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최적 제어법에 의한 타워크레인의 자동화에 관한 연구

Automation of Tower Cranes based on Optimal Control Method

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ABSTRACT

This paper is concerned with automation of tower cranes in view of the robust control of tower crane during take-off, load hoisting, load lowering and landing. The model equation of the tower crane is induced by using Lagrange's equation and it is linearized at equillibrium point. The control is realized by adopting the optimal regulator method. The effectiveness is proved through the experimental results for the oscillation control of cargo rope and the position controls of trolley and boom by the implementation of digital control using 16 bits microcomputer for the designed optimal control law.

국문요약

본 논문은 하역작업이나 제품의 권상, 권하시 타워크레인의 로바스트 콘트롤을 고려한 타워크레인의 자동화에 관한 것이다. 본 논문을 위한 타워크레인의 모델방정식은 라그랑즈 방정식을 사용하였으며, 동방정식은 평행점 근방에서 선형화 하였다.

본 논문의 제어법으로서는 최적 레귤레타법을 적용하였으며, 그 효용성은 설계된 최적 제어법을 위하여 16비트 마이크로컴퓨터를 이용하여 카고로우프의 진동제어와 크레인의 붐 및 트로리의 위치제어를 위한 실험결과로써 입증되었다.

1. Introduction

In serveral industrial fields requiring load lowering and landing, the necessity of the tower crane is successively increasing.

But because of inherence of the danger for large accident due to itself unstability and primitiveness in the side of production efficiency, it is successively increasing to demand about safety

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work, work efficiency and automation.

As the study to control crane, Maruko[1979] showed a control method to prevent the vibration of crane using the pulse motor and Mita[1979] showed a minimizing time control method. S. B. Kim[1992] studied the robust control for the container crane using servo system design method and digital redesigne method.

Recently, in the tower crane a robust control is required, that is, an insensitive control system with respect to oscillation of cargo rope and disturbance such as wind is required.

In this paper, as a basic study in order to automize tower cranes, the dynamic model equation is theoretically induced in view of control theory and a digital control method to implement the automation is introduced. The model equation of the tower crane is induced by using Lagrange's equation and it is linearized at equillibrium point. The control is realized by adopting the optimal regulator method. The effectiveness is proved through the experimental results for the oscillation control of cargo rope and the position controls of trolley and boom by the implementation of digital control using 16 bits microcomputer for the designed optimal control law.

2. Analysis of Experimental Apparatus

2.1 Configuration of Tower Crane Apparatus

The experimental apparatus used in this paper is shown schematically in Fig 2–1. Boom is rotated by a DC servomoter(DC 20V, 180rpm) with a reduction gear and a roller type of trolley is moved by a DC servomotor(DC 12V, 200rpm).

On the other hand, to measure the boom rotation and the pendulum oscillation attached to trolley, three potentiometers(J 50S, ±0.1%, 2k Ω copal) are used.

As the sensor measuring the moving motion of trolley, a rotation type of potemtiometer(R20K, 0.25%) is used.

2.2 Driving Circuit of DC Servo Motor

A pre-amplifier is used for inputing the output voltage of D/A converter in the range of 0 to 5 voltage, and then amplifies the input voltage into the range of -12 voltage to +12 voltage so as to drive two directions such as positive or negative of servo motor.

The plant outputs are converted using A/D converter(PCL 812) and the control inputs are made up through D/A converter. Control program is drawn up by C language.

2.3 Modelling

In order to analyze the dynamic characteristics of the mechanism schematized as Fig 2–1, it is assumed that the boom and the bar of tower crane is constructed by a riged bar.

