Trajectory Control of a Hydraulic Excavator using Disturbance Observer in H_∞ Framework

Jong-Hwan Choi*, Seung-Soo Kim**, Hyun-Cheol Cho***, Tae-Kyu Ahn***,
Buiquang Duoc***, and Soon-Yong Yang****

* Dept. of Intelligent and Mechanical Engineering, Pusan National University, Busan, Korea
(Tel : +82-52-259-1072; E-mail : jonghan@pusan.ac.kr)
** Research Center for Machine Parts and Materials Processing, University of Ulsan, Ulsan, Korea
(Tel : 82-52-259-1072; E-mail : sungsuk61@hotmail.com)
*** Dept. of Mechanical-Automotive Engineering, University of Ulsan, Ulsan, Korea
**** School of Mechanical-Automotive Engineering, University of Ulsan, Ulsan, Korea
(Tel : 82-52-259-1078; E-mail : soonyy@mail.ulsan.ac.kr)

Abstract: This paper presents a disturbance observer based on an H_∞ controller synthesis for the trajectory control of a hydraulic excavator. Compared to conventional robot manipulators driven by electrical motors, the hydraulic excavator has more nonlinear and coupled dynamics. In particular, the interactions between an excavation tool and the materials being excavated are unstructured and complex. In addition, its operating modes depend on working conditions, which make it difficult to not only derive the exact mathematical model but also design a controller systematically. In this study, the approximated linear model obtained through off-line system identification is used as nominal plant model for a disturbance observer. A disturbance observer based tracking controller which considers the effect of disturbance and model uncertainty is synthesized in H_∞ frameworks. Simulation results are used to demonstrate the applicability of the proposed control scheme.

Keywords: Hydraulic Excavator, Trajectory Control, Disturbance Observer, H_∞ Control scheme

1. INTRODUCTION

The hydraulic excavator that is mostly used in construction working has spread its role and function in construction, forest, mine, manufacturing and undersea etc. because of mechanical flexibility and high power, and a skilled operator who can handle it is very necessary. However, a lot of time and costs have been required in order to train a skilled operator and due to dangerous and poor working environments, the number of skilled operator have been decreasing, and then the automation of excavating task has been required for corresponding to a variety of tasks and conditions[1,2].

The hydraulic excavator is organized of mechanism with multi-joint links and hydraulic circuit which actuating the mechanism. The multi-joint mechanism involves the strong coupling and nonlinear, time-varying characteristics and the hydraulic system has various uncertain parameters difficult to estimate or describe. These make an exact mathematical modeling for excavator and the systematic design of a controller very difficult. Also, a natural frequency of each links of the attachment is small in a hydraulic and it is hard to do loop-gain greatly in the side of stability because a hydraulic cylinder is affected by a load variation directly. Hence, in order to track the attachments of an excavator on an arbitrary trajectory, a robust controller that insensitive to the variation of actuator parameters and external loads has been needed.

In this paper, we proposed an advanced trajectory controller design method using H_∞ control technique based on disturbance observer. Through experiments and off-line system identification methods, we obtain an approximated linear plant for designing controller. The controller with the structure of a disturbance observer is composed of a H_∞ controller for compensating disturbance observer and a feed-forward controller for tracking a reference trajectory. Finally the proposed control technique has been applied for an oblique straight trajectory motion of the end-effector, and its effectiveness has been investigated through computer simulations.

2. MATHMATICAL MODEL OF EXCAVATOR

2.1 Modeling of Hydraulic Actuator

The hydraulic system, which actuated the attachment, is composed of hydraulic pump, MCV(Main Control Valve), proportional control valve, hydraulic cylinder and auxiliary valves.

