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Manipulation with Tower Cranes Exhibiting Double-Pendulum Oscillations

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Abstract— **The payload oscillation inherent to all cranes makes it challenging for human operators to manipulate payloads quickly, accurately, and safely. Under certain conditions, the problem is compounded when the payload creates a double-pendulum effect. This paper presents an input-shaping control method for suppressing double-pendulum payload oscillations. Local and tele-operation experiments performed on a portable tower crane are used to verify the effectiveness of the method. Data from these experiments show that operators performed manipulation tasks faster and safer when input shaping was utilized to reduce payload sway. Furthermore, the tele-operation delays did not degrade the input shaping effectiveness.**

I. INTRODUCTION

Manipulation of heavy objects at disaster sites, nuclear plants, warehouses, construction sites, and shipyards is often accomplished with cranes. Human-controlled cranes are large, complex and powerful systems. Therefore, it is crucial that the control effort of the human operator be streamlined. For example, even a skilled crane operator can have difficulty maneuvering a payload without inducing large amounts of sway. Therefore, a secondary control scheme may be added to ensure low-sway motions. However, any secondary control scheme will modify the operator's intended commands. This can confuse or annoy operators and degrade performance.

Most previous work on crane control has concentrated on single-pendulum dynamics. Time-optimal commands that result in zero residual vibration can be generated [1], [2]. However, optimal controls based on nonlinear models can be difficult to generate [3], [4]. Even when optimal commands can be generated, implementation may be impractical because the boundary conditions (the move distance) must be known at the outset of the motion. When feedback measurements are available, adaptive controllers and combination open- and closed-loop control are possible [5]–[7].

If the crane behaves like a single pendulum, then experienced crane operators can eliminate much of the residual motion by causing an oscillation during deceleration that cancels the oscillation induced during acceleration. The success of this approach depends on the skill and diligence of the operator. However, for certain types of payloads, the system can behave like a double pendulum [8]. Under these conditions, the manual method of eliminating residual vibration becomes very difficult, even for the most skilled operators.

To achieve practical real-time oscillation suppression, a controller must filter out unwanted excitations from the command signal. Such a modification can be accomplished by convolving the human-generated command signal with a sequence of impulses [9], [10]. The result of the convolution is then used to drive the crane motors. This input-shaping process is demonstrated in Figure 1 with a pulse command and an input shaper containing two impulses. The proper timing and scaling of the steps in the shaped command ensures that the system will move without vibration. Input shaping has proven effective for controlling oscillation of single-pendulum cranes [7], [11]–[13] and on single pendulum cranes that undergo payload hoisting [14].

Input-shaping techniques were first developed in the 1950's [10]. The "posicast" control method developed by O.J.M. Smith modifies inputs by breaking them into two smaller magnitude components, one of which is delayed by one half period of the natural frequency, ω_m. The primary constraint equation used to calculate the components ensures there will be zero residual vibration when the system model is perfect. Therefore, Smith's posicast control is now commonly referred to as Zero Vibration (ZV) input shaping and it is equivalent to the input shaper shown in Figure 1.

Input shaping has been implemented on several large bridge cranes at nuclear facilities [13], [14], a 10-ton crane at Georgia Tech [7], [15], as well as portable cranes [16], [17]. The 10-ton crane at Georgia Tech has an overhead vision system that can track the motions of the payload. Figure 2 shows the responses of the crane payload for a typical maneuver under standard operation and also when input shaping is enabled. Under normal operation the payload response has large oscillations. However, input shaping

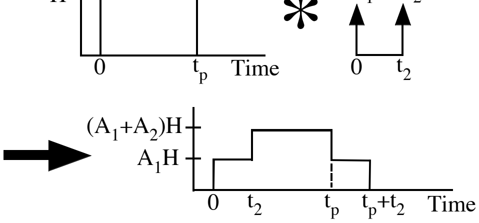


Figure 1. Input Shaping a Pulse Input.

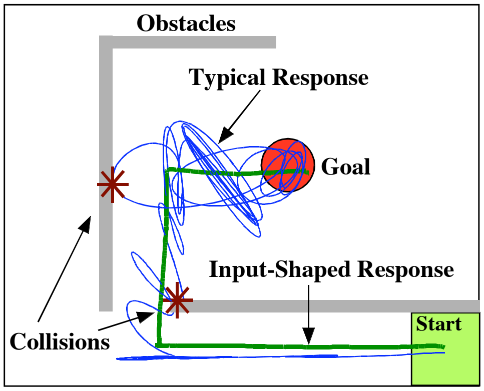


Figure 2. Typical Payload Responses.

