulic transformer's control angle is less than $0.5°$, it can improve the control precision of pressure transformer ratio.
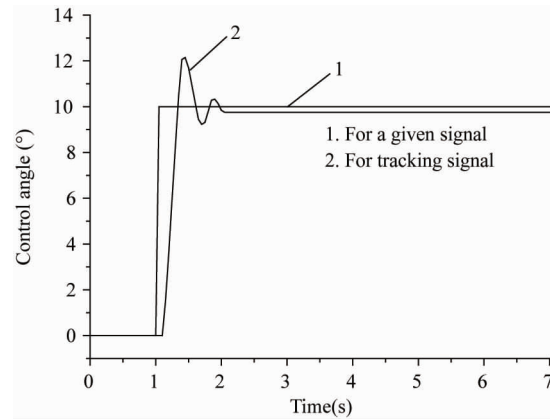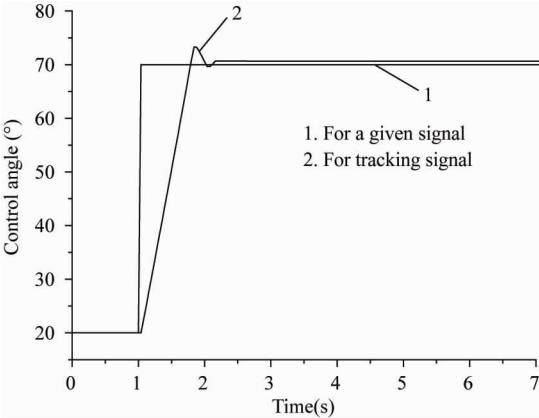

Fig. 9 Step response of control angle(amplitude $10°$)

Fig. 10   Step response of control angle (amplitude 50°)

Fig. 13   Slope response of control angle (slope 0.02°/s)

The ramp response curves of the hydraulic transformer's control angle are shown in Fig. 11, Fig. 12 and Fig. 13, in which 1 is the given signal, 2 is the response signal. Fig. 11 shows that when the slope of ramp signal is 40°/s the control angle can be well tracked. Fig. 12 shows that when the slope is 70°/s the error of control angle continues to expand. Fig. 13
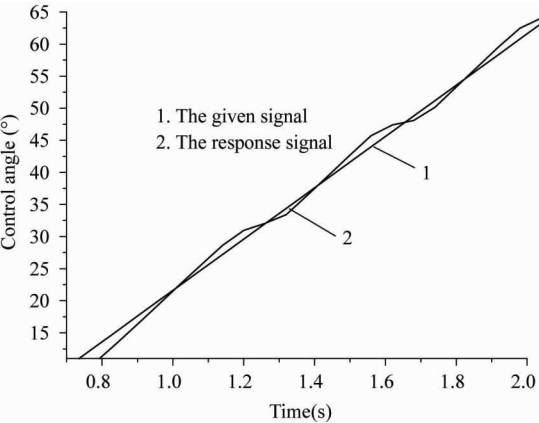
shows that when the slope of ramp signal is 0.02°/s the control angle produces crawl phenomenon, which is due to the compressibility of oil and change between static and dynamic friction, and the error within 0.03°.

4   Conclusion

Electro hydraulic servo integrated hydraulic transformer's control angle controlled by swing hydraulic motor implementation can achieve remote control of the pressure ratio and improve the control speed and control accuracy of the pressure ratio. Electro hydraulic servo integrated hydraulic transformer's control angle is able to track the maximum ramp in 70°/s, the control angle step response exists in the time delay of about 0.1s. The experimental results are in agreement with the simulation results, and verify the correctness of the simulation model.

Fig. 11   Slope response of control angle (slope 40°/s)

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Fig. 12   Slope response of control angle (slope 70°/s)

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