Linear Quadratic Optimal Control for Chase Shear System

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Abstract. Chase shear system is widely used in many industries such as pipe material cutting, since it has the advantages of high efficiency and low cost. In this paper, the hardware circuits are designed for the chase shear system. The operation principle of every module is described in detail. The flowchart of the program of the system is given as well. The linear quadratic optimal controller for the servo motor of the chase shear system is designed. The impact which the weight matrix has on the system performance is analyzed. The simulation results demonstrate the effectiveness of the proposed design method.

1. Introduction
In the continuous feeding mould industrial occasions such as pipe material, colour steel tile, paper plate and so on, the function of multi axes linkage and real-time phase synchronization are usually needed [1-3]. The operation modes of stop cut and stop shear are adopted mostly in the traditional process, which has high accuracy. However, the work efficiency is reduced greatly.

For many situations where the accuracy requirements are not strict, the chase and flying shears have great advantage of high efficiency [4, 5]. The technology of electronic cam is utilized effectively in the running modes of chase and flying shears [6, 7]. Electronic cam can be driven and controlled by software, which is more convenient and faster than the traditional mechanical cam [8, 9]. The cutting time can be reduced greatly. The industrial productions using electronic cam usually have very high production efficiency, and the production process is extremely stable. Therefore, in the cutting of pipe material, operation mode of chase shear is mostly utilized, which can avoid the deformation of materials.

Chase shear is referred to the dynamic cutting in the process of chase, which means that the material is cut in motion. The movement of the master and slave axes are synchronized. When the material is cut, the slave and master axes should be relatively static. There should be no friction and relative sliding between the two axes to ensure accuracy.

The following tasks can be completed by the chase shear system designed in this paper. The cut of fixed length and indication is made. The required material is sheared accurately under the circumstance of setting the length and quantity of the cutting. The colour label mode can be set. A series of marks are drawn on the raw materials. The shear is required according to the logo during the advancement of the master axis.

The rest of this paper is organized as follows. In section 2, the hardware circuits of the chase shear system is designed. The program of the chase shear system is presented in section 3. In section 4, the linear quadratic optimal controller for the servo motor of the system is designed. The effect of the system response is simulated. Conclusions are given in section 5.
2. Hardware Circuits Design of the System

The chase shear system is mainly composed of feed drive, the position and velocity feedback of the master axis, shear knife rest and knife rest drive. Most of the feed drivers are driven by servo or frequency converter. At the end of the master axis, roller encoder is used to detect the speed and distance of feeding material in real time. The shear knife rest can be driven by hydraulic, air pressure, or servo motor. Certain accuracy should be met in the drive of shear knife rest, so servo motor is the main driver.

The way of chase shear motion is mainly the feedback and forward movement of the shear knife rest driven by servo motor. The speed of material feed and the shear knife rest are synchronized in the synchronization area. The shearing action is completed. Then the origin is returned and the synchronization is traced again. The above action is repeated.

2.1. Diagram of the System

The diagram of the chase shear control system is shown in figure 1.

![Figure 1. Diagram of the system](image)

The system is composed of digital controller, human-machine interface (HMI), servo driver and servo motor. The programmable logic controller (PLC) is utilized as the digital controller. The PLC communicates with the HMI and is responsible for control. PLC sends commands to the servo driver to control the movement of the servo motor. The servo system consists of servo driver and DC servo motor. The controller controls the driver directly and completes the establishment and planning of the trajectory. The touch screen is adopted as the HMI. The operation of the servo motor can be monitored by the HMI.

2.2. Hardware Circuits Design

On the basis of the selected hardware devices, the wiring diagram of the whole chase shear system is shown in figure 2.
Three DC servo motor are incorporated in the system. A motor drives the master axis. Two motors drive the slave axis and shear knife respectively. The servo driver contains a number of terminal blocks. The function of every terminal block is different. The driver can be set diverse working condition via different modes of connection.

The wiring of the main circuit terminal is not so much and should be connected with the motor power line U, V, W, PE in order. Each line represents different contents and can not be interlaced. This part of the wiring is simple, but it is the key to the operation of the whole servo driver and motor. The interface of pulse and direction signal line is connected with PLC. There are many forms of the connection between the PLC and the driver. For example, the connection can be differential input and collector opening input. The appropriate connection should be selected according to the user manual. The servo driver has a built-in encoder. The feedback monitoring can be made through high speed counting. The encoder is connected to the servo motor directly using the corresponding encoder line. Then the connection can be completed.

