Anti-Sway Control of Crane System by Equivalent Force Feedback of Load

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***Abstract*—In this paper, assist-control of crane system for human operator is considered. The objective of this paper is to achieve easy operating with less sway. In previous work, it is proved that force feedback is effective to operate crane system. To improve the previous work, force feedback system with Lyapunov based controller is proposed. The effectiveness of Lyapunov based controller was proved in automatic control. Assisted force is inserted in the master system, therefore operator can feel how to control master system to reduce oscillation. Experimental results shows that better design of the automatic anti-sway control improve human-machine interaction.**

***Index Terms*—Crane system, Underactuated system, Anti-sway control, Assist-control, Lyapunov based control**

I. INTRODUCTION

Crane system has been widely used for transportation in harbors, farms and so on. To think about transporting load, the efficiency is required. In these environments, almost of all cranes are operated by human. When crane operators pick up and transfer payloads, it is difficult to position payloads accurately and fast. Especially for a beginner, suppressing oscillation is most important problem. Because of these reasons, assist-control for crane operater is desired.

In order to solve these problems, some researchers focused on automatic control. In 1950s, Smith [1] proposed Input Shaping method. This control method has widely used in cranes. They make a command signal to reduce vibration by convolving a sequence of impulses. Input shaping method is feedforward system, therefore it is weak for disturbances. Fang [2] proposed S-shape trajectory with adaptive control. In this method, the role of adaptive control is improving tracking trajectory performance. Sung [3] focused on the load motion and gave a new definition of the energy. W.Chen [4] used backstepping approach with high-order sliding mode differentiator that estimates derivative of outputs. Ishino [5] designed Lyapunov based controller. Input command for vibration suppression is designed to minimize the energy function of sway angle. To be accuracy of designing, he proposed sway angle disturbance observer that estimates disturbance at sway angle. In Ishino and Chen's approach, the command for vibration suppression is designed without considering trajectory tracking.

On the other hand, some researchers focused on operating crane. In [6], Kado analyzed skilled human for motion stabilization. Tervo [7] use variable gain considering human model. Kado and Tervo's research focused human model identification. On the other hand, assist-controls considering human senses are proposed. Vaughan [8] built up visual interface by using input-shaping method. Farkhatdinov [9] focused on haptic interface for anti-sway force feedback control. They proved importance of force feedback. That feedback force is proportional to sway angle velocity.

From these reasons, we describe force feedback system with Lyapunov based controller. We use a 2 link plane manipulator as master controller. The end-effector of the 2 link manipulator corresponds to crane's trolley position. Assisted force insert in the master system. Therefore operator can feel how to control master system to reduce the oscillation.

The next section presents a modeling of master controller and crane system. The section III is divided in 3 subsections, where we explain details of designing control system. The 1st subsection describes master control system and the 2nd subsection explain about how to control crane's trolley position. In the 3rd, force feedback system with Lyapunov based controller is obtained. The final section, experiment is conducted. We compared proposed force feedback system to conventional method [9].

II. MODELING

In this section, the modeling of master system and crane system are described. The 2 link manipulator shown in Fig.1 is introduced as master system. The 3-dimension crane system is shown in Fig.2.

A. Master system

In this paper, we use a 2 link plane manipulator as master system. The merit of this interface is that, the operator can operate intuitively. From Fig.1, the end-effecter position of the manipulator $\boldsymbol{x}_m$ is defined as $\boldsymbol{x}_m = [\ x_m \quad y_m\ ]^T$, the joint angle $\boldsymbol{q}_m$ is defined as $\boldsymbol{q}_m = [\ \theta_{m1} \quad \theta_{m2}\ ]^T$.

