Proceedings of the 2006 American Control Conference
Minneapolis, Minnesota, USA, June 14-16, 2006

Feedback Control for Suppression of Crane Payload Oscillation Using On-Off Commands

Keith A. Hekman, and William E. Singhose

Abstract— **When cranes move objects in a workspace, the payload frequently swings with large amplitude motion. Open loop methods have addressed this problem, but are not effective for disturbances. Closed loop methods have also been used, but require variable speed driving motors. This paper develops a feedback based method for controlling single speed motors to cancel the measured payload oscillations by intelligently timing the ensuing on and off motor commands. The oscillation suppression scheme is experimentally verified on a bridge crane.**

I. Introduction

Cranes are frequently used to transport objects in a cluttered workspace. One inherent problem with cranes is that the payload can swing freely. These oscillations pose safety hazards and can damage the payload or other objects in the workplace. Traditionally, an experienced crane operator has been required to keep the oscillations under control. More recently, various control approaches have been applied to augment the operator's skill. These approaches fall into open and closed loop categories.

One open loop approach used is input shaping, which has proven effective on cranes for reducing sway during and after the move [1,2,3], including during hosting [4]. Shapers can be designed with increased robustness to modeling inaccuracies [5] (i.e. cable length changing the frequency). Another open loop approach is optimal control, which calculates a motion trajectory off line based on the mathematical model of the system [6,7]. However, if the model is inaccurate, the performance will suffer. This is also the case with input shaping, but to a lesser degree. In addition, optimal control has not been used with current crane operator interfaces, as the path is not known beforehand.

System model uncertainties and external disturbances provide the motivation for feedback control. Controllers have used the position and velocity of the trolley and the cable swing angle [8,9,10,11] or the spreader inclination [12] to generate trolley commands that reduce payload oscillations. Wave absorption control adjusts the trolley velocity to absorb any waves that are being returned by the payload, thereby canceling the oscillation [13]. Feeding a delayed angle measurement back to the desired position has also been shown effective in reducing payload oscillations [14].

Manuscript received September 9, 2005. This work was supported by Siemens Automation and Drivers, who provided all of the equipment necessary in implementing the crane control. Furthermore, they provided financial support for graduate students to install and program the controller.

K. A. Hekman was with the American University in Cairo, Cairo 11511 Egypt. He is now with the Engineering Department, Calvin College, Grand Rapids, MI 49546 USA. (phone 616-526-7095, fax: 616-526-6501, e-mail hekman@calvin.edu)

W. E. Singhose is with the George W. Woodruff school of Mechanical Engineering, The Georgia Institute of Technology, Atlanta GA 30332 USA (e-mail:William.Singhose@me.gatech.edu)

Sorenson *et al.* [15] developed a control system that combined input shaping and PD feedback control. The feedback control used measurements from an overhead camera and compared the crane response to the modeled shaped response.

In another method to reduce the effect of a disturbance, Park and Chang [16] proposed a "commandless" input shaping method for a telescopic handler. To compensate for the vibrations from unloading the handler, they introduce a pulse that induces vibration equal in magnitude but opposite in direction of the vibration from unloading. They show the method's potential by using it to reduce vibration by about 75%. However, issues of properly timing the impulse and ease of calibration remain.

All of the feedback methods require the velocity or acceleration of the trolley to be precisely controlled. The research here is based on using measurement of payload swing to generate commands for simple on-off motors to cancel the payload swing, making it applicable to a broader range of cranes.

II. Vector Based Input Shaper Calculation

Booker [17] provides a framework for analyzing oscillations with vectors. Singhose *et al.* [18] provide insight into how vibration cancellation can be achieved in a vector-based analysis of input shapers. An impulse of magnitude A_1 applied to an undamped second-order system of unit mass will induce a response of

$$x(t) = A_1 \sin \omega t \,. \tag{1}$$

This has a magnitude A_1 and phase angle of zero. Similarly, if a second impulse of magnitude A_2 was applied at time T_2, then it would result in an output of

$$x(t) = A_2 \sin \omega(t - T_2) = A_2 \sin(\omega t - \omega T_2)\,,\ t>T_2. \tag{2}$$

This has a magnitude A_2 and phase angle $\theta=\omega T_2$. The magnitudes and angles can be transformed into vector notation as seen in Fig. 1. Summing these vectors gives the total vibration response, as seen in Fig. 2. The corresponding time response of these impulses is seen in Fig. 3. After the second impulse, the total response matches the amplitude and phase of A_R.