Fig. 1 represents the schematic of the hydraulic circuit of excavator, and boom, arm and bucket have all an identical structure. From the Bernoulli's equation, the flow rate entering the hydraulic cylinder is expressed;

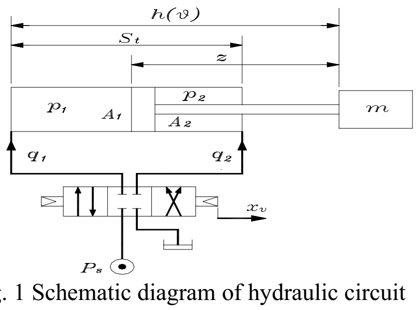


Fig. 1 Schematic diagram of hydraulic circuit

① $x_v > 0$:

$$
\begin{aligned}
q_1 &= c_d w x_v \sqrt{\frac{2}{\rho}(P_s - p_1)} \\
&= A_1 \frac{dh(\theta)}{dt} + \frac{V_1(\theta)}{K_m}\frac{dp_1}{dt} \\
q_2 &= c_d w x_v \sqrt{\frac{2}{\rho} p_2} \\
&= A_2 \frac{dh(\theta)}{dt} - \frac{V_2(\theta)}{K_m}\frac{dp_2}{dt}
\end{aligned}
\quad (1)
$$

② $x_v < 0$:

$$q_1 = c_d w x_v \sqrt{\frac{2}{\rho} p_1} = A_1 \frac{dh(\theta)}{dt} - \frac{V_1(\theta)}{K_m}\frac{dp_1}{dt} \qquad (2)$$

$$q_2 = c_d w x_v \sqrt{\frac{2}{\rho}(P_s - p_2)} = A_2 \frac{dh(\theta)}{dt} + \frac{V_2(\theta)}{K_m}\frac{dp_2}{dt}$$

where

x_v : spool displacement
ρ , c_d : working fluid density and orifice coefficient
K_m : bulk modulus of working fluid
A_1, A_2 : the areas cylinder head and rod side
P_s : the supply pressures
p_1 , p_2 : the pressures cylinder head and rod side

The chamber of single-rod cylinder as follows;

$$V_1(\theta) = A_1[h(\theta) - z]$$
$$V_2(\theta) = A_2[S_t + z - h(\theta)] \qquad (3)$$

On the other hand, the cylinder force acting the attachment is expressed by

$$F = A_1 p_1 - A_2 p_2 - D\dot{h}(\theta) \qquad (4)$$

where D is the viscous friction coefficient of cylinder.

2.2 Modeling of Attachment

Fig. 2 shows the coordinate systems and link parameters for the modeling of excavator's attachment. Where m and I denote the mass and the inertia moment of link, respectively. θ is the joint angle, g is the gravitational acceleration and L, l and δ are the constants of length and angle as defined in Fig. 2. The subscript 1, 2 and 3 mean the boom, arm and bucket, respectively.

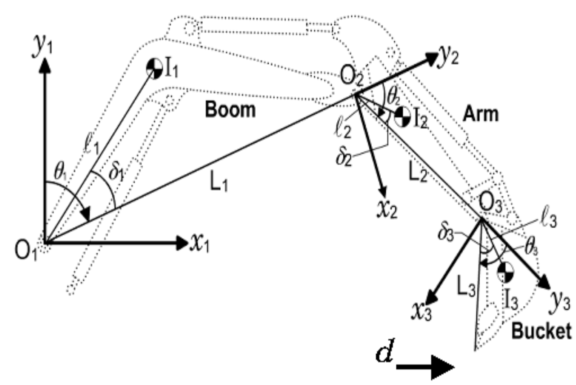


Fig. 2 Schematic diagram of excavator attachment

The dynamic equation of excavator attachment is derived using Euler-Lagrange equation as follows[3].

$$D(\theta)\ddot{\theta} + C(\theta,\dot{\theta})\dot{\theta} + G(\theta) = \tau \qquad (5)$$

where $D(\theta)$ is the inertia terms and a nonlinear function of θ, $C(\theta,\dot{\theta})$ is due to centrifugal and Coriolis forces, $G(\theta)$ is due to gravity, and τ represents the joint torques.

