Proceedings of the 6th World Congress on Intelligent Control
and Automation, June 21 - 23, 2006, Dalian, China

Anti-swing Control of Overhead Cranes

Lifu Wang, Xiangdong Wang, Zhi Kong

School of Information Science and Engineering
Shenyang University of Technology
Shengyang, Liaoning Province, China

wanglifu800907@163.com

***Abstract* - In this paper a controller is designed for the overhead cranes using the recently developed parallel differential (PD) eigenevalue assignment methodology. Using this theory, classical results for LTI control design carry over to the time-varying case. The main achievement of this paper is the first implementation of a controller designed using the PD eigenevalue theory in anti-swing control of overhead cranes, and the simulation results show the validity of this method.**

Index Terms* - *anti-swing control, overhead crane, parallel differential (PD) eigenevalue, linear time vary system

I. INTRODUCTION

Overhead cranes are widely used as an efficient means of moving heavy objects in factories, warehouses, and shipping yards. The proposed control of overhead cranes requires the control precision, speed and anti-swing. Trolley's moving in the horizontal orientation is controlled directly by motor. Thus control of the speed and precision of trolley is available. However anti-swing control of overhead cranes is difficult to control. At the present, most cranes are controlled manually by skilled operators. Load swing of overhead crane is controlled based on crane operator's experience by slowing the hoisting speed of overhead cranes or waiting for damping of load swing to a certain degree. The operation not only reduces the productivity and efficiency of crane operation but also make against safety. Therefore it is valuable to research the anti-swing control of overhead cranes.

With the development of electronic control and information technology, the approaches of electronic anti-swing more and more attract notice. To control the overhead travelling crane, many approaches have been proposed. The optimal controller, self-adaptive controller and fuzzy controller of overhead crane are designed and compared based on the simplified model [1]. An anti-swing controller based on sliding-mode method for overhead crane is proposed which belongs to a kind of underactuated systems [2]. A GA-based two-stage parameter-switching fuzzy controller is presented for the long-distance transporting performance of overhead crane. In this controller, two fuzzy sub-controllers were respectively built for swing damping and position control in [3]. Recently with the development of control theory, new control schemes are applied to study of anti-swing control of overhead cranes. Reference [4] proposes minimum-time control for the anti-swing control of overhead cranes, where a model-based control scheme is designed based on the Lyapunov stability theorem. Reference [5] develops a linear time varying state equation for hoisting and lowering operations of a crane system model. Showing that bang-bang control is time optimal and the number of switching is limited, a set of new control variables, that is a set of switching times, is defined. Through parametrization of switching times, a set of fuzzy control variables are extracted and a simple iterative switching time update scheme is devised to find a set of time optimal switching times. Reference [6] studies linear time varying model of crane and proposes a varying feedback gain control method of the plant parameter characteristic. Park etc. propose input shaping control method of varying rope length [7].

A part of the preceding approaches adopt tracking input shaping method, which depends on system mathematical model or inherent frequency. While in the practical control the accurate data are difficult to be obtained. Besides the approaches usually belong to open-loop control, which is difficult to restrain disturb. Some researchers design controller and observer of overhead cranes in close-loop which avail to restrain disturb, but require accurate mathematic model and necessary linearization and a mass of calculation. To avoid limit of mathematic model, fuzzy control method is adopted with more fuzzy rules that is used to enhance the control precision. It results in the disadvantage of choosing rules and consequence in real time, further more the design of parameter completely depend on experience so that the effects are hardly guaranteed. In this paper a controller is designed for the overhead cranes using the recently developed parallel differential (PD) eigenevalue assignment methodology and can overcome partly some disadvantage of above approaches. Results show the validity of this method for the anti-swing control of overhead cranes.

