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# Frequency-Modulation Input-Shaping Strategy for Double-Pendulum Overhead Cranes Undergoing Simultaneous Hoist and Travel Maneuvers

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**ABSTRACT** Large payloads hoisted by overhead cranes exhibit the same behavior as that of a double-pendulum. Changes in the hoisting cable length during payload transfer maneuvers give rise to time-dependent system frequencies rendering input-shaped commands ineffective. In this paper, a frequency-modulation input-shaping strategy that enables simultaneous hoist and travel maneuvers using single-mode input-shaping is presented. This strategy utilizes model-based feedback and partial feedback linearization techniques. Simulations are carried out using arbitrary travel and hoist commands combined with the common single-mode zero-vibration (ZV) and zero-vibration-derivative (ZVD) input-shapers. Sensitivity analysis reveals robust performance in the presence of high system uncertainties.

**INDEX TERMS** Frequency-modulation, input-shaping, double-pendulum, overhead crane, model-based feedback, partial feedback linearization.

## I. INTRODUCTION

Research on control of payload oscillations has been mostly based on simple-pendulum models of cranes [1], [2]. Controllers for the different types of cranes are developed based on this model [3]–[6]. However, For certain payloads and rigging configurations, cranes can exhibit significant double-pendulum dynamics. This double-pendulum behavior can be clearly observed in cases where the mass of the hook is significant compared to the mass of the payload [7]–[11]. It is also the case when the dimensional size of the payload is significant compared to the length of the hoisting cable [12], [13].

When a crane payload behaves like a single-pendulum, a skilled crane operator can reduce or eliminate most of the payload oscillations [14], [15]. However, when a crane payload behaves like a double-pendulum, manual methods of eliminating oscillations become very difficult, even for the most experienced operators. This complex behavior triggered a shift in the research on crane control towards cranes with double-pendulum behavior [11]–[14], [16]–[18].

A straight forward approach to tackle the double-pendulum behavior is to complement a simple-pendulum controller

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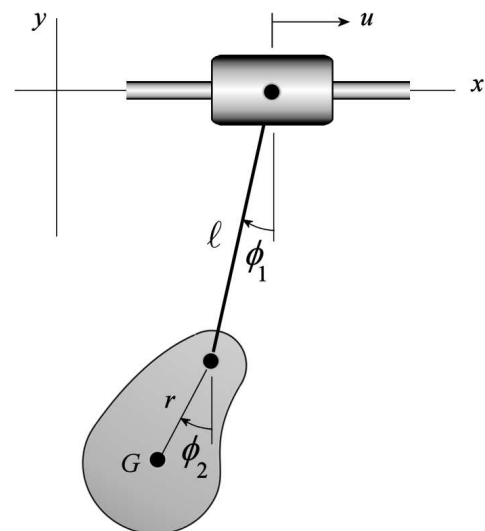


FIGURE 1. Double-pendulum model of an overhead crane.

with a second feedback controller to suppress second mode oscillations [19]–[21]. However, this approach requires extra hardware components, some of which are expensive and

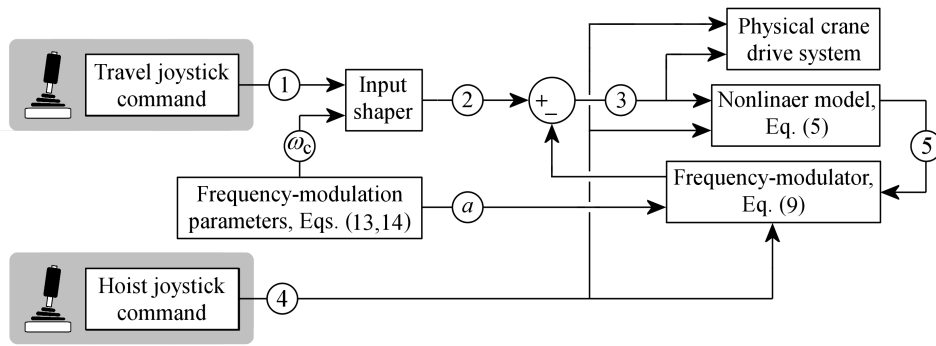


FIGURE 2. Schematic block diagram of the frequency-modulation system.

TABLE 1. Crane parameters.

Crane parameter	Maximum value
Jib acceleration	1 m/s <sup>2</sup>
Jib velocity	2 m/s
Hoisting acceleration	1 m/s <sup>2</sup>
Hoisting velocity	2 m/s
Hoisting cable length	20 m

challenging to implement. Other approaches are based on feedback control [21], proportional-integral-derivative (PID) control [18], and adaptive tracking control [22]. Open-loop control methods remain the most attractive and cost effective control approach. To develop an effective open-loop controller, the control approach should be able to handle both modes of oscillations of the double-pendulum simultaneously.

Command shaping is one of the most suitable open-loop control approaches for such application. Command shaping approach is based on using carefully designed command profiles to the crane actuators that would mitigate their own inertia-excited oscillations. Command shaping techniques can be classified into two categories; pre-shaped profiles [23] and operator-in-the-loop command shaping. Pre-shaped profiles vary from a simple two-step command introduced by Smith [24], [25] to the continuous waveform commands recently introduced by Alhazza and Masoud [26]–[28]. Operator-in-the-loop command shaping is widely known as input-shaping, which is one of the most widely used command shaping techniques. Input-shaping reduces the residual vibrations by convolving a sequence of carefully timed impulses with a general reference command signal.