In order to derive the relationship between the output cylinder force of the hydraulic system and the attachment motion, it is necessary to transform the cylinder length to the joint angle and the cylinder force to the joint torque. Then the relationship is simply expressed by introduce the link gain and the torque gain as follows[4]:

$$\dot{h}(\theta) = H(\theta)\dot{\theta} \qquad (6)$$
$$\tau(\theta) = G(\theta)F \qquad (7)$$

3. DISTURBANCE OBSERVER AND NOMINAL PLANT

3.1 Concept of Disturbance observer

Disturbance observer has been used to improvement the robustness of robot system and to simplify the algorithm for its force or position control[5]. As shown in Fig, 3, disturbance observer is composed of the inverse nominal model and a designing parameter J which determines the robust stability and disturbance suppression performance. Its basic concept is that the disturbance injected into a system can be compensated by an observer, although the disturbance can not be measured.

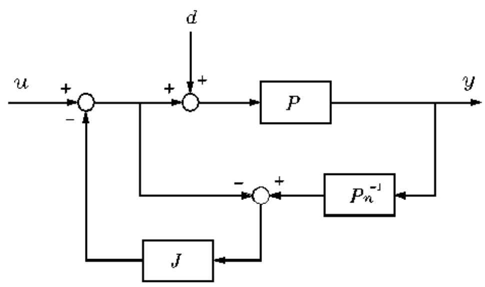


Fig. 3 Block diagram of disturbance observer

Output shown in Fig. 3 is expressed by;

$$y = G_{yu}(s)\,u + G_{yd}(s)\,d \qquad (8)$$

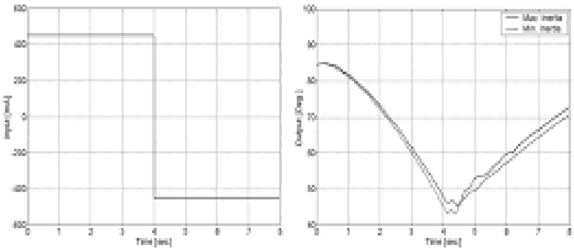
where

$$G_{yu}(s) = \frac{P P_n}{P_n + \{P - P_n\}J}$$
$$G_{yd}(s) = \frac{P P_n\{1 - J\}}{P_n + \{P - P_n\}J}$$

If a designing parameter J is the low pass filter, the transfer function at low frequencies are expressed by $G_{yu}(s) \approx P_n(s)$, $G_{yd}(s) \approx 0$. So, the effect of disturbance is close to zero and it is possible to design the 2 th order robust controller based on linearized nominal plant to be a good tracking performance.

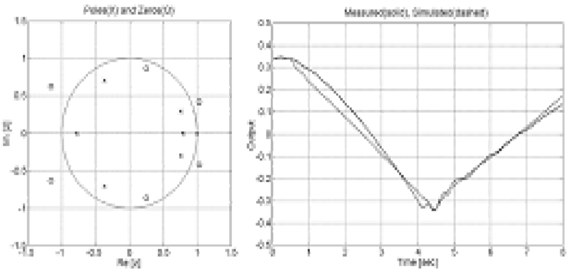
3.2 Linearized Nominal Model

In this paper, in order to design a disturbance observer based on $H\infty$ control theory, we obtain an approximated linear model through experiments and off-line system identification method for the whole excavator system. As the input signal for the system identification, the double step signal was used under the conditions that the saturation of a hydraulic cylinder doesn't happen and a link moves nearly the whole operation area[6]. And the experiments were performed