II. SYSTEM MODELING

Figure 1 shows the plane model of an overhead crane and its load, In this study, the mass and stiffness of the hoisting rope are neglected and the load is considered as a point mass. Then the equations of motion of the crane system are obtained as [2]

$$x : (m+M)\ddot{x} + ml(\ddot{\theta}\cos\theta - \dot{\theta}^2\sin\theta) = u \tag{1}$$

$$\theta : \ddot{x}\cos\theta + l\ddot{\theta} + g\sin\theta = 0 \tag{2}$$

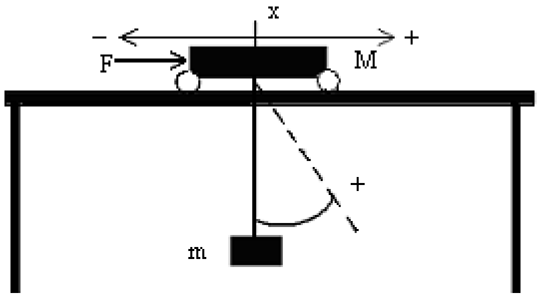

Fig. 1 Overhead crane model

where m is the load mass; M is trolley mass; x is horizontal displacement; l is hoisting rope length; θ is rope swing angle. In this paper, we assume that θ is small value and this fact denotes that $\sin\theta \approx \theta$, $\cos\theta \approx 1$, $\ddot{\theta}\cos\theta - \dot{\theta}^2 \sin\theta \approx \frac{d}{dt}\left(\dot{\theta}\cos\theta\right)$. Then the linearized dynamic equations of system are given by

$$\begin{cases} \ddot{\theta}(t) = -g\dfrac{(M+m)}{Ml}\theta(t) - \dfrac{1}{Ml}u(t) \\ \ddot{x}(t) = g\dfrac{m}{M}\theta(t) + \dfrac{1}{M}u(t) \end{cases} \tag{3}$$

Transformation equations (3) to a state-space model gives

$$\begin{bmatrix} \dot{x} \\ \ddot{x} \\ \dot{\theta} \\ \ddot{\theta} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \dfrac{mg}{M} & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\dfrac{(M+m)g}{Ml} & 0 \end{bmatrix} \begin{bmatrix} x \\ \dot{x} \\ \theta \\ \dot{\theta} \end{bmatrix} + \begin{bmatrix} 0 \\ \dfrac{1}{M} \\ 0 \\ -\dfrac{1}{Ml} \end{bmatrix} u \tag{4}$$

III. PD and SD Spectra for LTV Systems

This section will give a brief introduction to series and parallel D-spectra for linear time-varying systems. (For a detailed discussion of the topic see [8]).

Consider the nth - order differential equation

$$y^{(n)} + \alpha_n(t)y^{(n-1)} + \cdots + \alpha_2\dot{y} + \alpha_1(t)y = 0 \tag{5}$$

which can be represented as $D_\alpha(y) = 0$ using the scalar polynomial differential operator (SPDO)

$$D_\alpha = \delta^n + \alpha_n(t)\delta^{n-1} + \cdots + \alpha_2(t)\delta + \alpha_1(t) \tag{6}$$

Where $\delta = {}^{d}\!/_{dt}$ is the derivative operator. The differential algebraic spectral theory is based on the Floquet factorization of the SPDO

$$D_\alpha = [\delta - \lambda_n(t)]\cdots[\delta - \lambda_2(t)][\delta - \lambda_1(t)] \tag{7}$$

The basic composition arithmetic is as follows

$$\delta\delta(\cdot) = \delta^2(\cdot)$$

$$\lambda(t)\delta(\cdot) = \lambda(t)(\delta(\cdot))$$

$$\delta\lambda(t)(\cdot) = \delta(\lambda(t)(\cdot)) = \lambda(t)(\delta(\cdot)) + (\cdot)(\delta\lambda(t))$$

$$\lambda_i(t)\lambda_j(t)(\cdot) = \lambda_j(t)\lambda_i(t)(\cdot)$$

where $(\cdot)$ denotes the operand which is a time-dependent function. Applying these rules to a second-order system gives

