IOSR Journal of Electrical and Electronics Engineering (IOSR-JEEE)
e-ISSN: 2278-1676,p-ISSN: 2320-3331, Volume 11, Issue 2 Ver. III (Mar. – Apr. 2016), PP 28-34
www.iosrjournals.org

Output Based Input Shaping for Sway Control of a 3D Crane System

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Abstract*: this paper presents an output-based input shaping and a proportional integral derivative (PID) for load hoisting control of a 3D crane. Unlike conventional input shaping in which model parameters are used for designing the filter, output-based filter is designed using the signal output of the target system thus, problem of model uncertainties are avoided. Simulation results show that, precise payload positioning with negligible sway is achieved. The proposed hybrid control is robust and can easily be implemented on higher order system.*

Keywords*: 3D crane; PID, Hoisting, sway, output-based filter, conventional input shaping.*

I. Introduction

The current trend of achievements in the modern world would have been practically impossible without the use of Cranes. They are also known as Bridge or Overhead Cranes [1]. These are machines used for lifting and transferring heavy loads from one point to another. The faster the load is moved the lower will be the time it takes to reach the final desired destination [1]. But moving the load very fast will result in an unwanted sway in its final destination. The sway can be a threat to safety, and therefore minimization of this undesirable sway as well as the fast movement of the load for better system performance are of paramount importance. Gantry Cranes have been used in a wide range of applications including but not limited to Constructions, Transportation, Materials handling as well as cargo management [2].

Various techniques have been used in solving this problem, some of which are presented in this paper. Input shaping technique has been used in [3]–[8]. Akbar Assa et. al [1] have developed a four step design procedure for an improved fuzzy crane control. M.A Ahmad et. al [9], have conducted a comparison of active sway control of Gantry crane system using PD Controller and Delayed feedback signal (DFS). Mahmud Iwan Solihin et. al [10], have used kharitonov's stability to perform robust PID anti-swing control of an automatic Gantry crane. M.A Ahmad et. al [4], have proposed a comparative assessment of PD and PD –type fuzzy logic controller in sway control of Gantry crane system. Ayadin Yesildirek has proposed an intelligent control of gantry cranes using artificial neural network technique [2]. M.A Ahmad et.al [6], have proposed an anti-sway control of Gantry Crane using sliding mode control (SMC) and Delayed feedback signal (DFS) techniques. Yang Xia et. al [11], have conducted a research on the control of a suspension stiffness for the beams in Gantry machining centre. Ivan Burul et. al [12], have used h–infinity (H_∞) Control Theory on Gantry crane system to solve the sway problem, a better result was presented as compared to pole placement technique. M.A Ahmad et.al performed an experimental investigations of low pass filter techniques for sway control of a Gantry crane system [13], the result revealed that the higher the number of order of the low pass filter the better t the sway reduction. M.A Ahmad, Z. Zulkifely and M.A Zawawi have conducted an experimental investigations of input shaping schemes for sway control of Gantry crane system [6], the result shows that the higher the number of impulses the higher the sway level reduction. M.A Ahmad et.al [14], have investigated a feedforward technique for anti-sway control of 3-D Crane system, the result revealed acceptable anti-sway capability. Masood Askari et.al [15], have used model predictive control technique on Gantry crane system. Chuxiong Hu et. al [16], have used adaptive robust contouring controller in designing an industrial biaxial precision on Gantry crane system. Ning Sun and Yongchun Fang [17], have developed a new anty swing control method for under-actuated cranes with un modelled uncertainties. Yang Junqing and Sui Meie [18], have proposed an automatic identification system of real-time gantry crane (RTG) in container terminal. Z. khu, K liu et at [19], have presented an output based input shaping for suppressing residual vibrations. J. Han, Z. khu, Y He et at [20], have also proposed output based filter for residual vibration control and also compared with the conventional input shaping filter.

Unlike conventional input shaping, output based input shaping has a lots of advantages among which are, it is robust to changes in payload, the overall speed response of the system can be increase, the problem of parameters uncertainties are avoided.

II. Model Description

3D crane system is an industrial machine which is normally used to transport loads from one place to another in construction industries, nuclear plant, house wire, seaport, heavy machine installations, etc. In this paper, two degrees of freedom (2D) motion is considered. The main components of the system hardware are: a cart, a rail and a pendulum as shown in Figure 1.

