2011 11th International Conference on Control, Automation and Systems
Oct. 26-29, 2011 in KINTEX, Gyeonggi-do, Korea

Dual Stage Trolley Control System for Anti-swing Control of Mobile Harbor Crane

Dongho Kim[1], Youngjin Park[2], Youn-sik Park[3], Sangwon Kwon[4] and Eunho Kim[5]

[1] Department of Mechanical Engineering, KAIST, Daejeon, 305-701, Korea
(Tel : +82-2-350-3076; E-mail: kingli@kaist.ac.kr)
[2] Department of Mechanical Engineering, KAIST, Daejeon, 305-701, Korea
(Tel : +82-2-350-3036; E-mail: yjpark@kaist.ac.kr)
[3] Department of Mechanical Engineering, KAIST, Daejeon, 305-701, Korea
(Tel : +82-2-350-3020; E-mail: yspark0117@kaist.ac.kr)
[4] Mobile Harbor Center, KAIST, Daejeon, 305-701, Korea
(Tel : +82-2-350-6450; E-mail: sangwonkwon@kaist.ac.kr)
[5] Mobile Harbor Center, KAIST, Daejeon, 305-701, Korea
(Tel : +82-2-350-6449; E-mail: kimeunho@kaist.ac.kr)

Abstract: A work efficiency and safety of Mobile Harbor crane in the open sea condition are considered as serious problem because Mobile Harbor have 6 degree of freedom motion caused by external disturbance such as wave and wind. It is the core technology to suppress the sway and surge motion of containers during loading and unloading operation in this Mobile Harbor project. KAIST Mobile Harbor center proposed and implemented the dual stage control system to resolve this problem. In this paper, we proposed the anti-swing controller using this dual stage control system. To establish the system model, system parameters are characterized by system identification process with respect to the 1/20 scale D4 crane model and the LQR controller for anti-swing was designed based on decoupled of X- and Y-axis and linearized crane model. The performance of the designed anti-swing LQR controller is verified by experiments of 1/20 scale Mobile Harbor crane mounted on a shaky motion platform even though the mode of motion of container was excited.

Keywords: Mobile Harbor, cargo transfer, Crane, Anti-swing Control, LQR, dual-stage trolley

1. INTRODUCTION

The Mobile Harbor is a new maritime cargo transfer system used to load/unload containers from large container ship to smaller ship in the open-sea condition. Fig.1 shows the typical concept of mobile harbor system. During the transfer operation, the wave-induced 6-DOF motions(surge, sway, and heave in translational motions, and roll, pitch, and yaw in rotational motions) may cause pendulations of containers being supported on a boom of the quay side crane. In this work, we can't guarantee safe and efficient work due to aforementioned reasons. It is necessary to suppress swing motion of a container in the Mobile Harbor.

Many crane control systems have been already developed and studied to apply to various applications of crane in the industry. These systems are generally designed to reduce the swing motion during movement of the trolley or residual vibration after stop at target position. But in the Mobile Harbor system exposed by open sea conditions, it is more important to eliminate the oscillation due to the wave and wind than inertia forces.

Existing trolley system is only used to transport containers not to suppress swing motion. Therefore, a so -called dual stage trolley control system was proposed by KAIST mobile harbor center to solve this problem and implemented 1/20 scaled-down model to check the feasibility. In this paper, we proposed an anti-swing controller using sub-trolley control system based on optimal control strategy. The system identification process is also performed to extract parameters of trolley system. Finally, the performance of designed LQR anti-swing controller is verified by experiments.

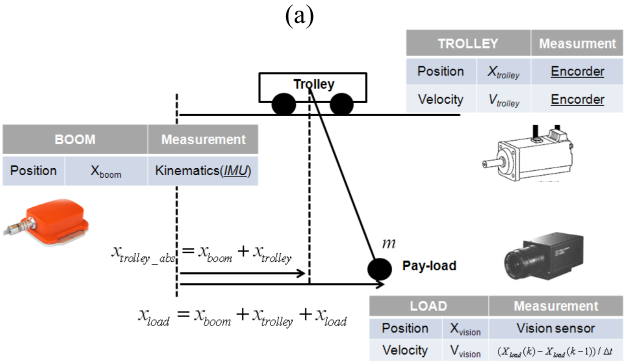
Fig. 1 The concept of Mobile Harbor.