$$\begin{aligned} D_\alpha &= [\delta - \lambda_2(t)][\delta - \lambda_1(t)] \\ &= \delta\delta - \delta\lambda_1(t) - \lambda_2(t)\delta + \lambda_2(t)\lambda_1(t) \\ &= \delta^2 - [\lambda_1(t)\delta + \dot{\lambda}_1(t)] - \lambda_2(t)\delta + \lambda_2(t)\lambda_1(t) \\ &= \delta^2 - [\lambda_1(t) + \lambda_2(t)]\delta + \lambda_2(t)\lambda_1(t) - \dot{\lambda}_1(t) \\ &= \delta^2 + \alpha_2(t)\delta + \alpha_1(t) \end{aligned} \tag{8}$$

$$\alpha_1(t) = \lambda_1(t)\lambda_2(t) - \dot{\lambda}_1(t) \tag{9}$$

$$\alpha_2(t) = -[\lambda_1(t) + \lambda_2(t)] \tag{10}$$

The $\lambda_i(t)$ satisfying (8) are called a series D-spectrum for D_α. It can be seen from (9) and (10) that for constant λ_i this result is exactly the same as for the conventional eigenvalue theory. However, if the eigenvalues are time-varying, one has to consider the derivative term $-\dot{\lambda}_1(t)$.

A parallel D-spectrum for D_α is a set $\gamma_\alpha = \{\rho_k(t)\}_{k=1}^{n}$ where $\rho_k(t) = \lambda_{1,k}(t)$ satisfies a factorization (8) as λ_1 and $\{y_k(t) = \exp\int\rho_k(t)dt\}_{k=1}^{n}$ constitutes a fundamental set of solutions to $D_\alpha(y) = 0$. Note that the PD-spectrum can be constructed from the SD-spectrum for the SPDO D_α. The well-known stability criterion for LTI system, which is that all eigenvalues have to be in the left half plane, can be extended to the time-varying case. Define,

$$em\{\sigma(t)\} = \lim_{T\to\infty}\sup_{t_0\geq 0}\frac{1}{T}\int_{t_0}^{t_0+T}\sigma(\tau)d\tau \tag{11}$$

A system is exponentially stable if and only if the extended mean of the real parts of the closed-loop PD eigenvalues is negative under the condition that the PD eigenvalues are bounded.

IV. PD Eigenvalue Assignment

The first step in the PD eigenvalue procedure is to transform the given state space model (4) into phase-variable canonical form. This can be done using the Silverman transformation $x = L(t)z$, which preserves stability [9]. The transformed system is given by

$$\dot{z} = (L^{-1}AL - L^{-1}\dot{L})z + L^{-1}Bu$$

Therefore,

$$A_p = L^{-1}AL - L^{-1}\dot{L}$$

$$B_p = L^{-1}B$$

Since the state-space model (4) is time-invariant, $\dot{L}=0$ and the Silverman transformation simplifies to a similarity transformation.

$$L^{-1} = \begin{bmatrix} Ml/g & 0 & Ml^2/g & 0 \\ 0 & Ml/g & 0 & Ml^2/g \\ 0 & 0 & -Ml & 0 \\ 0 & 0 & 0 & -Ml \end{bmatrix}$$

The next step is to design a state feedback for the system in phase-variable canonical form, which means that the resulting controller has to be transformed back to the original coordinate system by $K = K_p L^{-1}$.

Letting $u = K_p z$, the closed-loop A matrix to which the PD eigenvalues are assigned, is given by

$$\begin{aligned} A_c(t) &= A_p + B_p K_p(t) \\ &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 \end{bmatrix} \\ &+ \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \begin{bmatrix} k_1(t) & k_2(t) & k_3(t) & k_4(t) \end{bmatrix} \\ &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ -\beta_1(t) & -\beta_2(t) & -\beta_3(t) & -\beta_4(t) \end{bmatrix} \end{aligned} \tag{12}$$