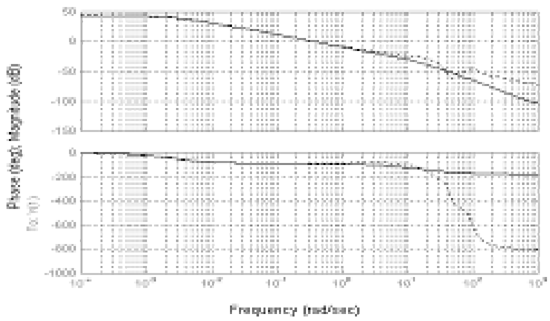
(a) step input (b) boom angle

Fig. 4 Input/output of ID experiment of boom

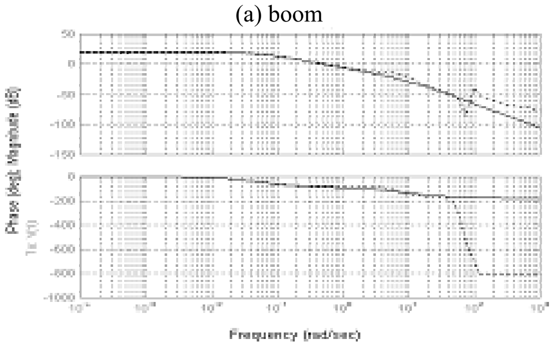


(a) pole & zero (b) plant & ARX model

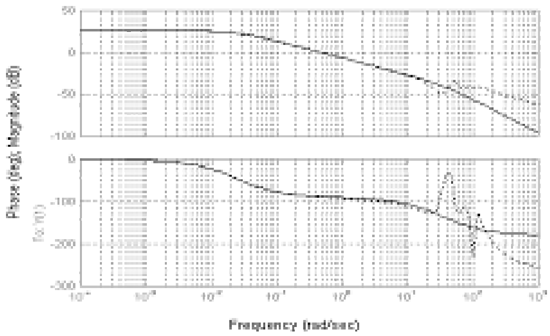
Fig. 5 ID results of ARX model of Boom



(a) boom



(b) arm



(c) bucket

Fig. 6 Bode diagram of transfer function of ID model

at the maximum and minimum of the inertial moment at each joint. Among the identification experiments for the dynamics of boom, arm, bucket, Fig. 4 shows only the experiment result of boom. Where, the solid line and the dotted line represent the outputs of maximum and minimum inertial moment respectively. Also, the identification experiments of arm and bucket were performed by the same method as the boom.

Fig. 5 shows the result of 7th ARX model[7]. The solid line represents the plant output obtained by the experiment, and the dotted line is the output of the identification model to the identical input. The arm and bucket system were identified as the 8th order and 10th order ARX model, respectively.

Fig. 6 shows the bode diagrams of the 7th ARX model(dotted line) and the 2th order transfer function(solid line). The frequency response is nearly consistent at the low frequency domain below about 1rad/sec. And the cases of arm and bucket are omitted.

An each transfer function is expressed by

BOOM : $$P_b(s) = \frac{5.4}{s^2 + 15s + 0.04} \quad (9)$$

ARM : $$P_a(s) = \frac{5}{s^2 + 10s + 0.5} \quad (10)$$

BUCKET : $$P_k(s) = \frac{16}{s^2 + 34s + 0.8} \quad (11)$$

4. DISTURBANCE OBSERVER BASED ON H_∞ CONTROL TECHNIQUE

4.1 Theoretical Background

Fig. 7 shows the structure of control system using an internally stabilizing disturbance observer and a feed-forward controller K_f for a good tracking performance. If P_n is a given nominal plant, Eq. (12) is a coprime factorization of P_n and if $M, N \in RH_\infty$ are coprime, then M, N satisfy the *Bezout Identity* such as Eq. (12).

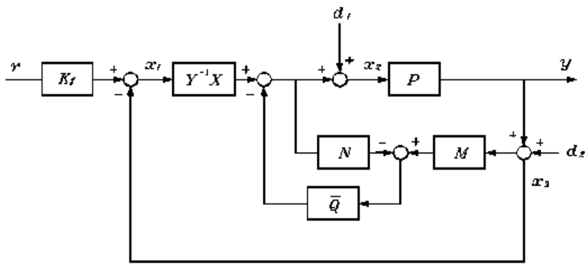


Fig. 7 Structure of control system

$$P_n = \frac{N}{M}, \quad NX + MY = I \quad (12)$$

Let the dynamics of real plant assume to undergo the perturbations within any bound, then it should be defined as the set. The set of real plant can be defined as;

$$\partial P = \left\{ \frac{N + \Delta N}{M - \Delta M} : [\Delta N \; \Delta M] \in RH_\infty, \; \| \Delta N \; \Delta M \|_\infty < \gamma^{-1} \right\} \quad (13)$$

where $P \in \partial P$, ΔN, ΔM are perturbations of coprime N, M and γ^{-1} is the maximum size of admissible perturbation.

Define the objective function for $\overline{Q}$ design;

$$\text{minimize} \ \| N\overline{Q}-1 \|_{\infty}, \quad \overline{Q} \in RH_{\infty} \tag{14}$$

Only the good $\overline{Q}$ design can completely not assure the stability against perturbations. Hence, the stability constraint for a plant against perturbations should be obtained.