Single-mode and multimode input-shaping systems have been extensively researched [29], [30]. Single-mode input-shapers are easier to implement, however, for the double-pendulum crane application, the more complex multimode input-shaping is used [7], [11], [14], [16], [17], [28], [31]. To enable the use of simple single-mode input-shapers for double-pendulum cranes, model-based feedback techniques have been developed such as the frequency-modulation input-shaping technique introduced

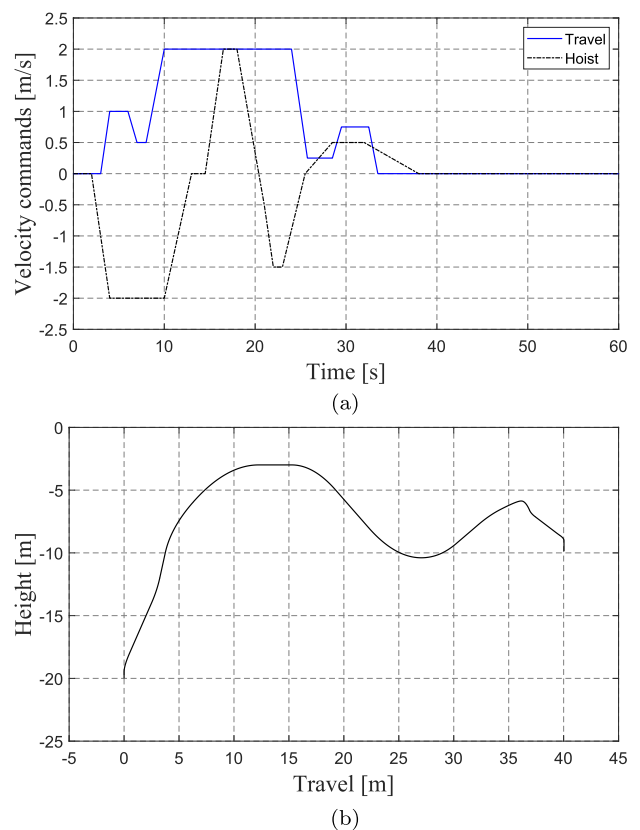


FIGURE 3. Illustrative transfer maneuver: (a) Travel and hoist velocity commands and (b) payload trajectory.

by Masoud *et al.* [12], [13]. The approach is based on the concept introduced by Singh and Hepler [32], which showed that a simple single-mode input-shapers can be used to eliminate vibrations in multimode systems provided that all ratios of the component mode frequencies to the design frequency of the input-shaper are odd and coprime. Model-based feedback is used to modulate the system frequencies to satisfy this condition.

Command-shaping control of cranes becomes more complex when simultaneous travel and hoist maneuvers

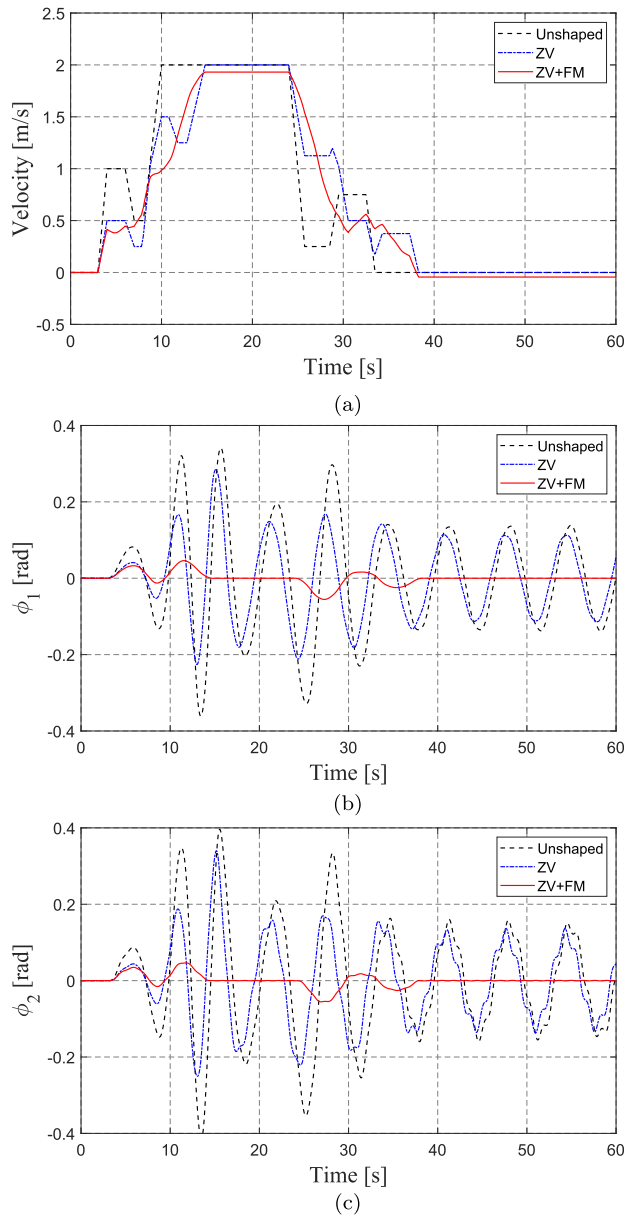


FIGURE 4. Transfer maneuver using ZV-FM shaper: (a) velocity commands, (b) and (c) oscillation angles.

