Automatic Coil-handling Crane Control System

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Abstract

Lots of researches and applications on the automated overhead cranes in shops have been done for some decades, but a few successful results are reported. A more reasonable control system fit to requirements of manufacturing industries is suggested in the study. The controller was designed in the continuous time domain by loop-shaping method. Sway of the rope is suppressed by anti-sway control method. The sway angle of the rope is measured by a sway angle sensor which is mechanically in contact with the rope. The real-time control law is comprised of the position and the anti-sway controller. Some algorithms required for coil yard operation as well as main control algorithms such as reference position generation, position control and anti-sway control have been designed and fully tested on a crane in the steel-making works. The designed crane control system showed satisfactory performance on position control accuracy and anti-sway of rope. The maximum positional error is 20mm and the maximum sway error is 0.07 degrees in the destination position.

Keywords: *Coil-handling, Crane Control System*

1. Introduction

Lots of researches and applications on the automated overhead cranes in shops have been done for some decades, but a few successful results are reported[1]. Integrated crane control systems designed by famous engineering companies are still expensive and are not satisfactory in view of maintenance and reliability. A coil-handling crane has long rope and short sheave distance, and therefore rope sway happens easily. Long sway period arose by the rope makes sway decay time-consuming and un-manned operation difficult. A more reasonable control system fit to requirements of coil-handling cranes was designed in the study.

Positions of the travelling and traverse axis are controlled by PID position controllers. The controller was designed in the continuous time domain by loop-shaping method and converted to the discrete form for computer code generation by z-transform. Sway of the rope is suppressed by anti-sway control method. The sway angle of the rope is measured by a sway angle sensor which is mechanically touched with the rope. The sway angle is consistently suppressed from the start point to the goal position by PD control law. The control frequency of the overall controller which is comprised of the position and the anti-sway controller is 25Hz on account of the dynamics of moving axes.

The some algorithms required for coil yard operations as well as main control algorithms such as reference position generation, position control and anti-sway control have been designed and fully tested on a 100 tons crane which can carry about 70 tons coil. The designed crane control system showed satisfactory performance on position control accuracy and anti-sway of rope. The maximum positional error is 20 mm and the maximum sway error is 0.07 degrees in the goal position.

A skilled human operator has intimate knowledge of the process at hand, and a keen ability to adapt as required to meet operational goals given an infinitely variable set of circumstances. Therefore, it is critical in the design and implementation of any automation system to assure that effects on the production rate in the plant should be minimized. For this reason, special attention has been given to the optimization of the crane movements required to carry out each type of work instruction, resulting in improvement in the crane cycle time. Simultaneous movement of the travelling, traverse and hoist axis has been realized over the collision-free height to reduce cycle time. The suggested control strategies have been successfully applied to some coil-handling cranes in works of a steel-making company and in commercial operation for a few years

2. Crane Dynamics

The girder of a crane moves in the traveling axis, the trolley moves in the traversing axis and the object transferred by the crane goes up and down. Their movements are described with positions and velocities in the X-Y-Z coordinates, as shown in Figure1[2][3].

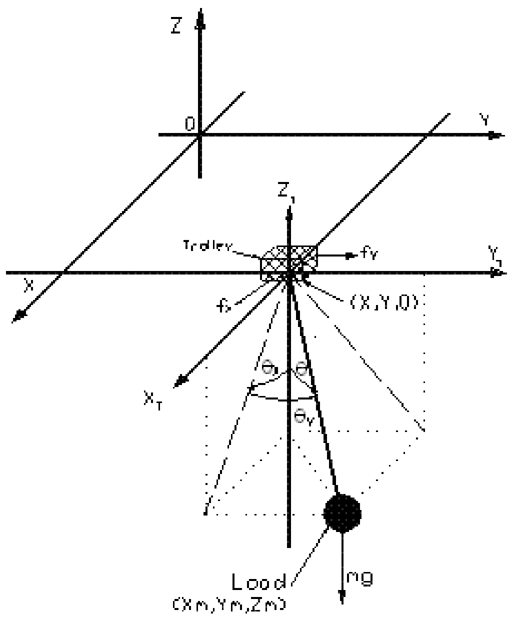

Figure 1. Crane coordinates and rope sway angle

The traveling axis are described with X axis, the traversing axis with Y axis and movement of the object in up and down direction with Z axis.

Calculating the position of mass hung by the rope are in the coordinates

$$x_m = x + l\sin\theta_x \cos\theta_y \qquad (1)$$

$$y_m = y + l \sin\theta_y \tag{2}$$
$$z_m = -l \sin\theta_x \cos\theta_y \tag{3}$$

where x_m, y_m and z_m are positions of the mass in the x, y and z direction, respectively. Determining its velocity,

$$v_m^2 = \dot{x}_m^2 + \dot{y}_m^2 + \dot{z}_m^2 \tag{4}$$

where v_m is the object velocity.