The mapping from (r, w1, w2) to [u, y]T is represented by[8];

$$\begin{bmatrix} u \\ y \end{bmatrix} = \begin{bmatrix} -(X+M\overline{Q}Y) \\ Y(1-N\overline{Q}) \end{bmatrix}\phi + \begin{bmatrix} MX \\ NX \end{bmatrix} r + \begin{bmatrix} MY(1-N\overline{Q}) \\ NY(1-N\overline{Q}) \end{bmatrix} d_1 + \begin{bmatrix} -M(X+M\overline{Q}Y) \\ -N(X+M\overline{Q}Y) \end{bmatrix} d_2 \tag{15}$$

All transfer functions of Eq. (15) can be stable for all plants under some constraints. Then the modeling error is expressed by;

$$\phi = [\ \Delta N \ \ \Delta M\ ] \begin{bmatrix} u \\ y \end{bmatrix} \tag{16}$$

If the 2-norm bound of modeling error is considered, we can get the next inequality by the assumption of the set of real plant;

$$\| \phi \|_2 < \gamma^{-1} \left\| \begin{bmatrix} u \\ y \end{bmatrix} \right\|_2 \tag{17}$$

If the small gain theorem[10,12] is applied to the mapping Eq. (15) and (16), then the stability condition can be shown as;

$$\left\| \begin{bmatrix} -(X+M\overline{Q}Y) \\ (1-N\overline{Q})Y \end{bmatrix} \right\|_{\infty} \le \gamma \tag{18}$$

If normalized coprime factorization[9] is used, since $\| N\ M \|_{\infty} = 1$, then we obtain below inequality;

$$\left\| \begin{bmatrix} -X-M\overline{Q}Y \\ Y-N\overline{Q}Y \end{bmatrix} \right\|_{\infty} \| N \ \ M \|_{\infty} < \gamma \tag{19}$$

If the closed-loop transfer function is defined by the stability constraint, then it is expressed by;

$$\| F_l(P, K) \|_{\infty} = \left\| \begin{bmatrix} (-X-M\overline{Q}Y)N & (-X-M\overline{Q}Y)M \\ (Y-N\overline{Q}Y)N & (Y-N\overline{Q}Y)M \end{bmatrix} \right\|_{\infty} \le \gamma \tag{20}$$

In Fig. 7, if we combine coprime factors, the feedback controller can be defined as;

$$K = (-X-M\overline{Q}Y)(Y-N\overline{Q}Y)^{-1} = (-X-MQ)(Y-NQ)^{-1} \tag{21}$$

4.2 Design of Controller

A generalization plant as shown in Fig. 8 is established in order to design a disturbance observer on a transfer function of each links and as follows;

$$P = \begin{bmatrix} W_1P_n & W_1 & W_1P_n \\ 0 & 0 & W_2 \\ P_n & I & P_n \end{bmatrix} \tag{22}$$

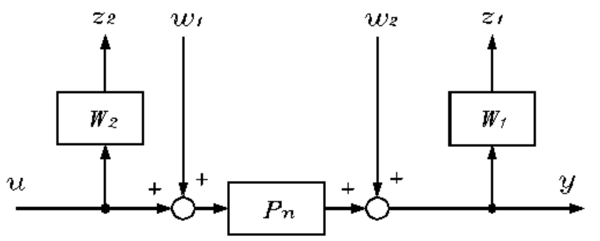


Fig. 8 Generalized plant

The weighting function $W_1 \in RH_{\infty}$ is considered for stability about a modeling error of a high frequency and the weighting function $W_2 \in RH_{\infty}$ is considered to be satisfied with condition..

$$W_1(s) = \frac{20(s+1)}{s+2}, \quad W_2(s) = 0.1 \tag{23}$$

Consider a generalized plant as follow;

$$\overline{P} = \left[\begin{array}{c|cc} A & B_1 & B_2 \\ \hline C_1 & 0 & D_{12} \\ C_2 & D_{21} & 0 \end{array} \right] \tag{24}$$