2. MOBILE HARBOR SUB-TROLLEY SYSTEM

The dual stage trolley control system is composed of macro-trolley with 1 DOF (an outer frame in Fig. 2(a)) moves along the boom as a conventional trolley and a micro-trolley (a inner frame in Fig. 2(a)) which has additional 2 DOFs in motion in X- and Y-axis). By independent movement of two micro-trolley in the plane, it is possible to compensate the trolley position and suppress swing motion of containers effectively. The dual stage trolley control system can be driven by velocity servo motor controllers which is designed to PI controller using position information of encoder. And the CCD camera(640x480 resolution, maximum 110 fps frame rate) is equipped with the macro-trolley and infrared rays(IR) source marker is installed in the spreader which provide the relative position between the macro-trolley and each micro-trolley in real-time for accurate position control. Additionally, the IMU(Inertial Measurement Unit) sensor is also installed on the body of mobile harbor, roll, pitch and yaw angle are used to calculate reference positions of a container based on kinematic equation determined by specifications of Mobile Harbor. These measured real-time data is used for anti-swing control. Fig. 2(b) shows available sensors and actuators in dual stage trolley control system.

.

(a)



(b)

Fig. 2 Dual stage trolley control system: (a) micro-trolley with 2 DOFs in motion, (b) sensors and actuators in dual stage trolley control system

3. SYSTEM MODELING AND IDENTIFICATION

3.1 System model

In Mobile Harbor crane, it is possible to control the position of each micro trolley in X- and Y-axis using dual stage trolley control system. 2DOF cane model is necessary to express the swing motion of container. If the swing motion is small, 2DOF nonlinear and coupled crane model is approximated to two linearly independent and decoupled crane model in each axis. The effect of swing motion of container and nonlinearity are expressed by stiffness. In assumption that a rope mass is ignored and the spreader and container are point mass, the linearized equation of motion as follows:

$$(m_t + m)\ddot{x}_t + c\dot{x}_t + kx = Ku_x \quad (1)$$

$$l\ddot{x}_m + gx_m = -l\ddot{x}_t \quad (2)$$

where x_t is trolley position, x_m is container position, m_t is trolley mass, m is spreader and container mass, c is damping coefficient, k is stiffness, K is control input gain, and l is rope length. Using Laplace transformation, transfer functions of trolley dynamics and container swing dynamics as follow:

$$P(s) = \frac{X_t(s)}{X_r(s)} = \frac{K}{m_t s^2 + cs + k} \quad (3)$$

$$\frac{X_m(s)}{X_t(s)} = \frac{-ls^2}{ls^2 + g} \quad (4)$$

3.2 System identification

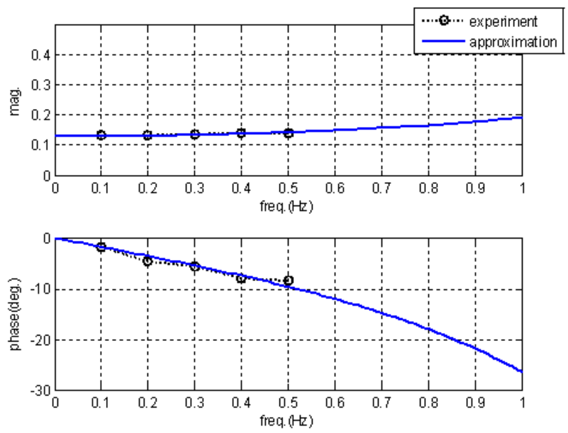
Parameters of trolley dynamics should be identified by experiment. But swing dynamics is already determined by known parameter, we don’t need to perform the system identification. Generally, for system identification, external force with broadband frequency or white noise is used to excite the system. In this system, it is impossible to impose these forces. The sinusoidal function which has finite magnitude and frequency is used for reference signal. Excitation frequency bandwidth is from 0.1Hz to 0.5Hz with 0.1Hz interval. Parameters are extracted by approximated transfer function using response of trolley position via reference signal. Transfer functions of each axis between reference signal and output signal in frequency domain are shown as Fig. 3 and are written as (5), (6). Approximated transfer functions are well identified enough to describe second order trolley system as like Fig. (3).