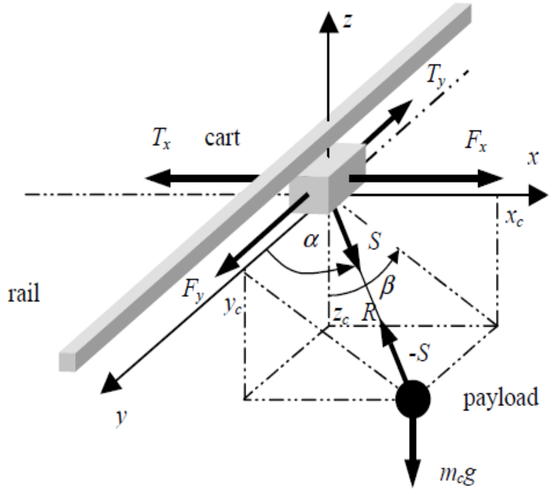

Figure 1: system description

With XYZ as the coordinates of the system, α is the angle of lift-line with Y axis and β is the angle between the negative part of Z axis and the projection of the payload cable onto the XZ plane. T is a reaction force in the payload cable acting on the trolley, Fx and Fy are the forces driving the rail and trolley respectively, Fz is a force lifting the payload and fx, fy and fz are corresponding frictional forces. These are defined as:

$$\mu_1 = \frac{m_p}{m_t}, \mu_2 = \frac{m_p}{m_t + m_r}$$

$$u_1 = \frac{F_x}{m_t}, u_2 = \frac{F_y}{m_t + m_r}, u_3 = \frac{F_z}{m_p}$$

$$f_1 = \frac{f_x}{m_t}, f_2 = \frac{f_y}{m_t + m_r}, f_3 = \frac{f_z}{m_p}$$

$$K_1 = u_1 - f_1, K_2 = u_2 - f_2, K_3 = u_3 - f_3$$

In which; m_p, m_t and m_r are the payload mass, trolley mass and moving rail respectively. l is the length of the lift-line. The dynamic equations of motion of the crane can be obtained as [15].

$$\ddot{x}_t = K_2 + \mu_2 K_3 \sin\alpha \sin\beta \tag{1}$$

$$\ddot{y}_t = K_1 + \mu_1 K_3 \cos\alpha \tag{2}$$

$$\begin{aligned} \ddot{x}_p &= \ddot{x}_t + (\ddot{l} - l\dot{\alpha}^2 - l\dot{\beta}^2)\sin\alpha\sin\beta + 2l\dot{\alpha}\dot{\beta}\cos\alpha\, \\ &+ (2\dot{l}\dot{\alpha} + l\ddot{\alpha})\cos\alpha\sin\beta + (2\dot{l}\dot{\beta} + l\ddot{\beta})\sin\alpha\cos\beta \end{aligned} \tag{3}$$

$$\ddot{y}_p = \ddot{y}_t + (\ddot{l} - l\dot{\alpha}^2)\cos\alpha - (2\dot{l}\dot{\alpha} + l\ddot{\alpha})\sin\alpha \tag{4}$$

$$\begin{aligned} \ddot{z}_p &= (-\ddot{l} + l\dot{\alpha}^2 + l\dot{\beta}^2)\sin\alpha\cos\beta + 2l\dot{\alpha}\dot{\beta}\cos \\ &-(2\dot{l}\dot{\alpha} + l\ddot{\alpha})\cos\alpha\cos\beta + (2\dot{l}\dot{\beta} + l\ddot{\beta})\sin\alpha\sin \end{aligned} \tag{5}$$

Where, x_p, y_p and z_p are position of payload in *X*, *Y* and *Z* axes respectively. x_t and y_t are positions of trolley in *X* and *Y* axes respectively. The Dots are the derivative of the respective quantities.
The parameters of the system are shown in Table 1.

Table 1. System parameter

Variables	**Values**
Mass of payload, m_p	1 kg
Mass of trolley, m_t	1.155 kg
Mass of moving rail, m_r	2.2 kg
Cable length, *l*	0.72 m
Gravitational constant, *g*	9.8 m/s^2
Corresponding friction forces, f_x, f_y, f_z	100, 82, 75 Ns/m

III. Logarithmic Decrement

For the simplicity of design, logarithmic decrement techniques as in [21], [22], is used to determine the damping ratio and natural frequency of the system, so as to reduce the order of the system. This technique can be explain using an under damped system as shown in Figure 2. And these parameters are determined using the following relations;

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}}\ ; \qquad \omega = \frac{\delta}{\zeta\lambda} \tag{6}$$

Where

$$\delta = \ln\left(\frac{y_1}{y_2}\right) \quad \text{and} \quad \lambda = t2 - t1 \tag{7}$$

IV. Output Based Input Shaping

In this technique, the filter is design using the signal output of the target system, reference system is designed based on the dynamic response of the system then Filter gains are obtained using MATLAB program.