The model equation are induced by using the following Lagrange's equation :

$$\frac{d}{dt}\left[\frac{\partial T}{\partial \dot{g}i}\right]-\frac{\partial T}{\partial qi}+\frac{\partial D}{\partial \dot{g}i}$$

$$+\frac{\partial D}{\partial \dot{g}i}=\tau \quad \cdots\cdots\cdots\cdots\cdots \quad (2\text{–}1)$$

where qi : parameter(i=1, 2, 3…)
T : kinetic energy
U : potential energy
D : friction energy

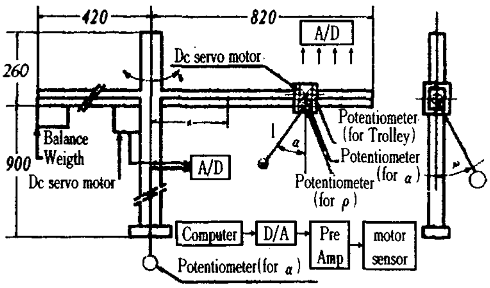


Fig. 2–1 Configuration of tower crane system

The dynamic differential equation for boom can be get as the following :

$$(J+mL^2+ml^2+\sin^2\rho)\ddot{\theta}-mLl\cos\rho\ddot{\rho}$$

$$+ 2ml^2 \sin\rho \cos\ddot{\rho}\,\dot{\theta} + mLl\rho^2 \sin\rho$$
$$+ D_\theta \dot{\theta} = \tau_\theta \quad \cdots\cdots (2\text{–}2)$$
$$ml^2\ddot{\rho} - mLl\cos\rho\,\ddot{\theta} - ml^2 \sin\rho \cos\rho\ \dot{\theta}^2$$
$$+ D_\rho \dot{\rho} + mgl\sin\rho = 0 \quad \cdots\cdots (2\text{–}3)$$

The dynamic differential equation for trolley can be get as following[14) :

$$(N+m)\ddot{x} - ml\ddot{\alpha}\cos\alpha + ml\dot{\alpha}^2\sin\alpha$$
$$+ D_x\dot{x} = \tau_x \quad \cdots\cdots (2\text{–}4)$$
$$ml^2\ddot{\alpha} - ml\ddot{x}\cos\alpha + D_\alpha\dot{\alpha} + mgl$$
$$\sin\alpha = 0 \quad \cdots\cdots (2\text{–}5)$$

Since eqs. (2–2), (2–3), (2–4) and (2–5) are nonlinear differential equation, in order to get the state equation incorporating the well known linear control theory, those differential equations may be linearized at the equillibrium point such as $\theta = (\sin\theta \cong \theta,\ \cos\theta \cong 1,\ \dot{\theta} \cong 0)$, $\rho = 0$ as the following;

$$(N+m)\ddot{x} - ml\ddot{\alpha} + D_x\dot{x} = \tau_x \quad \cdots\cdots (2\text{–}6)$$
$$ml^2\ddot{\alpha} - ml\ddot{x} + D_\alpha\dot{\alpha} + mgl\alpha = 0 \quad \cdots (2\text{–}7)$$
$$(J + mL^2)\ddot{\theta} - mLl\ddot{\rho} + D_\theta\dot{\theta}$$
$$= \tau_\theta \quad \cdots\cdots (2\text{–}8)$$
$$ml^2\ddot{\rho} - mLl\ddot{\theta} + D_\rho\dot{\rho} + mgl\rho$$
$$= 0 \quad \cdots\cdots (2\text{–}9)$$

Therefore, the state equation for eqs. (2–6) (2–7)(2–8) and (2–9) can be given by the form :

$$\frac{dx}{dt} = Ax + Bu \quad \cdots\cdots (2\text{–}10a)$$
$$y = Cx \quad \cdots\cdots (2\text{–}10b)$$

where

$$x = [x\ \alpha\ \rho\ \theta\ \dot{x}\ \dot{\alpha}\ \dot{\rho}\ \dot{\theta}]^T$$