are involved. Several methods have been proposed to produce shaped commands for crane maneuvers involving simultaneous travel and hoist including average operating frequency input-shaping [33], graphical profile generation [34], partial feedback linearization (PFL) [35], [36], wave-form profiles [27], iterative learning control [37], discrete-time command profiles [38], and output-based command shaping (OCS) techniques [39]. Others used the concept of equivalent frequency and the equivalent damping ratio to take into account the variable hoist length for optimal path planning [40]. Most recently, an adaptive Kalman filter has been used to account for unmodeled disturbances such as friction in a model-based feedback crane control system [41].

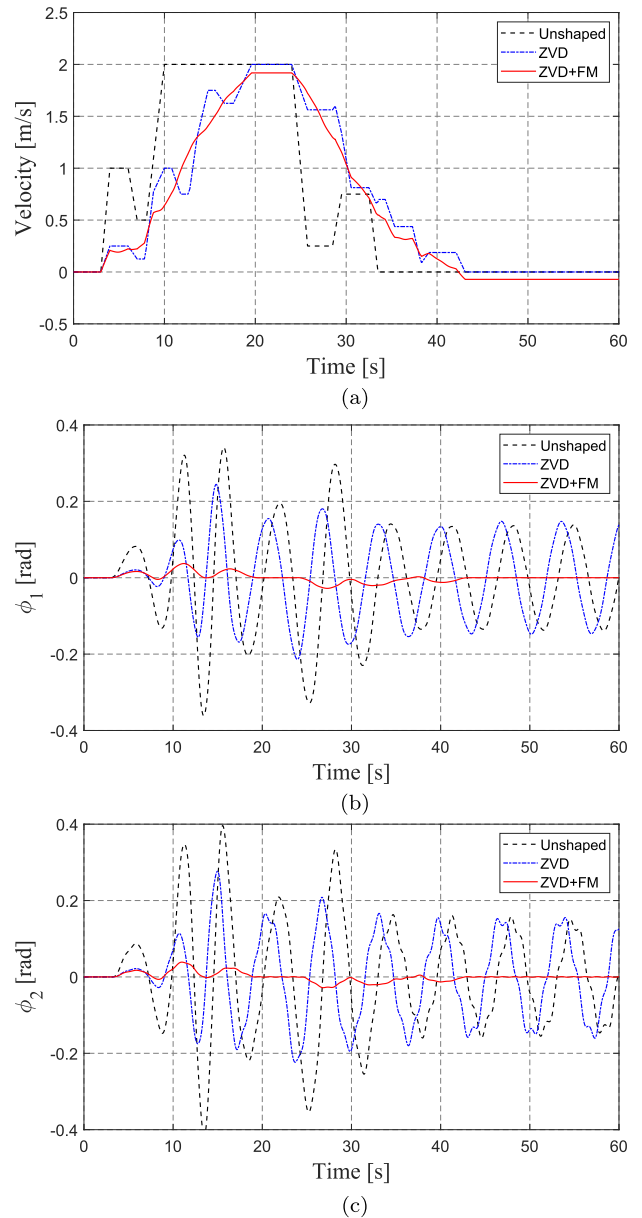


FIGURE 5. Transfer maneuver using ZVD-FM shaper: (a) velocity commands, (b) and (c) oscillation angles.

Arabasi and Masoud [42] presented a frequency-modulation input-shaping control scheme that allows for simultaneous hoist and travel maneuvers of simple-pendulum overhead cranes. The approach is based on the use of model-based feedback to match the simple-pendulum frequency to a single-mode input-shaper.

In this work, a frequency-modulation (FM) input-shaping strategy is presented for a double-pendulum crane. While the FM modulation approach for a double-pendulum crane has been presented earlier [13], the work did not address the situation of cranes undergoing simultaneous hoist and travel maneuvers, which is the main goal of this work. The FM technique uses model-based feedback with partial