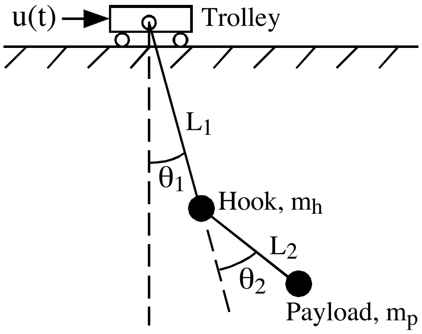


Figure 3. Double-Pendulum Crane.

virtually eliminates the oscillations.

When input shaping was implemented on a 15-ton bridge crane at Savannah River Technology Center (SRTC), the oscillations were also greatly reduced [13], even when the payload underwent hoisting [14]. The hook used to attach payloads to the SRTC crane weighs approximately 300 kg. It contains a motor that allows the hook to rotate the payload about the vertical axis. The large mass of the hook can lead to double-pendulum effects [8] that degrade the effectiveness of the input shaping if the input shaper is designed only for single-mode oscillations.

In this paper, the dynamics and control of cranes that exhibit double-pendulum dynamics are investigated. The importance of the double-pendulum effect is characterized as a function of the crane parameters such as suspension length and hook mass. An input-shaping scheme is then developed in Section III to mitigate the double-pendulum effects and improve positioning accuracy. Section IV presents experimental results from a tower crane that document the effectiveness of input-shaping when an operator drives a double-pendulum crane. Both local and tele-operation studies are discussed.

II. DOUBLE-PENDULUM DYNAMICS

Figure 3 shows a schematic representation of a planar double-pendulum crane. The crane is moved by applying a force, $u(t)$, to the trolley. A cable of length L_1 hangs below the trolley and supports a hook, of mass m_h, to which the payload is attached using rigging cables. The rigging and payload are modeled as a cable, of length L_2, and point mass, m_p. Assuming that the cable and rigging lengths do not change during the motion, the linearized equations of motion are:

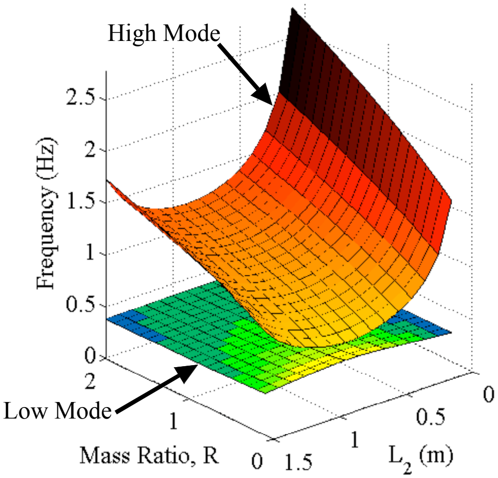


Figure 4. Variation of First and Second Mode Frequencies when $L_1 + L_2 = 1.8m$.

$$\begin{aligned}\ddot{\theta}_1(t) &= -\left(\tfrac{g}{L_1}\right)\theta_1 + \left(\tfrac{gR}{L_1}\right)\theta_2 - \tfrac{u(t)}{L_1}\\ \ddot{\theta}_2(t) &= \left(\tfrac{g}{L_1}\right)\theta_1 - \left(\tfrac{g}{L_2} + \tfrac{gR}{L_2} + \tfrac{gR}{L_1}\right)\theta_2 + \tfrac{u(t)}{L_1}\end{aligned} \tag{1}$$

where θ_1 and θ_2 describe the angles of the two pendulums, R is the ratio of the payload mass to the hook mass, and g is the acceleration due to gravity.

The linearized frequencies of a double-pendulum are [18]:

$$\omega_{1,2} = \sqrt{\frac{g}{2}}\sqrt{(1+R)\left(\frac{1}{L_1} + \frac{1}{L_2}\right) \mp \beta} \tag{2}$$

where,

$$\beta = \sqrt{(1+R)^2\left(\frac{1}{L_1} + \frac{1}{L_2}\right)^2 - 4\left(\frac{1+R}{L_1 L_2}\right)} \tag{3}$$

The frequencies depend on the two cable lengths and the mass ratio. Information on how the frequencies change as a function of the system parameters can be used to design an effective input shaper.