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \left(-\frac{mg}{N}\right) & 0 & 0 & \left(-\frac{D_x}{N}\right) & \left(-\frac{D_\alpha}{N1}\right) & 0 & 0 \\ 0 & \left(-\frac{(N+m)g}{N1}\right) & 0 & 0 & \left(-\frac{D_x}{N1}\right) & \left(-\frac{(N+m)D_\alpha}{Nml^2}\right) & 0 & 0 \\ 0 & \left(\frac{(J+mL^2)g}{J1}\right) & 0 & 0 & 0 & \left(-\frac{(J+mL^2)D_\rho}{JmL^z}\right) & \left(-\frac{(D\theta)}{J}\right) & \\ 0 & 0 & \left(-\frac{mL^g}{J}\right) & 0 & 0 & 0 & \left(-\frac{LD_\rho}{J1}\right) & \left(-\frac{(D\theta)}{J}\right) \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ \left(-\frac{1}{N}\right) & 0 \\ \left(-\frac{1}{N1}\right) & 0 \\ 0 & \left(\frac{L}{J1}\right) \\ 0 & \left(-\frac{1}{J}\right) \end{bmatrix}$$

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

$$u = \begin{bmatrix} \tau x \\ \tau_\theta \end{bmatrix}$$

3. Parameter Measurement of System

3.1 On Moving of Trolley

The hardware block diagram for the parameter measurement is shown in Fig. 3−1 The parameters of the tower crane are defined by the following;

vu : output of D/A converter
e : output of attenuation circut
ep : output of pre-amplifier
p : output of potentiometer
y : output of A/D

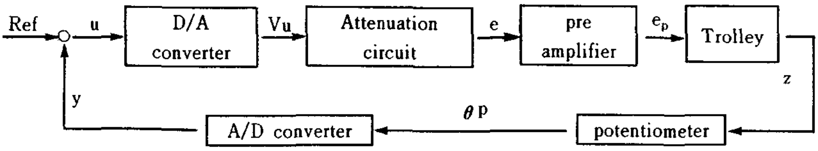


Fig. 3−1 Control diagram for parameter measurement

The dynamic equation of trolley can be written by

$N\ddot{z} + D_x\dot{z} = a_{ox}\,u$ ·························· (3−1)

and the control system of Fig. 3−1 can be expressed as the following;

$y_x = r_{ox}^{-1}\,z$ ····································· (3−2)

$u = r^{-}y_x$ ····································· (3−3)

Substituting eqs. (3−2) and (3−3) into eq. (3−1), we can rewrite eq. (3−1) as following;

$Nr_o y\ddot{x} + D_x r_{ox}\dot{y}_x = a_{ox}(r - y_x)$ ·········· (3−4)

Eq. (3−4) can be expressed as the following diffential equation

$\ddot{y}_x + 2\xi_x\,\omega_{nx}\,\dot{y}_x + \omega_{nx}^2\,y_x = \omega_{nx}^2\,r$ ························· (3−5)

By comparing the output response eq. (3−4) and eq. (3−5) for step reference input, parameter N can be obtained as the following :

$N = \frac{ao\,\tau_x^2}{4r_o(\pi^2 + \lambda x^2)}$ ··················· (3−6)

and the friction coefficient Dx can be rewretten as the follwing;

$D_x = \frac{4\lambda_x N}{\tau_x}$ ····························· (3−7)

On the othet hand , let to the equation of pendulum oscillation be as follows;

$J_\alpha\ddot{\alpha} + D_\alpha\dot{\alpha} + mgl\sin\alpha = 0$ ········ (3−8)

Using $\sin\alpha \cong \alpha$ for small α, we can derive the linearized equation with respect to $\delta\ \alpha$ about $\alpha = 0$ from eq. (3−8), then eq. (3−8) can be given by

$J_\alpha\ddot{\alpha} + D_\alpha\dot{\alpha} + mgl\ \alpha =$ ············ (3−9)

and eq. (3−9) can be expressed as the following dynamic differential equation;

$\ddot{\alpha} + 2\xi_a\omega_{na}\dot{\alpha} + \omega_{na}^{2\alpha} = 0$ ·········· (3−10)

