Input Shaping Techniques for Anti-sway Control of a 3-DOF Rotary Crane System

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Abstract—This paper presents development of input shaping for anti-sway control of a 3 degree-of-freedom (3-DOF) rotary crane system. A nonlinear equation of motion in a state space form obtained using Euler-Lagrange technique is considered for the crane’s tower in order to control and reduce the sway angle during the rotation. An unshaped square-pulse current input is implemented to determine the characteristic parameters of the system for design and evaluation of the input shaping control techniques. Positive and modified Specified Negative Amplitude (SNA) input shapers with the derivative effects are designed based on the properties of the system. Simulation results of the response of the rotary crane system to the shaped inputs are presented in time and frequency domains. Performances of the control schemes are examined in terms of sway angle reduction and time response specifications. Moreover, the robustness of the feed-forward control schemes is discussed. Finally, a comparative assessment of the proposed control techniques is presented and discussed.

Keywords—rotary crane; anti-sway control; input shaping

I. INTRODUCTION

The main purpose of controlling a crane is transporting the load as fast as possible without causing any excessive swing at the final position. However, most of the common crane results in a swing motion when payload is suddenly stopped after a fast motion [1]. The performance of precision motion depends on damping capacity of the system. The damping capability of a dynamical system can be enhanced by passive or active damping methods. In the passive approach, oscillation damping is increased by deploying external dampers such as dashpots or viscous dampers [2]. Feedback control can also be used as an active approach in a wide band of insensitivity

Various techniques in controlling cranes system based on open loop and closed loop systems have been proposed. In closed loop system, fuzzy logic controller has also been proposed for controlling the crane system by several researchers [3, 4]. In [4], the proposed fuzzy logic controllers consist of position as well as anti-sway controllers. However, the fuzzy logic designed still need to struggle in finding the satisfactory rules, membership function, fuzzification and defuzzification parameter heuristically [5].

Various researchers used Neural Network (NN) as the controller in their crane systems. Recurrent NN are used in three degree of freedom rotary crane with particle swarm optimization (PSO) and a binary-coded genetic algorithm (GA) in [6]. Furthermore, [7] applies three-layered NN as a controller with genetic algorithm based (GA-based) training in order to control load swing suppression for the rotary crane system. On the other hand, [8] used Radial Basis Function Networks together with PSO in order to control the position and sway of the crane respectively.

Another closed loop approach using H∞ has been implemented by [5] in order to control the payload positioning of the gantry crane with minimal swing. Besides that, a stabilization method of rotary crane via switching control has been proposed in [9].

Another approach in controlling the crane system is using feed-forward control techniques. Feed-forward control schemes are mainly developed for sway suppression and involve developing the control input through consideration of the physical and swaying properties of the system, so that system sways at response modes are reduced. The earliest incarnation of this self-canceling command generation was developed by Smith [10] but his technique was extremely sensitive to modeling errors [11]. Singer and Seering developed reference commands that were robust enough to be effective on a wide range of systems [12]. This new robust technique is named as input shaping.

Input shaping is a command filtering technique used to reduce motion-induced oscillation. It has been used to mitigate unwanted oscillation in cranes [13-15]. Input shaping is implemented by convolving a sequence of impulses, called an input shaper, with a baseline command [16, 17]. The convolution product, instead of the original baseline command, is then issued to the system. For baseline commands that reach a steady-state value and for correctly designed input shapers, a linear system will exhibit zero residual oscillation in response to the modified command [18]. The process has the effect of placing zeros near the locations of the flexible poles of the oscillatory system. In the input shaper, the amplitudes and time locations of the impulses are determined by solving the set of constraints [19]. Most existing crane control systems are designed to maximize speed, in an attempt to minimize system sway and achieve good positional accuracy in a minimum duration [20].

This paper presents the development of control schemes for anti-sway control of a rotary crane system. A nonlinear rotary crane system is considered and the dynamic model of the system is derived using the Euler-Lagrange formulation.
An unshaped square pulse current input is used to determine the characteristic parameters of the system for design and evaluation of the input shaping control techniques. The input shapers are then designed based on the properties of the system for anti-sway control. Simulation results of the response of the rotary crane system to the shaped inputs are presented in time and frequency domains. Performances of the shapers are examined in terms of swing angle reduction and time response specifications. The robustness of the input shaping control schemes is also discussed. Finally, a comparative assessment of the control techniques is presented and discussed.

II. THE 3-DOF ROTARY CRANE SYSTEM

The 3-DOF rotary crane system as shown in Fig.1 consists of three subsystems which are payload, jib and tower systems. The crane’s tower performs as the main component in the 3-DOF rotary crane system which capable to travel in a rotary motion. The horizontal component in the gantry system which is also known as a jib or boom is mounted at the tower. The clockwise and anticlockwise motions can be controlled by using a motor for actuation.