This implies the control law

$$\begin{aligned} K_p(t) = [&-\beta_1(t)-\alpha_1 \quad -\beta_2(t)-\alpha_2 \\ &-\beta_3(t)-\alpha_3 \quad -\beta_4(t)-\alpha_4] \end{aligned}$$

where the α_i are given by the plant model (12) and the $\beta_i(t)$ can be synthesized from the desired closed-loop PD eigenvalues $\rho_i(t)$ by the following procedure [10].

$$\beta_k = \frac{\tilde{v}_{k,n+1}(t)}{\det V_n(\rho_1(t),\cdots,\rho_n(t))} \tag{13}$$

where $V_n(\rho_1,\cdots,\rho_n)$ is the canonical PD-modal matrix associated with $\{\rho_i(t)\}_{i=1}^n$ given by

$$V_n(\rho_1,\cdots,\rho_n) = \begin{bmatrix} 1 & 1 & 1 & 1 \\ D_{\rho_1}\{1\} & D_{\rho_2}\{1\} & \cdots & D_{\rho_n}\{1\} \\ \vdots & \vdots & \ddots & \vdots \\ D_{\rho_1}^{n-1}\{1\} & D_{\rho_2}^{n-1}\{1\} & \cdots & D_{\rho_n}^{n-1}\{1\} \end{bmatrix}$$

with $D_{\rho_i} = \delta + \rho_i$, and $D_{\rho_i}^k = D_{\rho_i}^{k-1} D_{\rho_i}$, and $\tilde{v}_{ij}(t)$ denotes the algebraic cofactor of v_{ij} in the $(n+1)\times(n+1)$ matrix

$$\begin{aligned} V_{n+1}(\rho_1,\cdots,\rho_n,\rho) &= [v_{ij}] \\ &= \left[\begin{array}{ccc|c} & V_n(\rho_1,\cdots,\rho_n) & & \begin{matrix} 1 \\ D_\rho\{1\} \\ \vdots \end{matrix} \\ \hline D_{\rho_1}^n\{1\} & \cdots & D_{\rho_n}^n\{1\} & D_\rho^n\{1\} \end{array}\right] \end{aligned}$$

For all PD eigenvalues we choose one time-varying scaling factor $\omega(t)$, which leads to a simpler synthesis formula for the $\beta_i(t)$, the conjugate complex PD eigenvalues can be parametrized as

$$\rho_i(t) = (-\xi \pm j\sqrt{1-\xi^2})\omega(t) = \bar{\rho}_i \omega(t)$$

where the $\bar{\rho}_i$ are the constant conjugate complex poles.
Letting:

$$\bar{\rho}_{1/2} = -0.4240 \pm j1.2630$$
$$\bar{\rho}_{3/4} = -0.6260 \pm j0.4141$$

Therefore,

$$\rho_{1/2}(t) = (-0.4240 \pm j1.2630)\omega(t)$$
$$\rho_{3/4}(t) = (-0.6260 \pm j0.4141)\omega(t)$$

Applying the extended mean criterion (11) ensures exponential stability for all positive $\omega(t)$.

Applying the synthesis formula (13) gives

$$\beta_1(t) = \bar{\rho}_1\bar{\rho}_2\bar{\rho}_3\bar{\rho}_4\omega^4(t) \tag{14}$$

$$\begin{aligned} \beta_2(t) = &-(\bar{\rho}_1\bar{\rho}_2\bar{\rho}_3 + \bar{\rho}_1\bar{\rho}_2\bar{\rho}_4 + \bar{\rho}_1\bar{\rho}_3\bar{\rho}_4 + \bar{\rho}_2\bar{\rho}_3\bar{\rho}_4)\omega^3(t) \\ &-(\bar{\rho}_1\bar{\rho}_2 + \bar{\rho}_1\bar{\rho}_3 + \bar{\rho}_1\bar{\rho}_4 + \bar{\rho}_2\bar{\rho}_3 + \bar{\rho}_2\bar{\rho}_4 \\ &+ \bar{\rho}_3\bar{\rho}_4)\omega(t)\dot{w}(t) - 15\frac{\dot{\omega}^3(t)}{\omega^3(t)} + (\bar{\rho}_1 + \bar{\rho}_2 + \bar{\rho}_3 \\ &+ \bar{\rho}_4)\ddot{\omega}(t) + 10\frac{\dot{\omega}(\mathrm{t})}{\omega^2(t)}\ddot{\omega}(t) - 3(\bar{\rho}_1 + \bar{\rho}_2 + \bar{\rho}_3 \\ &+ \bar{\rho}_4)\frac{\dot{\omega}^2(t)}{\omega(t)} - 3\frac{\omega^{(3)}(t)}{\omega(t)} \end{aligned}$$