By comparing the output response eq. (3−9) and eq. (3−10) for step reference input, J_α and D_α can be obtained as the follow :

$J_\alpha = \frac{mgl\,\tau_\alpha^2}{4(\pi^2 + \lambda_\alpha^2)}$ ················· (3−11)

$D_\alpha = 2\xi_\alpha\omega_{n\alpha}J_\alpha$ ···················· (3−12)

3.2 On Rotating of Boom

The dynamic equation of boom can be written by;

$J_\theta\ddot{\theta} + D_\theta\dot{\theta} = a_{o\theta}\,u$ ················ (3−13)

where

$y_\theta = r_{o\theta}^{-1}\,\theta$ ··················· (3−14)

$u = r - y_\theta$ ······················ (3−15)

and the dynamic equation of pendulum can be written by;

$J_\rho\ddot{\rho} + D_\rho\dot{\rho} + mgl\rho = 0$ ··········· (3−16)

By applying similarly the measurement method of trolley parameters : N, and D_x on the basis of above equations, boom parameters, J_θ and D_θ are obtained as follows;

$$J_\theta = \frac{a_{o1}}{\omega^2_{n\theta} r_{o1}} = \frac{a_{o1}\,\tau^2_\theta}{4r_{o1}(\pi^2 + \lambda^2_\theta)}$$

$$= \frac{a_{o1}}{a_{2\theta}\, r_{o1}} \quad \cdots\cdots (3\text{-}17)$$

$$D_\theta = 2J_\theta\,\xi_\theta\,\omega_{n\theta} = \frac{4\lambda_\theta J_\theta}{\tau_\theta}$$

$$= J_\theta a_{1\theta} \quad \cdots\cdots (3\text{-}18)$$

On the other hand, pendulum parameters, J_ρ and D_ρ are obtained as follows;

$$J_\rho = \frac{mgl}{\omega^2_{n\rho}} = \frac{mgl\,\tau^2_\rho}{4(\pi^2 + \lambda^2_\rho)} \quad \cdots\cdots (3\text{-}19)$$

$$D_\rho = \frac{\lambda_\rho mgl\,\tau_\rho}{\pi^2 + \lambda^2_\rho} \quad \cdots\cdots (3\text{-}20)$$

3.3 Measurement Result of the Parameter

From experimental results using the circuit of Fig. 3-1, those element values of the state equation matrix which are deteriminated by parameter values can be obtained as the following table.

Table 3-1 Element values of the state equation matrix

elements of matrix	calculated value
$-mg/N$	−3.579
$-D_x/N$	−3.465
$-D_a/Nl$	−0.002846
$-(N+m)g/Nl$	−29.73
$-D_x/Nl$	−7.700
$-(N+m)D_a/Nml^2$	−1.1563
$-(J+mL^2)g/Jl$	−22.689
$-(J+mL^2)D_\rho/Jml^2$	−0.0116
$-D_\theta L/Jl$	−1.378
$-mLg/J$	−0.500
$-LD_\rho/Jl$	−0.00025
$-D_\theta/J$	−0.756
$1/N$	0.869
$1/Nl$	1.932
L/Jl	0.27
$1/J$	0.148

Using the element values of state equation matrix as Table 3-1 eq. (2-10) can be specified as the following :

$$\dot{x} = Ax + Bu \quad \cdots\cdots (3\text{-}21a)$$

$$y = cx \quad \cdots\cdots (3\text{-}21b)$$

$$A = \begin{bmatrix} 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \\ 0 & -3.579 & 0 & 0 & -3.465 & -0.0028 & 0 & 0 \\ 0 & -29.73 & 0 & 0 & -7.700 & -1.1563 & 0 & 0 \\ 0 & 0 & -21.778 & 0 & 0 & 0 & -0.0116 & -1.378 \\ 0 & 0 & -0.500 & 0 & 0 & 0 & -0.00025 & -0.756 \end{bmatrix}$$

$$B = \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0.869 & 0 \\ 1.932 & 0 \\ 0 & 0.27 \\ 0 & 0.1481 \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \end{bmatrix}$$

4. Design of Control System

The optimal control problem for a linear multivariable system with the quadratic criterion function is one of the most common problems in linear system theory.

