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Research on Backlash Nonlinearity in AC Servo-driven Precision Transmission System

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Abstract

   AC servo-driven precision transmission system is mainly composed of AC servo motor, mechanical transmission parts and control parts. Because of mutual coupling between various parts, particularly transmission system in mechanical coupling vibration in non-smooth transition, it will be of great harm to safe operation of the system. This paper made some overview and built the model of AC servo-driven precision transmission system mainly from the perspective of backlash nonlinear characteristic and with simulation tool of Matlab/Simulink to analyze the influence of backlash on the precision of servo system, and then corresponding simulation curve and conclusions were shown in this paper. Do hope the work above will have certain reference significance to actual engineering application.

Keywords: AC servo-driven precision transmission system, backlash, nonlinearity

1. Introduction
   Currently, electromechanical system is developing towards complex, precision and miniaturization. Research on these coupling process and establishment of dynamic model is indispensable for condition detection, design of system parameters, optimization analysis and fault diagnosis of electromechanical system. At the same time, AC servo-driven precision transmission system is widely used in electromechanical systems. It is necessary to study its electromechanical coupling process. In production practice, there are always singular conditions, even production accuracy is seriously affected [1]. For example, in servo system of precision transmission device, mechanical harmonic vibration and transmission clearance nonlinear factors will affect the steady state and dynamic characteristics of servo system, thereby reducing the precision of system [2]. In addition, the electromechanical coupling vibration of AC servo system in nonlinear process has a great influence on safety of system. Therefore, analysis of the impact of electromechanical servo system factors on the performance of system is of great significance.
   In the areas of high running accuracy requirements of system, such as servo precision drive systems, backlash nonlinearity has been one of the main directions of research. As early as the 1940s, there were some people who began to research the problem of backlash nonlinear control. Even now it also attracts much attention. For example, some scholars have studied the effect of backlash on dynamics of the entire system on the condition of friction and time-varying mesh stiffness [3]. Some scholars also have simulated and analyzed the influence of backlash on the precision of radar servo system [4]. Besides, some scholars have made some practice research in workshop. Some of them studied the occurrence of backlash phenomena at the mechanical transmission system and the effects of these malfunctions in the electrical equipment in cement industry [5], some studied servo pneumatic actuators considering the effect of servo valve backlash zone [6]. This paper mainly studies the influence of backlash on the precision of system, which reveals the influence mechanism of servo system precision, it plays an important role in improving overall performance of system.

2. An Overview of AC Servo-driven Precision Transmission System
   AC servo-driven precision transmission system which is composed of AC servo motor, precision drive system, control system, load system and other subsystems, is one of typical

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complex electromechanical systems and shown in Figure 1. In the complex electromechanical systems, there are three forms of electromechanical coupling as follows: drive source coupled to strong electromagnetic fields and transmission control variables and mechanical micro-electromechanical coupling body movement, and external load coupling which affects main motion. In order to better study mutual coupling phenomenon of servo precision drive system between various subsystems, servo motor can be simplified into one of output torque, namely T PTO based on coupling diagram of the analysis. And gear transmission is the most commonly used in the electrical system drive, including ordinary gear, planetary gear train, and harmonic gear drive, worm wheel and WORM-drive, and so on. In general, these drive devices can be simplified as a spring-mass-damper system.
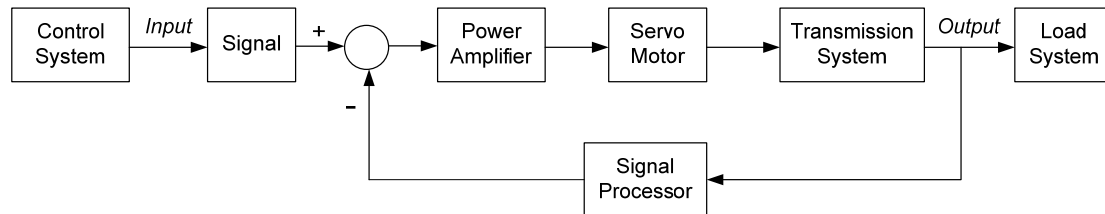