$$\beta_3(t) = (\bar{\rho}_1\bar{\rho}_2 + \bar{\rho}_1\bar{\rho}_3 + \bar{\rho}_1\bar{\rho}_4 + \bar{\rho}_2\bar{\rho}_3 + \bar{\rho}_2\bar{\rho}_4 + \bar{\rho}_3\bar{\rho}_4)\omega^2(t) + 3(\bar{\rho}_1 + \bar{\rho}_2 + \bar{\rho}_3 + \bar{\rho}_4)\dot{\omega}(t) + 15\frac{\dot{\omega}^2(t)}{\omega^2(t)} - 4\frac{\ddot{\omega}(t)}{\omega^2(t)}$$

$$\beta_4(t) = -(\bar{\rho}_1 + \bar{\rho}_2 + \bar{\rho}_3 + \bar{\rho}_4)\omega(t) - 6\frac{\dot{\omega}(t)}{\omega(t)}$$

Again, choosing the PD eigenvalues to be constant, e.g., $\omega(t) \equiv 1rad/s$ gives the same result as using the conventional eigenvalue assignment approach.

V. Simulation Results

In this section we choose parameters of the crane system as paper [11], that is, $M = 1kg$, $m = 0.8kg$, $l = 0.305m$. The initial condition is $X_0 = (0 \quad 0 \quad 0 \quad 0)$, desired value is $x^d = 2m$, $\dot{x}^d = 0$, $\theta^d = 0$, $\dot{\theta}^d = 0$, where x^d and $\dot{x}^d$ are desired displacement and speed, respectively; θ^d and $\dot{\theta}^d$ are desired swing angle and angular velocity, respectively. The desired results require system reach the target position ($x^d = 2m$) from the static initial point, and achieve anti-swing(both swing angle and angular velocity equal zero).

Letting

$$\omega_1(t) = \begin{cases} 0.4 & 0 \le t < 0.4 \\ 1.063 + 0.5\sin(t - 0.4) & 0.4 \le t < 0.4 + \pi/2 \\ 1.5 & \text{t} \ge 0.4 + \pi/2 \end{cases}$$

$$\omega_2(t) = \begin{cases} 1 & 0 \le t < 0.7 \\ 1.5 + 0.5\sin[8(t - 0.7) - \pi/2] & 0.7 \le t < 0.7 + \pi/16 \\ 1.5 & \text{t} \ge 0.7 + \pi/16 \end{cases}$$

Figure 2,5 show the trolley horizontal displacement profile; Figure 3,6 show the load swing angle profile; Figure 4,7 show controlling force profile of the crane.

From figures, we can see, the value of $\omega(t)$ is crucial for the system performance. In some extent, the smaller $\omega(t)$ is, the faster system respond, but the swing angle is a little larger; oppositely, the larger $\omega(t)$ is, the more slowly system respond and the load has smaller swing. Therefore, $\omega(t)$ is the crucial factor for the system performance.

