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Anti-Sway Crane Control Based on Dual State Observer with Sensor-Delay Correction

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***Abstract*—Recently, a container crane is requested to operate smoothly and quickly. For this purpose, the control system of container crane should have an anti-sway control technique to suppress its vibration phenomenon. A vision sensor system to detect the sway angle is often used. However, since the control system with vision sensor has the delay time in detection, it sometimes has the deterioration of control performance owing to the delay time influence. In order to overcome this problem, this paper proposes a new anti-sway crane control based on dual state observer with sensor-delay correction. The effectiveness of the proposed method is verified by the numerical simulation results and the experimental results.**

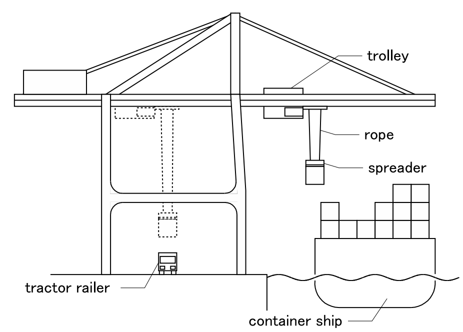


Fig. 1. Schematic image of container crane.

I. Introduction

Recently, a container crane is requested to operate smoothly and quickly. The sway of crane cargo container decreases the work efficiency and the safety. Since the swing phenomenon is generally happened by the manual actuation of operator, the operator must have its skillfulness. Fig. 1 is the container crane handling the container which is the cargo from the container ship in port. The container crane has been expanded in recent years. As the rope of container crane becomes long, it is difficult to realize the anti-sway control of the load by manual movement. Moreover, the anti-sway control techniques for the container crane becomes the important specification on the view point of the demand of efficiency and automation. Therefore, the control system of container crane should have an anti-sway control technique to suppress its vibration phenomenon.

In the anti-sway control, the sway angle must be detected. A vision sensor system to detect the sway angle is often used. The marker is put in the spreader grasping the container and is usually taken the photo with the camera fitted on trolley. The use of vision system takes the processing time from 20[msec] to 300[msec]. Hence, the control system has the delay time in detection and has the deterioration of control performance owing to the delay time influence.

In order to overcome this problem, this paper proposes a new anti-sway crane control based on the state observer of sway angle. This paper contracts the sway angle observer estimating the sway angle of container which is based on the crane motion equation. The angular velocity sensor is mounted on the container and the sway angle is estimated by the state observer [1], [2]. The state observer estimates the sway angle accurately, and compensates the feedback information of the sway angle for the long sampling time of vision sensor detection system. However, when the container crane has the parameter variation such as the rope length variation and the load weight variation, the state observer does not estimate the sway angle accurately and has the estimation error. In order to overcome this problem, this paper proposes another state observer of the sway angle to compensate the estimation error caused by the parameter variation such as the rope length variation and the load weight variation. As the results, this paper proposes a new anti-sway crane control based on dual state observer with sensor-delay correction.

The speed-controlled trolley drive system of container crane is implemented in the state feedback based on the plant system equation. Many documents on the anti-sway control has been represented [3], [4], [5]. However, as these references are complicated in the calculation, it is difficult to realize these control algorithms in the actual application field. Additionally, in this paper, the possibility of versatile controller is considered in the speed-controlled trolley drive system. This paper proposes the anti-sway control only using the trolley speed and the sway

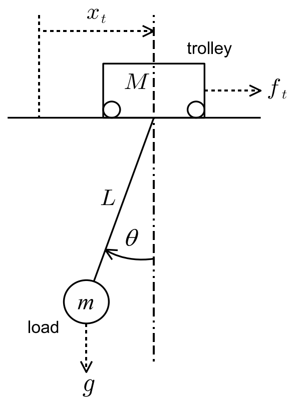


Fig. 2. Dynamics model of a crane.

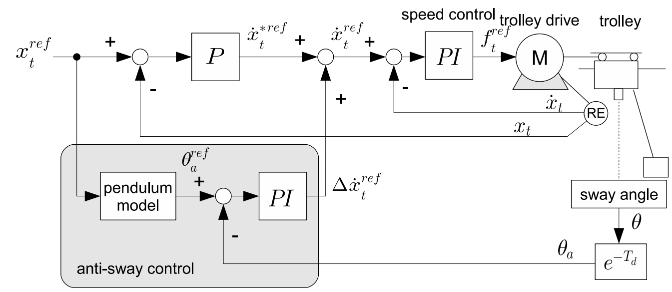


Fig. 3. Block diagram of the conventional control system.