Figure 1. Electrical System Coupling Diagram

There are 3 main aspects of servo system performance, namely stability, speed and accuracy, and its main characteristic indexes are precision, stability and response speed. The basic requirements of AC servo systems are shown as follows: First, it is good stability. Under the condition of a given input and interference, Servo system can reach a new equilibrium state, or return to the original equilibrium state after short transition process. Good stability and full of stability margin is the prerequisite for reliable operation of servo system. Second, it is high precision. Accuracy of servo system refers to the degree of precision of output follows input, which is also the indicator of static characteristic and dynamic characteristic of system is excellent or not. Third, it is fast dynamic response. That is fast response and small overshoot. Quick response is an important sign of servo system dynamic quality, which requires that transition time is short while tracking command signal, and overshoot is small when speed changes, and when load changes suddenly, the climbing rate of transient process must be big, recovery time must be short, and it must be with non oscillation.

2. Modeling of AC Servo-driven Precision Transmission System

There are more and more research on the modeling of complex electromechanical systems, and also have made some valuable research results [7, 8]. For the convenience of study, the electromechanical system model can be simplified as mass-spring-damping system driven by AC motor. The simplified model is shown in Figure 2.
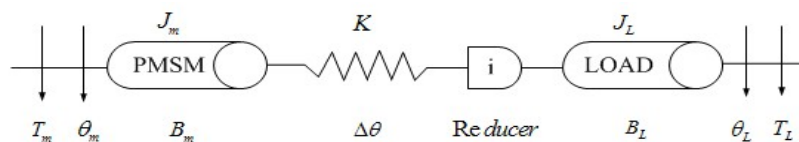

Figure 2. Electromechanical Coupling Model of AC Servo-driven Precision Transmission System

The figure above is a simplified multi-degree of freedom system of "Quality-spring-damper" driven by AC motor. Ultimately, a servo motor-precision transmission-load system electromechanical coupling model is built. In the figure, T_m is output torque of servo motor, θ_m is the angle of the drive shaft, θ_L is the angle of the load shaft, B_m and B_L is respectively

viscous damping coefficient of the driving wheel and the driven gear, J_m and J_L is respectively equivalent inertia of drive shaft and the load shaft, T_L is the load torque, K is torsional stiffness coefficient of drive shaft, $\Delta\theta$ is the twist angle of drive shaft, i is the transmission ratio of the gear train.

According to Figure 2, balance equations of the system input shaft can be deduced by dynamic principle of mechanical system:

$$T_m = J_m \frac{d^2\theta_m(t)}{dt^2} + B_m \frac{d\theta_m(t)}{dt} + K\Delta\theta \tag{1}$$

$$\Delta\theta = \theta_m - i\theta_L \tag{2}$$

The balanced equation of the output shaft shows as follows：

$$ik\Delta\theta = J_L \frac{d^2\theta_L(t)}{dt^2} + B_L \frac{d\theta_L(t)}{dt} + T_L \tag{3}$$

Laplace transform of formula (1) and (3) above can obtain:

$$T_m(s) = J_m s^2 \theta_m(s) + B_m s\theta_m(s) + k\Delta\theta \tag{4}$$

$$i\, k\Delta\theta = J_L s^2 \theta_L(s) + B_L S\theta_L(s) + T_L(s) \tag{5}$$

The equivalent inertia can be defined as follows:

$$J_e = J_i + \frac{1}{i^2} J_L \tag{6}$$

Equivalent damping coefficient is:

$$B_e = B_m + \frac{1}{i^2} B_L \tag{7}$$

The transfer function of load port speed can be deduced from formula (1)~(7), and shows as follows:

$$\dot{\theta}_L(s) = \frac{iT_m(s) - \left[1 + \frac{1}{K}(J_m s^2 + B_m S)\right] T_L(s)}{\frac{1}{K}(J_L S + B_L)(J_L S + B_m)S + (i^2 J_m + J_L)S + (i^2 B_m + B_L)} \tag{8}$$