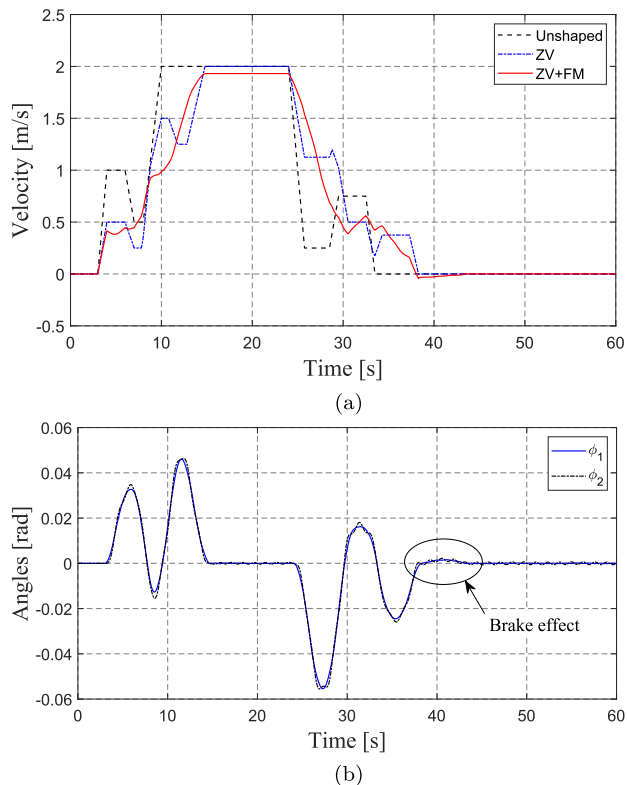


FIGURE 6. Transfer maneuver using ZV-FM shaper with braking: (a) velocity commands and (b) oscillation angles.

feedback linearization. The frequency-modulation stage is used to derive a design frequency such that both ratios of the double-pendulum frequencies to this design frequency are odd and coprime. Satisfying this condition enables the use of single-mode input-shaping to eliminate vibrations in both modes of the double-pendulum. The FM technique is used in conjunction with a primary single-mode input-shaper tuned to the derived design frequency. Different types of single-mode input-shapers can be utilized as primary input-shapers for the FM input-shaping strategy. The FM input-shaping strategy is simulated using primary zero-vibration (ZV) and zero-vibration-derivative (ZVD) input-shapers. It is important to emphasize that the main goal of the proposed FM input-shaping strategy is to facilitate the use of single-mode input-shaping techniques for a time-varying double-pendulum crane. The FM input-shaping strategy is nearly as fast and as robust as the primary input-shaping technique itself.

## II. MATHEMATICAL MODEL

The overhead crane is modeled here as a double-pendulum with a variable length hoisting cable, as shown in Fig. 1. The payload of the crane is modeled as a rigid body of mass  $m$  attached to the end of a massless inextensible rigid cable of variable length  $\ell$ . The distance from the end of the cable to the center of gravity of the payload is  $r$ . The nonlinear equations of motion of the model are derived using the

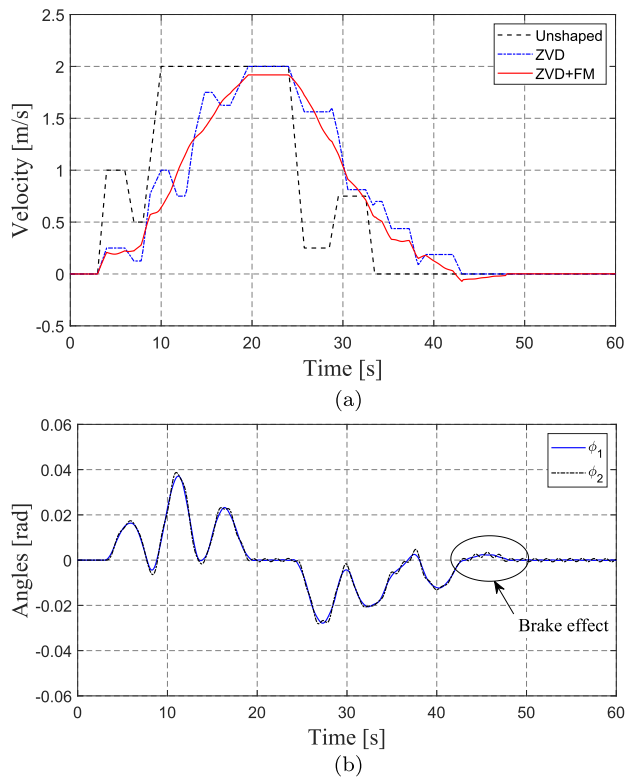


FIGURE 7. Transfer maneuver using ZVD-FM shaper with braking: (a) velocity commands and (b) oscillation angles.

Lagrangian approach. The position of the center of gravity of the payload changes according to

$$x = u - \ell \sin \phi_1 - r \sin \phi_2, \quad (1)$$

$$y = -\ell \cos \phi_1 - r \cos \phi_2, \quad (2)$$

where  $u$  is the motion of the crane jib. The kinetic and potential energies of the system are