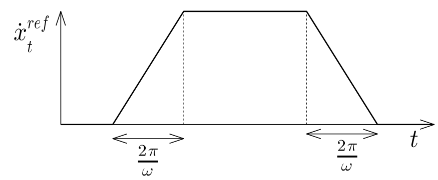


Fig. 4. Velocity reference pattern of container crane.

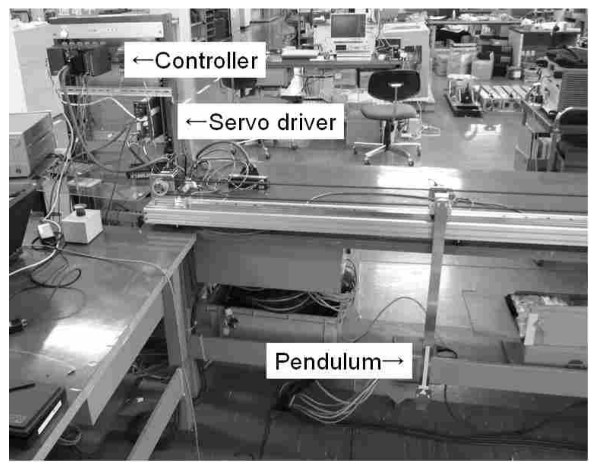


Fig. 5. Tested experimental equivalent system of container crane.

angle. The effectiveness of the proposed method is verified by the numerical simulation results and the experimental results.

II. System and Sway Angle Observer

A. Target of control and System Equation

The schematic image of container crane is indicated as shown in Fig.1. The garter is built between the dock and the container ship. The trolley is driven by the motor drive unit and moves on the garter. The spreader is being hung by the rope in this trolley, and holds the container. Fig.2 shows the simplified model which explains the motion of crane, where M is the trolley mass, m is the total mass of the container and the spreader, L is the rope length. From Fig.2, the discrete-time state equation of crane is induced as shown in (1) - (5). T_s is sampling period. θ is the sway angle. x_t is the position of trolley. $\dot{\theta}$ is the sway angular speed. $\dot{x}_t$ is the trolley speed. f_t is the generated force of trolley drive system. $\dot{x}_t$, θ and $\dot{\theta}$ are the state variables of $z[k]$ in (1), and f_t is the input variable of $u[k]$ in (1).

$$z[k+1] = Az[k] + Bu[k] \tag{1}$$

$$y[k] = Cz[k] \tag{2}$$

$$A = \begin{bmatrix} 1 & \frac{gm}{\omega M}\sin\omega T_s & \frac{gm}{\omega^2 M}(1-\cos\omega T_s) \\ 0 & \cos\omega T_s & \frac{1}{\omega}\sin\omega T_s \\ 0 & -\omega\sin\omega T_s & \cos\omega T_s \end{bmatrix} \tag{3}$$

$$B = \begin{bmatrix} \frac{T_s}{M} - \frac{m}{M(M+m)}\left(T_s - \frac{\sin\omega T_s}{\omega}\right) \\ -\frac{1}{g(M+m)}(1-\cos\omega T_s) \\ -\frac{\omega}{g(M+m)}\sin\omega T_s \end{bmatrix} \tag{4}$$

$$C = \begin{bmatrix} 1 & 0 & 0 \end{bmatrix} \tag{5}$$

ω is the natural resonance frequency, which is expressed in (6).

$$\omega = \sqrt{\frac{(M+m)g}{ML}} \tag{6}$$

B. Conventional Anti-sway Control

The block diagram of conventional anti-sway control system is shown in Fig.3, the detection sway angle is directly inputted to the anti-sway controller, even though it has the time-delay. The position reference x_t^{ref} is determined by the velocity reference pattern $\dot{x}_t^{ref}$ as shown in Fig.4. The validity of conventional anti-sway control is confirmed by using the tested experimental equivalent system as shown in Fig.5.