1) Kinematics: Jacobian $\boldsymbol{J}_m$ is obtained as Eq.(1), Eq.(2).

$$\dot{\boldsymbol{x}}_m = \boldsymbol{J}_m \dot{\boldsymbol{q}}_m \tag{1}$$

$$\boldsymbol{J}_m = \begin{bmatrix} -l_m S_{m1} & -l_m S_{m1m2} \\ l_m C_{m1} + l_m C_{m1m2} & l_m C_{m1m2} \end{bmatrix} \tag{2}$$

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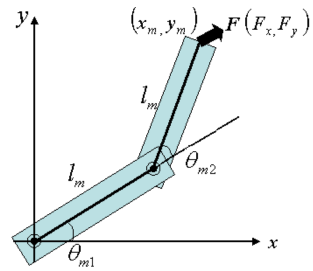

Fig. 1. Master model

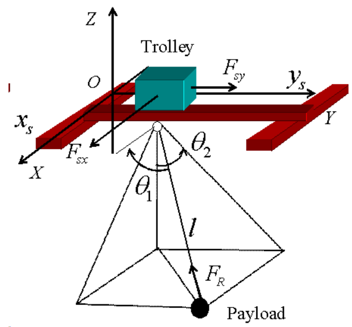

Fig. 2. Crane model

where C_{mi} and S_{mi} represent $\cos\theta_{mi}$ and $\sin\theta_{mi}$ respectively. Jacobian $\boldsymbol{J}_m$ is used to transform from joint space to operational space. The velocity of joint angle $\dot{\boldsymbol{q}}_m$ is described as Eq.(3)

$$\dot{\boldsymbol{q}}_m = \boldsymbol{J}_m^{-1}\dot{\boldsymbol{x}}_m \quad (3)$$

2) Dynamics: Dynamics equation of master system is derived by Lagrange's equation. Kinematic energy K_1 about link 1 and K_2 about link 2 are obtained as follows.

$$K_1 = \frac{1}{2}m_1\dot{x}_{g1}^2 + \frac{1}{2}m_1\dot{y}_{g1}^2 + \frac{1}{2}I_1\dot{\theta}_1^2 \quad (4)$$

$$K_2 = \frac{1}{2}m_2\dot{x}_{g2}^2 + \frac{1}{2}m_2\dot{y}_{g2}^2 + \frac{1}{2}I_2(\dot{\theta}_1^2 + \dot{\theta}_2^2) \quad (5)$$

$$K = K_1 + K_2 \quad (6)$$

where $\bigcirc_g$ are position of the center of gravity. Position energy from gravity is 0 because of flatness. Dynamics is expressed as Eq.(7)

$$\boldsymbol{\tau} = \boldsymbol{M}_m(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}}) \quad (7)$$

$$\boldsymbol{M}_m = \begin{bmatrix} M_{m11} & M_{m12} \\ M_{m21} & M_{m22} \end{bmatrix} \quad (8)$$

$$\boldsymbol{h} = \begin{bmatrix} h_1 \\ h_2 \end{bmatrix} \quad (9)$$

$$\boldsymbol{\tau} = \begin{bmatrix} \tau_1 \\ \tau_2 \end{bmatrix} \quad (10)$$

B. Crane system

The dynamics of crane system is described as follows. Parameters are shown in TableI

TABLE I
PARAMETERS ABOUT CRANE

Variables	Definition
u_1	$\frac{F_{sx}}{m_t+m_b}$
u_2	$\frac{F_{sy}}{m_t}$
u_3	$\frac{F_R}{m_p}$
T_1	$\frac{T_x}{m_t}$
T_2	$\frac{T_y}{m_t+m_b}$
T_3	$\frac{T_R}{m_p}$
μ_1	$\frac{m_p}{m_t}$
μ_2	$\frac{m_p}{m_t+m_b}$
m_p	Load mass [kg]
m_t	Trolley mass [kg]
m_b	Boom mass [kg]
F_{sx}	Force driving the cart with boom [N]
F_{sy}	Force driving the cart [N]
F_R	Force controlling the length of lope [N]
T_x, T_y, T_R	Friction coefficients
g	Gravity acceleration