3. Software Design
According to the servo driver, servo motor and wiring mode adopted in the second section, the program is written. The flowchart of the main program is shown in figure 3.
Figure 3. Flowchart of the main program

In the main program, the PLC sends the initialization program firstly, then the servo enable signal is sent and the movement to the origin starts to run. When the condition is met, the cam is initialized and bound. Otherwise the movement to the origin is still waited. Synchronous signal is given and the speed impulse is waiting for sent. If the material of the master axis runs to the target position, velocity synchronization impulse is sent and the material is sheared. When the material is finished shearing, the servo decelerates.

When all the requirements are input and the start key is pressed, the system will automatically run all the synchronization actions by themselves. All the data can be modified at the man-machine interface. The current target state in the human-machine interface is detected. In the process of detection, all the parameters on the touch screen are open to the outside world, that is, they can be modified at will. The general change will affect the operation of the whole system. The stability of the system may also be changed.

4. Optimal Controller Design of Servo Motor

For the given controlled system and the corresponding performance index, the optimal controller is usually designed so that the state of the system is transferred from the initial state to the target state. The performance index is optimal at the same time. Linear quadratic optimal control is one of the common optimal control methods [10].

In the chase shear system, the main way of motion is that the shear knife rest moves feedback and forward driven by servo motor. The core is the control of the motor. In this section, the optimal controller is designed for the servo motor of the system. Considering the servo motor model of the system, the sampling period is assumed to be 0.04s. The state space representation of the servomotor can be written as [11]:

\[
\begin{align*}
    x(k+1) &= Ax(k) + Bu(k) \\
    y(k) &= Cx(k)
\end{align*}
\] (1)
where \( A = \begin{bmatrix} 1.12 & 0.213 & -0.335 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \), \( B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \), \( C = \begin{bmatrix} 0.0541 & 0.115 & 0.0001 \end{bmatrix} \).

The performance index of the system is

\[ J = \sum_{k=0}^{\infty} \left[ x^T(k)Qx(k) + u^T(k)Ru(k) \right] \]  

(2)

where the weight matrices \( Q = \begin{bmatrix} 2 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \), \( R = 1 \).

The following state feedback control law is assumed to be used.

\[ u(k) = -Kx(k) \]  

(3)

where \( K \) is the gain matrix to be designed.

According to the optimal control theory, the linear quadratic optimal controller is as follows.

\[ u(k) = -Kx(k) = -\left[ R + B^T PB \right]^{-1} B^T PAx(k) \]  

(4)

where \( P \) is the solution of the Riccati equation

\[ P = Q + A^T PA - A^T PB \left( R + B^T PB \right)^{-1} B^T PA \]  

(5)

The linear quadratic optimal controller can be obtained \( K = \begin{bmatrix} 0.9810 & 0.1379 & -0.2886 \end{bmatrix} \).

The initial state is assumed to be \( \begin{bmatrix} 1 & -2 & -1 \end{bmatrix} \), the state trajectories and control input controlled by the designed controller are shown in figure 4 and figure 5.
From the simulation results, it can be seen that the system is stable controlled by the designed linear quadratic optimal controller.

The changes of weight matrices have effect on the system performance. \( Q = \begin{bmatrix} 200 & 0 & 0 \\ 0 & 200 & 0 \\ 0 & 0 & 100 \end{bmatrix} \), the linear quadratic optimal controller is \( K = \begin{bmatrix} 1.1181 \\ 0.21183 \\ 0.3343 \end{bmatrix} \). The state trajectories and control input are shown in figure 6 and figure 7.

\[
\begin{bmatrix} Q \\ R \end{bmatrix} = \begin{bmatrix} 200 & 0 & 0 \\ 0 & 200 & 0 \\ 0 & 0 & 100 \end{bmatrix}, \quad K = \begin{bmatrix} 1.1181 \\ 0.21183 \\ 0.3343 \end{bmatrix}.
\]

It is concluded from the simulation that when the weight matrix \( Q \) is increased, the system adjustment time is shortened and the control input is increased.

When the matrix \( R = 100 \), the linear quadratic optimal controller is \( K = \begin{bmatrix} 0.2937 \\ -0.0139 \\ -0.0909 \end{bmatrix} \). The state trajectories and control input are shown in figure 8 and figure 9.
It is inferred from the simulation that when the weight matrix $R$ is increased, the adjustment time of the system becomes longer and the control input is decreased.

5. Conclusions
Chase shear is one of the most used methods in material cutting. In this paper the hardware circuits of the chase shear control system are designed. Then the program framework of the system is described. Finally the linear quadratic optimal controller for the servo motor of the chase shear system is designed.

6. Acknowledgments
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7. References
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