The parameters of the tested experimental equivalent system are shown in Table.1, which is $1/50$ size equivalent model. The numerical simulation results and the experimental results are shown as Fig.6, Fig.7 and Fig.8. Fig.6 shows the numerical simulation results of conventional anti-sway control system with no parameter variation and delay time 240[msec] which is 24 times value of the sampling time T_s. Fig.6 point outs that the conventional system has an almost good motion response

TABLE I
PARAMETERS OF PLANT SYSTEM.

description	symbol	value
rope length	L	0.6 m
trolley weight	M_t	0.3 kg
load weight (spreader)	m_s	0.15 kg
rated torque	τ_r	0.637 Nm
rated speed	ω_r	3000 r/min
inertia rotor	J_m	0.135 kgcm^2
pulley diameter	D	0.0955 m

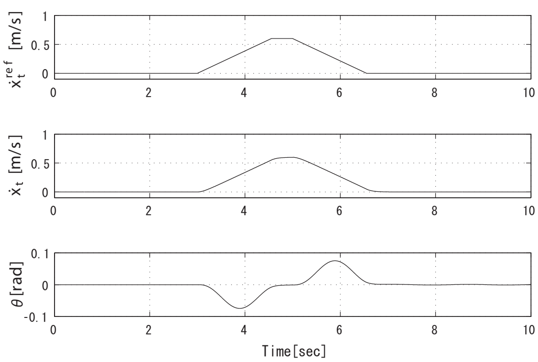


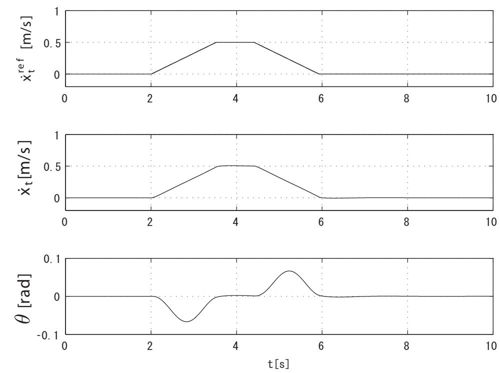
Fig. 6. Numerical simulation results of conventional anti-sway control system with no parameter variation and delay time 240[msec].

on condition of no parameter variation and the delay time 240[msec]. Hence, the conventional system has the robust structure on only delay time.

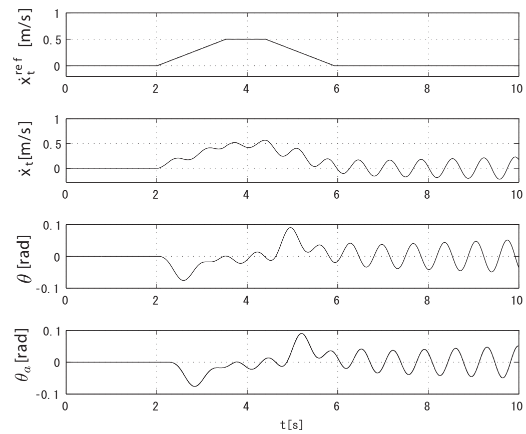
Fig.7 shows the numerical simulation results of conventional system with parameter variation. The parameter variation is the variation of rope length L such as 95% of the nominal length. Fig.7 (a) point outs that the conventional system also has an almost good motion response on condition of parameter variation and no delay time. Hence, the conventional system has the robust structure on only parameter variation such as the rope length variation 95% L. On the contrary, Fig.7 (b) point outs that the conventional system has an oscillated response on condition of both parameter variation and delay time.

Fig.8 shows also the experimental results of conventional anti-sway control system with same parameter variation. Similarly, Fig.8 (a) also point outs that the conventional system has an almost good motion response on condition of parameter variation and no delay time. Fig.8 (b) also point outs that the conventional system has an oscillated response on condition of both parameter variation and delay time. Therefore, in Fig.7 and Fig.8, the conventional system cannot have the robust structure on both parameter variation and delay time.

In anti-sway control of container crane, in order to detect the sway angle, the vision sensor system is often used. The use of vision system takes the processing time from 20[msec] to 300[msec]. Therefore, its anti-sway control system often has the delay time from 20[msec] to 300[msec]. Moreover, the container crane always has influence on the parameter variation such as the rope length variation and the load weight variation. Hence, the anti-sway control system of container



(a) without delay time



(b) with delay time 240[msec]

Fig. 7. Numerical simulation results of conventional anti-sway control system with parameter variation 95% L.

crane is always request to have the robust structure on both parameter variation and delay time.