If the system has damping, then this method needs to be modified. First, the angle θ changes to

$$\theta = \sqrt{1-\zeta^2}\,\omega T \,. \tag{3}$$

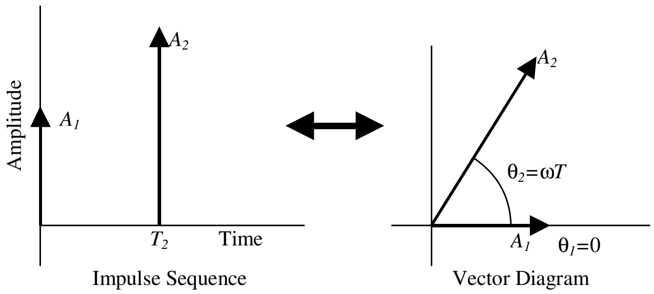


Fig. 1. Impulse sequence and corresponding vector diagram

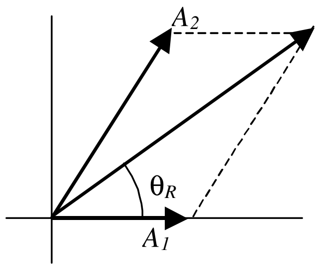


Fig. 2. Summing two vectors to get the total response

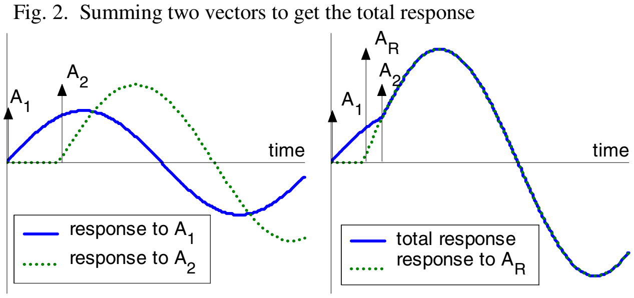


Fig. 3. Time response of impulses (adapted from [18])

Second, damping causes the amplitude to decay over time. To account for the decay, calculations use the effective amplitude at t=0 that results in the required amplitude at T_2 of

$$A_{2_{eff}} = A_2 e^{\zeta\theta/\sqrt{1-\zeta^2}}\,. \tag{4}$$

A shaper can be designed such that the sum of all the effective impulses results in zero vibration, as seen in Fig. 4. To do this, the A_{3eff} is chosen to be the negative of A_R from Fig. 2. To get the magnitude of this canceling impulse, it must be converted to the time it will occur using (3) and

$$A_3 = A_{3_{eff}} e^{-\zeta\theta/\sqrt{1-\zeta^2}}\,. \tag{5}$$

In reality, systems are not moved with impulses. To create a practical command, the impulse sequence is convolved with the desired command. For example, Fig. 5 shows a step command convolved with two impulses produces a stair step command. The resulting command will not produce any residual vibrations.

III. Payload Oscillation Cancellation.

The goal of this research is not to create commands that result in no residual oscillation for point-to-point motion. Rather, the measured payload swing is used to create commands for simple on-off motors that cancel any oscillation once it occurs. When creating such commands, the magnitude of the actuator force vector cannot be

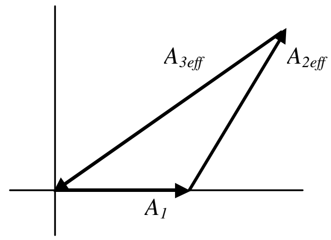


Fig. 4. Summing three vectors to get zero vibration

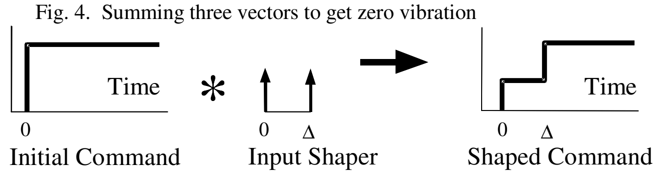


Fig. 5. Creating a stair step command by convolution

arbitrarily chosen, as the motor can only be turned on and off. However, turning the motor on or off will cause payload oscillations, which can be represented as vectors. Unlike a pure impulse, these vectors will not have zero phase angles, as the motor does not instantly stop or accelerate to full speed. Therefore, by the time the command is completed, the payload will have some displacement and some velocity, giving a vector representation similar to Fig. 6. The vector for turning the motor off should have a similar magnitude, but in the opposite direction, assuming that the acceleration and deceleration dynamics are similar. If not, it can be represented by its own unique amplitude and phase.