Althogh many kinds of functions can be considered as criterion fuctions, in this paper, only the quadratic criterion function is adopted since it is mathematically tractable and thus commonly used for the design of controls for linear multivariable systems.

The above stated optimal control problem can be expressed by the follwing[7] : For the linear controllable multivariable system

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t) \;:\; A \in R^{n\times n},\; B \in R^{n\times n} \quad \cdots\cdots (4\text{-}1)$$

with controllable pair(A, B), we consider the following quadratic criterion function

$$J = \int_0^\infty (\|x(t)\|^2_Q + \|u(t)\|^2_R)\,dt \quad \cdots\cdots (4\text{-}2)$$

where R is a symmetric positive definite matrix, and Q is a symmetric positive semidefinite matrix.

The optimal control input for the controllable system(4-1) which minimizes the criterion function(4-2) can be given by the references[6),7)]

$$u(t) = -Fx(t) \quad \cdots\cdots (4\text{-}3)$$

$$F = R^{-1} B^T P$$

where P is a positive definite solution satisfying the Riccati differential equation

$$A^T + PA + Q - PBR^{-1} B^T P = 0 \cdots (4-4)$$

Substituing eq. (4–3) into eq. (4–1), the optimal closed system is given by

$$\frac{dx(t)}{dt} = (A - BR^{-1}B^TP)x(t) \cdots\cdots\cdots (4-5)$$

and is called the optimal regulator.

5. Experimental Results

Using the optimal requlator method described in the chapter 4, the experiment based on the real time control by micro computer is carried out. The sampling time for digital control is taken as 15 msec and the experiment results are shown in the following two cases :

case 1 : Experiment for step reference

case 2 : Experiment for disturbance and step refenence

5.1 Construction of Optimal Regulator

Let a symmetric positive definite matrix R and a symmetric positive semidefinite matrix Q be given as the following :

$$Q = \mathrm{diag}[100, 100, 100, 100, 100, 100, 100, 100]$$

$$R = \mathrm{diag}[50, 50]$$

Then a feedback matrix F which minimizes the criterion function J can be obtained as

$$F = \begin{bmatrix} 1.41421D+00 & 1.51552D+00 & 1.63684D-15 & -6.08743D-15 \\ -3.02248D-17 & -5.29903D-17 & 1.25911D+00 & 1.41421D-00 \\ 7.85244D-01 & 5.37344D-01 & -8.10156D-16 & -5.10330D-15 \\ -2.21958D-16 & -1.08198D-16 & 1.23093D+00 & 1.84179D+00 \end{bmatrix}$$

$$\begin{aligned} \lambda_i(A-BF);\quad [&-1.93824D-01 \pm j4.75705D+00, && -2.88929D-01 + j0.00000D+00 \\ &-3.37073D-01 + j0.00000D+00, && -6.95959D-01 + j0.00000D+00 \\ &-1.56620D+00 \pm j5.01839D+00, && -2.87235D+00 + j0.00000D+00] \end{aligned}$$

5.2 Observer Design

In this experimental system, since only distance and angles can be measured using potentiometers, an observer estimating the other states which cannot be measured, is required.

As an obsever to estimate the nonmeasurable states, in the design method, a minimal order observer is used, i.e;

$$\dot{m}(t) = \hat{A}\, m(t) + \hat{B}\, y(t) + \hat{J}\, u(t) \cdots (5-1)$$

$$\hat{x}(t) = \hat{C}\, m(t) + \hat{D}\, y(t) \cdots\cdots\cdots (5-2)$$

In the case of assigning the poles of the observer as -1000, -1000, -1000, -1000, the matrices of eq. (5–1) and (5–2) can be obtained as;