As the rotary motion is crucial in this particular system, in this simulation study, the pendulum and payload can be considered as point masses. Only crane’s tower will be considered in this study in order to control the sway angle during the rotation mode. Thus, the modeling development for the rotary crane system will be discussed in the next section.

III. DYNAMIC MODELING OF THE ROTARY CRANE

Modeling of the crane system is necessary and crucial in controller design procedure. In 3-DOF rotary crane system, the tower subsystem can be modeled as a rotary gantry crane by assuming the trolley position is fixed, the payload sway angle in the horizontal component, \( \gamma \) is always zero and the payload height is fixed. Thus the only moving joint is the jib pivoting about the tower and payload sway angle, \( \alpha \) which is perpendicular to the jib [21].

Fig. 2 shows the schematic diagram and description of the rotary crane system or tower subsystem where the jib is modeled as a rigid rotary arm and it is assumed that the trolley remain stationary at the end of the jib with a distance of \( l_p \) from the crane’s tower. The payload is assumed to be fixed at the height of \( l_p \) from the trolley pulley and is modeled as a pendulum system.

![Figure 1. The 3-DOF rotary crane system.](image1)

![Figure 2. Description of the rotary crane system.](image2)

The rotary crane system is modeled in state space form by considering the nonlinear equation of motion that obtained using Euler-Lagrange technique. The state space equation is given as

\[
\dot{x}(t) = Ax(t) + Bu(t)
\]

and the output system can be obtained as

\[
y(t) = Cx(t) + Du(t)
\]

where

\[
A = \begin{bmatrix}
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1 \\
\frac{m_p^2 l_p^2 l_j g}{J_a J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_a} & 0 & 0 & 0 \\
-\frac{m_p^2 l_p^2 l_j g (m_p l_j^2 + J_\theta)}{J_a J_\theta + J_\theta m_p l_p^2 + m_p l_j^2 J_a} & 0 & 0 & 0
\end{bmatrix}
\]
Parameter as vibration equation. This yields a four-impulse sequence with shaper, is designed by solving the derivatives of the system
The constraint in (5) yields useful shapers as they can be used with a wide variety of inputs. However, the increase in the speed of system response achieved using the SNA input shapers is at the expense of some tradeoffs and penalties. The shapers containing negative impulses have tendency to excite unmodeled high modes and they are slightly less robust as compared to the positive shapers. Besides, negative input shapers require more actuator effort than the positive shapers due to high changes in the set-point command at each new impulse time location.

To overcome the disadvantages, the modified SNA input shaper is introduced, whose negative amplitudes can be set to any value at the centre between each normal impulse sequences. In this technique, the previous SNA input shaper [22] has been modified by locating the negative amplitudes at the centre between each positive impulse sequences with even number of total impulses. This will result the shaper duration to one-fourth of the sway period of an undamped system as shown in Fig. 2. The modified SNA known as negative Zero-Vibration-Derivative-Derivative (NZVDD) shaper is applied in this work by adding more negative impulses in order to enhance the robustness capability of the controller while increasing the speed of the system response. Moreover, by considering the form NZVDD shaper shown in Fig. 3, the amplitude summation constraints equation can be obtained as

\[ 2a + 2c - 2b - 2d = 1 \]  

The values of \( a, b, c \) and \( d \) can be set to any value that satisfy the constraint in (6). However, the suggested values of \( a, b, c \) and \( d \) are less than \( |1| \) to avoid the increase of the actuator effort.
V. IMPLEMENTATION AND RESULTS

In this investigation, input shaping control schemes are implemented and tested within the simulation environment of the rotary crane system and the corresponding results are presented. The square-pulse input current of 1 A is applied to the motor shaft of the rotary crane. For the sway suppression schemes, positive and modified SNA input shapers with the derivative effects respectively are designed based on the sway frequencies and damping ratios of the rotary crane system. In this investigation, the first mode of sway of the system is considered, as these dominate the dynamic of the system. The responses of the rotary crane system to the unshaped input were analyzed in time-domain and frequency domain (spectral density). These results were considered as the system response to the unshaped input and will be used to evaluate the performance of the input shaping techniques. Simulation results for the unshaped input have shown that the steady-state for the tower rotation angle, \( \theta \), was achieved within the rise and settling times and overshoot of 0.489 s, 2.925 s and 1.15\% respectively. However a significant amount of sway occurs at the hoisting angle, \( \alpha \), of the payload during the movement of the arm. The sway angle response was found to have a maximum oscillation between \( \pm 25 \) deg. The sway frequencies of the rotary system were obtained as 0.5859 Hz for the first mode of sway.