$$\ddot{x}_s = N_1 + N_3\mu_1\cos\theta_1 \quad (11)$$

$$\ddot{y}_s = N_2 + N_3\mu_2\sin\theta_1\sin\theta_2 \quad (12)$$

$$\ddot{\theta}_1 = \frac{\sin\theta_1 N_1 - \cos\theta_1\sin\theta_2 N_2}{l} + \frac{(\mu_1 - \mu_2\sin^2\theta_2)\cos\theta_1\sin\theta_1 N_3 + V_5}{l} \quad (13)$$

$$\ddot{\theta}_2 = \frac{-(\cos\theta_2 N_2 + \mu_2\sin\theta_1\sin\theta_2\cos\theta_2 N_3 + V_6)}{\sin\theta_1 l} \quad (14)$$

$$\ddot{l} = -\cos\theta_1 N_1 - \sin\theta_1\sin\theta_2 N_2 - (1 + \mu_1\cos^2\theta_1 + \mu_2\sin^2\theta_1\sin^2\theta_2)N_3 + V_7 \quad (15)$$

where N and V are defined as follows.

$$N_1 = u_1 - T_1\dot{x}_s \quad (16)$$

$$N_2 = u_2 - T_2\dot{y}_s \quad (17)$$

$$N_3 = u_3 - T_3\dot{l} \quad (18)$$

$$V_5 = \cos\theta_1\sin\theta_1\dot{\theta}_2^2 l - 2\dot{l}\dot{\theta}_1 + g\cos\theta_1\cos\theta_2 \quad (19)$$

$$V_6 = 2\dot{\theta}_2(\cos\theta_1\dot{\theta}_1 l + \sin\theta_1\dot{l}) + g\sin\theta_2 \quad (20)$$

$$V_7 = \sin^2\theta_1\dot{\theta}_2^2 l + g\sin\theta_1\cos\theta_2 + \dot{\theta}_1^2 l \quad (21)$$

Using state vector $\boldsymbol{q}_s = [x_s \;\; y_s \;\; \theta_1 \;\; \theta_2 \;\; l]^T$ and output vector $\boldsymbol{u} = [u_1 \;\; u_2 \;\; u_3]^T$, Eq.(15) can be rewritten as Eq.(22)

$$\boldsymbol{M}_s(\boldsymbol{q}_s)\ddot{\boldsymbol{q}}_s + \boldsymbol{d}(\boldsymbol{q}, \dot{\boldsymbol{q}}) = \boldsymbol{u} \quad (22)$$

III. Design of Control Systems

In this section, control system is described. We divided in three parts, master system, trolley position control and force feedback system with Lyapunov based controller. In crane system, we can consider x-axis movement and y-axis one independently. Therefore, we consider only y-axis in this paper.

A. Master system

In this subsection, control system about master system is obtained. We designed master controller to adjust operational feeling.

1) Disturbance observer(DOB): DOB [10] is introduced for compensating friction, interactive torque and parameter error. By using disturbance observer, we target to improve robustness. The equation of motor dynamics is expressed as Eq.(23)

$$J_{mn}\ddot{\theta_m} = K_{tn}I^{ref} - \tau_{dis} \tag{23}$$

where K_{tn} and J_{mn} are the nominal torque coefficient and nominal inertia respectively, and τ_{dis} is total disturbance inserted to motor. The total disturbance τ_{dis} is defined as Eq.(24)

$$\begin{aligned}\tau_{dis} &= \tau_{int} + \tau_{ext} + F_{fric} + D\dot{\theta} \\ &\quad +(J_m - J_{mn})\ddot{\theta} + (K_{tn} - K_t)I^{ref} \end{aligned} \tag{24}$$

where the 1st term is interactive torque, the 2nd term is the reaction torque by doing force task. The 3rd and 4th term are friction torque. The 5th and 6th are parameter errors from nominal values. From Eq.(23), τ_{dis} is estimated by Eq.(25)

$$\begin{aligned}\hat{\tau}_{dis} &= \frac{g}{s+g}(K_{tn}I^{ref} - s^2 J_{mn}\theta) \\ &= \frac{g}{s+g}g(K_{tn}I^{ref} + sJ_{mn}\theta) - gsJ_{mn}\theta \end{aligned} \tag{25}$$

Low-pass filter is introduced to avoid high frequency noise.