III. SWAY ANGLE OBSERVER

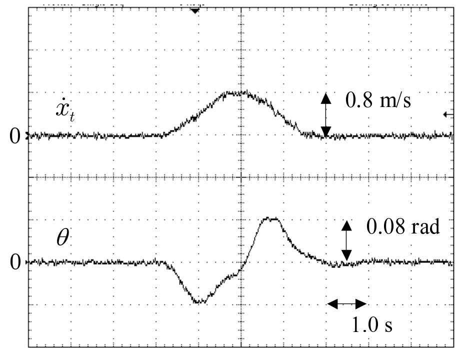
In order to overcome this problem, this paper a new anti-sway crane control based on dual state observer with sensor-delay correction. At first, this chapter constructs the sway angle observer which is the state observer to estimate the sway angle θ and the sway angular speed $\dot{\theta}$, which is configured by using Gopinath's method. This observer is indicated by the discrete state equation in (7) - (13). $\hat{\theta}$ and $\hat{\dot{\theta}}$ are the estimated values of θ and $\dot{\theta}$ which are the output variables $\hat{z}[k]$ in the sway angle observer. Hence, the sway angle observer estimates the sway angle θ of container which is based on the crane motion equation. $\hat{v}$ is state quantity of observer.

$$\hat{v}[k+1] = \hat{A}\hat{v}[k]+\hat{B}y[k]+\hat{J}u[k] \tag{7}$$

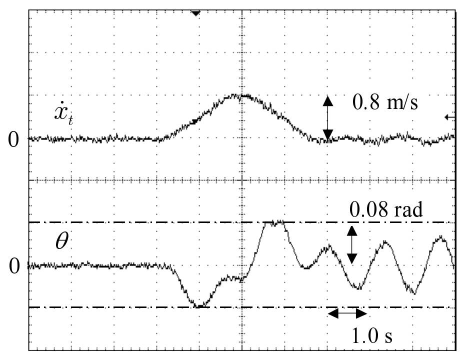
$$\hat{z}[k] = \hat{C}\hat{v}[k]+\hat{D}y[k] \tag{8}$$

$$\left\{ y[k] = \dot{x}_t[k] \;, \quad u[k] = f_t[k] \right\}$$

$$\hat{A}=\begin{bmatrix} \hat{a}_{11} & \hat{a}_{12} \\ \hat{a}_{21} & \hat{a}_{22} \end{bmatrix} \tag{9}$$



(a) without delay time



(b) with delay time 240[msec] (dashed line: scale limit)

Fig. 8. Experimental results of conventional anti-sway control system with parameter variation 95% L.

$$\left(\begin{array}{l} \hat{a}_{11} = \cos\omega T_s - l_1 \dfrac{gm}{\omega M} \sin\omega T_s \\ \hat{a}_{12} = \dfrac{1}{\omega} \sin\omega T_s - l_1 \dfrac{gm}{\omega^2 M}(1-\cos\omega T_s) \\ \hat{a}_{21} = -\omega \sin\omega T_s - l_2 \dfrac{gm}{\omega M} \sin\omega T_s \\ \hat{a}_{22} = \cos\omega T_s - l_2 \dfrac{gm}{\omega^2 M}(1-\cos\omega T_s) \end{array}\right)$$

$$\hat{B} = \left[\begin{array}{cc} \hat{b}_1 & \hat{b}_2 \end{array}\right]^T \tag{10}$$
$$\left(\begin{array}{l} \hat{b}_1 = \hat{a}_{11} l_1 + \hat{a}_{12} l_2 - l_1 \\ \hat{b}_2 = \hat{a}_{21} l_1 + \hat{a}_{22} l_2 - l_2 \end{array}\right)$$