The controller developed here will use two command switches (on-off) to eliminate the position and velocity components of the vibration. The controller needs to calculate the appropriate times for these commands in real time.

To make this calculation, a vector triangle is used, as seen in Fig. 7. The three sides of the triangle are the current vibration level (A_{vib}), and the vibration amplitudes of "on" and "off" commands. If the triangle can be created, then the oscillations can be forced back to zero (the origin of the vector diagram.) Assuming that the operator wants the crane to be moving, then the command sequence would be "off", wait, then "on" again. Certain components of the triangle are known: the magnitude of the current vibration and the effect of turning the crane on (A_{on}) and off (A_{off}). The

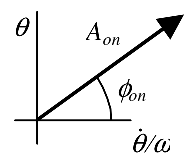


Fig. 6. Vector representation for turning the motor on.

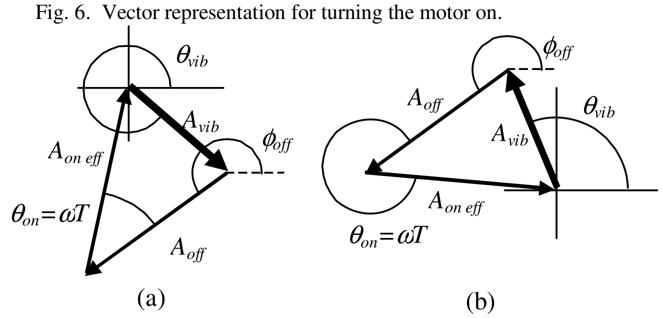


Fig. 7. Vector diagram for calculating time to turn motor off.

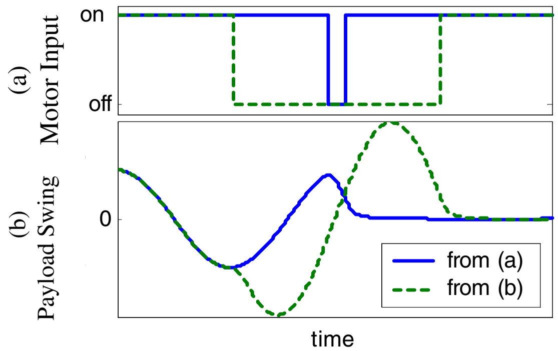


Fig. 8. Time Response from vector diagram of Fig. 7.

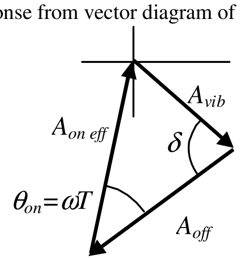


Fig. 9. Angles used to calculate command initiation time.

unknowns are the time until the crane is turned back "on" again (T), and at what existing vibration phase angle the crane should be turned "off" (θ_{vib}). Since it is a triangle, there are two possible solutions as shown in Fig. 7. The time response of these solutions is given in Fig. 8. The solution in Fig. 7a is preferable as it has a smaller angle $\theta_{on}=\omega T$, so the time until the vibration is canceled is shorter. Also, the swing angle is less.