In designing input shaping control schemes, PZVDD and NZVDD shapers were designed for single mode utilizing the properties of the system. With the exact natural frequency of 0.5859 Hz, the time locations and amplitudes of the impulses for PZVDD shaper were obtained by solving (6). However, the amplitudes of the NZVDD shaper were deduced as \([0.3 -0.1 0.5 -0.2 0.5 -0.2 0.3 -0.1]\) while the time locations of the impulses were located at the half of the time locations of PZVDD shaper as shown in Fig.3. For evaluation of robustness, input shapers with error in natural frequencies were also evaluated. With the 30\% error in natural frequency, the system sways were considered at 0.7617 Hz for the single mode of sway frequency. Similarly, the amplitudes and time locations of the input shapers with 30\% erroneous natural frequency for both PZVDD and NZVDD were calculated.

Fig.4 shows the rotation angle of the tower, \( \theta \), sway angle of the payload and its power spectral density of the rotary crane to the exact and erroneous shaped inputs. It is noted that the PZVDD control scheme is capable of reducing the system sway. With the exact frequency, the magnitudes of sway of the system have significantly been reduced. Moreover, the sway angle response was found to have a maximum magnitude of \( \pm 3 \) deg. and achieved almost zero sway within 5 s. As expected with the erroneous frequencies, the level of sway reduction of the rotary crane is slightly less than the case without error. The maximum magnitude of sway angle response was achieved as \( \pm 4.5 \) deg. The corresponding rise time, settling time and overshoot of the tower rotation angle for PZVDD is depicted in Table 1. It is noted that a slower tower rotation angle response for input shaping control schemes, as compared to the unshaped control, was achieved. Moreover, a faster response is noted with the erroneous natural frequencies, as the length of the PZVDD is shorter. Table 1 summarizes the levels of sway reduction of the system responses at the first mode of sway. Higher levels of sway reduction were obtained using PZVDD with exact frequencies as compared to the PZVDD with erroneous frequencies.

Fig.5 shows the rotation angle of the tower, sway angle of the payload and its power spectral density of the rotary crane to the exact and erroneous NZVDD shaper. It is noted with exact frequency that the system sway have significantly been reduced. The sway angle was found to have a maximum magnitude of \( \pm 5 \) deg. However the payload continues to oscillate even until 30 s. In addition, as demonstrated in the tower rotation angle response, an acceptable overshoot occurs during movement of the rotary crane. However, the overshoot is slightly higher than the case of positive input shaping. The robustness of the technique is demonstrated with the erroneous NZVDD shaped input. As evidenced in the sway angle response, relatively small reduction in system sway was achieved. The maximum magnitude of sway angle was obtained as \( \pm 5 \) deg., which is the same with the exact shaped input. The corresponding rise time, settling time and overshoot of the tower rotation angle for NZVDD shaper is depicted in Table 1. It is noted that a faster tower rotation angle response than the case without error is achieved. Table 1 also summarizes the levels of sway reduction of the system responses at the first mode. Higher levels of sway reduction were obtained using NZVDD shaper with exact frequency as compared to the NZVDD shaper with erroneous frequency.

By comparing the results presented in Table 1, it is noted that the higher performance in the reduction of sway of the system is achieved using PZVDD shaper. This is observed and compared to the NZVDD shaper at the first mode of sway. It is also noted that the settling time of the tower rotation angle by using the positive ZVDD shaper is larger than the case using the NZVDD shaper. It shows that the speed of the system response can be improved by using the NZVDD shaper.
Figure 4. Response of the rotary crane using PZVDD with exact and erroneous frequency.

Figure 5. Response of the rotary crane using NZVDD with exact and erroneous frequency.
VI. CONCLUSION

The development of PZVDD and NZVDD shapers for anti-sway control of a rotary crane system has been presented. The performances of the control schemes have been evaluated in terms of level of sway reduction and time response specifications. Acceptable anti-sway capability has been achieved with both control strategies. A comparison of the results has demonstrated that the PZVDD shapers provide higher level of sway reduction as compared to the cases using NZVDD shapers. In addition, by using the NZVDD shapers, the speed of the response is slightly improved in term of settling time. It has also demonstrated that input shaping techniques is very robust to errors in natural frequencies.

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REFERENCES


<p>| TABLE I. LEVEL OF SWAY REDUCTION OF THE HOISTING ANGLE OF THE PENDULUM AND SPECIFICATION OF HUB ANGLE RESPONSE |</p>
<table>
<thead>
<tr>
<th>Frequency</th>
<th>Types of shaper</th>
<th>Attenuation (dB) of sway of the payload</th>
<th>Specification of tower rotation angle response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exact</td>
<td>PZVDD</td>
<td>46.64</td>
<td>Rise time (s)</td>
</tr>
<tr>
<td></td>
<td>NZVDD</td>
<td>19.7</td>
<td>Settling time (s)</td>
</tr>
<tr>
<td>Error</td>
<td>PZVDD</td>
<td>21.16</td>
<td>Overshoot (%)</td>
</tr>
<tr>
<td></td>
<td>NZVDD</td>
<td>17.11</td>
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