$$\hat{J} \;=\; \left[\begin{array}{cc} \hat{j}_1 & \hat{j}_2 \end{array}\right]^T \tag{11}$$
$$\left(\begin{array}{l} \hat{j}_1 = -\dfrac{1}{g(M+m)}(1-\cos\omega T_s) \\ \qquad -l_1 \left\{ \dfrac{T_s}{M} - \dfrac{m}{M(M+m)} \left(T_s - \dfrac{\sin\omega T_s}{\omega} \right) \right\} \\ \hat{j}_2 = -\dfrac{\omega}{g(M+m)}(\sin\omega T_s) \\ \qquad -l_2 \left\{ \dfrac{T_s}{M} - \dfrac{m}{M(M+m)} \left(T_s - \dfrac{\sin\omega T_s}{\omega} \right) \right\} \end{array}\right)$$

$$\hat{C} = \left[\begin{array}{cc} 1 & 0 \\ 0 & 1 \end{array}\right] \tag{12}$$
$$\hat{D} = \left[\begin{array}{cc} l_1 & l_2 \end{array}\right]^T \tag{13}$$

As the estimation sway angle $\hat{\theta}$ is estimated by the above calculation of the sway angle observer, the anti sway control can be realized without the practical sway angle. In other word, the anti sway control based on the sway angle observer can be carried out without vision sensor system.

IV. Anti-Sway Crane Control Based on Dual State Observer with Sensor-Delay Correction

In the anti-sway control system, a vision sensor system to detect the sway angle is often used. The use of vision system takes the processing time from 20[msec] to 300[msec]. Hence, the detection system of actual sway angle has the delay time from 20[msec] to 300[msec].

As the container crane has the parameter variation such as the rope length variation and the load weight variation, the state observer does not estimate the sway angle accurately and has the estimation error. When the anti sway control based on the sway angle observer has the information of the actual sway angle θ, the estimated sway angle $\hat{\theta}$ of the sway angle observer can be corrected to the actual sway angle θ. In this case, the state variables of the sway angle observer also must be corrected to the fitted state variables.

Therefore, in the actual anti-sway control system, considering the delay time, the state variables of the sway angle observer must be corrected to the fitted state variables. In order to overcome all of these problems, this paper proposes another state observer of the sway angle to compensate the estimation error caused by the parameter variation such as the rope length variation and the load weight variation. As the results, this paper proposes a new anti-sway crane control based on dual state observer with sensor-delay correction.

The first sway angle observer is the general state observer, which calls "state estimation observer". The estimated sway angle $\hat{\theta}$ of this observer becomes the feedback signal for the anti-sway control system. The sampling time T_{se} of this observer is the same as the sampling time T_u of the anti-sway control system. The sate equations of "state estimation observer" are eqaul to (7) and (8)

The second sway angle observer is the correction observer of the first sway angle observer, which calls "time correction observer". The sampling time T_{tc} of this observer is the same as the sampling time T_d of the detection delay time of the detected sway angle θ_a from the vision sensor system. The sate equations of "time correction observer" are also essentially eqaul to (7) and (8), as shown in (14) - (16). Moreover, in "time correction observer", using the detected sway angle θ_a from the vision sensor system, the state variables of both sway angle observers are be correcting to the fitted state variables.

$$\bar{\hat{v}}'_c \;=\; \left[\begin{array}{cc} \hat{v}'_{c1} & \hat{v}_{c2} \end{array}\right]^T \tag{14}$$
$$\hat{v}'_{c1}[k-1] \;=\; \theta_a[k] - l_1 y_1[k-1] \tag{15}$$

$$\left\{\begin{array}{l} \bar{\hat{v}}'_c[k] = \hat{A}_c \bar{\hat{v}}'_c[k-1] + \hat{B}_c y[k-1] \\ \qquad + \hat{J}_c u[k-1] \\ \bar{\hat{v}}'_c[k+1] = \hat{A}_c \bar{\hat{v}}'_c[k] + \hat{B}_c y[k] + \hat{J}_c u[k] \end{array}\right. \tag{16}$$

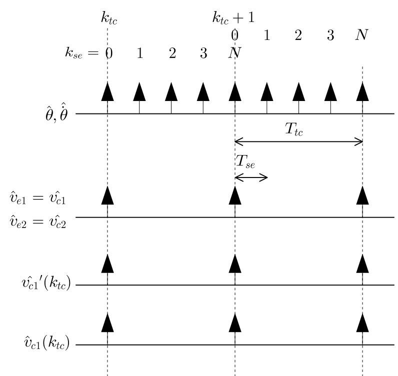


Fig. 9. Time diagram of proposed anti-sway crane control based on dual state observer with sensor-delay correction.

