Research on Motion Control System Simulation of Butt Girth Welds Scanner for Oil and Gas Pipeline

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***Abstract*— Because of the special working environment, the butt girth welds of oil and gas pipelines were inevitably damaged. Automatic ultrasonic testing （AUT）equipment for girth weld pipeline was designed to monitor the girth welds. The motion control system of scanner was the most important component of the AUT equipment. The mathematical model of closed-loop speed control system for traveling framework was established and simulated. The simulation results showed that the control system had good accuracy and quick dynamic response characteristics, fulfilling the engineering requirements, and providing a theoretical basis for the design of the control system.**

***Key words*— oil and gas pipeline ; girth weld; scanner; control system ; simulation**

I. INTRODUCTION

Oil and gas pipelines were always in special work environments, so pipeline girth welds were inevitably damaged, which may bring security risks, so butt girth welds of the pipelines need to be tested. For the unique advantages, the Automatic Ultrasonic Testing (AUT) technology was most widely used to detect the pipeline girth welds. In recent years, the number of new pipelines dramatically increased. It was important to design intelligent AUT equipment to ensure the reliability and efficiency of pipeline girth weld detection. [i]

The motion control system of scanner was the most important component of the AUT equipment. The control system of traveling framework in pipeline girth weld scanner was studied. The mathematical model of closed-loop speed control system for traveling framework was established and simulated. The simulation results showed that the control system had good accuracy and quick dynamic response, providing a theoretical basis for the design of hardware and software of the control system.

II. DESIGN OF SCANNING CONTROL SYSTEM

Closed-loop control system constituted of the controller, the controlled object and the feedback loop. In the closed-loop control system, as long as the captive amount deviating from given value, the system would generate the appropriate control action to eliminate deviation. Therefore, the closed-loop control system had the ability to suppress interference, and to make the system not sensitive to the changes in device's characteristics, improving the system response.

To ensure the scanner moved along annular lead rail at an invariable speed in the process of detecting pipeline girth weld. A motion control system of scanner was designed, including SCM (Single Chip Micyoco) control module, power driven module and communication module. The host computer set the expected velocity of scanner for microcontroller, and the actual velocity of scanner was real-time feedback to the microcontroller by encoder. Then differentials of the expected velocity and the actual velocity were compared by microcontroller, and then the speed of the motor was adjusted through the digital PID control algorithm. The closed-loop speed control system of scanner was shown in Figure 1.

As shown in Figure 1，the motion system of canner consisted of the traveling framework, DC servo motor, planetary gear reducer and encoder. The host computer input walking velocity of scanner to microcontroller in advance, then microcontroller drove DC servo motor to rotate the driving wheel which would drive scanner to move along the annular lead rail. The end of the driven axle was connected to encoder which would measure the speed of the driving wheel. The speed was a feedback signal to control the speed of the DC motor, so that the scanner could move along the annular lead rail at a pre-set speed, ensure the inspection accuracy of pipeline girth weld.

III. ESTABLISHMENT FOR MATHMATICAL MODEL OF MOTION CONTROL SYSTEM OF SCANNER

The working principle of the motion system of canner was analyzed, and then the motion control system of the canner was gained, as shown in Figure 2. JM, TM,θM, θ_M represented the moment of inertia of the motor' s rotor, the electromagnetic torque, angle and speed individually; Tf represented friction torque; B represented viscous friction coefficient; JL, TL represented moment of inertia and torque of the load individually; i represented reduction ratio of the reducer. The stiffness of the model was ignored, so that the transmission mechanism was rigid.