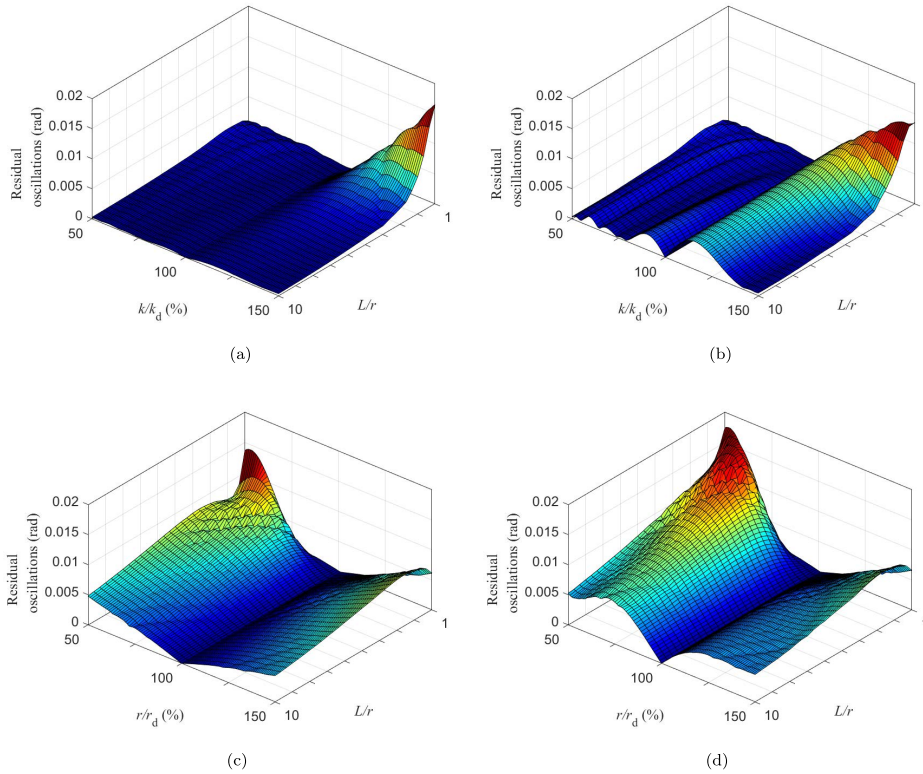
$$T = \frac{1}{2}m(\dot{u} - \dot{\ell} \sin \phi_1 - \ell \cos \phi_1 \dot{\phi}_1 - r \cos \phi_2 \dot{\phi}_2)^2 + \frac{1}{2}m(-\dot{\ell} \cos \phi_1 + \ell \sin \phi_1 \dot{\phi}_1 + r \sin \phi_2 \dot{\phi}_2)^2 + \frac{1}{2}J\dot{\phi}_2^2, \quad (3)$$

$$V = mg(-\ell \cos \phi_1 - r \cos \phi_2), \quad (4)$$

where  $J = mk^2$  is the mass moment of inertia of the payload, and  $k$  is its radius of gyration. The nonlinear equations of motion of the system are

$$\ddot{\phi}_1 + \frac{r}{\ell} \cos(\phi_1 - \phi_2) \ddot{\phi}_2 + 2\frac{\dot{\ell}}{\ell} \dot{\phi}_1 + \frac{r}{\ell} \sin(\phi_1 - \phi_2) \dot{\phi}_2^2 + \frac{g}{\ell} \sin \phi_1 = \frac{1}{\ell} \cos \phi_1 \ddot{u}, \quad (5a)$$

$$\frac{r}{\ell} \cos(\phi_1 - \phi_2) \ddot{\phi}_1 + \frac{k^2 + r^2}{\ell^2} \ddot{\phi}_2 + 2\frac{r\dot{\ell}}{\ell^2} \cos(\phi_1 - \phi_2) \dot{\phi}_1 - \frac{r}{\ell} \sin(\phi_1 - \phi_2) \dot{\phi}_1^2 + \frac{r\dot{\ell}}{\ell^2} \sin(\phi_1 - \phi_2) + \frac{gr}{\ell^2} \sin \phi_2 = \frac{r}{\ell^2} \cos \phi_2 \ddot{u}. \quad (5b)$$



**FIGURE 8.** Sensitivity of residual oscillations using ZV-shaped commands in (a)  $\phi_1$  and (b)  $\phi_2$  to uncertainties in  $k$ , and in (c)  $\phi_1$  and (d)  $\phi_2$  to uncertainties in  $r$ .

Using the small angle approximation in (5) yields the following simplified equations of motion

$$\ddot{\phi}_1 + \frac{r}{\ell}\ddot{\phi}_2 + 2\frac{\dot{\ell}}{\ell}\dot{\phi}_1 + \frac{g}{\ell}\phi_1 = \frac{1}{\ell}\ddot{u}, \quad (6a)$$

$$\begin{aligned} \frac{r}{\ell}\ddot{\phi}_1 + \frac{k^2 + r^2}{\ell^2}\ddot{\phi}_2 + 2\frac{r\dot{\ell}}{\ell^2}\dot{\phi}_1 \\ + \frac{r\ddot{\ell}}{\ell^2}\phi_1 + \frac{r}{\ell^2}(g - \ddot{\ell})\phi_2 = \frac{r}{\ell^2}\ddot{u}. \end{aligned} \quad (6b)$$

### III. FREQUENCY-MODULATION

Common multimode input-shapers are designed for a specific set of constant frequencies. When variable frequencies arise due to time-varying models, the input-shaper is designed based on an average values of the variable frequencies. In contrast, a frequency-modulation design is based on the actual values of the varying frequencies.

The goal of our FM input-shaping strategy is to derive a frequency ( $\omega_c$ ) using model-based feedback such that the frequencies of the feedback system satisfy the following:

$$\omega_1 = m_1\omega_c, \quad (7a)$$

$$\omega_2 = m_2\omega_c, \quad (7b)$$

where  $m_1$  and  $m_2$  are both odd and coprime. Having the conditions in (7) satisfied, conventional single-mode input-shaping using  $\omega_c$  as a design frequency, can be used to eliminate vibrations in both modes of the double-pendulum simultaneously [32].

