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Container Crane Control using Sliding Mode Control

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***Abstract* - The path control of a moving object with strict specifications is not an easy task.Control of container crane sway angle using sliding mode controller is discussed in this paper. A sliding surface is designed so that it reduces the sway angle of the payload associated with the container. An adaptation law controller gain is varied to transform system to sliding mode. Sliding mode control performance is checked with conventional PID control.**

Keywords-sliding mode control, container crane, PID control, sway angle, trolley position.

I.INTRODUCTION

The non linear dynamic models of the onshore container crane system are developed in this paper based on various assumptions. The different types of models developed are a) Two dimensional non linear model with constant rope length (horizontal transportation stage) b) wind load model.

The container crane is highly vulnerable to wind, as it is located in seaports. The wind has two impacts on the container crane system – on its structure stability and on its payload. The structural stability of the container crane system is not in the scope of this project.

Fig .1 : Container Cranes at International Container Transhipment Terminal (ICTT), Vallarpadam, Kochi, Kerala, India [2]

In [3], the input shaping technique is used to reduce the swing of the payload . For applying this method we need to know natural frequency and damping ratio. It is very difficult.

Another method is to use open-loop optimal controller to generate ideal trajectories for the container trolley. In [5] to regulate the trolley to a desired position while reducing the pendulation of the payload a series of energy-based controllers are used.Another method utilizes fuzzy logic for reducing the sway angle as in [7]. Unfortunately, fuzzy sets and corresponding fuzzy rules are very difficult for tuning for a crane system.

Section II deals with the mathematical modeling of container crane system.Section III and IV deals with the open loop responsesand closed responses using PID controller.Section V deals with Sliding Mode Controller and then finally the Conclusion.

II. MATHEMATICAL FORMULATION

The non linear dynamic model of the onshore container crane system is developed in this section.Consider the container crane model illustrated in Fig.2.

Let
x- Trolley position along the X –axis from the reference (m)
θ - Angular swing of the payload (rad)
g - Gravitational acceleration (m/s^2)
m_t -mass of the trolley (kg)
m_p- mass of the payload (kg)
f_x - control force applied to the trolley (N)
l - length of the rope (m)

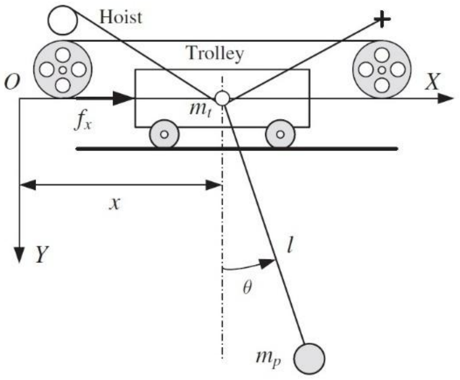

Fig. 2 Trolley-Pendulum Model of Container Crane [9].

The following are the modeling assumptions:

1.In an actual crane, we use four ropes to hoist the spreader
(including the payload). But , for simplicity, only one rope is assumed here.

2.It is also assumed that the the spreader and the rope move . in the vertical plane, that is, the X –Y -plane

3.Payload is considered as point mass.
4.Rope is assumed to be mass-less, rigid.
5.During the overall transferring process, payload is beneath
the trolley.
6.All frictional elements in trolley are ignored.
7.Air resistance is ignored.
8.External disturbances like wind are neglected.

When we consider the motions of the trolley and the payload in the two-dimensional (2D) plane, the co-ordinates of the payload (x_p , y_p) is given by

$$x_p = x + l\sin\theta,\ y_p = -l\cos\theta \tag{2.1}$$

The kinetic energy T of the entire system is given by

$$T = \frac{1}{2}m_t\dot{x}^2 + \frac{1}{2}m_p v_p^2 \tag{2.2}$$

where $v_p$is the velocity of the payload,

$$v_p^2 = \dot{x}_p^2 + \dot{y}_p^2 \tag{2.3}$$

Substituting (2.3) in (2.2), we have

$$T = \frac{1}{2}m_t\dot{x}^2 + \frac{1}{2}m_p\left[\left(\dot{x} + l\dot{\theta}\cos\theta\right)^2 + \left(l\dot{\theta}\sin\theta\right)^2\right]$$

$$T = \frac{1}{2}\left(m_t + m_p\right)\dot{x}^2 + \frac{1}{2}m_p l^2\dot{\theta}^2 + m_p\dot{x}\dot{\theta}\, l\cos\theta \tag{2.4}$$

The potential energy U of the entire system is given by

$$U = m_p g l(1 - \cos\theta) \tag{2.5}$$

Taking $\boldsymbol{q} = (x,\theta)$ as the generalized coordinates corresponding to the generalized forces $\boldsymbol{f} = (f_x,\ 0)$, and using Lagrange's equation