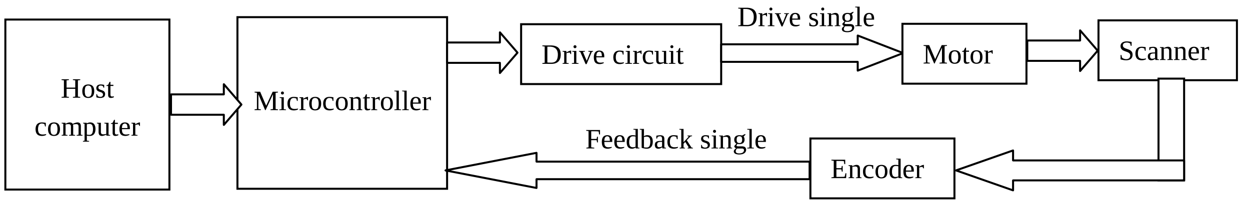

Fig. 1 Speed Closed-loop Control System Block Diagram of Scanner

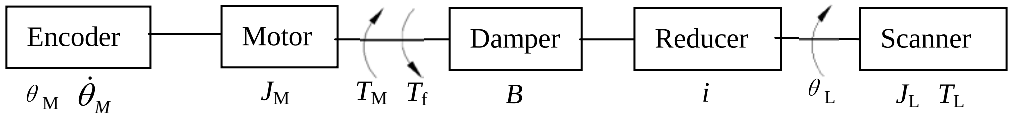

Fig. 2 Mathematical Model of Motion Control System of Scanner

A. DC Motor Model

When the motor armature resistance was relative large, the motor torque T_M was as follows:

$$T_M = K \cdot i_a \tag{1}$$

In (1), the term K designated torque constant of the motor; the term i_a(A) designated armature current of the motor t[1,2].

The movement balance equation of the motor's shaft could be obtained as follows:

$$T_M = J \cdot \frac{d\omega_M}{dt} + B \cdot \omega_M + 4T_f + T_L \tag{2}$$

In (2), the term $\omega_M = \frac{d\theta_M}{dt}$ (rad / s) designated angular velocity of the motor's output shaft; the term J designated equivalent moment of the inertia of motor's output shaft; the term B designated equivalent friction coefficient of the motor's output shaft.

The equation of magnetic circuit was as follows:

$$u_a = L_a \cdot \frac{di_a}{dt} + R_a \cdot i_a \tag{3}$$

In (3), the term u_a (V) designated armature voltage of the motor; the term L_a(H) designated armature inductance of the motor; the term R_a (R) designated armature resistance of the motor.

Then the DC motor's transfer function was as follows:

$$G_M(s) = \frac{\Omega(s)}{U_a(s)} = \frac{K}{(L_a s + R_a)(Js + B)} \tag{4}$$

B. Load Model

Load model was shown in Figure 3. Assuming that scanner moving from the point A counterclockwise along the annular lead rail, scanner need to overcome the load torque to move circularly along the rail to complete the pipeline girth welds inspection.

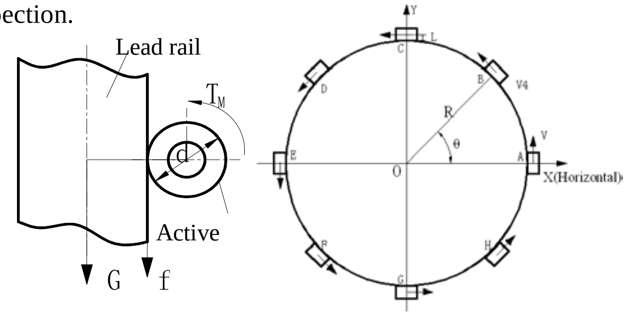

Fig. 3 Simplified Load Model

When the scanner was in equilibrium, the load equation of the scanner was as follows:

$$T_L = G\cos\theta \cdot L \tag{5}$$

In (5), the term T_L (N • m) designated the load torque of the scanners; the term G (N) designated the weight of the scanners; the term L (mm) designated the vertical distance between scanner's center of gravity and the surface of the lead rail; the termθ designated the angle between the scanner and the horizontal.

The scanner used driven wheel to clamp the annual lead rail, and then moved along the annual lead rail. So the relationship between the angular displacements of the motor's output shaft (angular displacement of driving wheel) and the arc distance of the annular lead real was as shown:

$$\theta \cdot R = \frac{1}{2}\theta_M \cdot d \tag{6}$$

In (6), the term R (mm) designated the radius of the annular lead real; the term d (mm) designated the diameter of the driving wheel.