To find θ_{vib}, the intermediate angles seen in Fig. 9 are used. From the law of cosines,

$$A_{on\,eff}^{\ 2} = A_{off}^{\ 2} + A_{vib}^{\ 2} - 2A_{off}A_{vib}\cos\delta \tag{6}$$

$$A_{vib}^{\ 2} = A_{off}^{\ 2} + A_{on\,eff}^{\ 2} - 2A_{off}A_{on\,eff}\cos\theta_{on}\,. \tag{7}$$

From (7)

$$\theta_{on} = \cos^{-1}\left(\frac{A_{off}^{\ 2} + A_{on\,eff}^{\ 2} - A_{vib}^{\ 2}}{2A_{off}A_{on\,eff}}\right) \tag{8}$$

If there is no damping, then the solution can be solved directly since $A_{on\ eff}=A_{on}$. Note that most cranes have near zero damping, but if the damping is significant, then the same equation can be used to solve for θ_{on}, but it must be solved iteratively, with

$$A_{on\,eff} = A_{on}e^{\zeta\theta_{on}/\sqrt{1-\zeta^2}}\,. \tag{9}$$

Equation (8) is initially calculated using ζ=0. After θ_{on} is found, δ from Fig. 9 can be calculated using

$$\delta = \cos^{-1}\left(\frac{A_{off}^{\ 2} + A_{vib}^{\ 2} - A_{on\,eff}^{\ 2}}{2A_{off}A_{vib}}\right) \tag{10}$$

Once δ is known, θ_{vib} can be calculated using

$$\theta_{vb} = \phi_{off} - \delta + \pi \tag{11}$$

Once the controller has turned off the crane, it then waits until the angle of the vibration is opposite in direction to ϕ_{on}. At this point, the controller turns the motor back on. If the calibration is perfect, oscillations will be eliminated.

If the operator desires the crane to be stopped, then vibrations can be canceled by moving the overhead support either forward or backward. This results in two different phase angles of vibration that can be used for the controller, as seen in Fig. 10. In part (a), the reverse direction, the diagram is basically the same as Fig. 7a, except the on and the off are exchanged. Based on this,

$$\theta_{off} = \cos^{-1}\left(\frac{A_{on}^{\ 2} + A_{off\,eff}^{\ 2} - A_{vib}^{\ 2}}{2A_{on}A_{off\,eff}}\right)$$

$$\delta = \cos^{-1}\left(\frac{A_{on}^{\ 2} + A_{vib}^{\ 2} - A_{off\,eff}^{\ 2}}{2A_{on}A_{vib}}\right) \tag{12}$$

$$\theta_{vb1} = \phi_{on\,r} - \delta + \pi$$

For Fig. 10b, the vector diagram has the same geometry for δ as (a), only rotated by π radians. Therefore

$$\theta_{vb2} = \phi_{on\,f} - \delta + \pi\,. \tag{13}$$

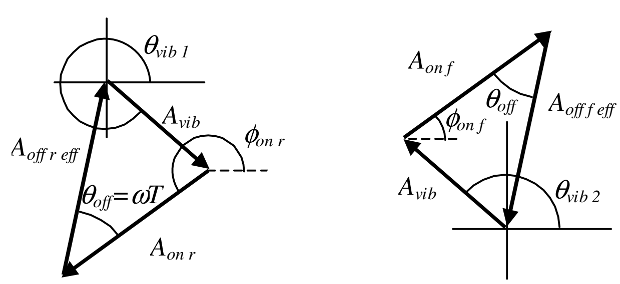
The controller compares the existing vibration phase angle to (12) and (13) and uses whichever angle occurs first. Once the crane is stopped, then the controller waits until the oscillation phase angle is opposite to that of the "on" command. Then, the motor is turned back on.

The maximum oscillation magnitude that can be canceled using an on-off command is approximately twice the oscillation induced by an "on" command. If the current oscillation magnitude is larger than this, then the controller calculations are based on the maximum cancellation level. As a precaution, this maximum level can be reduced to limit the distance moved in canceling the oscillations, thus limiting the angle θ_{on} and T.

A limitation of this oscillation cancellation method is that it assumes that superposition can be applied for the vector representations of induced vibration. This is only true if the motor has time to reach its steady state velocity between the vectors, so small payload oscillations cannot be eliminated. Therefore, an oscillation magnitude threshold is used.

IV. CONTROLLER IMPLEMENTATION

The proposed controller using the oscillation cancellation techniques from Section III was implemented on a large bridge crane. The crane has a camera mounted on the trolley to measure the payload swing in the horizontal plane. The camera can also measure the height of the payload. All of the control actions were based on a single payload height.



(a, reverse) (b, forward)

Fig. 10. Vector diagram for when to turn on motor.

The system could be calibrated at different heights and the timings would be based on the camera measured height.