1. Basic principle

To explain the basic principles of this technique, a second order system is considered as in [19].

$$G(s) = \frac{Kw_n^2}{s^2 + 2\xi w_n s + w_n^2} \tag{8}$$

Let the reference system be design as follows;

$$M(s) = \frac{k_m w_m^2}{s^2 + 2\xi_m w_m s + w_m^2} \tag{9}$$

If the filter is designed as;

$$F_{O(S)} = \frac{k_m w_m^2 s^2 + 2\xi w_n s + w_n^2}{Kw_n^2 s^2 + 2\xi_m w_m s + w_m^2} \tag{10}$$

Hence, the product of $G(s)$ *and* $F_0(s)$ will gives $M(s)$ thus adequate static gain, damping ratio and bandwidth can be achieved by choosing k_m, ξ_m, w_m respectively.
Thus;

$$F(s) = \frac{s^2 a_2 + a_1 s + a_0}{s^2 + 2\xi_m w_m s + w_m^2} \tag{11}$$

The aim is to obtain the values of a_o, a_1, a_2 so that zeros of $F(s)$ will cancel the poles of $G(s)$, as $F(s) = F_0(s)$ and poles of $G(s)$ are identical.

2. Designing output-based filter

The filter is designed by first designing the reference system, in which a critically damped system is normally considered, which can be realized as;

$$G_r(s) = \frac{w^2{}_c}{(s+w_c)^2} \tag{12}$$

Where w_c is the bandwidth of the system, and is selected based on the time response of the system.

This system has little or zero vibration. The cost function is used to minimize the difference between the output of the reference system and that of the target system [19], [20].

Thus;

$$E(s) = w(t)\int_0^T (\ \mathrm{y}(\mathrm{t}) - y_r(t) \ ) d_t \tag{13}$$

Where $w(t)$ is the weighting factor, $y(t)$ is the output of the target system, and $y_r(t)$ is the output of the reference system.

Thus;

$$E(a_{1,} a_2, ...a_n) = \int_0^T \ w(t) \ ((\sum_{i=0}^{m} a_i y_i(t)) - \ y_r(t))^2 \tag{14}$$

In which;

$$a_1 \, a_2 \, ...a_n \text{ are the filter gains and } a_0 = w_c{}^2$$

To achieve the minimum value of E, the derivative of (14) is set to zero as;

$$\frac{\delta E}{\delta a_k} = 0, k = 1,2,3..m \tag{15}$$

And

$$\int_0^T w(t) y_k(t) \ ((\sum_{i=0}^{m} a_i y_i(t)) - \ y_r(t)) dt = 0 \tag{16}$$

Thus, it is further simplifying as;

$$S_{\alpha,\beta} = \int_0^T w(t) y_\alpha(t) y_\beta(t) \tag{17}$$

Where

$$\alpha = 0,1,2,3...m$$
$$\beta = 0,1,2,3,...m$$

And

$$S_{\alpha,r} = \int_0^T w(t) y_\alpha(t) y_r(t) \tag{18}$$

In which

$$\alpha = 0,1,2,3...m$$

Simplifying (16), (17) and (18) yield;

$$\sum_{i=0}^{m} a_k S_{k,i} - \ S_{k,r} = 0 \tag{19}$$

Where

$$K = 0,1,2,3....m$$

In this paper, the gantry crane is reduced to second order for simplicity of design. Reference system was designed by selecting $w_c = 2$, it is selected based on the response time of the gantry crane.

Thus;

$$G_r(s) = \frac{4}{s^2 + 4s + 4} \qquad (20)$$

Hence, software (which software) was used to calculate the filter gains in the following forms;

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} S_{11} & S_{12} \\ S_{21} & S_{22} \end{bmatrix} \begin{bmatrix} S_{1r} \\ S_{2r} \end{bmatrix} \qquad (21)$$

Therefore, the gains are obtained as;

$$a_0 = 4, a_1 = 0.0144, and\ a_2 = 0.1916$$

Hence, simplifying in (11), the filter was obtained as;

$$F(s) = \frac{0.1916s^2 + 0.0144s + 4}{s^2 + 4s + 4} \qquad (22)$$

V. Result And Discussion

In this section, results and hybrid control actions are discussed. The Second order system is obtained from the nonlinear model of the gantry crane system, using logarithmic decrement. An output-based filter was designed using the output signal of the system to suppress payload sways. The filter was then incorporated with PID for precise positioning of payload. The filter and PID gains were obtained as $a_0 = 4, a_1 = 0.0144, a_2 = 0.1916$ and $p = 2, I = 2.5, D = 0.5$ respectively. This hybrid control was simulated, and sways in both x and y direction was suppressed as in Figure 3 and Figure 4. In addition, the precise payload position was achieved as shown in Figure 5 and Figure 6. Using the time response analyses, the trolley and rail position has a settling time of 2.3sec; overshoot 0, rise time 1.8 sec. Hence, simulation results show that an output-based filter is one of the best techniques in controlling residual vibrations.