Choosing  $m_1 = 1$  and  $m_2 = n$ , (7) becomes

$$\omega_1 = \omega_c, \quad (8a)$$

$$\omega_2 = n\omega_c, \quad (8b)$$

where  $n = 3, 5, \dots$  is an odd integer. Single-mode input-shapers are designed for a fixed design frequency. Therefore, a control law is required to eliminate the dependency of the model frequencies on the length of the cable and impose the condition in (8). To this end, we will suggest the following model-based feedback control system:

$$\ddot{u} = -(a - \ell)\ddot{\phi}_1 - b\dot{\ell}\dot{\phi}_1, \quad (9)$$

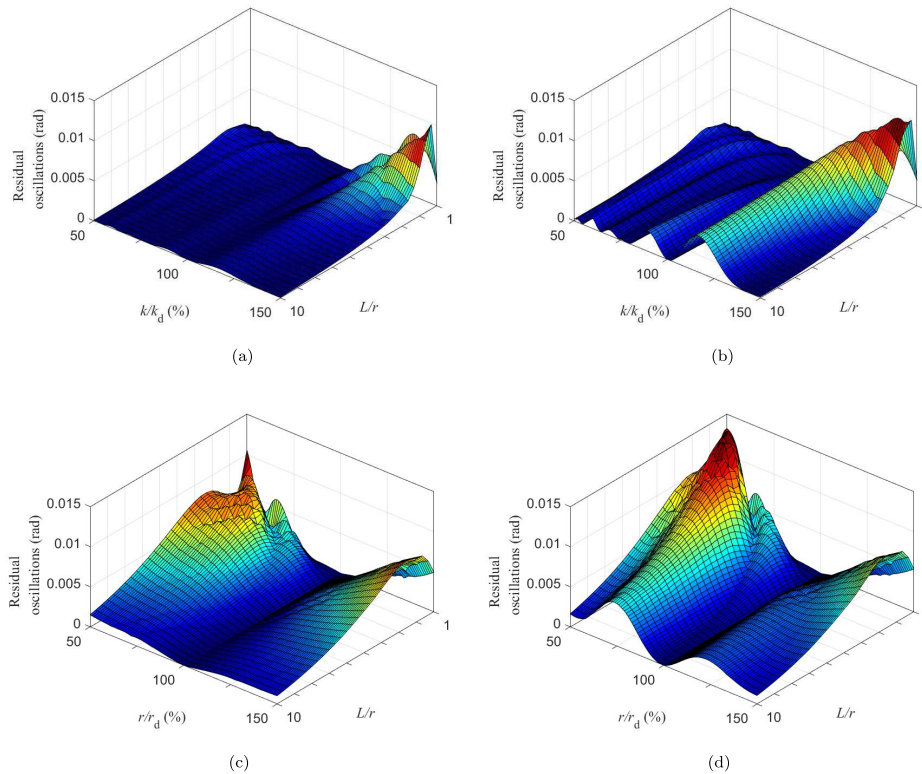
where  $a$  and  $b$  are control parameters. To further simplify (6), and since  $\ddot{\ell} \ll g$ , it can be dropped out without compromising the integrity of the simplified model. Applying the control law in (9) to the simplified equations of motion of the system yields

$$a\ell\ddot{\phi}_1 + \ell r\ddot{\phi}_2 + (2 + b)\ell\dot{\ell}\dot{\phi}_1 + \ell g\phi_1 = 0, \quad (10a)$$

$$ra\ddot{\phi}_1 + (r^2 + k^2)\ddot{\phi}_2 + (2 + b)r\dot{\ell}\dot{\phi}_2 + g r\phi_2 = 0. \quad (10b)$$

Setting the  $b$  parameter to  $b = -2$ , will eliminate the nonlinear damping term  $\dot{\ell}\dot{\phi}_1$ . Substituting this value of the parameter  $b$  in (10), the characteristic equation of the system becomes

$$\lambda^2 - \frac{k^2 + r^2 + ar}{ak^2}g\lambda + \frac{rg^2}{ak^2} = 0. \quad (11)$$



**FIGURE 9.** Sensitivity of residual oscillations using ZVD-shaped commands in (a)  $\phi_1$  and (b)  $\phi_2$  to uncertainties in  $k$ , and in (c)  $\phi_1$  and (d)  $\phi_2$  to uncertainties in  $r$ .

Imposing the condition (8), the characteristic equation must satisfy the form

$$\lambda^2 - (n^2 + 1)\omega_c^2\lambda + n^2\omega_c^4 = 0. \quad (12)$$

Equating corresponding coefficients in (11) and (12), closed form solutions for the controller parameter  $a$  and the frequency  $\omega_c$  can be derived as

$$\omega_c^2 = \frac{rg \left( n^2 + 1 \pm \sqrt{(n^2 - 1)^2 - 4r^2n^2/k^2} \right)}{2n^2(k^2 + r^2)}, \quad (13)$$

$$a = \frac{rg^2}{n^2\omega_c^4k^2}. \quad (14)$$

It can be observed that the design frequency  $\omega_c$  is independent of the cable length, which results in a constant value for any given crane maneuver. This is a necessary condition for using conventional single-mode input-shaping techniques.