To solve for the family of H controllers, we must solve two Riccati equations[8,10].

$$X_{\infty} = Ric\begin{bmatrix} A & \gamma^{-2}B_1B_1^T - B_2B_2^T \\ -\overline{C}_1^T\overline{C}_1 & -A^T \end{bmatrix} \tag{25}$$

$$Y_{\infty} = Ric\begin{bmatrix} A^T & \gamma^{-2}C_1^TC_1 - C_2^TC_2 \\ -\overline{B}_1\overline{B}_1^T & -A \end{bmatrix}$$

where

$$\overline{B}_1 = B_1(I - D_{21}^TD_{21})$$

$$\overline{C}_1 = (I - D_{12}D_{12}^T)C_1$$

$$F = -B_2^TX_{\infty}$$

$$H = -Y_{\infty}C_2^T$$

$$Z_{\infty} = (I - \gamma^{-2}Y_{\infty}X_{\infty})^{-1}$$

Given a generalized plant suppose the plant for the double coprime factorization satisfying as[9,12];

$$P_s = \left[\begin{array}{c|c} A_s & Z_{\infty}B_2 \\ \hline C_2 & 0 \end{array} \right] \tag{26}$$

where

$$A_s = A + \frac{1}{\gamma^2}B_1B_1^TX_{\infty} - \frac{1}{\gamma^2}Z_{\infty}Y_{\infty}X_{\infty}B_2F$$

The plant is expressed by;

$$P_s = N_rM_r^{-1} = M_l^{-1}N_l \tag{27}$$

where

$$\begin{bmatrix} Y_r & X_r \\ -N_l & M_l \end{bmatrix} = \left[\begin{array}{c|cc} A_r & Z_\infty B_2 & -Z_\infty H \\ \hline -F & I & 0 \\ -C_2 & 0 & I \end{array}\right] \quad (28)$$

$$\begin{bmatrix} M_r & -X_l \\ N_r & Y_l \end{bmatrix} = \left[\begin{array}{c|cc} A_l & Z_\infty B_2 & -Z_\infty H \\ \hline F & I & 0 \\ C_2 & 0 & I \end{array}\right] \quad (29)$$

where

$$A_r = A + \frac{1}{\gamma^2} B_1 B_1^T X_\infty - \frac{1}{\gamma^2} Z_\infty Y_\infty X_\infty B_2 F + Z_\infty H C_2$$

$$A_l = A + \frac{1}{\gamma^2} B_1 B_1^T X_\infty + B_2 F$$

In this case, All stabilizing controller is described as follows[12]

$$\overline{K} = F_l(R, Q) \quad (30)$$

where

$$R = \begin{bmatrix} -Y_r^{-1} X_r & -Y_r^{-1} \\ Y_l^{-1} & Y_l^{-1} N_r \end{bmatrix}, \quad Q = N_r^{-1} Y_l J \quad (31)$$

The feedback controller for generalized plant is represented by;

$$\begin{aligned} K &= S_2 \overline{K} S_1 \quad (32) \\ &= \sqrt{1-\gamma^{-2}}\, I \times F_l(R, Q) \times I \end{aligned}$$

5. SIMULATION RESULTS

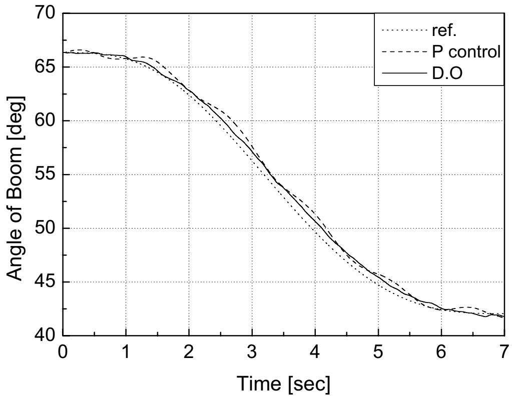
The computer simulations have been performed for a constant angle excavating task using the proposed controller. The mathematical model for simulations is constructed using simulink and the design of a H_∞ controller is aided by MatLab toolbox. The trajectory applied in this study is selected as a declined straight-line motion of end-effector and the path is a straight-line of horizontal distance 3[m] and vertical distance 1[m] to high and inward from low and outward during 7[sec]. The disturbance is assumed as a harmonic variation of load toward the direction obstructing bucket tip's movements.

