Research on Grab Swing Control Method Based on Time Delay Filter

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Abstract. Grab swing during crane acceleration and deceleration will have an impact on work efficiency and safety. In this regard, the swing amplitude of the grab during the operation must be controlled within a certain range. According to the mechanical analysis of bridge crane's grab, the mathematical model between crane's horizontal movement and grab swing is established. A time delay filter technique is applied to shape the acceleration control signal, thus effectively control the swing angle of the grab. Simulation results show that the control method with time delay filter could eliminate the swing of the grab even without measuring the swing angle, and is feasible for engineering applications.

1. Introduction

Grab swing during crane acceleration and deceleration will have an impact on work efficiency and safety. In this regard, the swing amplitude of the grab during the operation must be controlled within a certain range. The electric control devices of existing bridge cranes are mainly composed of cam controller or master controller and winding motor [1], and the speed regulation mode is series resistor regulation with step speed. The controller cannot achieve the smooth adjustment of the crane in the operational stage of starting and braking, and unable to ensure a proper acceleration of the breaking, which results in a lower work efficiency. So efficient control of the motor and achieve synchronous control of both the parking position and grab swing is the key point to the crane control system design.

At present, most of the research on grab control is based on the optimal control theory, the optimal time control method based on expert experience [2], or some feedback control scheme to achieve the control target [3]. However, the cost of feedback control is high, and it is inevitably to increase the displacement sensor. Even when the measuring parameter is not displaced quantity, there may be measurement difficulties. In this paper, a feed forward time-delay filter technique is adopted to eliminate the swing of the grab and achieve a good control effect.
2. Mathematical model of grab swing

The schematic diagram of the bridge crane is shown in Fig. 1, in which \( u \) is the horizontal acceleration control signal, \( x \) is the displacement of the trolley under control of signal \( u \), \( g \) is the gravity acceleration, \( \theta \) is the angle of suspension rope with vertical direction, and \( L \) is the length of the cable.

![Figure 1. Basic structure model of crane grab](image)

To simplify the analysis, according to the operation condition of crane, following assumptions and requirements are set: 1) the quality of the cable is negligible with respect to the quality of grab and load, the stiffness of the cable is large enough and the change of length is negligible; 2) the resistance of grab and suspension rope during operation is not counted; 3) the maximum swing angle of the grab is required to be \( \theta \leq 10^\circ \), and the linearization error does not exceed 0.5%. Then, through the analysis of the force, the linearized model of the grab swing can be obtained as:

\[
\begin{align*}
L \dot{\theta} + g \theta &= u(t) \\
\dot{\theta} + \left(\frac{g}{L}\right) \theta &= \frac{u(t)}{L}
\end{align*}
\]  

(1)

Taking the Laplace transform on Eq(1), transfer function of the grab is

\[
G(s) = \frac{\theta(s)}{u(s)} = \frac{1/L}{s^2 + g/L}
\]  

(2)

According to Eq(1), let \( t=0, \theta=0, \dot{\theta}=0 \), then we can obtain the solution as follows:

\[
\begin{align*}
\theta &= \frac{u}{g} \left(1 - \cos \sqrt{\frac{g}{L}} t\right) \\
\dot{\theta} &= \frac{u}{\sqrt{g/L}} \sin \sqrt{\frac{g}{L}} t
\end{align*}
\]  

(3)

From Eq (3) we can see that the swing of the grab is periodically changed with time, and the swing and swing speed are proportional to the horizontal acceleration of the crane.

3. The design of time delay filter

The Time Delay Filter technique [4] known as input shaper is a major branch of time-delay control [5,6]. As a feed forward type open-loop control method, TDF can fundamentally avoid the vibration mode of the excitation object to eliminate residual oscillation, and has received extensive attention in suppressing the residual oscillation of high-precision positioning systems.

The time-delay filter acts as a feed forward unit in the open-loop system, consciously introduces a time-delay link in the filter, and solves equations that constrain the performance of the system to obtain...
input signals of different amplitudes. Then, convolving the input of desired system with pulse sequences of different magnitudes can be used to obtain a shaped input to drive the system, i.e. input shaping.