2) Reaction torque observer: The reaction torque observer [11] is introduced for estimating operator's force. Then estimated value $\hat{\tau}_{ext}$ is given by Eq.(26)

$$\begin{aligned}\hat{\tau}_{ext} &= \frac{g}{s+g}\left(K_{tn}I^{ref} + gJ_{mn}\dot{\theta}_m - T_{int} - \tau_f\right) \\ &\quad -gJ_{mn}\dot{\theta}_m \end{aligned} \tag{26}$$

$$\tau_f = F_{fric} + D\dot{\theta}_m \tag{27}$$

T_{int} is calculated from Eq.(9) and τ_f is given by motor test.

3) Impedance control: To improve the operability, we introduce the impedance controller as Eq.(28)

$$M_c\ddot{\theta}_c^{ref} + D_c\dot{\theta}_c^{ref} + K_c\theta_c^{ref} = \hat{\tau}_m^{hum} \tag{28}$$

where M_c, D_c and K_c are virtual impedance gain and $\hat{\tau}_m^{hum} = \hat{\tau}_{ext}$ We adjust virtual impedance gain and we can change operability. The acceleration reference $\ddot{\theta}_m^{ref}$ is defined as Eq.(29)

$$\ddot{\theta}_m^{ref} = \ddot{\theta}_c^{ref} + K_{pi}(\theta_c^{ref} - \theta_m^{res}) + K_{vi}(\dot{\theta}_c^{ref} - \dot{\theta}_m^{ref}) \tag{29}$$

In the DOB based controller, $\ddot{\theta}_m^{ref} = \ddot{\theta}_m^{res}$ is achived. From this assumption, the transfer function from τ_m^{hum} to θ_m can be calculated as Eq.(30)

$$\theta_m = \frac{\frac{K_c}{M_c}}{s^2 + \left(\frac{D_c}{M_c}\right)s + \left(\frac{K_c}{M_c}\right)}\frac{\hat{\tau}_m^{hum}}{K_c} \tag{30}$$

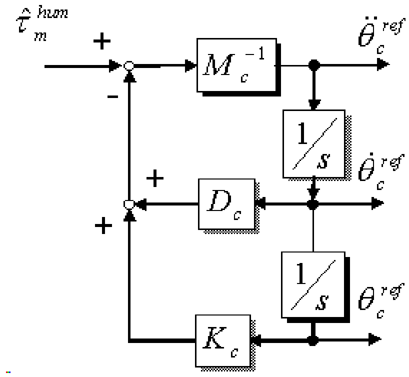

Fig. 3. Impedance control

Therefore, in the impedance controller, natural angular frequency ω_f and damping coefficient ζ_f are defined in Eqs.(31) and (32).

$$\omega_f = \sqrt{\frac{K_c}{M_c}} \tag{31}$$

$$\zeta_f = \frac{D_c}{2\sqrt{M_cK_c}} \tag{32}$$

To avoid overshoot, we set ζ_f to be less or equal to 1.

$$D_c \leq 2\sqrt{M_cK_c} \tag{33}$$

B. Position control

In this study, the end-effecter of the master system corresponds to trolley position of crane system. To control trolley position, acceleration reference $\ddot{y}_s^{ref}$ is given as follow.

$$\ddot{y}_s^{ref} = \alpha\ddot{y}_m^{ref} + K_p(\alpha y_m^{ref} - y_s^{res}) + K_v(\alpha\dot{y}_m^{ref} - \dot{y}_s^{ref}) \tag{34}$$

Here, α is a scaling rate from master system to crane system. From Eq.(34), the transfer function from y_m to y_s is calculated as Eq.(35)

$$\frac{y_s}{y_m} = \frac{\alpha(s^2 + K_vs + K_p)}{(s^2 + K_vs + K_p)} = \alpha \tag{35}$$

Therefore, following equation is achieved by the DOB based controller.

$$y_s = \alpha y_m \tag{36}$$

C. Force feedback for vibration suppression

We explain how to design force feedback system for vibration suppression. At the beginning, we design acceleration reference $\ddot{y}_{lya}$ based on Lyapunov controller, and transfer it from crane scale to master system. To design $\ddot{y}_{lya}$, we introduce the sway angle disturbance observer.