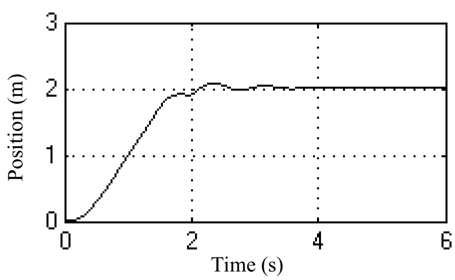

Fig. 2 At $\omega(t) = \omega_1(t)$ trolley displacement

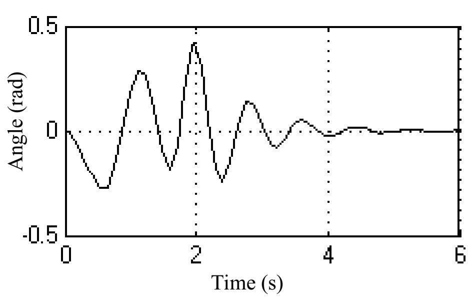

Fig. 3 At $\omega(t) = \omega_1(t)$ load swing angle

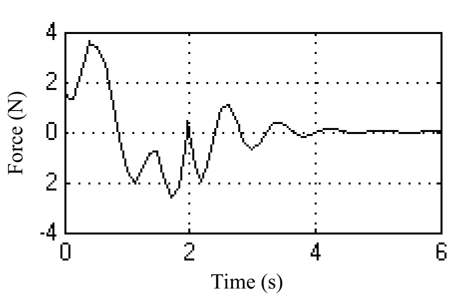

Fig. 4 At $\omega(t) = \omega_1(t)$ controlling force

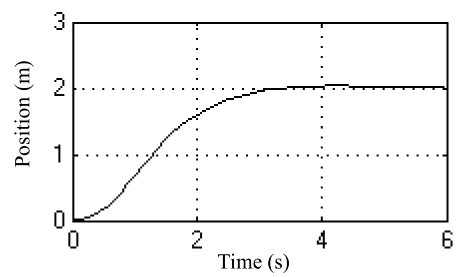

Fig. 5 At $\omega(t) = \omega_2(t)$ trolley displacement

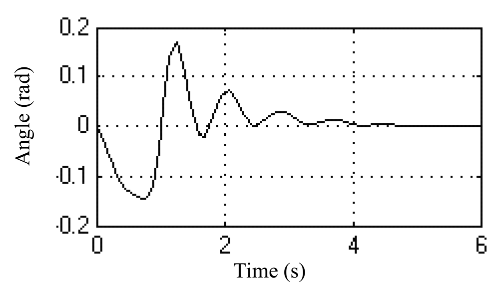

Fig. 6 At $\omega(t) = \omega_2(t)$ load swing angle

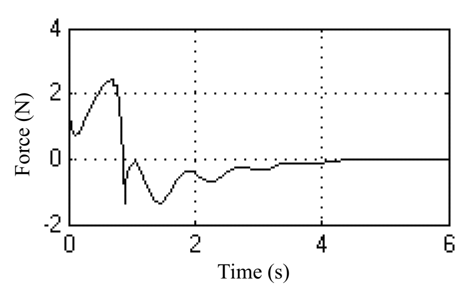

Fig. 7 At $\omega(t) = \omega_2(t)$ controlling force

When

$$\omega_3(t) = \begin{cases} 1.64 + 0.4\sin(t - \pi/2) & 0 \le t < \pi/2 \\ 1.5 & t \ge \pi/2 \end{cases}$$

Figures 8,9,10 show trolley horizontal displacement profile, the load swing angle profile, controlling force profile of the crane, respectively. It can been seen that using PD eigenevalue assignment methodology trolley can quickly reach the desired value while the load swing and the controlling force of overhead crane obviously is reduced by contrast with sliding-mode method [2]. Results also show the validity of this method for the anti-swing control of overhead cranes.