A. System Calibration

The controller calculations (8)-(13) require the magnitude and phase angle of the oscillations caused by turning the motor "on" and "off". These can be calculated by plotting the crane input and response on the same graph, as seen in Fig. 11. Fig. 11a shows the motor being turned off at about 5.5 seconds while the crane is moving forward. The motor takes about a second to come to rest after the command is issued. Fig. 11b shows the payload swing angle θ and the oscillation level m given by

$$m = \sqrt{\theta^2 + \left(\dot{\theta}/\omega\right)^2} \tag{14}$$

where ω is the natural frequency of the system.

The times of the zero crossing of the swing angle before (t_b) and after (t_a) the input change (t_i) were recorded. The phase angles of the oscillation before (ϕ_b) and after (ϕ_a) the input can be calculated using

$$\phi_b = 2\pi\left(t_b + t_p - t_i\right)/t_p \qquad \phi_a = 2\pi\left(t_a - t_p - t_i\right)/t_p \tag{15}$$

where t_p is the time of one oscillation period. The complex vector A of the input transition is given by

$$A = m_a e^{-i\phi_a} - m_b e^{-i\phi_b} = A_{off\ f} e^{i\phi_{off\ f}}. \tag{16}$$

where m_b and m_a are the amplitudes of the oscillation before and after the input the subscript f denotes forward motion. A similar procedure can be done for the remaining vectors.

Graphically, the A's can be plotted for starting and stopping, for both forward and reverse, as seen in Fig. 12. On average the oscillation had an amplitude of a=0.052 radians at an angle of ϕ=1.11(+π) radians (63.6 (+180)°).

B. Controller Response for User Motion

Fig. 13 shows the response of the crane to a user request to move backward. In Fig. 13a, the user input is shown using a line with circles. The resulting trolley speed is seen with a dashed line. As shown in Fig. 13b, the crane motion excites oscillations in the payload. Fig. 13c shows the phase angle of the oscillations given by