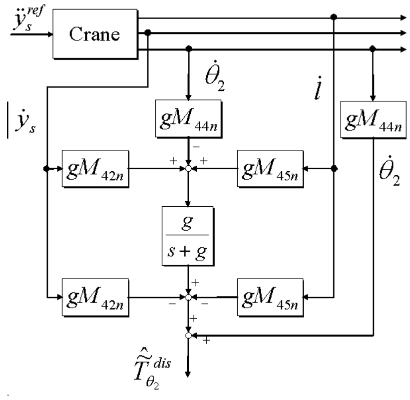

Fig. 4. Sway angle disturbance observer

1) Sway angle disturbance observer(SADOB): Sway angle disturbance observer(SADOB) estimates disturbance at sway angle. The disturbance is calculated from acceleration of trolley position, lope length and sway angle. Here follows the computations of the disturbance along y-direction. To begin with, the motion equation about θ_2 is given as Eq.(37) from Eq.(22)

$$M_{44s}\ddot{\theta}_2 = M_{42s}\ddot{y}_s + M_{45s}\ddot{l} + T^{dis}_{\theta_2} \tag{37}$$

where M is as follows.

$$\begin{aligned} M_{44s} &= 1 \\ M_{42s} &= \frac{-\cos\theta_2}{\sin\theta_1 l} \\ M_{45s} &= \frac{\mu_2 \sin\theta_1 \sin\theta_2 \cos\theta_1}{\sin\theta_1 l} \end{aligned} \tag{38}$$

To consider about parameter errors, Eq.(39) is obtained.

$$\begin{aligned} \ddot{\theta}_2 = &\frac{M_{42sn}\ddot{y} + M_{45sn}\ddot{l}}{M_{44sn}} \\ &+ \frac{\Delta M_{42s}\ddot{y} + \Delta M_{45s}\ddot{l} - \Delta M_{44s}\ddot{\theta}_2 + T^{dis}_{\theta_2}}{M_{44sn}} \\ = &\frac{1}{M_{44sn}}\left(M_{42sn}\ddot{y} + M_{45sn}\ddot{l}\right) + \tilde{T}^{dis}_{\theta_2} \end{aligned} \tag{39}$$

Then, a low-pass filter is inserted to reduce the noise. Using low-pass filter, the construction of SADOB is shown in Eq.(40)

$$\begin{aligned} \hat{\tilde{T}}^{dis}_{\theta_2} &= \frac{g}{s+g}\tilde{T}^{dis}_{\theta_2} \\ &= \frac{g}{s+g}s^2\left(M_{44n}\theta_2 - M_{42n}y - M_{45n}l\right) \\ &= \frac{g}{s+g}gs\left(M_{42n}y + M_{45n}l - M_{44n}\theta_2\right) \\ &- \; gs\left(M_{44n}\theta_2 - M_{42n}y - M_{45n}l\right) \end{aligned} \tag{40}$$

Fig.4 shows the construction of SADOB.