A block diagram describing the implementation of the FM technique on an input-shaped manually operated crane is shown in Fig. 2. The raw command of the travel joystick (Signal 1) is passed through the input shaper to produce the shaped command (Signal 2). The shaped signal is passed to the model-based FM loop. Since the input-shaper is tuned to the design frequency ( $\omega_c$ ) of the FM loop, residual oscillations in the output of the FM loop are eliminated. The FM command signal (Signal 3) of the FM loop is then used

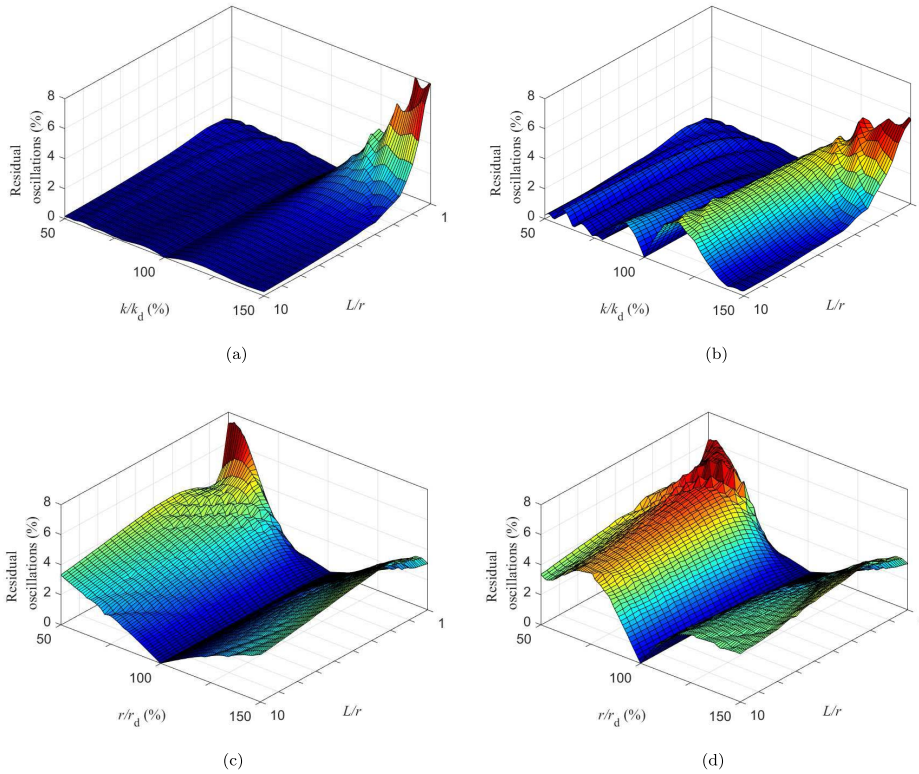
to drive the actual physical crane. Since the FM command eliminates residual oscillations of the nonlinear model in the FM loop (Signal 5), it will not excite residual oscillations in the physical system as well. The feedback command of the frequency modulator (9) receives hoisting information directly from the hoist joystick (Signal 4).

A major advantage in the proposed FM technique is that the design frequency ( $\omega_c$ ) of the modulated system, and the feedback gains ( $a$  and  $b$ ) of the model-based feedback loop are independent of the payload states and the crane maneuver commands and are fixed throughout the different crane maneuvers. The FM parameters are also independent of the input-shaping technique used. The frequency-modulation is performed simultaneously with the input-shaping process leading to seamless and uninterrupted crane operation.

#### IV. ILLUSTRATIVE EXAMPLE

To illustrate the performance of the proposed control strategy, an example will be demonstrated. The crane parameters are listed in Table 1. Numerical simulations are performed using the full nonlinear model of the double-pendulum crane in (5). A 3-m long rod is used to simulate the payload of the crane. The rod is hoisted from one of its ends in a vertical orientation allowing it to swing freely.

The frequency ratio of the uncontrolled double-pendulum model at the maximum cable length of 20 m, rounded to



**FIGURE 10.** Percentage sensitivity of residual oscillations using ZV-shaped commands in (a)  $\phi_1$  and (b)  $\phi_2$  to uncertainties in  $k$ , and in (c)  $\phi_1$  and (d)  $\phi_2$  to uncertainties in  $r$ .

the nearest odd integer, is used as the design frequency ratio  $n$ . The choice of using the maximum cable length for determining the design frequency ratio is not a necessary condition for the proposed FM technique. However, this decision is made only to obtain a slower design frequency for smoother crane operations. The natural frequencies of the double-pendulum model at the maximum cable length are 0.675 rad/s and 4.59 rad/s. The frequency ratio is 6.81 which is rounded up to  $n = 7$  for the required design frequency ratio.

Using (13), we calculated the design frequency to be  $\omega_c = 0.655$  rad/s. This frequency will be used as the base frequency for the input-shapers used in this example. We calculated the feedback gain  $a$ , using (14), to be 21.32. For the sake of this example, we will use two of the most common single-mode input-shapers, namely; the zero-vibration (ZV) and zero-vibration-derivative (ZVD) input-shapers.