A simple TDF usually consists of two pulses, the first pulse oscillates at zero-time, and a reversed phase and same amplitude pulse with time delay is taken as the second pulse used to eliminate oscillation. As shown in Fig. 2, the oscillations of pulse1 \( A_1 \) and pulse2 \( A_2 \) are superimposed and completely eliminated, which is realized by an appropriate amplitude. Generally, the amplitude and pulse time can be obtained by solving the constraint equations in a basic form as: 

\[ C(s) = A_1 + A_2 \exp(-st) \]

**Figure 2.** Oscillation elimination process of dual-pulse filter

Considering a second-order damping system 

\[ G(s) = \frac{\omega^2}{s^2 + 2\xi\omega + \omega^2} \]

(0<\(\xi\)<1), by using of TDF, the remained flutter can be described as a function of the natural frequency \( \omega \) and the damping \( \xi \)

\[ V(\omega, \xi) = \exp(-\xi t) \sqrt{C(\omega, \xi)^2 + S(\omega, \xi)^2} \] (4)

where,

\[ C(\omega, \xi) = \sum_{i=1}^{2} A_i \exp(\xi t_i)\cos(\omega\sqrt{1-\xi^2} t_i) \] (5)

\[ S(\omega, \xi) = \sum_{i=1}^{2} A_i \exp(\xi t_i)\sin(\omega\sqrt{1-\xi^2} t_i) \] (6)

\( A_i \) and \( t_i \) are respectively the amplitudes and corresponding time lag of the pulse sequence. Eq(4) provides a method for designing TDF that realize a zero-amplitude of remained flutter at the frequency and damping of the controlled system. To achieve above control, the sum of all sinusoidal and cosines must also be kept as zero, i.e.

\[ \sum_{i=1}^{2} A_i \exp(\xi t_i)\cos(\omega\sqrt{1-\xi^2} t_i) = 0 \] (7)

\[ \sum_{i=1}^{2} A_i \exp(\xi t_i)\sin(\omega\sqrt{1-\xi^2} t_i) = 0 \] (8)

In order to obtain the same output for either shaped or unshaped input, the sum of the pulse amplitudes must satisfy the gain constraint as \( \sum_{i=1}^{2} A_i = 1 \). At the same time, the amplitude of the pulse should be positive, i.e. \( A_i \geq 0 \). By solving above equations, we can obtain \( K = \exp[-\xi\pi/(1-\xi^2)^{1/2}] \), \( \Delta T = \pi/\omega_0(1-\xi^2)^{1/2} \), \( A_1 = 1/(1+K) \), \( A_2 = K/(1+K) \), \( t_1 = 0 \), \( t_2 = \Delta T \). Then, the obtained two-pulse sequence is zero-oscillation digital filter with zero vibration, which satisfies the constraint and the system residual oscillation is zero.
4. Simulation results and analysis
Taking a bridge crane as an example, the maximum horizontal acceleration value is 0.2 m/s², the maximum horizontal speed is 0.8 m/s, the acceleration and deceleration time is 4 s, the cable length is \( L = 10 \) m, and \( g = 10 \) N/m². Then the mathematical model of the system is

\[
G(s) = \frac{0.1}{s^2 + 1}
\]  

According to the mathematical model of the system, the ZV type time-delay filter is designed as \( C(s) = 0.5 + 0.5 \cdot \exp(-3.14s) \). By introducing the time-delay filter, in a complete working process of accelerated start, constant speed and deceleration stop, under the control of acceleration signal, the control curve and response curve of the grab are shown in Fig. 3 and Fig. 4.

![Figure 3. Comparison of acceleration control curve](image)

![Figure 4. Response curve of the grab](image)

From the simulation curve we can see that the control curve is stepped with a shaped time delay filter on acceleration signal. In the starting process, the grab is just swing in the opposite direction of the moving direction, the shim is eliminated and the amplitude of the swing is greatly reduced. With the time optimization control method, the crane still swings back and forth after the crane stops. When the cable length increased by 12 m, the response curve of the system is shown in Fig. 5 with the same time delay filter mentioned above. In this simulation, the grab swing is suppressed within a certain range, and which testify the robust of this method to model errors.

![Figure 5. Swing offset angle with 12 m cable length](image)

5. Conclusion
According to the force analysis of the crane grab, the mathematical model of the relationship between the horizontal operation of the crane and the swing of the grab is established, and a time-delay filter technique that can suppress the residual oscillation of the system is used to effectively control the swing
angle of the grab. The time-delay filter only shapes the acceleration control signal, and does not need to measure the swing angle of the grab. Compared with the time optimization method, it not only achieves good system performance, but also greatly simplifies the design process. The simulation results show that the method can effectively eliminate the grab swing and is easy to be applied in engineering.

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