Table 1. Parameters of excavator used in computer simulation

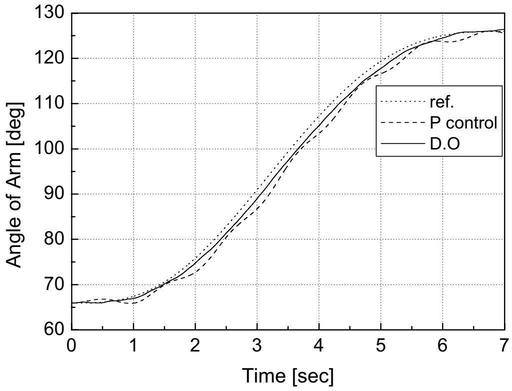
Para		Value	Para	Value
Boom	A_1	0.03 [m²]	m_1	1260 [kg]
	A_2	0.015 [m²]	m_2	638 [kg]
	z	1.88 [m]	m_3	562 [kg]
Arm	A_1	0.02 [m²]	I_1	3.1×10^4 [kg·m²]
	A_2	0.01 [m²]	I_2	2.6×10^3 [kg·m²]
	z	1.97 [m]	I_3	6.8×10^2 [kg·m²]
Bucket	A_1	0.017 [m²]	L_1	5.64 [m]
	A_2	0.0085 [m²]	L_2	3.03 [m]
	z	1.62 [m]	L_3	1.29 [m]
P_s		10×10^6 [N/m²]	l_1	3.09 [m]
K_m		1.7×10^9 [N/m²]	l_2	0.89 [m]
C_d		0.7 [-]	l_3	0.72 [m]
ρ		900 [kg/m³]	δ_1	10.8 [deg.]
D		5000 [N·s/m]	δ_2	14.4 [deg.]
			δ_3	30 [deg.]

Table 1 shows parameters for computer simulation.

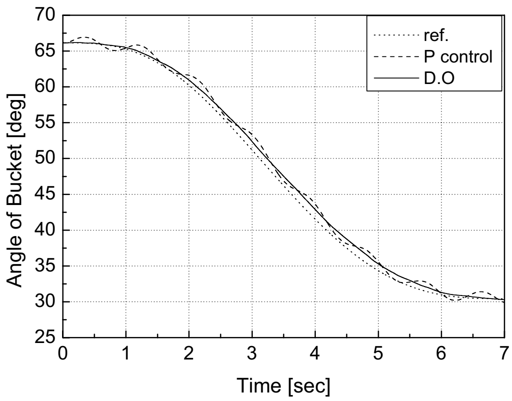
Fig. 12(a)~(c) show the trajectory tracking results of boom, arm, bucket, respectively. The gain of P controller about each links was selected with 15, 10, 15 based on transient response after composing output feedback loop. At the initial and final time, the angular velocity of boom, arm and bucket are zero.