Thus the relationship between rotational angle of DC motor and the angle from the scanner to the horizontal was as follows:

$$\theta = \frac{\theta_M \cdot d}{2R} \tag{7}$$

Substitution of (7) into (5), load torque of the scanner was as follows:

$$T_L = G \cdot L \cos \frac{\theta_M \cdot d}{2R} \tag{8}$$

C. Friction Model

The static friction torque and kinetic friction torque were considered, although the friction was just one part of the system loads, but it was different from the other loads. The static friction would generate if the system was trend to move, and increase with the driving torque. When the output torque of the motor T_M was less than the maximum static friction torque, the value of T_M was equal to the value of the friction torque, the direction of T_M was opposite to the direction of friction torque, and the actual driving torque on the loads was zero, so the system was relatively static. When the output torque of the motor T_M was greater than the maximum static friction torque, the system produced relative motion, and the friction torque was converted to kinetic friction torque, and its direction was opposite to the direction of the load. According to the characteristics of static friction torque and kinetic friction torque, the following expression was got:

$$T_f = \begin{cases} T_M & |T_M| \le T_s, \dot{\theta}_M = 0 \\ F \cdot \mu & \dot{\theta}_M \ne 0 \end{cases} \tag{9}$$

In (9), the term T_S (N·m) designated the maximum static friction torque; the term F (N) designated the clamping force of driving (driven) wheels on the lead rail; the termμdesignated the friction coefficient of the driving (driven) wheels and the lead rail[3].

D. Planetary Gear Reducer Model

When the DC motor drove the scanner, the load's moment of inertia J_L was exerted to the motor's output shaft through the speed reducer, that was the converted load to the output shaft of the motor J_L/i^2 [4].

IV. SIMULATION FOR MATHMATICAL MODEL MOTION CONTROL SYSTEM OF SCANNER

Because of nonlinear expressions in the mathematical model of controlled object, the controlled objects can't be expressed by transfer function directly. Matlab / Simulink model was adapted to describe the controlled objects. Combined with equation (4)- DC motor transfer function, model of DC Motor based on Matlab / Simulink was shown in Figure 4, where U_a denoted voltage of the motor's armature, which was the input signal; ω_M denoted angular velocity of the motor's output shaft, which was the out put signal; K_b denoted the constant of the encoder.

The expressions of Load model and friction model were both nonlinear, so the expressions were M-files written by Matlab language. According comprehensive analysis, Matlab / Simulink model of the system was established, as shown in Figure 5