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \frac{\partial T}{\partial q_i} + \frac{\partial U}{\partial q_i} = f_i,\ i=1,2 \tag{2.6}$$

The equations of motion can be obtained as

$$\left(m_t + m_p\right)\ddot{x} + m_p l\ddot{\theta}\cos\theta - m_p l\dot{\theta}^2\sin\theta = f_x$$

$$\ddot{x}\cos\theta + l\ddot{\theta} + g\sin\theta = 0 \tag{2.7}$$

The equations can be written in the matrix form as

$$\begin{bmatrix} m_t + m_p & m_p\ l\ cos\theta \\ m_p\ cos\theta & m_p\ l \end{bmatrix}\begin{bmatrix}\ddot{x} \\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix} m_p\ l\ \dot{\theta}^2\ sin\theta + f_x \\ -m_p\ g\ sin\theta \end{bmatrix} \tag{2.8}$$

Inverting the matrix on the left hand side to get $\ddot{x}$ and $\ddot{\theta}$,

$$\begin{bmatrix}\ddot{x} \\ \ddot{\theta}\end{bmatrix} = \begin{bmatrix} \dfrac{m_p\ l\ \dot{\theta}^2\ sin\theta\ +\ m_p\ g\ sin\theta\ cos\theta\ + f_x}{m_t + m_p sin^2\theta} \\ -\dfrac{(m_t+m_p)\ g\ sin\theta\ +\ m_p\ l\ \dot{\theta}^2\ sin\theta\ cos\theta\ + f_x\ cos\theta}{l\ (m_t + m_p sin^2\theta\ )} \end{bmatrix} \tag{2.9}$$

The state variables of the 2 dimensional constant rope length container crane systemare given asX $=\left[x, \dot{x}, \theta, \dot{\theta}\right]T$. The output variables are given by y = $[x, \theta]T$

Let

x_1= x (Horizontal displacement of trolley from the reference in m)

x_2= $\dot{x}$(Velocity of the trolley in m/s)

x_3= θ (Angular swing of the payload in rad)

x_4= $\dot{\theta}$ (Angular velocity of the payload in rad/sec)

$u = f_x$ (Control force applied to the trolley in N)

The nonlinear model can be represented as follows:-

$$\dot{x}_1 = x_2$$

$$\dot{x}_2 = \frac{m_p\ l\ {x_4}^2\ sinx_3\ +\ m_p\ g\ sinx_3\ cosx_3}{m_t\ +\ m_p sin^2 x_3} + \frac{1}{m_t\ +\ m_p sin^2 x_3}\ u$$

$$\dot{x}_3 = x_4$$

$$\dot{x}_4 = \frac{(m_t+m_p)\ g\ sin\, x_3\ +\ m_p\ l\ {x_4}^2\ sin\, x_3\ cos\, x_3}{l\ (m_t + m_p sin^2 x_3\ )} - \frac{cos\, x_3}{l\ (m_t + m_p sin^2 x_3\ )}\ u \tag{2.10}$$

The state space model is obtained as

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & \dfrac{m_p}{m_t} g & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & -\dfrac{m_t + m_p}{m_t\, l} g & 0 \end{bmatrix} \quad B = \begin{bmatrix} 0 \\ \dfrac{1}{m_t} \\ 0 \\ \dfrac{-1}{m_t\, l} \end{bmatrix}$$

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

III. OPEN LOOP RESPONSE

The unit step response of the open loop 2D 2DOF model of the container crane system is obtained in this section The parameters used in the analysis are given in Table 1.

Parameter	**Value**	**Unit**
m_t (mass of the trolley)	1000	Kg
m_p (mass of the payload)	100	Kg
g(gravitational acceleration)	9.81	m/s^2
l (length of the rope)	1	M

Table 1. Parameter values used for analysis of open loop 2D 2DOF model

This section deals with the impact of wind on the payload of the container crane as shown in Fig.3, causing it to sway along a horizontal axis.

Fig 3. Wind Force on the Payload of Container Crane

According to the Indian standard IS0 4302 : 1981 Cranes -Wind Load Assessment [11], the wind load on any crane structure is given by

$$F_w = C_f A\, p_z \tag{2.11}$$

where A is the effective frontal area of the part under consideration, in square metres, i.e. the solid area projection on to a plane perpendicular to the wind direction, p_z is the wind pressure correspondingto appropriate design condition in kilonewtons per square metre, C_f is the force coefficient in the direction of the wind, for the payload structure.

$$p_z = .6\times V_z^2 \tag{2.12}$$

where$V_z$is the design wind speed in m/s at any height z.

$$V_z = V_b \times K_1 \times K_2 \times K_3 \tag{2.13}$$

where V_b is the basic wind speed obtained from the wind speed map of india, K_1 is the probability factor or risk co-efficient decided by the mean probable design life of structure in years and on the regional basic wind speed (its value is 1.0 for a design life of 50 years), $K_2$is the factor decided by the terrain, height and size of the structure (its value is 1.05 for a Category-1 (open area/treeless plains) terrain and Class A (structure dimension less than 20m) structure size), $K_3$is the topography factor.