Both of "state estimation observer" and "time correction observer" are executed at the same time, as shown in (17) - (20). The operation timing is shown as Fig.9. k_{se} is the time interval of "state estimation observer", and k_{tc} is the time interval of "time correction observer". k_{tc} is N times time interval of k_{se}.

($k_{tc} = Nk_{se}$)

$$\hat{v}_e[k_{se}+1] = \hat{A}_e \bar{\hat{v}}_c'[k_{tc}] + \hat{B}_e y[k_{se}] + \hat{J}_e u[k_{se}] \quad (17)$$

$$\hat{z}_e[k_{se}] = \hat{C}_e \bar{\hat{v}}_c'[k_{tc}] + \hat{D}_e y[k_{se}] \quad (18)$$

($k_{tc} \neq Nk_{se}$)

$$\hat{v}_e[k_{se}+1] = \hat{A}_e \hat{v}_e[k_{se}] + \hat{B}_e y[k_{se}] + \hat{J}_e u[k_{se}] \quad (19)$$

$$\hat{z}_e[k_{se}] = \hat{C}_e \hat{v}_e[k_{se}] + \hat{D}_e y[k_{se}] \quad (20)$$

V. NUMERICAL SIMULATION RESULTS AND EXPERIMENTAL RESULTS

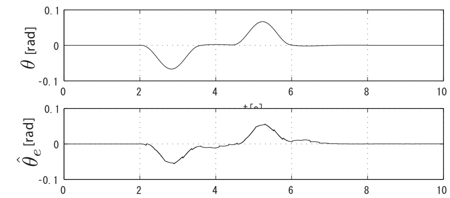
A. Configuration of Tested Experimental System

Fig.10 shows the proposed anti-sway crane control system based on dual state observer with sensor-delay correction. Here, the estimate sway angle $\hat{\theta}_e$ estimated with the observer is fed into the anti sway controller. The speed control system is constructed by PI controller whose cut-off frequency is $100[rad/s]$, and the position control system is constructed by P control whose cut-off frequency is $2[rad/s]$. Moreover, the anti-sway crane control system is also constructed by PI controller whose cut-off frequency is $10[rad/s]$.

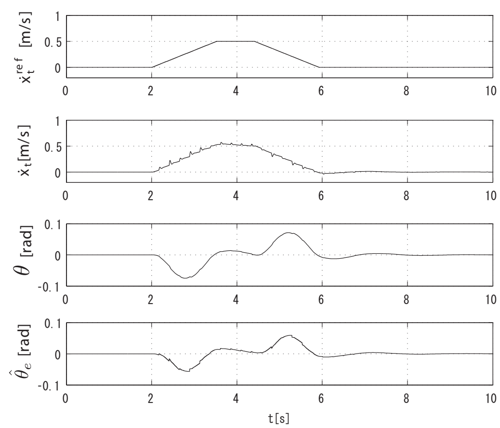
The sampling period T_u of "state estimation observer" and the proposed anti-sway crane control systems $6[msec]$, and the sampling period T_d of "time correction observer" and the delay time of detected sway angle is $240[msec]$.

B. Numerical Simulation Results

Fig.11 shows the numerical simulation results of anti-sway crane control system based on dual state observer with sensor-delay correction on condition of same parameter variation. The parameter variation is also the variation of rope length L such as 95%. Fig.11 (a) point outs that the proposed system has



(a) without delay time



(b) with delay time 240[msec]

Fig. 11. Numerical simulation results of proposed anti-sway crane control system based on dual state observer with parameter variation 95% L.

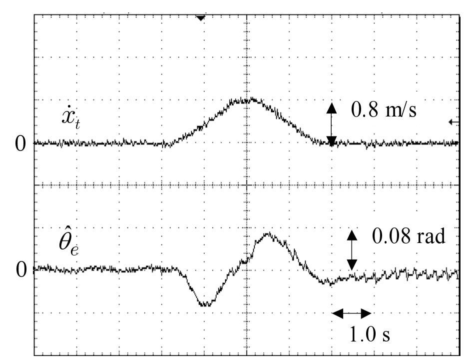


Fig. 12. Experimental results of proposed proposed anti-sway crane control system based on dual state observer with parameter variation 95% L and delay time 240[msec].

a fine motion response on condition of parameter variation and no delay time. The estimated sway angle $\hat{\theta}_e$ of the state estimation observer coincides with the actual sway angle θ. Moreover, Fig.11 (b) point outs that the proposed system has a fine response on condition of both parameter variation and delay time, which has no oscillated response in comparison with that of Fig.7 (b).