Given the large range of possible physical parameters and crane uses, a complete investigation of double-pendulum dynamics is beyond the scope of this paper. Therefore, we will examine a subset of crane manipulation tasks where the crane is used to move payloads that remain near the ground. That is, hoisting up and down is kept to a minimum and the sum of the two cable lengths stays roughly constant.

Figure 4 shows the two oscillation frequencies as a function of both the rigging length and the mass ratio when the total length (cable length plus rigging length) is held constant at 1.8 m. The low frequency is maximized when the two cable lengths are equal. Note that over the wide range of parameter values shown in Figure 4, the low frequency only varies ±10% from its median value of 0.42 Hz. In contrast,

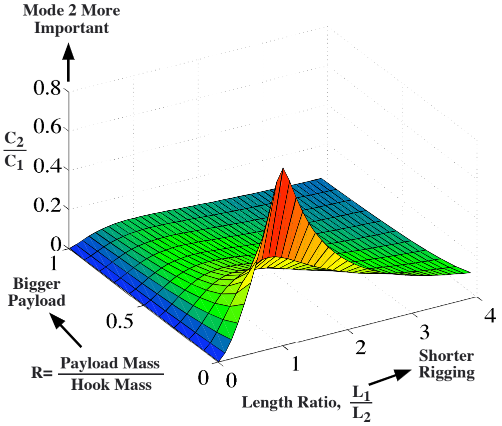


Figure 5. Ratio of High-Mode Amplitude to Low-Mode Amplitude when $L_1 + L_2 = 1.8m$.

the second mode deviates ±34% over the same parameter range.

These results seem to indicate that an oscillation control scheme would need more robustness to variations in the second mode than in the first mode. However, if the amplitude of the second mode is very small compared to the amplitude of the first mode, then the controller does not need to address the second-mode. The relative contribution of the two modes can be examined by breaking the overall dynamic response into components arising from ω_1 and ω_2.

If we assume small angles, then the payload response from a series of impulses, A_j, can be expressed as [8]:

$$x(t) = C_1 sin(\omega_1 + \psi_1) + C_2 sin(\omega_2 + \psi_2) \tag{4}$$

where,

$$C_1 = \frac{\omega_1 L_1 \left(1 + \omega_2^2 \alpha (L_1 + L_2)\right)}{k} * \sqrt{\left(\sum_{j=1}^{n} A_j cos(\omega_1 t_j)\right)^2 + \left(\sum_{j=1}^{n} A_j sin(\omega_1 t_j)\right)^2} \tag{5}$$

$$C_2 = \frac{\omega_2 L_1 \left(1 + \omega_1^2 \alpha (L_1 + L_2)\right)}{k} * \sqrt{\left(\sum_{j=1}^{n} A_j cos(\omega_2 t_j)\right)^2 + \left(\sum_{j=1}^{n} A_j sin(\omega_2 t_j)\right)^2} \tag{6}$$

$$\alpha = \frac{-g(1+R)}{\omega_1^2 \omega_2^2 L_1 L_2}, \quad and \quad k = \beta L_1 g \tag{7}$$

The coefficients, C_1 and C_2, indicate the contributions of each mode to the overall response. Given $\omega_1 \neq \omega_2$, the maximum amplitude is found by adding the maximum amplitudes due to each frequency:

$$V_{max} = |C_1| + |C_2| \tag{8}$$

Using this decomposition, the contribution of the second mode to the overall vibration becomes apparent and indicates when single-mode input shaping might be an insufficient solution. Figure 5 shows the ratio of the high-mode contribution to the low-mode contribution for a large range of length and mass ratios, again assuming an overall length of 1.8 m. The surface indicates that double-pendulum input shaping will be necessary for systems with low payload-to-hook mass ratios. The second mode contribution is particularly large when the suspension and rigging lengths are approximately equal.

III. INPUT SHAPING FOR DOUBLE PENDULUMS

When the second mode causes the payload oscillation to exceed tolerable levels, it must be taken into account when designing an input shaper. There are a number of methods for designing multi-mode input shapers [19]–[22]. In this section, a technique is developed to suppress the two frequencies of a double-pendulum crane. Furthermore, the technique is made robust to any expected variation in the two modes.