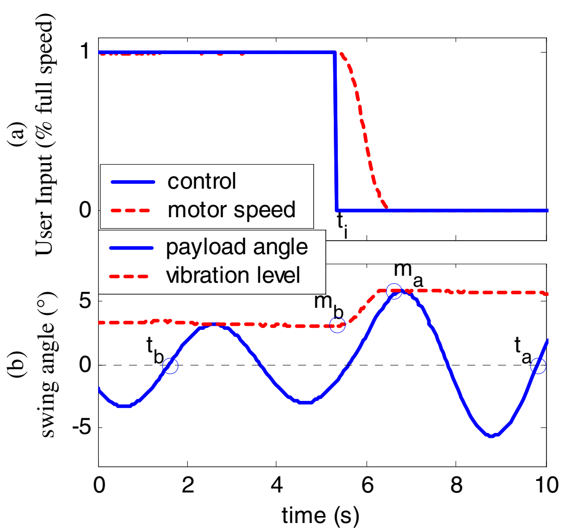


Fig. 11. Measured bridge crane response to an "off" command

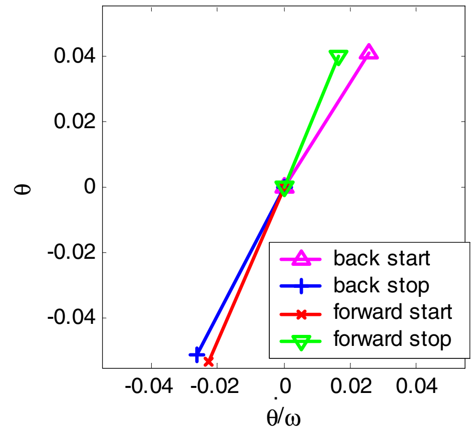


Fig. 12. Oscillation vectors for different commands

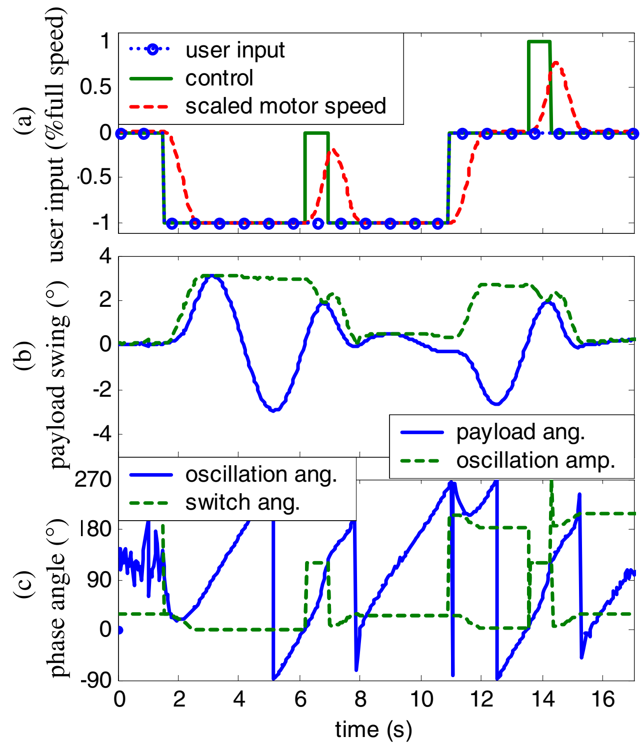


Fig. 13. Response to an operator input of reverse

$$\phi = \tan^{-1}\left(\frac{\theta}{\dot{\theta}/\omega}\right). \tag{17}$$

It also shows the switch angle calculated from (11)-(13). At the initial crossing (at about 2 seconds), the oscillation level is not large enough (1.7°) to trigger a control action. It is one period later (at about 6 seconds) that the oscillation canceling control action takes place. At this point, the controller briefly turns off the crane motor, as seen in Fig. 13a by the solid line. At this point the switch angle jumps to the angle to turn back on the motor. At 7 seconds, this angle occurs, and the crane motor is turned back on. When the crane reaches full speed (at about 8 seconds), the oscillation level is quite small (about a half degree).

The operator stops pressing the reverse button at about 11 seconds, as seen by the sold line in Fig. 13a. When the crane stops, oscillations are again induced. When the desired command is at rest, there are two switch angles given by (12) and (13), as the crane can cancel the oscillation by going both forwards and backwards. The first angle occurs at a little after 13 seconds, and the crane moves forward slightly to cancel the oscillations. Once the crane is back at rest very little oscillations remain.

C. Controller Response for Disturbance Rejection

Fig. 14 shows the response of the crane to a disturbance when the bridge is at rest. At a little after 1 second, the payload was disturbed. At about 3 seconds, the oscillation phase angle matched the switch angle condition, and the controller commanded the trolley to move forward. At a little past 4 seconds, the phase angle matched again, and the trolley was commanded to stop. When the trolley came to rest at about 5.5 seconds, the payload swing was small.

Fig. 15 shows the response to a very large disturbance. At about 1 second, the payload was pushed with a disturbance that is larger than a single on-off command can suppress. In this case, the first on-off control action suppressed the maximum amount, and then the second control action canceled the remaining oscillations by going in the opposite direction. This resulted in little oscillation after the crane had completed the second command at 6 seconds.

The controller can also eliminate disturbances while the crane is moving, as seen in Fig. 16. While the crane was moving forward with little oscillation, the payload was disturbed at about 1 second. The controller initially gives a stop command at about 1.5 seconds, which ceases shortly afterward (before the oscillation phase angle matched the switch angle, not eliminated. The controller then waited until the appropriate phase angle, and then stopped the trolley at a time of about 6 seconds. At the appropriate time (7.5 seconds), the crane began accelerating but based on the