$$\hat{A} = \begin{bmatrix} -1.00000D+03 & 0.00000D+00 & 0.00000D+00 & 0.00000D+0 \\ 0.00000D+00 & -1.00000D+03 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & -1.00000D+03 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & -1.00000D+03 \end{bmatrix}$$

$$\hat{B} = \begin{bmatrix} -1.00000D+06 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & -1.00003D+06 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & -1.00002D+03 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & -1.0000D+06 \end{bmatrix}$$

$$\hat{J} = \begin{bmatrix} 1.00000D+00 & 0.00000D+00 \\ 2.22000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.82000D+00 \\ 0.00000D+00 & 1.00000D+00 \end{bmatrix}$$

$$\hat{C} = \begin{bmatrix} 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 1.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+00 \end{bmatrix}$$

$$\hat{D} = \begin{bmatrix} 1.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+00 \\ 1.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+00 \end{bmatrix}$$

Assume that eqs. (5-1) and (5-2) are discretized by sampling time 15msec. Then those equation can be expressed as the following discrete observer equation;

$$m(k+1) = \hat{A}D\ m(t) + \hat{B}D\ y(t) + \hat{J}D\ u(t) \quad \cdots\cdots\cdots\cdots \quad (5\text{-}3)$$

$$\hat{X}(t) = \hat{C}D\ m(t) + \hat{D}_D\ y(t) \quad \cdots\cdots\cdots\cdots \quad (5\text{-}4)$$

$$\hat{A}D = \begin{bmatrix} 3.05029D-07 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 3.05029D-07 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 3.05029D-07 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 3.05029D-07 \end{bmatrix}$$

$$\hat{B}D = \begin{bmatrix} -9.99999D+02 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & -1.00002D+03 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & -1.00002D+03 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & -9.99999D+02 \end{bmatrix}$$

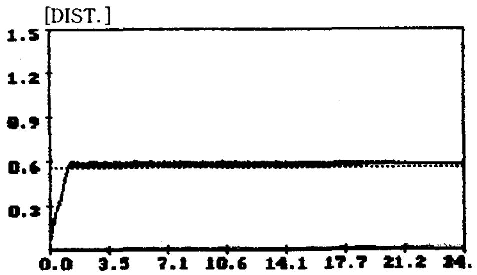
$$\hat{J}_D = \begin{bmatrix} 9.99999D-04 & 0.00000D+00 \\ 2.21999D-03 & 0.00000D+00 \\ 0.00000D+00 & 1.81999D-03 \\ 0.00000D+00 & 9.99999D-04 \end{bmatrix}$$

$$\hat{C}_D = \begin{bmatrix} 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 1.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+00 \end{bmatrix}$$

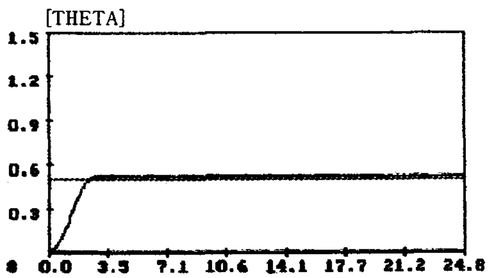
$$\hat{D}_D = \begin{bmatrix} 1.00000D+00 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+00 \\ 1.00000D+03 & 0.00000D+00 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 1.00000D+03 & 0.00000D+00 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 1.00000D+03 & 0.00000D+00 \\ 0.00000D+00 & 0.00000D+00 & 0.00000D+00 & 1.00000D+03 \end{bmatrix}$$