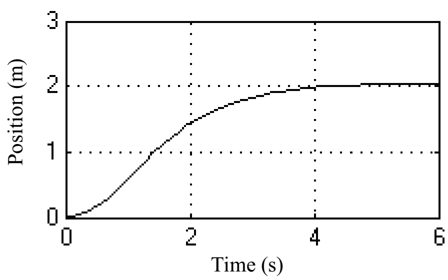

Fig. 8 At $\omega(t) = \omega_8(t)$ trolley displacement

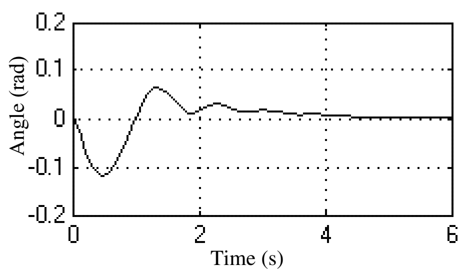

Fig. 9 At $\omega(t) = \omega_3(t)$ load swing angle

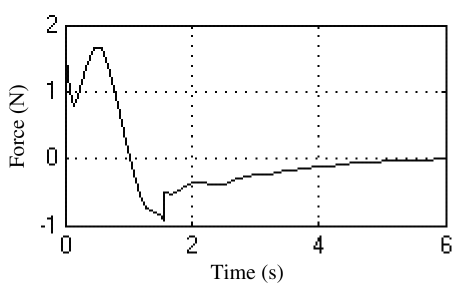

Fig. 10 At $\omega(t) = \omega_3(t)$ controlling force

VI. CONCLUSION

The results have shown that the proposed control guarantees both accurate position control and prompt damping of load swing for the overhead crane. This paper also shows that PD eigenvalue assignment actually works in reality. Once the β_i from (14) are implemented, e.g., as a block diagram in Simulink, adjusting the $\omega(t)$ become easy. Moreover, the block diagram can be used for any fourth order system, only the A matrix has to be changed. Topics for future research would be to change the $\omega(t)$ online depending on certain parameters or on the input to the system. Once $\omega(t)$ is adjusted properly, the control result is perfect. Therefore the proposed control has advantage for high performance anti-swing control of industrial overhead cranes.

REFERENCES

[1] HUA Keqian, Anti-swing fuzzy control of overhead crane, Journal of Civil Aviation University of China, Vol.18, No.3, 2000.6.

[2] WANG Wei, YI Jianqian,etc. Anti-swing control of overhead cranes based on sliding-mode method, Control and Decision, Vol.19, No.9, 2004.9

[3] LIU Diantong, YI Jianqian, Two- stage fuzzy control for long- distance transportation of overhead crane. Control Theory and Application, Vol. 20, No.6, 2003.12.

[4] Ho-Hoon Lee, Seung-Gap Choi. A model-based anti-swing control of overhead cranes with high hoisting speeds [A]. Proc of the 2001 IEEE Int conf on Roboctic & Automation[C]. Seoul, 2001. 2547-2552

[5] Myung S Moon, Hugh F VanLandingham, Yvan J Beliveau. Fuzzy time optional control of crane load [A]. Proc of the 35th Conf of Decision and Control[C]

[6] Giorgio Corriga,Alessandro Giampaolo Usai.An implicit gain-scheduling controller for cranes[J].IEEE Trans on Control Systems Technology, 1998,6(1):15-20

[7] PARK B, HONG K, HUH C. Time- efficient input shaping control of container crane systems [A]. Proc of the 2000 IEEE Int Conf on Control Application [C]. Anchorage, Alaska: IEEE Service Centre, IEEE Control System Society, 2000:80 – 85

[8] J.J.Zhu. Well Defined Series and Parallel D-spectra For Linear Time-Varying Systems, Proceedings, American Control Conference, Baltimore, MD, pp. 734-738, June 1994

[9] L. M. Silverman, Transformation of time-variable systems to canonical (phase-variable) form, *IEEE Transactions on Automatic Control,* vol. 11, pp. 300-303, 1966

[10] J.J.Zhu. Nonlinear Tracking and Decoupling by Trajectory Linearization. June 1998

[11] Yong-Seok Kim,Ham-Suk Seo,Seung-Ki Sul.A new anti-sway control scheme for trolley crane system[A].Conf Rec IEEE-IAS Annu Meeting [C].Chicago,2001.548-552.