There are two methods for determining the dynamic equation of moving object: one is Newtonian method and the other is Lagrangian one(Gonzales, 1986). The Lagrangian-Euler method is applied in this study. Lagrangian is calculated with kinetic energy K and potential energy P of the crane and the object.
Dynamic equations for the crane and the object can be derived from Lagrange-Euler equation. They are simplified with the assumption that velocity and acceleration change of the rope length during crane movement are nearly zero, $\dot{l} \approx \ddot{l} \approx 0$.

$$= \frac{1}{2}(M_x \dot{x}_m^2 + M_y \dot{y}_m^2)$$
$$+ \frac{m}{2} v_m^2 + mgl \sin\theta_x \cos\theta_y \tag{5}$$

Rewriting the above equation for x and y axis,

$$(\quad _x \quad) \quad _x \quad _x \quad _y \; _x$$
$$- ml \sin\theta_x \sin\theta_y \ddot{\theta}_y - ml \sin\theta_x \cos\theta_y \dot{\theta}_x^2$$
$$- 2ml \cos\theta_x \sin\theta_y \dot{\theta}_x \ddot{\theta}_y$$
$$- ml \sin\theta_x \cos\theta_y \dot{\theta}_y^2 = f \tag{6}$$
$$l \cos\theta_y \ddot{\theta}_x + \cos\theta_x \ddot{x} + g \sin\theta_x$$

$$2l \sin\theta \; \dot{\theta} \; \dot{\theta} \quad 0 \tag{7}$$
$$(M_y + m)\ddot{y} + D_y \dot{y} + ml \cos\theta_y \ddot{\theta}_y$$

$$- ml \sin\theta_y \dot{\theta}_y^2 = f_y \tag{8}$$
$$l \theta_y + \cos\theta_y \ddot{y} + g \cos\theta_x \sin\theta_y$$

$$+ l \cos\theta \; \sin\theta \; \dot{\theta}^2 \quad \sin\theta \; \sin\theta \; \ddot{x} = 0 \tag{9}$$

where M_x , M_y and m are the mass of the crane body, the trolley and the object, respectively and D_x and D_y are viscosity coefficients in the x and y axis.

Since they are nonlinear differential equations, they need to be more simplified to design a control law. Since the sway angle and the angle velocity of the rope are small and the object mass is much smaller than the crane mass in real crane movement, the following assumptions are reasonable to get simpler equations.
$|\theta| << 1$, $|\dot{\theta}| << 1$ and $M >> m$
Linear differential equations for the crane and the rope sway are obtained with the assumptions above mentioned.

$$M_x \ddot{x} + D_x \dot{x} = f_x \tag{10}$$
$$l\ddot{\theta}_x + \ddot{x} + g\theta_x = 0 \tag{11}$$
$$M_y \ddot{y} + D_y \dot{y} = f \tag{12}$$

$$l\ddot{\theta}_y + \ddot{y} + g\theta_y = 0 \quad (13)$$

The transfer functions of the crane velocity $G_t(s)$ and the transfer functions of the rope sway $G_l(s)$ are obtained by Laplace transform.

$$\frac{V(s)}{F(s)} \equiv G_t(s) = \frac{1}{Ms + D} \quad (14)$$

$$\frac{\Theta(s)}{X(s)} \equiv G_l(s) = \frac{-s}{l\ {}^{2}} \quad (15)$$

The actual transfer functions of the crane velocity in the X direction and Y direction are given by experiments, respectively.

$$G_{tx}(s) = \frac{0.24}{3\ \ 1} \quad (16)$$

$$G_{ty}(s) = \frac{0.219}{0\ 5\ \ 1} \quad (17)$$

3. Design of position and sway control law

Positions of the travelling and traverse axis are controlled by PID position controllers. The controller was designed in the continuous time domain by loop-shaping method and converted to the discrete form for computer code generation by z-transform. The open-loop Bode plot for $G_{tx}(s)$ is shown in Figure 2.