In addition, as synchronous motor rotor pole axis and D-Axis coincides, the motor current initial phase angle is 90°, namely $i_d=0$, thereby achieving D and Q axis uncoupled in the magnetic field orientation of the vector-control method. The voltage of motor and electromagnetic torque can be expressed as:

$$U_q = R_s i_q + L_q \frac{di_q}{dt} + \omega\Psi_f \tag{9}$$

$$T_e = P_n \Psi_f i_q \tag{10}$$

Control block diagram of electromechanical coupling system driven by AC motor can be deduced from (8)~(10), and shows as Figure 2.
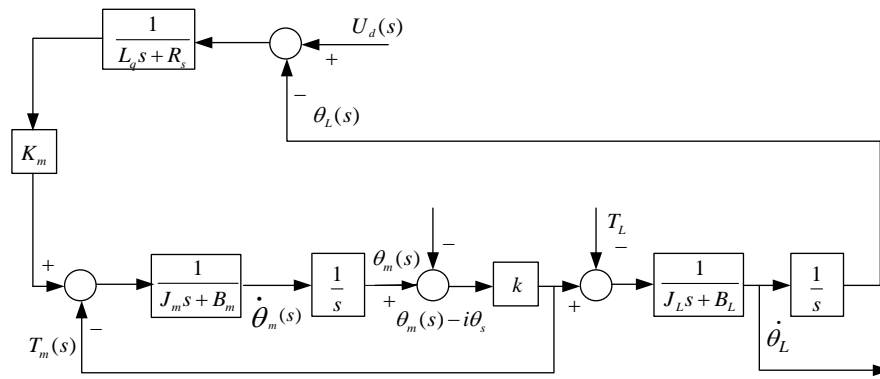
Figure 2. Electromechanical Coupling Control Block Diagram of Servo System

At the same time, simulink dynamic charts of servo system can be inferred from Figure 2 and shows as Figure 3.
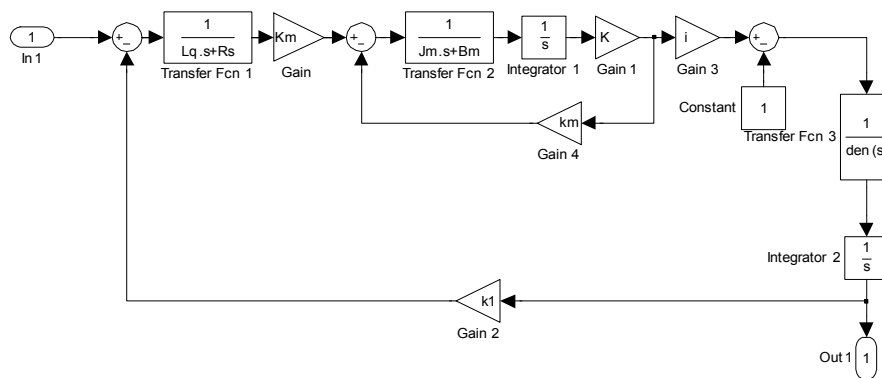

Figure 3. Simulink Simulation Model of Servo System

3. Effects of Backlash on AC Servo-driven Precision Transmission System

Backlash nonlinearity widely exists in the precision gear drive system, and mostly the clearance factor is inevitable because of the limit of processing. Taking the precision gear drive as the example, its meshing drawing is shown in Figure 4. In the figure, θ_{in} is the angle of drive shaft, θ_{out} is the angle of moving shaft, and α is the angle of Backlash. If there is no backlash in the transmission chain, then the relationship between input angle and output angle will be linear, just shown in Figure 5.
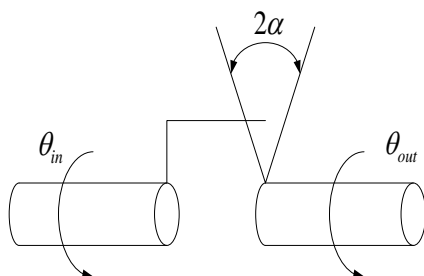