2) Lyapunov based controller: The objective of controlling crane system is suppressing sway angle. To achieve this purpose, we use Lyapunov based controller. The Lyapunov function candidate V is defined as follow.

$$V = \frac{1}{2}K_{s1}\theta_1^2 + \frac{1}{2}K_{s2}\dot{\theta}_1^2 + \frac{1}{2}K_{s3}\theta_2^2 + \frac{1}{2}K_{s4}\dot{\theta}_2^2 \tag{41}$$

where K_s are positive gain. The derivative of the V is calculated as follow.

$$\begin{aligned} \dot{V} &= K_{s1}\theta_1\dot{\theta}_1 + K_{s2}\dot{\theta}_1\ddot{\theta}_1 + K_{s3}\theta_2\dot{\theta}_2 + K_{s4}\dot{\theta}_2\ddot{\theta}_2 \\ &= \dot{\theta}_1\left(K_{s1}\theta_1 + K_{s2}\ddot{\theta}_1\right) + \dot{\theta}_2\left(K_{s3}\theta_2 + K_{s4}\ddot{\theta}_2\right) \end{aligned} \tag{42}$$

Then, we define following equations.

$$-K_{s5}\dot{\theta}_1 = K_{s1}\theta_1 + K_{s2}\ddot{\theta}_1 \tag{43}$$

$$-K_{s6}\dot{\theta}_2 = K_{s3}\theta_2 + K_{s4}\ddot{\theta}_2 \tag{44}$$

From Eqs.(42)-(44), is rewritten as follow.

$$\dot{V} = -K_{s5}\dot{\theta}_1^2 - K_{s6}\dot{\theta}_2^2 \leq 0 \tag{45}$$

From Eq.(45) and Lasalle's theorem, it is guaranteed that sway angle converge to 0[deg]. Then, substituting Eq.(37) into Eq.(44), Eq.(46) is given.

$$-K_{s6}\dot{\theta}_2 = K_{s3}\theta_2 + K_{s4}\left(\frac{M_{42sn}\ddot{y} + M_{45sn}\ddot{l}}{M_{44sn}} + \tilde{T}^{dis}_{\theta_2}\right) \tag{46}$$

From Eq.(46), acceleration reference $\ddot{y}_{lya}$ is calculated as follows.

$$\begin{aligned} \ddot{y}_{lya} = &\frac{M_{44sn}}{M_{42sn}}\left(\frac{K_{s3}}{K_{s4}}\theta_2 + \frac{K_{s6}}{K_{s4}}\dot{\theta}_2\right) \\ &- \frac{1}{M_{42sn}}\left(M_{45sn}\ddot{l} + \hat{\tilde{T}}^{dis}_{\theta_2}\right) \end{aligned} \tag{47}$$

where $\hat{\tilde{T}}^{dis}_{\theta_2}$ is estimated by SADOB.

3) Force feedback system: We design the feedback force by using acceleration reference $\ddot{y}_{lya}$. From Eq.(36), the relation between the end-effector of master $\ddot{y}_m$ and crane's trolley position $\ddot{y}_s$ is obtained as follow.

$$\alpha\ddot{y}_m = \ddot{y}_s \tag{48}$$

Then assisted acceleration for operator is defined as Eq.(49).

$$\ddot{y}^{lya}_m = \frac{\ddot{y}_{lya}}{\alpha} \tag{49}$$

The assisted acceleration reference $\ddot{y}_{lya}/\alpha$ is transformed from the crane system to master system equivalently.

D. whole control system

The block diagram of whole system is shown in Fig.5. The crane's trolley position is controlled by position controller. $\ddot{y}_{lya}/\alpha$ is designed by using Lyapunov based controller and it inserts to master system. The master position response is expressed as Eq.(50)

$$Y^{res}_m(s) = Y^{ref}_c(s) + \frac{1}{s^2 + K_{vi}s + K_{pi}}Y^{lya}_m(s) \tag{50}$$