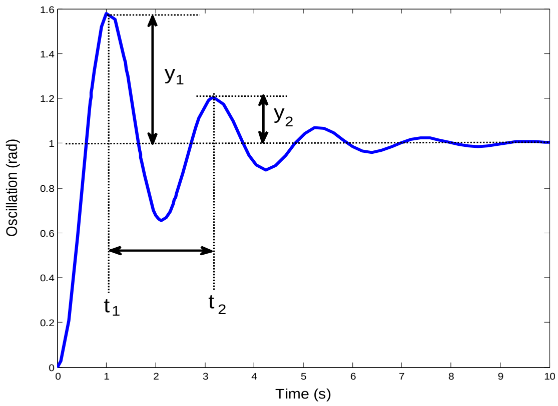

Figure 2. Logarithmic decrement process

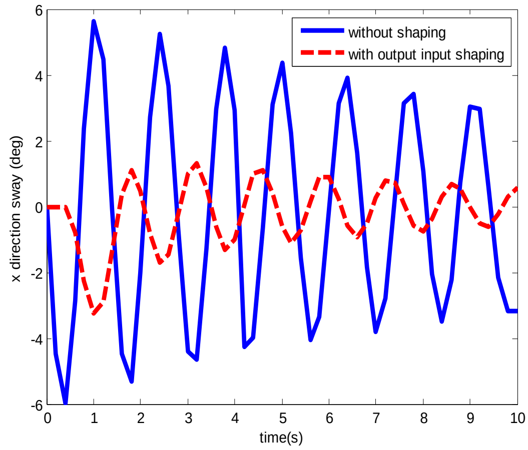

Figure 3. Trolley payload sways

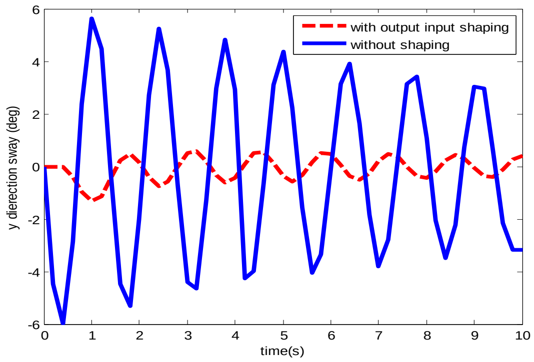

Figure 4. Rail payload sways

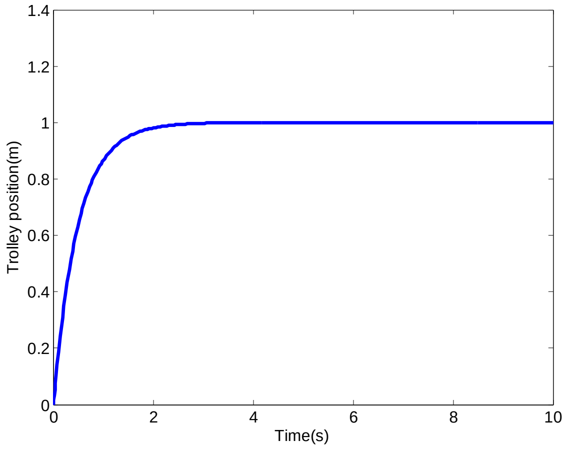

Figure 5. Trolley position

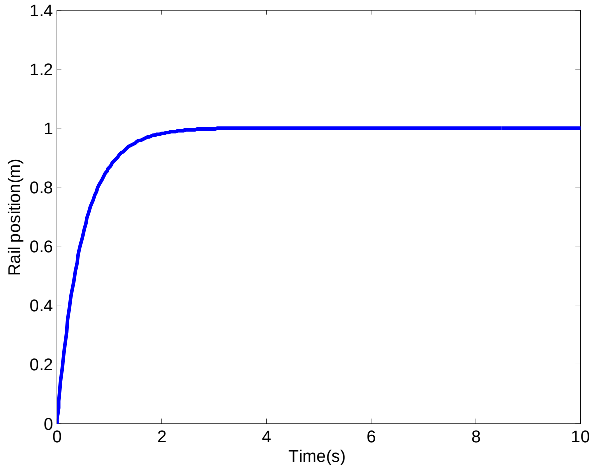

Figure 6. Rail position

VI. Conclusion

An output-based filter incorporates with PID for residual vibration suppression and precise payload positioning was presented. The filter was designed to suppress residual vibrations while PID was used for position control. The hybrid control was simulated and analyzed, and the control performance has been investigated. Simulation results show that, residual vibration suppression and precise positioning of payload was achieved.

Acknowledgment

The authors are grateful to Abubakar Tafawa Balewa University (ATBU) Bauchi, Nigeria and Assoc. Professor Zaharuddin Mohamed of Universiti of Teknologi Malaysia (UTM) for providing research resources and financial assistants.

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