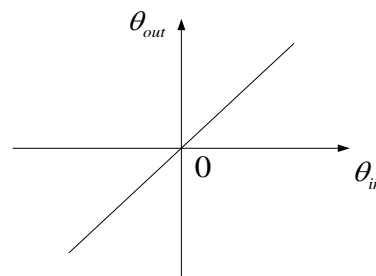Figure 4. Diagram of Meshing with Backlash

Figure 5. Relationship between Input and Output without Backlash

However, in the most situations, backlash always exists in the transmission chain. In this occasion, if the rotated angle of drive shaft is α, the driven shaft will not rotate. Only when the rotated angle of drive shaft is greater than α, the driven shaft will rotate with drive shaft as the relationship shown in Figure 5. When the drive shaft rotates in reverse, the driven shaft cannot follow immediately. Only when the rotated angle of drive shaft is greater than 2α, the driven shaft will rotate with drive shaft in reverse. In the servo system, backlash is often considered to locate after the motor. Output backlash non-linear system structure shown in Figure 6.
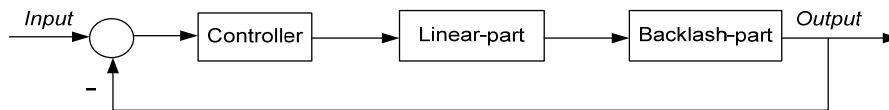

Figure 6. System Block Diagram of Backlash Nonlinearity on the Output Terminal

Backlash nonlinearity is caused by transmission gap, mainly occurred in the reversing and the start time of servo device, and the gap will affect accuracy and vibration characteristic of servo system [9, 10]. Backlash nonlinearity effects on output mainly in reversing time and it would cause output lags. Simulation model of Backlash nonlinearity is shown in Figure 7, and corresponding simulation curve is shown in Figure 8.
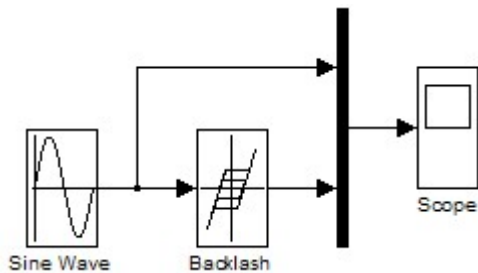

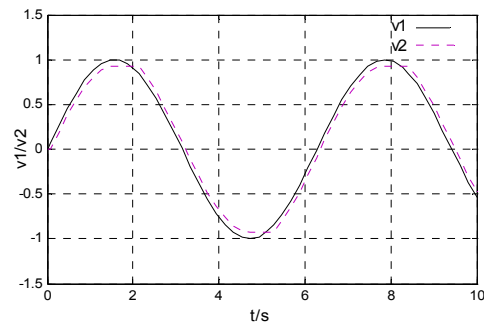Figure 7. Simulation Model of Clearance Nonlinearity

Figure 8. Simulation Curve of Clearance Nonlinearity

Backlash characteristics of simulation model of servo precision drive system is shown in Figure 9. In order to see response time more intuitively, it is reasonable to set step signal module (ie, the figure step module) and step time of 0.5s. And other parameters set as follows: L_q = 8.5mh, R_s=0.1Ω, K_m=0.5, J_m=20kg·m^2, B_m =B_L=0.05, K=5N/mm, i=1.8, J_L=5 kg·m^2, k_1=1.
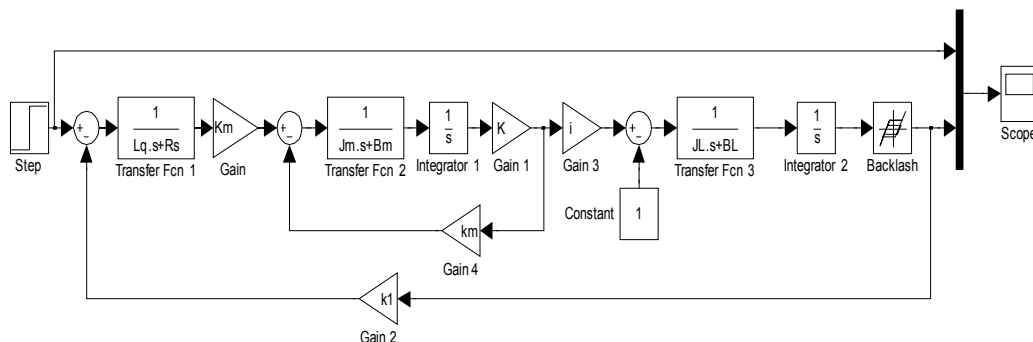