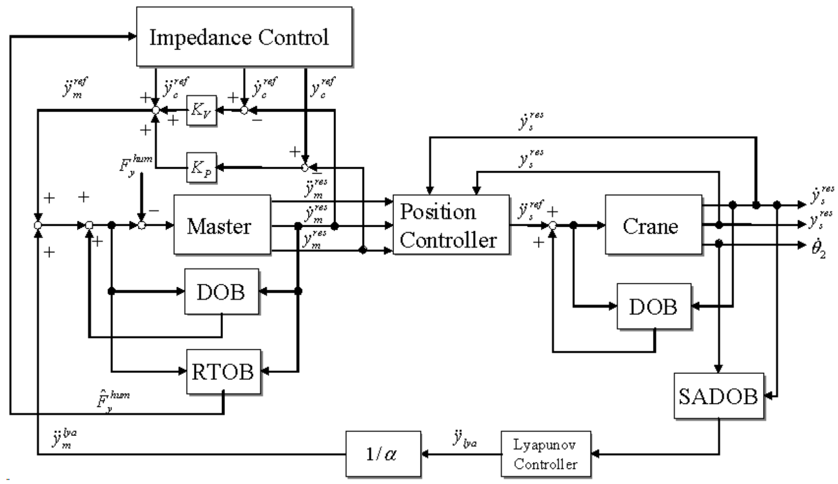

Fig. 5. Block diagram of whole system

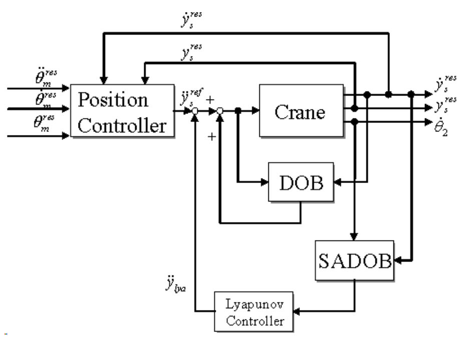

Fig. 6. Feedback to crane system

IV. Experimental Results

A. Experimental setup

In the experiment, a laboratory scale crane system is constructed. That picture is shown in Fig.7. To evaluate the validity of proposed method, we compare the performance between four controllers as follows.

a) unassisted
b) feedback to crane system shown in Fig.6
c) conventional method [9]
d) proposed method shown in Fig.5

In the method(b), anti-sway command is inserted only in crane system, therefore operator can not feel any force from master controller. On the otherhand, in conventinal method, the assisted force $\ddot{y}_m^{assi}$ which inserted in the master system is expressed as Eq.(53).

$$\ddot{y}_m^{assi} = \frac{1}{\alpha}(K_{d\theta_2}\dot{\theta}_2) \tag{51}$$

where $K_{d\theta_2}$ is a positive gain. Parameters and gain are shown in Table II.

The control performances were tested only by one operator. wd did two sets of 5 test each for each controller. In the first set, the operator get used to the crane system. In the second set, we get the real data. The task is transfering the trolley from an initial point to the final point(0.55m). The trolley is driven

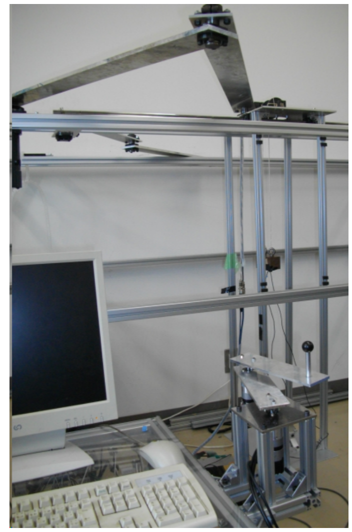

Fig. 7. Experimental setup

TABLE II
Parameters of experiment

K_{pi}, K_{vi}	Impedance control gain	900,60
K_p, K_v	Position control gain	730,53
g	Cut off frequency	100
K_{s3}, K_{s4}, K_{s6}	Lyapunov control gain	250,1,32
M_c, D_c, K_c	Virtual Impedance gain	0.08,0.8,0.0

only along y axis and lope is constant. In order to analyze the control effect, we use three indices.

- the time taken for the operator to get the trolley closer than 0.03m (t_{set}[s])
- the maximum amplitude of oscillation during the task (θ_{max}[deg])
- the amplitude of oscillation at t_{set}[s] (θ_{fin}[deg])

B. Results and discussions

The numerical results are shown in Tables III-VI, and averages of each result are shown in Figs.8-10. Most important index is the amplitude of oscillation at destination because of safety. Fig.10 shows that proposed method is better than conventional method(b). In proposed method, the control input for vibration suppression is designed by using Lyapunov function and observer. The effectiveness of this control input is proved in paper [5]. This control input is designed for automatic control but this one also makes better performance in operating situation. From these reasons, improving vibration suppression performance in automatic control also makes benefits in human operating system.