$$\frac{X_t}{U_x} = \frac{13.42}{s^2 + 4.972s + 102} \quad (5)$$

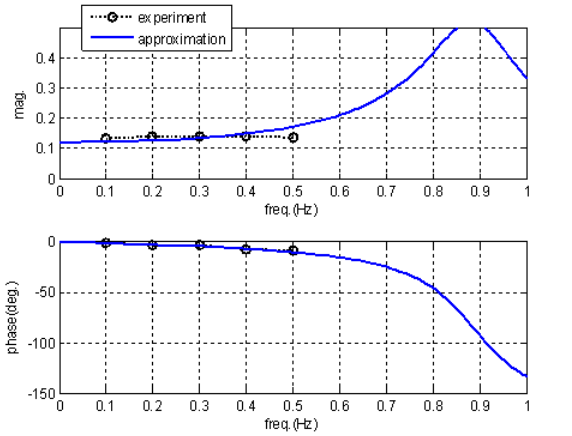
$$\frac{Y_t}{U_y} = \frac{3.79}{s^2 + 1.316s + 31.53} \quad (6)$$

4. DESIGN OF LQR CONTROLLER

In this paper, we used the LQR(Linear Quadratic Regulator) control scheme which is widely used for getting a optimal control gain based on system model. The state space models of crane in each axis are established by using determined system parameters of trolley in previous chapter.



(a)



(b)

Fig. 3 comparison of experiment result and approximated transfer function between reference position and trolley position: (a) X axis (b) Y axis

$$\begin{aligned} \mathbf{x} &= \mathbf{Ax} + \mathbf{Bu} + \mathbf{Ew} \\ \mathbf{y} &= \mathbf{Cx} \end{aligned} \tag{7}$$

$$\begin{bmatrix} \dot{x}_t \\ \dot{x}_m \\ \ddot{x}_t \\ \ddot{x}_m \end{bmatrix} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\dfrac{k}{m_t} & 0 & -\dfrac{c}{m_t} & 0 \\ \dfrac{k}{m_t} & -\dfrac{g}{l} & \dfrac{c}{m_t} & 0 \end{bmatrix} \begin{bmatrix} x_t \\ x_m \\ \dot{x}_t \\ \dot{x}_m \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ \dfrac{1}{m_t} \\ -\dfrac{1}{m_t} \end{bmatrix} u \tag{8}$$

$$y = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} x_t \\ x_m \\ \dot{x}_t \\ \dot{x}_m \end{bmatrix} \tag{9}$$

The objective of anti-swing control is to minimize the trolley position error and relative position between trolley position and container position. The cost function is defined as:

$$V = \int_0^\infty \{x^T Q x + u^T R u\} dt \tag{10}$$

where

$$Q = C^T \begin{bmatrix} \rho_1 & 0 \\ 0 & \rho_2 \end{bmatrix} C, \quad R = \rho_3, \quad \rho_1, \rho_2, \rho_3 > 0 \tag{11}$$

where ρ_1 is weighting factor of trolley position error, ρ_2 is weighting factor of relative motion between trolley position and container position, and ρ_3 is weighting factor of control input. The control performance can be determined by ratio of these weighting factors. The anti-swing controller of LQR is designed by solving Riccati equation.

$$K_x = [24.92 \quad -18.66 \quad 8.67 \quad 6.47] \tag{12}$$

$$K_y = [24.38 \quad -23.10 \quad 10.14 \quad 5.47] \tag{13}$$

5. EXPERIMENT RESULT

Experiments of developed Mobile Harbor crane are performed to verify the performance of anti-swing controller designed of LQR[2]. We equipped the 1/20 scale Mobile Harbor crane on Stewart platform as shown in Fig. 4. Then we generated the motion of platform to simulate open sea condition. To measure data on the movement in real time, we used an infra-red based motion capture system.