5.3 Experimental Results

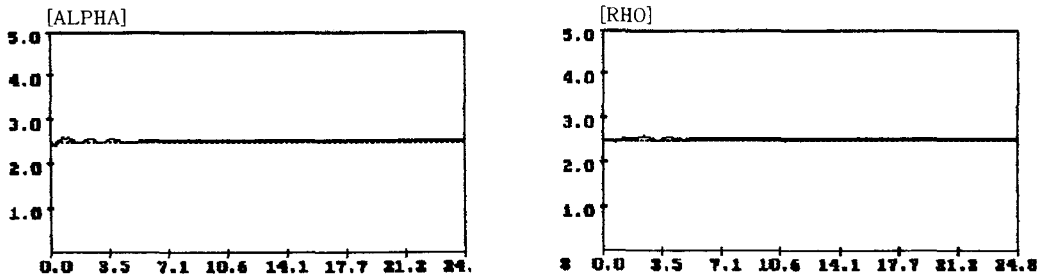
Using the optimal regulator proposed in Chapter 4 where Q and R of the Riccati differential equation are the weighting matrices, experimental results of the tower crane system depicted in Fig. 2–1 show Fig. 5–1 for step reference, and Fig. 5–2 for disturbance and step reference.



(a) Moving of Trolley

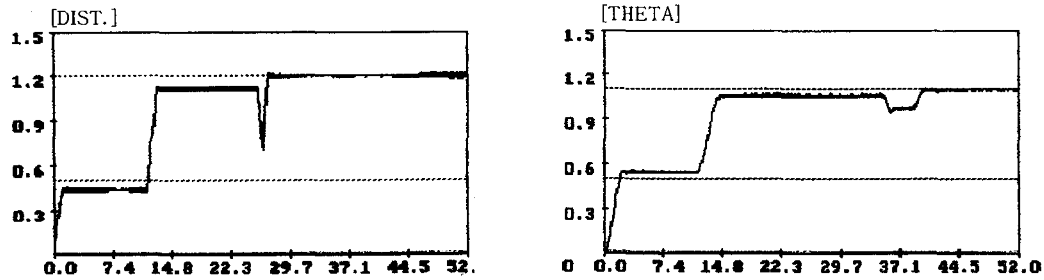


(b) Rotation of Boom

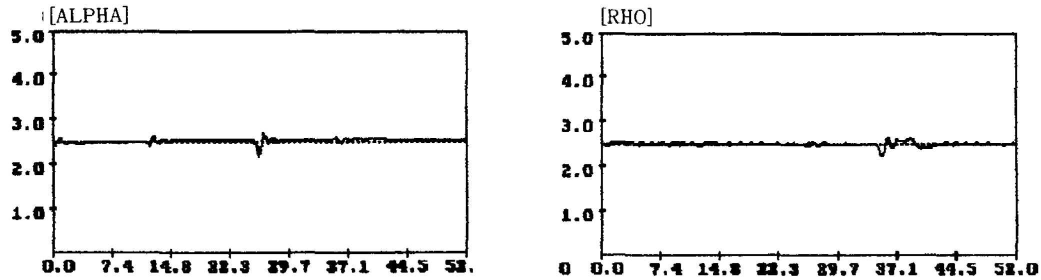


(c) Pendulum Oscillation for Moving of Trolley (d) Pendulum Oscillation for Rotation of Boom

Fig. 5—1 Experimental results for step reference



(a) Moving of Trolley (b) Rotation of Boom



(c) Pendulum Oscillation for Moving of Trolley (d) Pendulum Oscillation for Rotation of Boom

Fig. 5—2 Experimental results for disturbance and step reference

6. Conclusion

In this papers as a basic study to automize tower cranes, the dynamic model equation is theoretically induced in view of control theory and a digital control method to implement the automation is introduced.

The model equation of the tower crane is induced by using Lagrange's equation and it is linearized at equillibrium point.

The control is realized by adopting the optimal regulator method. The effectiveness is proved through the experimental results for the oscillation control of cargo rope and the position controls of trolley and boom by the implementation of digital control using 16 bits microcomputer for the designed optimal control law.

It is observed from the experimental results that the digital control method adopted in the paper is effective for control of the tower crane and it shows robustness properties to the disturbance.

Furthermore, it may be expected that the result of the paper can be contributed to automation of industrial tower cranes in the point of view the working efficiency and the guarantes of safety.

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