The importance of force feedback is mentioned in the paper [9]. Fig.9 and Fig.10 also shows effectiveness of force feedback. The sway angle response in proposed method(d) is less than the controller without force feedback(b).

TABLE III
CONTROL PERFORMANCE: A)UNASSISTED

Trial round	1	2	3	4	5
t_{set}[s]	6.19	5.10	4.61	5.95	5.99
θ_{max}[deg]	11.3	8.81	8.64	8.92	8.47
θ_{fin}[deg]	2.15	3.15	2.89	3.40	6.35

TABLE IV
CONTROL PERFORMANCE: B)FEEDBACK TO CRANE

Trial round	1	2	3	4	5
t_{set}[s]	2.93	2.78	2.82	2.77	2.58
θ_{max}[deg]	4.60	7.23	7.49	5.63	6.38
θ_{fin}[deg]	1.58	2.02	1.94	1.43	1.44

TABLE V
CONTROL PERFORMANCE: C)CONVENTIONAL METHOD

Trial round	1	2	3	4	5
t_{set}[s]	3.81	3.17	3.27	3.61	2.66
θ_{max}[deg]	4.18	5.09	5.18	7.24	7.04
θ_{fin}[deg]	1.82	1.85	1.62	1.57	2.20

TABLE VI
CONTROL PERFORMANCE: D)PROPOSED METHOD

Trial round	1	2	3	4	5
t_{set}[s]	2.66	2.82	3.05	3.15	2.83
θ_{max}[deg]	4.55	5.18	3.20	6.75	5.21
θ_{fin}[deg]	1.39	1.55	1.19	1.62	1.79

V. CONCLUSION

In this paper, we proposed force feedback system with Lyapunov based controller. Anti-sway control is designed in automatic control system and it apply to master control system equivalently. Assisted force is inserted in the master controller, therefore operator can feel that force and adjust the operator's force. Experimental results indicate 2 conclusions. 1)A better designing for anti-sway control in automatic one also makes benefit in human operating system. 2)A force feedback system is effective for operator. The combination of operator's manipulation with assisted force make good performance for vibration suppression.

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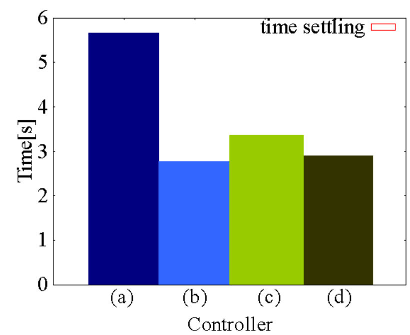

Fig. 8. Average time t_{set}[s]

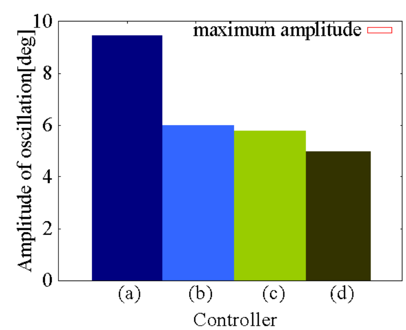

Fig. 9. Average sway angle θ_{max}[deg]

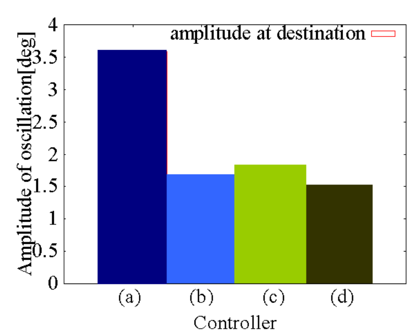

Fig. 10. Average sway angle θ_{fin}[deg]