Fig. 4 Stewart platform for imitation of a sea wave motion

As open sea condition of Mobile Harbor, the motion platform mounting the Mobile Harbor crane was excited to simulate the wavy sea state. The conditions are as follows: 0.5degree of excitation amplitude, 0.45Hz of excitation frequency which is equal to the natural frequency of swing motion of container to make severe condition and a phase delay of $\pi/2$ between roll and pitch motions.

Experiment results are shown in Fig. 5. This figure shows the trajectories of the container in the X-Y plane measured by a motion capture system. Without any control, swing of the container rapidly increased because mode of suspended container (rope length is 1.2m) was excited. The periodical swing motion occurred as shown in the dotted lines in Fig. 5. With the proposed anti-swing control, the swing motion of the container(solid trajectories in Fig. 5) remarkably reduces within 20mm bound (solid red line in Fig. 5) to guarantee safe and efficient loading/unloading operations.

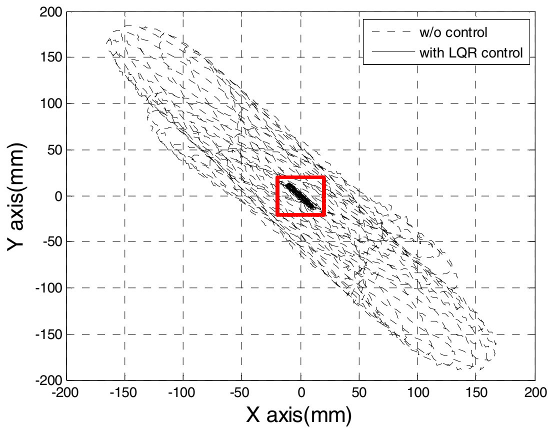


Fig. 5. Trajectories of the container in the X-Y plane without and with control

6. CONCLUSION

The Mobile Harbor is an innovative maritime cargo transfer system that allows the container handling in a wavy open sea. It is difficult to load/unload the containers because of wave induced motion of Mobile Harbor. To solve this problem, Mobile Harbor center proposed two stage trolley control system of the Mobile Harbor crane. 1/20 scale Mobile Harbor crane was implemented as prototype for evaluating the feasibility of the proposed system. Using this prototype model, we designed anti-swing controller based on LQR. LQR controller was based on independent and decoupled crane model of each axis, of which parameters are identified by experiment. The performance of controller was evaluated by implemented Mobile Harbor crane mounted on a shaky motion platform. The experiment results show the feasibility of the two stage trolley control system in practice.

ACKNOWLEDGEMENT

This work was supported by the Industrial Technology Development Program,(10036235, Development of the core technology of light weight crane for Mobile Harbor) funded by the Ministry of Knowledge Economy(MKE, Korea) and the Brain Korea 21 Project.

REFERENCES

[1] H.H.Lee, S.K.Cho, "Position and Swing Angle Control for Loads of Overhead Cranes", *Transactions of the KSME(A),* Vol.21, pp.297-304, 1997

[2] D. O. Anderson and J. B. Moore, "Optimal Control : Linear Quadratic Methods", *Prentice-Hall*, 1989.

[3] E. H. Kim, Y. S. Jung, Y. G. Yu, S. W. Kwon, H. J. Ju, S. H. Kim, B. M. Kwak, I. G. Jang, K. S. Kim, "An advanced controlled crane system for at-sea cargo transfer"*, IEEE/ASME Transaction on Mechatronics*, to be published