The open loop response of the container crane model for both with and without wind disturbance is shown in figure.4.

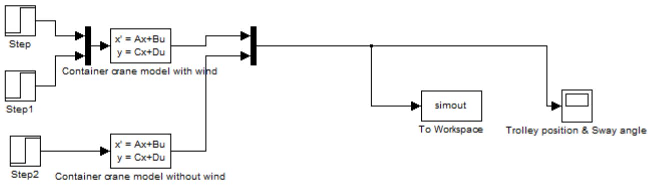

Fig 4. Simulink model of a container crane for open loop response comparison (with and without wind disturbance)

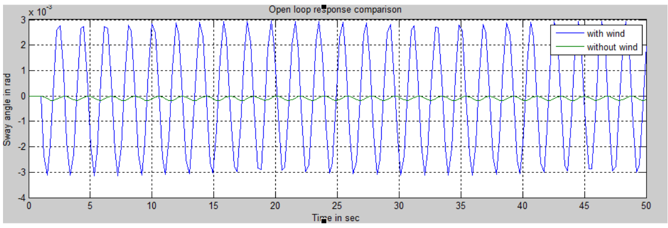

Fig 5. Open loop responses of the system with and without wind disturbance

As seen from the fig. 5, the open loop system is not stable - the swing angle exhibits an oscillatory behavior (undamped oscillations due to the vibratory motion of the payload caused by the trolley movement).In case of wind disturbance,the magnitude of oscillations is very high compared to the other case.

IV. CLOSED LOOP RESPONSE USING PID CONTROLLER

Using PID controller the step response we obtained by considering no wind disturbance is shown in fig.6.where the pid controller parameters are given by $K_p = -129944.933170473$, $K_I = -38781.80470079$, $K_D = -39709.606361$

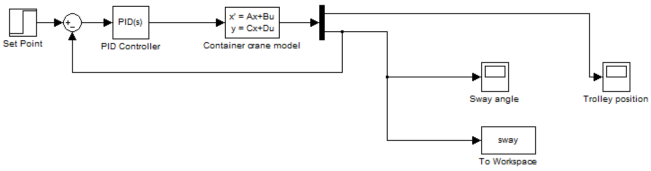

Fig 6. Simulink model of the system with PID controller (without disturbance)

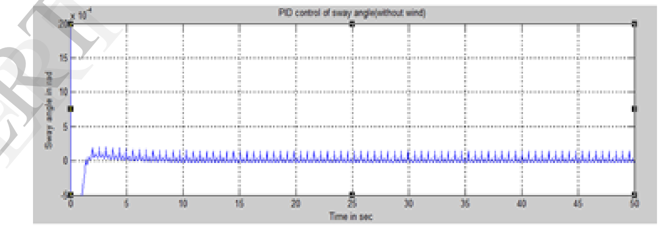

Fig 7. Closed loop response using PID controller (without wind disturbance)

When wind is considered the step response is shown in fig.9 Where $K_p = -129944.933170473$, K_I=-38781.80470079, K_D=-39709.6063617319

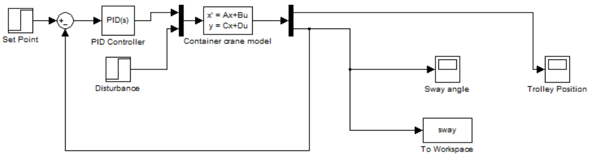

Fig 8. Simulink model of the system with PID controller (with disturbance)

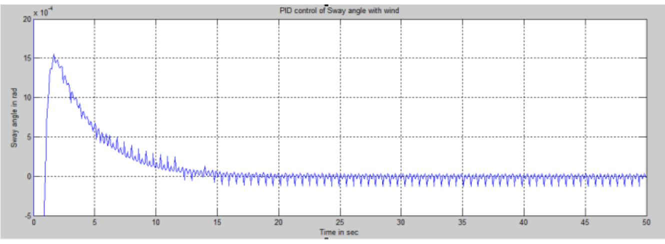

Fig 9. Closed loop response using PID controller (with wind disturbance)

V. SLIDING MODE CONTROLLER (SMC)

To reduce the effect of external disturbance and to ensure robust control, we are introducing SMC. In SMC two modes are there.One is reaching mode and the other is sliding mode.Firstly it forces the system state to reach the hyperplane and keeps them sliding on the hyperplane.So we have to design a hyperplane and a controller.Hyperplane is designed through pole placement technique as in state space approach.Controller design is done based on sliding condition.