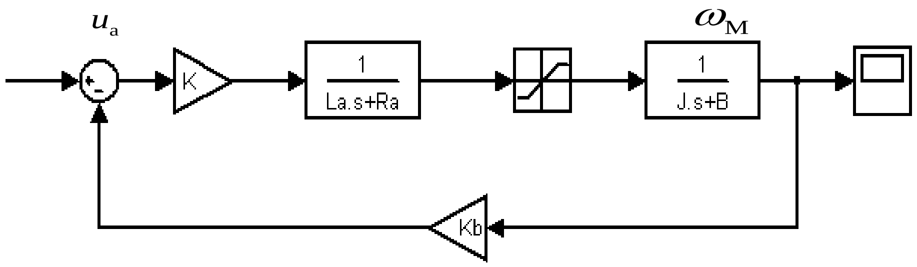

Fig. 4 Simulation Model of DC Motor Based on Simulink

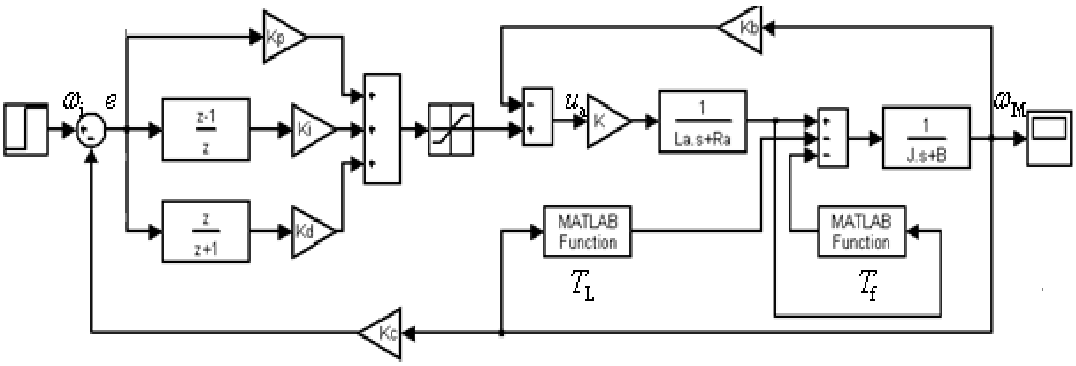

Fig. 5 Simulation Model of Motion Control System of Scanner Based on Simulink

In Figure 5, according to the deviation signal of the system, PID controller obtained the control law through proportional operation, integral operation and differential operation [5, 6]. The deviation signal of the control system was reflected by the proportional operation sector proportionally. Once producing deviation, the controller restrained it immediately; static error was eliminated mainly by the integral operation sector which could improve error-free degrees of the system; the changing trend of the deviation signal was reflected by the differential operation sector which could improve the dynamic response of the system [7].In Figure 5, the output of T_L module was the load converted to a motor's shaft, the output of T_f module was friction. The motion speed of the scanner was the given signal of digital PID controller, the speed of the motor was the output signal, which was multiplied by the coefficient K_c to get the speed of scanner. The deviation between the calculated speed and the given speed was the input signal of PID controller.

The parameters of the system: $R_a = 0.4\Omega$, $L_a = 2\text{mH}$, $J=1.5\times10^{-5}\text{kg}\cdot\text{m}^2$, $B=4\times10^{-5}$, i=50. The PID parameters: K_p =0.01, K_i =15, K_d =0.32. The mathematical model of the system in Figure 5 was simulated. The simulation result of the system with no load was shown in Figure 6, and the simulation result of the system with 20kg load was shown in Figure 7.

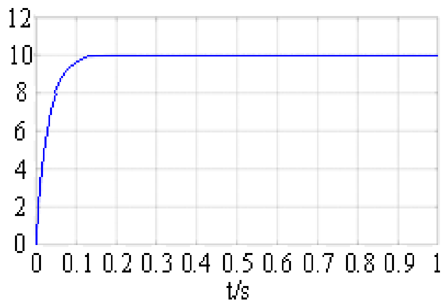

Fig.6 Speed Response Curves with No Load

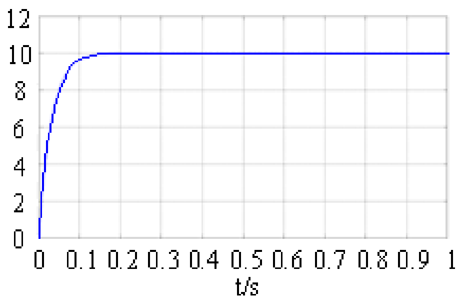

Fig.7 Speed Response Curves with 20kg Load

As shown in Figure 6 and Figure 7, when applying different loads to the system, there was almost no change of the step response and no overshoot, and the systems' stability time of response curve was about 0.15s. It was known that the design of the controller fulfilled the requirements of the scanner's motion system[3, 4].

The following curve of the scanner's speed was shown in Figure 8, which showed that the actual speed of the scanner was almost the same to the given speed. The closed-loop speed control system of the scanner had quick dynamic response characteristic, fulfilling the requirements of the motion system of the scanner.

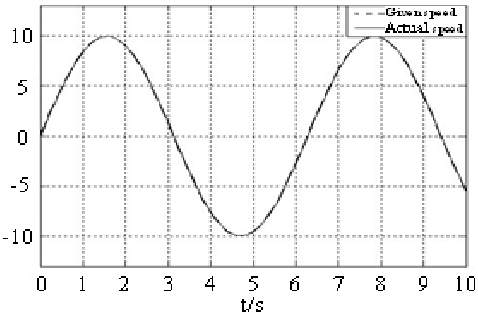

Fig.8 Following Curve of Scanner's Speed

V. CONCLUSIONS

To ensure the detecting accuracy of the pipeline girth weld, while the scanner could move along annular lead rail at an invariable speed, the mathematical model of closed-loop speed control system for traveling framework is established and simulated. The simulation results show that the control system has good accuracy and quick dynamic response characteristics. In further, the software and the hardware of the control system are designed individually. The testing results of pipeline girth weld scanner in AUT engineering machine confirm the rationality of the design, and good effect of the detection, fulfilling the system's requirements.

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