We can use (8) as a design constraint by requiring that the maximum residual vibration amplitude, V_{max}, be less than some tolerable threshold, V_{tol}. In the limiting case, when V_{tol} is set equal to zero at two frequencies, ω_1 and ω_2, the constraints are equivalent to the two-mode Zero Vibration (ZV) constraints previously presented in the literature [19], [20]. It has been shown that robustness can be improved if the vibration is limited to a small value, rather than forced to be exactly zero [23]. Therefore, the benefit of (8) for input shaper design is realized when the residual vibration is not forced to zero, but rather to some acceptable level:

$$V_{tol} \geq V_{max} = |C_1| + |C_2| \tag{9}$$

The vibration caused by an input shaper can be limited by (9). However, if the input shaper impulse amplitudes are not constrained, their values can range between positive and negative infinity. There are two possible solutions to this problem: limit the magnitude of the impulses to less than a specific value or require all the impulses to have positive values. To streamline the discussion, the shapers in this paper will contain only positive impulses:

$$A_i > 0, \qquad i = 1, ..., n \tag{10}$$

where n is the number of impulses in the shaper. If negative impulses are allowed, then the rise time will improve, but potential drawbacks such as excitation of unmodeled high modes and actuator saturation must be addressed. Techniques for managing the challenges of negative input shapers have been well documented [24]. The engineer desiring the highest level of performance should combine the methods presented in this paper with the techniques for using negative impulses previously presented.

A second amplitude constraint must be enforced so that the shaped command reaches the desired setpoint; the impulse

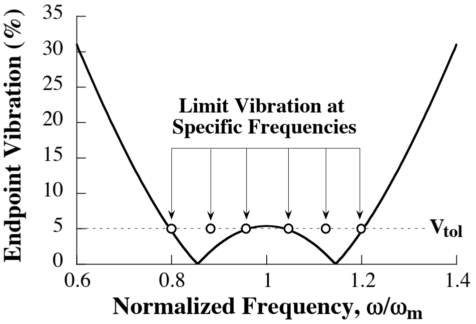


Figure 6. Frequency Sampling to Ensure Robustness.

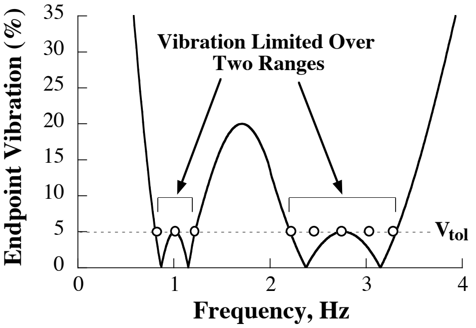


Figure 7. Frequency Sampling Over Two Ranges.

amplitudes must sum to one:

$$\sum_{i=1}^{n} A_i = 1 \tag{11}$$

The residual vibration constraint of (9) can be used to limit the vibration at a single set of frequencies (ω_1 and ω_2). If the actual crane frequencies coincide with those used in (9) to design the shaper, then the oscillation will be eliminated. However, to ensure robustness to modeling errors and parameter variations, the oscillation must remain small over a range of frequencies. Robustness can be ensured by suppressing vibration at several points near the modeling frequency. This process, known as parameter sampling [25], is demonstrated in Figure 6 for a single mode system. In this case, the vibration has been limited at six frequencies near the model frequency, ω_m. Because this approach allows the designer to specify the frequency range over which the vibration is suppressed, the resulting shapers are called Specified Insensitivity (SI) shapers [25]. Given a double-pendulum crane, we must extend the single-mode SI method by placing vibration constraints over frequency ranges near both of the expected frequencies. This approach is illustrated in Figure 7 for a case where modes near 1 Hz and 2.5 Hz are suppressed.

A. *Solution Procedure*

Due to the transcendental nature of the residual oscillation equations, there are an infinite number of solutions. To select among these solutions and ensure that the rise time is as fast as possible, the shaper duration must be made as short as possible. Therefore, the final necessary design constraint minimizes the time of the final input shaper impulse.

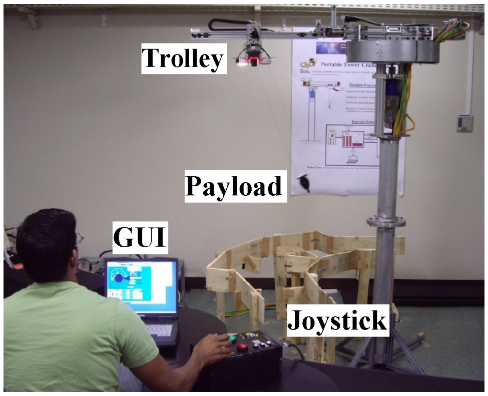


Figure 8. Portable Tower Crane.