Sliding surface is given by the given equation,

$$s = G1 * e1 + G2 * e2 + G3 * e3 + G4 * e4$$

Where G1,G2,G3,G4 are controller gains and e1,e2,e3,e4 are error variables.

Using SMC the response we obtained by considering no wind disturbance is in fig.10

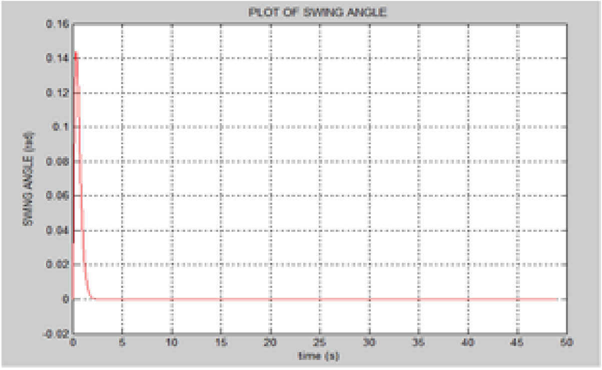

Fig. 10. Sway angle response using SMC (without wind disturbance)

Then the control input for the above case is given in fig.11

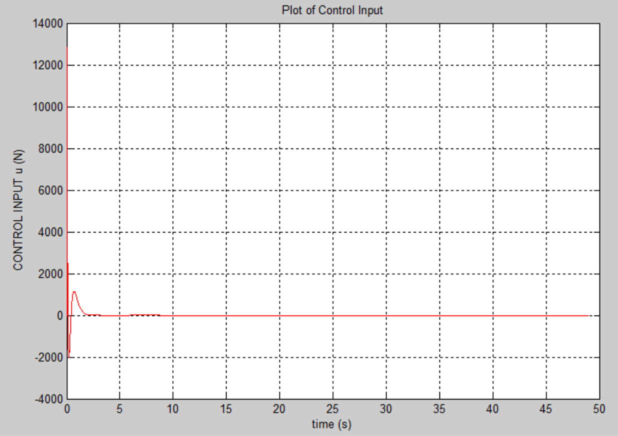

Fig. 11. Control input (without wind disturbance)

With wind disturbance the sway angle response is in fig. 12.

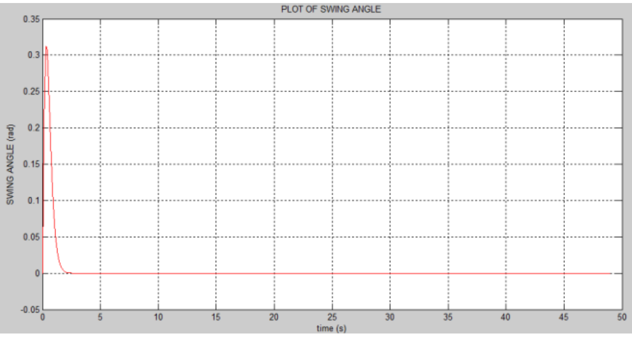

Fig.12.Sway angle response using SMC (with wind disturbance)

Then the control input is given in fig.13.

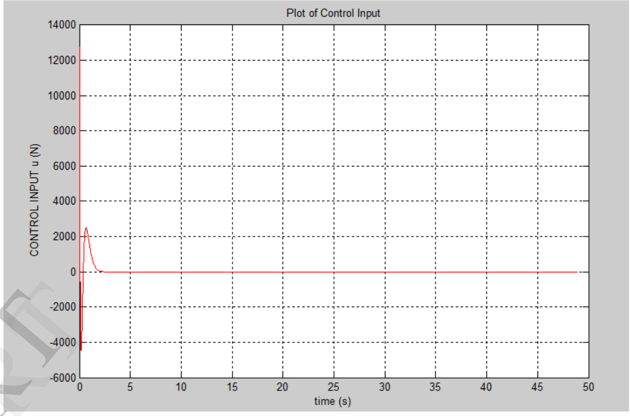

Fig. 13. Control input (with wind disturbance)

VI. COMPARISON

Characteristic parameters	PID		SMC	
	Without disturbance	With disturbance	Without disturbance	With disturbance
peakvalue	0.0002	0.00155	0.14	0.32
Settling time	15sec	20sec	3sec	4sec
oscillations	yes	yes	no	No

VII. CONCLUSION

From the above sections we can conclude that SMC is better than a PID controller for controlling swing angle of a container crane. A PID controller reduces the magnitude of oscliiations in sway angle output .But there will be small oscillations persist. In off shore ports always there will be wind disturbances.SMC provide better performance without wind disturbance as well as with wind disturbance.In this paper we have considered the 2DOF model.We can extend the model to 3DOF with variable rope length.

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