C. Experimental Results

Fig.12 shows also the experimental results of anti-sway crane control system based on dual state observer with sensor-delay correction on condition of same parameter variation and the delay time $240[msec]$. Therefore, Fig.12 also point outs that the proposed system has a fine motion response on condition of both parameter variation and delay time, which has no oscillated response in comparison with that of Fig.8

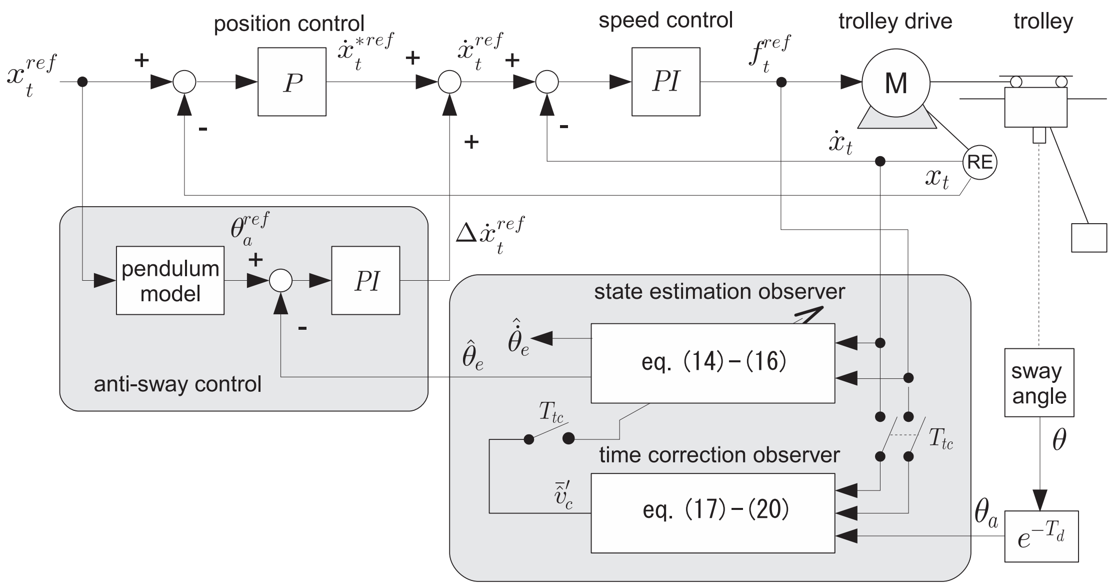


Fig. 10. Block diagram of the proposed anti-sway crane control system based on dual state observer with sensor-delay correction.

(b). Therefore, from the view points of Fig.11 and Fig.12, the proposed anti-sway crane control system based on dual state observer with sensor-delay correction has the robust structure on both parameter variation and delay time.

VI. Conclusion

This paper proposes a new anti-sway crane control based on dual state observer with sensor-delay correction. This paper contracts the sway angle observer estimating the sway angle of container which is based on the crane motion equation. In this paper, the possibility of versatile controller is considered in the speed-controlled trolley drive system. The proposed anti-sway control system is realizes by using only the trolley speed and the sway angle.

The first sway angle observer is the general state observer, which calls "state estimation observer". The estimated sway angle of this observer becomes the feedback signal for the anti-sway control system. The sampling time of this observer is the same as the sampling time of the anti-sway control system.

The second sway angle observer is the correction observer of the first sway angle observer, which calls "time correction observer". The sampling time of this observer is the same as the sampling time of the detection delay time of the detected sway angle from the vision sensor system. In "time correction observer", using the detected sway angle from the vision sensor system, the state variables of both sway angle observers are be correcting to the fitted state variables.

The effectiveness of the proposed method is verified by the numerical simulation results and the experimental results.

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