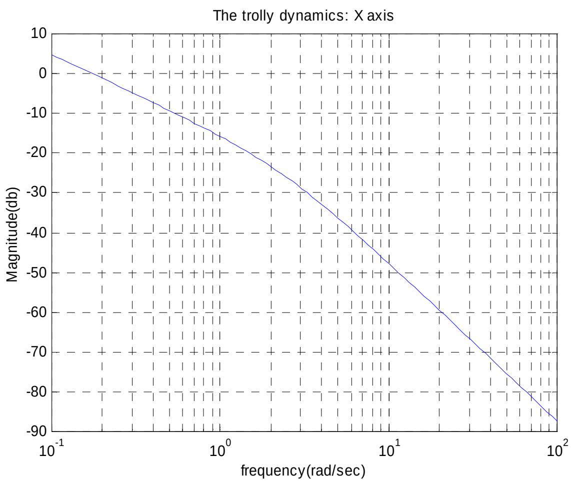

Figure 2. Bode plot of the trolley dynamics (open loop)

The roll-off rate of in the cross-over frequency is -20 db/dec. But if a large proportional gain is used in the feedback controller, the loop shape necessarily goes up, and the roll-off rate in the cross-over frequency will be -40 db/dec. It should maintain -20db/sec. for the control system to have good performance and stability.
So insertion of two finite zeros near cross-over frequency and an integrator guarantees that the target loop will have -20 db/dec. The shaped plant is obtained by inserting a loop compensator ,where -0.4 and -0.5 are assigned to T_1 and T_2, respectively. Another pole is introduced to satisfy properness of the transfer function. The kp is chosen to be 100 to sufficiently attenuate position error. The feedback control system with the designed

compensator will have a nice transient response. It also illustrates that the higher roll-off rate in the higher-frequency region gives robustness to measurement noise. Figure 3 shows the Bode plot of the compensated system with weighted function.

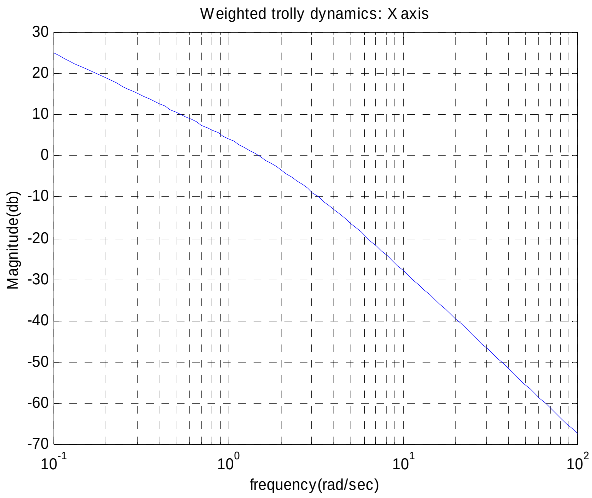

Figure 3. Bode plot of the trolley dynamics (weighted open loop)

As shown in the transfer function of sway dynamics $G_l(s)$ whose input is trolley position and output is sway angle, it has two undamped poles and two zeros at origin. The zeros near origin dominates plant dynamics and undamped poles make decay of rope sway very hard. Figure 4 shows Bode plot of the rope sway dynamics. Rope sways in the travelling direction and traversing direction are suppressed by PD control laws to give more damping the sway suppression control.

The position controller and the anti-sway controller designed in the continuous domain is transformed to a discrete-time domain controller through bilinear transformation. The position controller and the anti-sway controller designed in the continuous domain is transformed to a discrete-time domain controller through bilinear transformation. Figure 5 shows an overall block diagram of the position and anti-sway control system. It is assumed that the transfer functions of the dynamic model of position control system on the traveling and traversing axes are 2nd-order systems. The digital codes were written in PASCAL language for actual control in PLC, and are executed every 40 msec.

4. Simultaneous motion of 3 axes

Typical functions of the yard crane consist of a sequence of motions such as vertical hoisting, traversing, traveling, traversing and vertical dropping. Skilled crane operators perform two motions at the same time to reduce the cycle time. However the speed of each motion depends on the level of skill.

The new crane control system generates an optimal trajectory in the safety zone for each job and performs 3-axis motions simultaneously to minimize cycle times as shown in Figure 6.