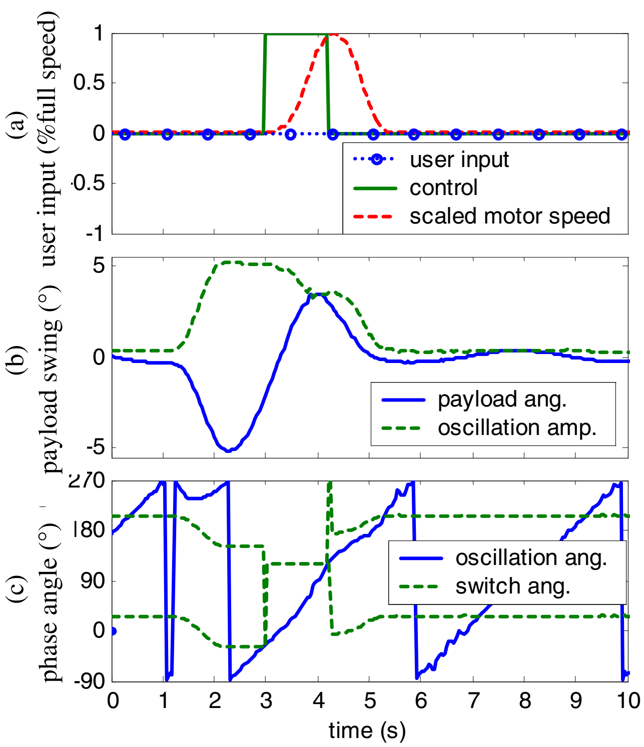


Fig.14. Response to a disturbance while crane is at rest

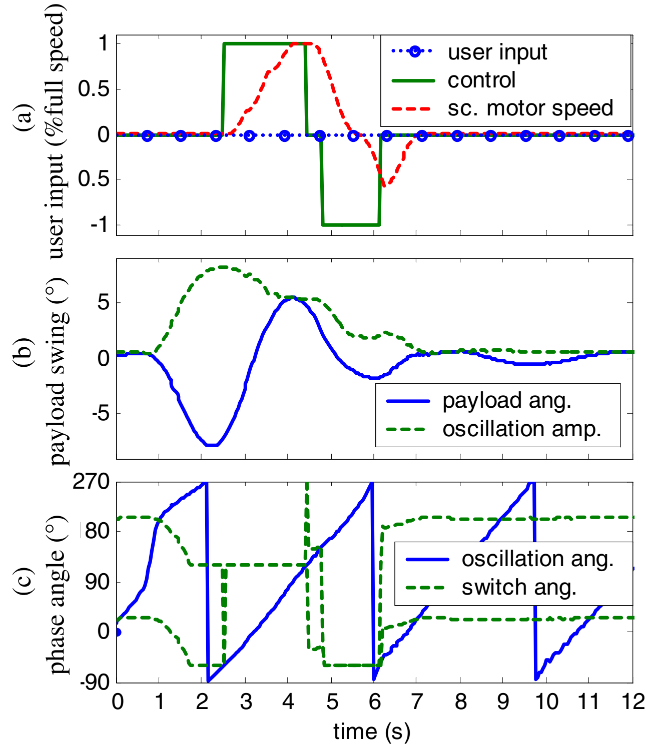


Fig. 15. Response to a large disturbance

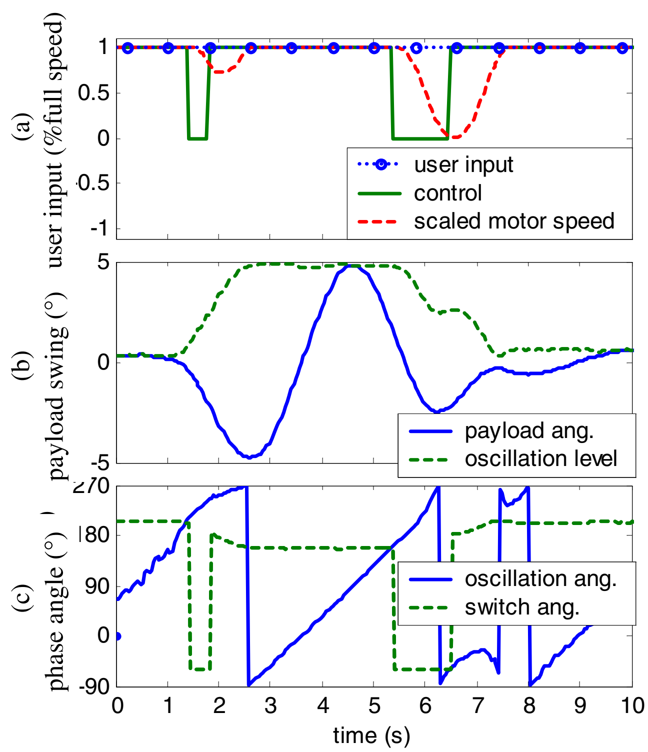


Fig. 16. Response to a disturbance when moving

time safety factor from θ_{off}.) However, the payload was still being disturbed so the oscillations were, resulting in little oscillation when the crane had returned to full speed.