(a) Trajectory tracking of boom



(b) Trajectory tracking of arm



(c) Trajectory tracking of bucket

Fig. 12 Tracking of the boom, arm and bucket

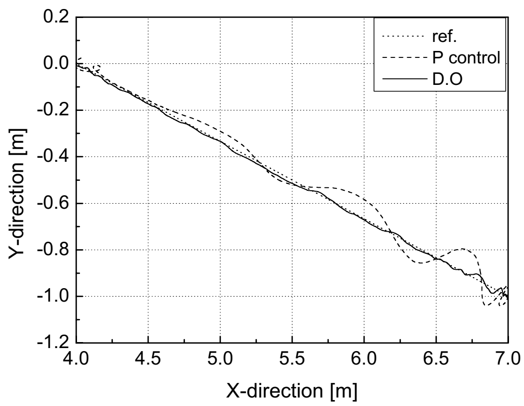


Fig. 13 Trajectory tracking of the bucket's end-effector

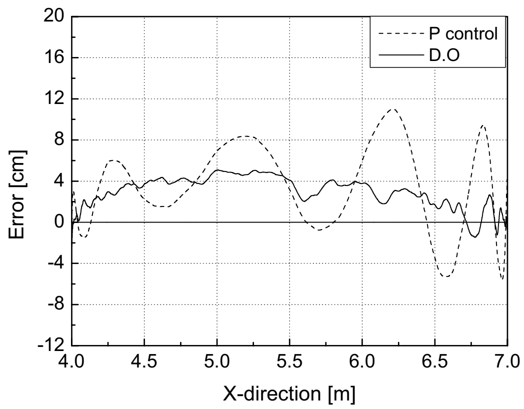


Fig. 14 Output errors on the reference trajectory

Fig. 13 shows the tracking performances of the end-effector for the trajectories of an oblique straight line. It has been illustrated that the proposed disturbance observer can improve the tracking performance compared with P controller.

Fig. 14 shows the absolute error of reference trajectory using the proposed disturbance observer and P controller.

However, there is hardly an influence of periodic disturbance in case of disturbance observation banner, and an error is occurring in largest 5[cm], too.

6. CONCLUSION

This study has applied a H_∞ control technique having a structure of disturbance observer to the trajectory control of excavator's attachments.

Through experiments and system identification methods, the approximated 2^{th} order linear models which reflect main characteristics of whole system of excavator have been derived and used as nominal models for designing controllers. For uncertainty and disturbance of the trajectory tracking control system in a hydraulic excavator, disturbance observer applied H_∞ control theory has been proposed. It is illustrated by computer simulations that the proposed control system gives satisfactory performance in the trajectory tracking and the robustness to disturbances.

Hereafter, we will apply the proposed control system for actual excavator and evaluate the robustness to external load variation and trajectory tracking.

ACKNOWLEDGMENTS

This work was supported by the Korea Science and Engineering Foundation(KOSEF) through the Research Center for Machine Parts and Material Processing at University of Ulsan.

REFERENCES

[1] Ha, Q. P., Nguyen, Q. H., Rye, D. C., Durrant- Whyte, H. F., "Fuzzy Sliding-Mode Controllers with Applications," *IEEE Trans. Industrial Elec*tronics, Vol. 48, No. 1, pp. 38-46, 2001.

[2] Tafazoli, S., Salcudean, S. E., Hashtrudi-Zaad, K., Lawrence, P. D., "Impedance Control of a Teleoperated Excavator," *IEEE Trans. Control Systems Technology*, Vol. 10, No. 3, pp. 355-367, 2002.

[3] Spong, M. W. and Vidyasagar, M., *Robot Dynamics and Control*, New York: Wiley, 1989.

[4] Morita, T., Sakawa, Y., "Modeling and Control of a Power Shovel," *計測自動制御學會論文集*, Vol. 22, No. 1, 1986.

[5] Ohnishi, K., "A New Servo Method in Mechatronics," *Trans. Japaness Society of Electrical Engineers*, Vol. 107-D, pp. 83-86, 1987.

[6] Mao-Hsiung, C., "Adaptive Achsregelung fur Hydraulikbagger," *Aachen, Techn. Hochsch., Diss*., 1998.

[7] Ljung, L., *System Identification : Theory for the user*, 2nd edition, New Jersey, Prentice-Hall, 1999.

[8] Choi, Y. J., Chung, W. K. and Youm, Y. I., "Disturbance Observer in H_∞ Frameworks," *Proceedings of the 1996 IEEE IECON 22nd International Conference on*, Vol. 3, 1996.

[9] Vidyasagar, M., *Control System Synthesis : A Factorization Approach*, MIT Press, 1985.

[10] Doyle, J. C., Glover, K., Khargonekar, P. P. and Francis, B. A., "State Space Solution to Standard H_2 and H_∞ Control Problem," *IEEE Trans. Automatic Control*, Vol. 34, No. 8, 1989.

[11] Green, M., Limebeer, D. N*., Linear Robust Control*, Prentice-Hall, 1994.

[12] Skogestad, S., Postlethwaite, I., *Multivariable Feedback Control Analysis and Design*, John Wiley & Sons, 1996.