To summarize, two-mode specified-insensitivity input shapers are designed by minimizing the shaper duration while enforcing (9) over two frequency ranges that contain the expected frequencies and satisfying (10) and (11). The input shapers designed for this paper were obtained using the MATLAB Optimization Toolbox.

IV. HUMAN OPERATOR STUDIES ON A TOWER CRANE

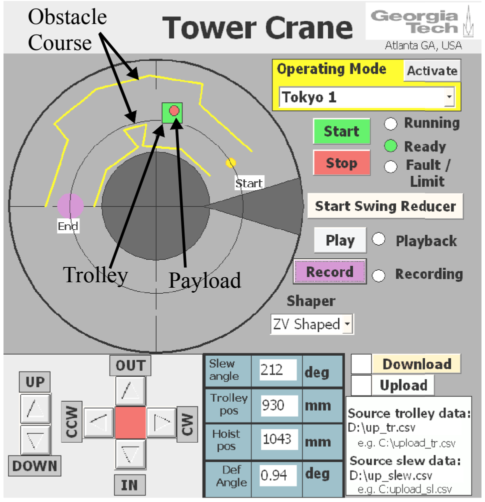
Past experiments with double-pendulums have shown the effectiveness of two-mode SI shaping for reducing residual oscillation of the crane payload [26]. However, the input-shaping process slightly modifies the human-generated commands. Therefore, it is important to study the effect of input shaping when human operators are driving the crane [15].

To investigate the human-compatibility issue, a series of experiments were conducted on a portable tower crane, shown in Figure 8, located at the Tokyo Institute of Technology. The crane can be driven using a joystick and push buttons or via a graphical user interface (GUI). The crane is driven by velocity commands that are sent to the crane's motors when an operator uses the joystick or the GUI.

A human operator drove a double-pendulum payload through an easy and a difficult obstacle course. Figure 9 shows the layout of the easy obstacle course, along with the crane control buttons on the GUI. The easy course was converted to the difficult course by narrowing the passages.

The movement of the payload is tracked by a camera attached to the crane trolley. As the crane is driven through the obstacle course, the position of the trolley and payload is shown on the GUI as a green square and a red circle, respectively. The operator can select different input shapers with the Shaper pull-down menu next to the lower right of the obstacle course. To remotely control the tower crane, the GUI can be accessed by any computer with an internet connection.

Experimental tests were conducted locally, where the human operator uses the joystick to control the tower crane in Tokyo. The operator drove the crane without shaping and then with shaping enabled. The local tests were repeated on



Operating Mode: Tokyo 1

Shaper: ZV Shaped

Slew angle: 212 deg

Trolley pos: 930 mm

Hoist pos: 1043 mm

Def Angle: 0.94 deg

Source trolley data:
D:\up_tr.csv
e.g. C:\upload_tr.csv

Source slew data:
D:\up_slew.csv
e.g. C:upload_sl.csv

Figure 9. GUI Showing Easy Obstacle Course.

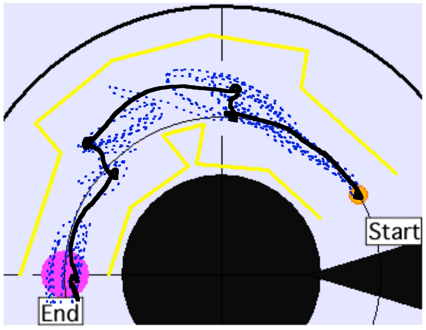


Figure 10. Local Operation on Easy Course.

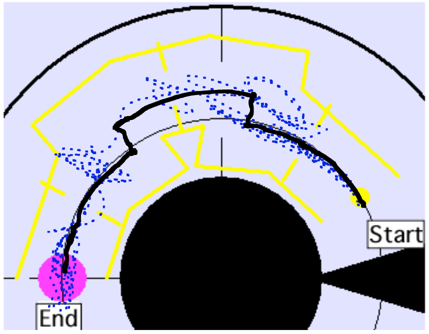


Figure 11. Remote Operation on Difficult Course.

the difficult course with and without shaping. The operator then returned to the United States and used the GUI on a computer in Atlanta to drive the tower crane.