V. Conclusion

A control strategy has been developed for on-off motors to eliminate bridge crane payload oscillations. The control uses the swing angle of the payload, and its derivative, to decide when to turn the crane on and off. The method can reduce the oscillations when the crane is moving or at rest. The strategy was implemented on a large bridge crane. Numerous experiments demonstrated the control systems effectiveness.

VI. REFERENCES

[1] Starr, G. P., "Swing-Free Transport of Suspended Objects With a Path-Controlled Robot Manipulator," *J. of Dynamic Systems, Measurement and Control*, vol. 107,1985, pp. 97-100.

[2] Feddema, J., Petterson, B. and Robinett, R., Operator Control Systems and Methods for Swing-Free Gantry-Style Cranes. U. S. Patent 5,785,191. 1998

[3] Singer, N., Singhose, W., and Kriikku, E., "An Input Shaping Controller Enabling Cranes to Move Without Sway," presented at ANS 7th Topical Meeting on Robotics and Remote Systems, Augusta, GA, 1997.

[4] Singhose, W., Porter, L., Kenison, M. and Kriikku, E., "Effects of Hoisting on the Input Shaping Control of Gantry Cranes," *Control Engineering Practice*, vol. 8(10), 2000, pp. 1159-1165.

[5] Singhose, W. E., Seering, W. P. and Singer, N. C., "Input Shaping for Vibration Reduction with Specified Insensitivity to Modeling Errors," *Japan-USA Sym. On Flexible Automation*, Boston, MA. 1996

[6] Auernig and Troger, "Time Optimal control of overhead cranes with hoisting of the load," *Automatica*. Vol 23(4) 1987 pp. 437-447

[7] Hamalainen, J.J., Marttinen, A., Baharova, L., and Virkkunen, J., "Optial path planning for a trolley crane: fast and smooth transfer of load," *IEE Proceedings Control Theory and Applications*, Vol. 142(1), 1995 pp 51-57.

[8] Ridout, Anti-swing control for the overhead crane using linear feedback," *Journal of Electrical and Electronics Engineering, Australia* Vol 9, 1989 pp 17-26.

[9] Moustafa and Ebeid, "Nonlinear modeling and control of overhead crane load sway." *Journal of Dynamic Systems, Measurement, and Control* Vol. 110, 1988 pp 266-271

[10] Nguyen, H. T., "State-variable feedback controller for an overhead crane." *Journal of Electrical and Electronics Engineering, Australia.* Vol. 14(2) 1994, pp 75-84

[11] Lee, H. "Modeling and Control of a Three-Dimensional Overhead Crane." *Journal of Dynamic Systems, Measurement, and Control*, Vol. 120 (4) 1998 pp 471-476.

[12] Kim, Y. S., Hong, K. S., and Sul, S. K., Anti-Sway Control of Container Cranes: Inclinometer, Observer, and State Feedback, *International Journal of Control, Automation, and Systems*, Vol. 2 (4), Dec 2004, 435-449

[13] O'conner, W.J., A gantry crane problem solved, *ASME Journal of Dynamics Systems, Measurement and Control* Vol. 125(4) Dec. 2003, 569-576

[14] Masoud, Z. N., and Nayfe, A.H., "Sway reduction on container cranes using delayed feedback controller," *Nonlinear Dynamics*, Vol. 34(3-4) 2003, pp 347-358.

[15] Sorensen. K. L. and Singhose, W. E., "A Controller Enabling Precise Positioning and Sway Reduction in Cranes with On-Off Actuation," presented at IFAC, Prague, 2005.

[16] Park, J. Y. Chang, P. H. "Vibration control of a telescopic handler using time delay control and commandless input shaping technique" *Control Engineering Practice*, v 12, n 6, June, 2004, p 769-780

[17] Booker, H. G. *A Vector Approach to Oscillations*, Academic Press, New York, 1965.

[18] Singhose, W., Seering, W. and Singer, N., Residual Vibration Reduction Using Vector Diagrams to Generate Shaped Inputs, 1994, *ASME Journal of Mechanical Design*, Vol. 116(June), pp. 654-659.