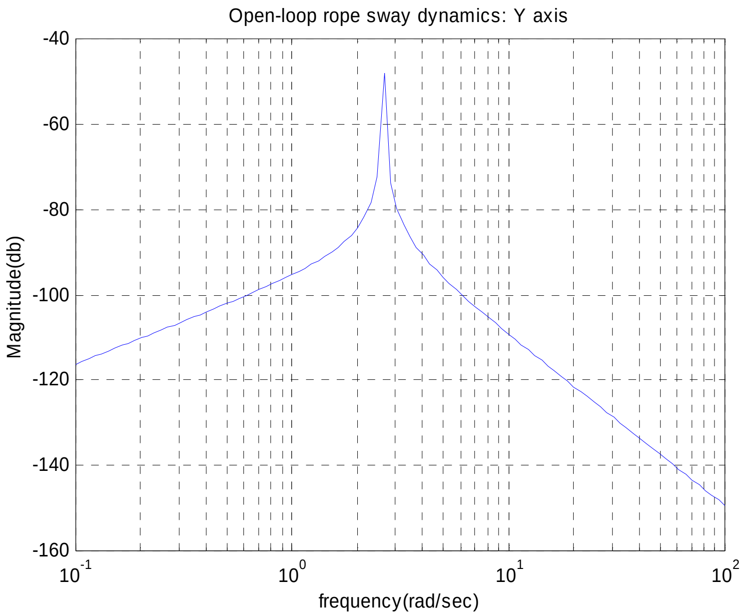

Figure 4. Bode plot of the sway dynamics

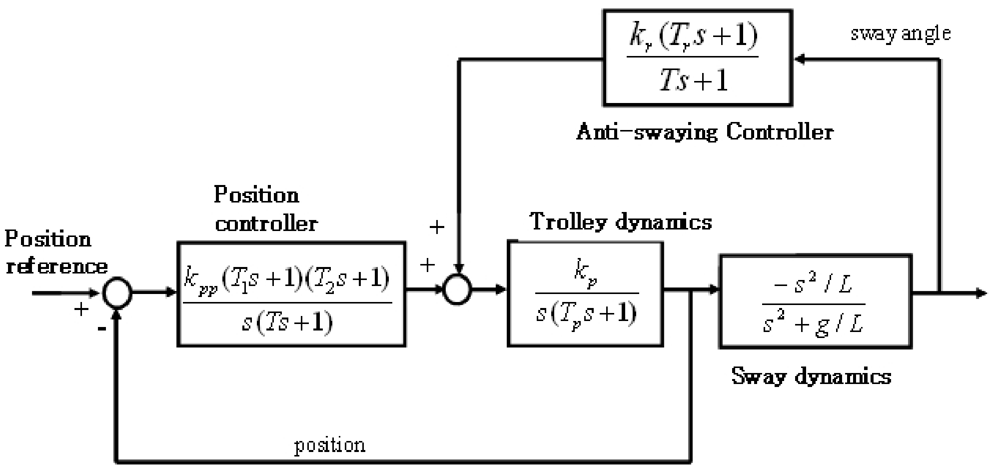

Figure 5. Overall control block diagram

The safe yard height (h1) is set by considering the height of the largest coil or facilities in the yard and the safe coil height (h2) is set by calculating the half outer radius of coil carried by the coil lifter. Then the safe travel height (h3) where the crane can carry a coil without collision with coils or facilities in the yard is set as h3 = h1 + h2. The distance(d) for starting to hoist down a coil before destination position is 500mm in the traveling direction, and 300mm in the traverse direction, respectively.

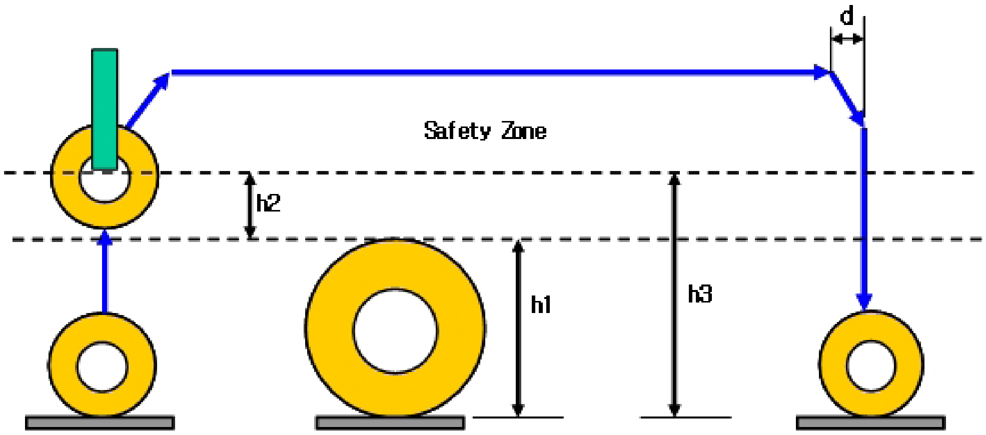

Figure 6. 3-axis linked movement process

5. Conclusions

A more reasonable control system fit for requirements of cranes was designed and applied to a rolling plant. Positions of the travelling and traverse axis are controlled by PID position controllers. The controller was designed in the continuous time domain by loop-shaping method. Sway of the rope is suppressed by anti-sway control method. The sway angle is consistently suppressed from the starting position to the goal position by PD control law. The overall controller is comprised of the position and the anti-sway controller.

The designed crane control system showed satisfactory performance on position control accuracy and anti-sway of rope. Special attention also has been given to optimization of the crane movement, resulting in improvement in the crane cycle time. Simultaneous movement of the travelling, traverse and hoist axes has been realized over collision-free height to reduce cycle time. The suggested control strategies have been in commercial operation in the works of a steel-making company for a few years.

References

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