Figure 9. System Simulation Model of Clearance Nonlinearity

Backlash nonlinearity has a huge impact on system accuracy and vibration characteristics. In this paper, the impact of Backlash nonlinearity on the performance of system will be shown by modifying the data of Backlash. The simulation results of different Backlash are shown in Figure 10 ~ 12.
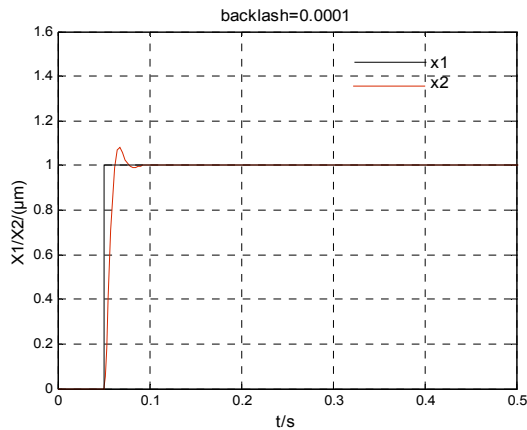
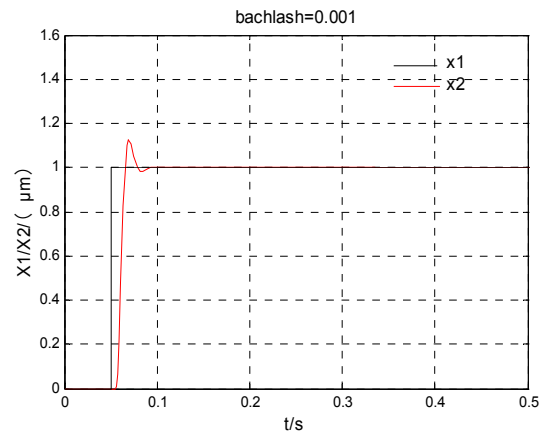Figure 10. System Response Curve as the Value of Backlash is 0.0001

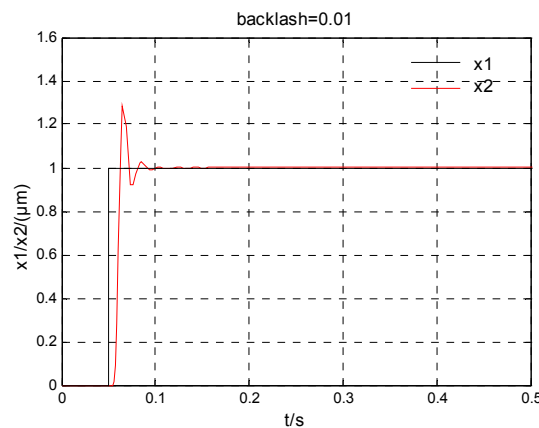Figure 11. System Response Curve as the Value of Backlash is 0.001

Figure 12. System Response Curve as the Value of Backlash is 0.01

4. Conclusion

This paper has analyzed the modeling method of AC servo-driven precision transmission system. AC servo-driven precision transmission system was decomposed into two parts of electrical networks and mechanical network. Various parts of kinetic models were set up by electromagnetic and mechanical system dynamics and dynamic model of AC servo-driven precision transmission system was established by coupling of the parameters. Finally, several simulations were made by Matlab/simulink tool and analyzed the impact of Backlash nonlinearity on system performance, with the following conclusions: the unit step response increases as the gap adds. When the gap reaches a certain value, Step Response overshoot increases. It means that, because of the action of the closed loop correction, small clearance will only cause lag, and have little influence on output precision. With the increasing of gap, the system will have a greater change of accuracy, vibration will increase, and the system overshoot increases, thus will affect system stability and accuracy.

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