Figure 10 shows the payload response when the crane was driven locally through the easy obstacle course. For these tests, the suspension length (L_1) was approximately 1.3 m and the rigging length (L_2) was approximately 0.5 m. The unshaped run is shown as a dotted line and the SI-shaped run as a solid line. Without input shaping, the oscillations of the double-pendulum payload were very complex and made the crane difficult to maneuver through the obstacle course. However, the SI shaper vastly improved the maneuvers of the payload, and the operator easily drove through the course with no collisions.

TABLE I. Average Completion Time for Easy Course.

	Payload	Local (sec)	Remote (sec)
Unshaped	Light	261	238
	Heavy	208	64
SI Shaped	Light	45	41
	Heavy	41	38

TABLE II. Average Collisions Per Operator.

	Payload	Local	Remote
Unshaped	Light	5.3	7.0
	Heavy	4.7	8.7
SI Shaped	Light	0.0	0.3
	Heavy	1.3	0.3

Figure 11 shows the position of the payload when the crane was driven remotely from Atlanta through the difficult course. The control problem was exacerbated by the internet time delay [27]. However, once again, the SI shaping nearly eliminated the oscillation and greatly simplified the manipulation task. Comparing the two figures, it is clear that the remote operation of the tower crane did not degrade the effectiveness of the SI input shaper. Note that without input shaping, there were numerous collisions with the obstacles.

To test the robustness of the input shaping control, additional human-operators tests were conducted on the easy course, shown in Figures 9 and 10. Similar to the first set of experiments, three operators drove the tower crane locally and remotely, but this time with two different payloads. The time to complete the course and the number of collisions were recorded. The course completion time began when the operator first pushed a button and stopped when the payload settled inside the END circle.

The average completion times for shaped and unshaped runs with the two payloads are shown in Table I. For both local and remote operation, the time to complete the easy course without shaping is much longer than with shaping. Obviously, the operators had difficulty driving the crane through the course without exciting the two frequencies and colliding with obstacles. When shaping was enabled, the operators easily drove the crane through the course. Furthermore, the course completion time for remote operation was similar to that of local operation when input shaping was enabled. However, the completion time without shaping was shorter for remote operation than local operation. This was probably the result of more aggressive and reckless driving when the operators were remotely driving the crane. This is suggested by the number of collisions discussed in the following paragraph.

The number of collisions per operator is shown in Table II. When input shaping was enabled, the number of collisions decreased dramatically. However, more collisions were recorded for remote operation than local. This effect can partially be attributed to the time delay of the payload position signal being sent to the operator and another delay of the operator's response signal being sent back to the crane.

TABLE III. Average Deflection of Hook.

	Payload	Local (cm)	Remote (cm)
Unshaped	Light	8.9	9.3
	Heavy	7.5	6.9
SI Shaped	Light	1.9	2.6
	Heavy	2.1	1.8

This time delay inhibits the operator's ability to make quick corrective actions. Also, because the operator could not see the actual course and crane payload, they drove aggressively through the course. They could not really see or feel the collisions. This also explains the result of shorter completion times for remote operation. However, when input shaping was enabled, the number of collisions were similar for local and remote operation. Therefore, input shaping alleviates some of the negative effects of the tele-operation delay.

Table III shows the average deflection of the hook. The deflection of the hook decreased when input shaping was enabled for both local and remote operation. However, there was no significant difference in hook deflection between the local and remote operation.

V. CONCLUSIONS

For certain payloads and rigging configurations, cranes can exhibit important double-pendulum dynamics. The second mode becomes important when the mass of the hook is significant when compared to the mass of the payload. Furthermore, the second mode contribution is maximized when the suspension length and rigging length are equal. When the second mode is important, an input shaper can be designed to suppress the multi-mode vibration. Furthermore, the input shaper can be made robust to modeling errors and parameter variations by suppressing a range of possible frequencies or anticipated parameter variations. Operator studies on a portable tower crane showed that when input shaping was enabled, throughput increased and the number of collisions decreased. For remote operation, the course was more difficult to complete and there were more collisions than for local operation. However, when input shaping was enabled, the completion time and number of collisions were similar to local operation. As a result, input shaping was shown to be effective and practical for both local and tele-operation of double-pendulum cranes.

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