The impulse amplitude and the impulse time of the ZV and ZVD input-shapers [29] are

$$ZV = \begin{bmatrix} A_i \\ t_i \end{bmatrix} = \begin{bmatrix} \frac{1}{1+K} & \frac{K}{1+K} \\ 0 & \frac{1}{2}\tau_d \end{bmatrix}, \quad (15)$$

$$ZVD = \begin{bmatrix} A_i \\ t_i \end{bmatrix}$$

$$= \begin{bmatrix} \frac{1}{1+2K+K^2} & \frac{2K}{1+2K+K^2} & \frac{K^2}{1+2K+K^2} \\ 0 & \frac{1}{2}\tau_d & \tau_d \end{bmatrix}, \quad (16)$$

where  $A_i$  is the impulse amplitude,  $t_i$  is the impulse time,  $\tau_d$  is the damped period of oscillation, and

$$K = e^{-\zeta\pi\sqrt{1-\zeta^2}}, \quad (17)$$

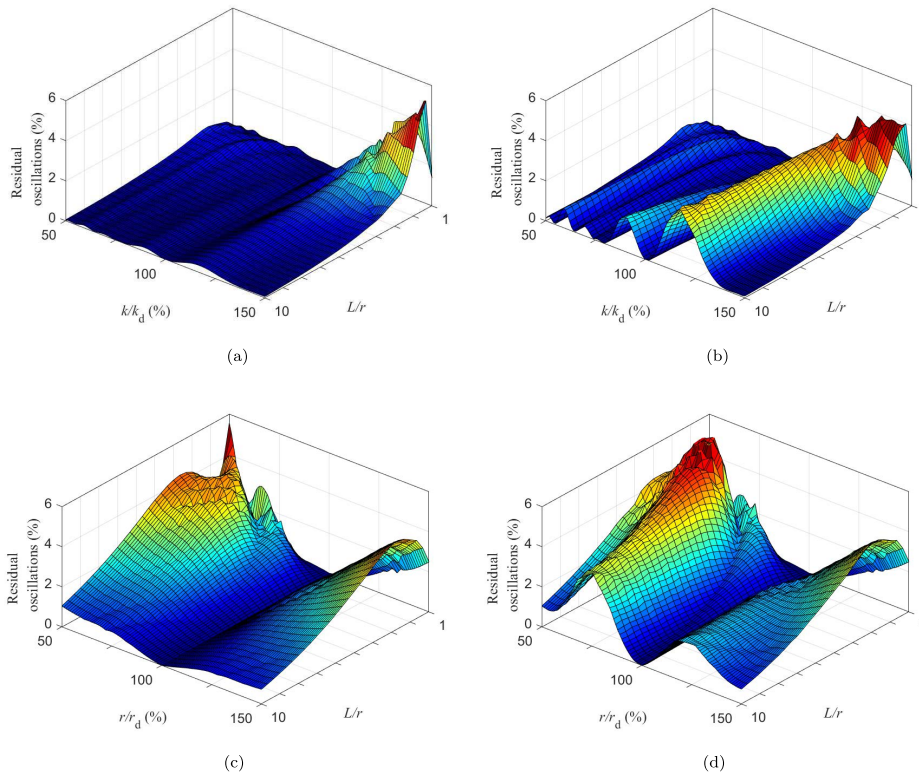
where  $\zeta$  is the damping ratio. Since the damping term has been eliminated by the control law, leading to  $K = 1$ . Therefore, shapers' impulse matrices become

$$ZV = \begin{bmatrix} 0.5 & 0.5 \\ 0 & 4.8 \end{bmatrix}, \quad (18)$$

$$ZVD = \begin{bmatrix} 0.25 & 0.5 & 0.25 \\ 0 & 4.8 & 9.6 \end{bmatrix}. \quad (19)$$

A transfer maneuver simulating harsh joystick operator travel and hoist commands is presented in this example. The maneuver involves arbitrary hoisting between the 20-m and 3-m levels below the jib of the crane. All while performing a 40-m travel maneuver with an arbitrary velocity joystick command (Fig. 3(a)). The resulting payload motion trajectory is shown in Fig. 3(b).

The travel velocity command (Signal 1 in Fig. 2), the ZV shaped command (Signal 2 in Fig. 2), and the



**FIGURE 11. Percentage sensitivity of residual oscillations using ZVD-shaped commands in (a)  $\phi_1$  and (b)  $\phi_2$  to uncertainties in  $k$ , and in (c)  $\phi_1$  and (d)  $\phi_2$  to uncertainties in  $r$ .**

frequency-modulated ZV command (Signal 3 in Fig. 2), are shown in Fig. 4(a). The hoisting command (Signal 4 in Fig. 2) is not altered and is shown in Fig. 3(a).

MATLAB Simulink environment was used to construct the nonlinear model of the crane in (5) and implement the FM input-shaping process.

The FM-ZV process has a smoothing effect on the velocity command as can be seen in Fig. 4(a), which reduces jerks in the jib motion. In addition, frequency modulation does not add any delay to the joystick commands. The delay between the joystick command and the FM-ZV command is only due to the time added by the ZV input shaper. The oscillation angles of the hoisting cable  $\phi_1$  and the payload  $\phi_2$  in Fig. 4(b) and (c), are significantly reduced (approximately 85% reduction).

The transfer maneuver is repeated using the ZVD input-shaping matrix, (19). Simulation results are shown in Fig. 5. Similar performance is achieved. By design, ZVD introduces a one-period time delay between the unshaped and shaped signal. This is to emphasize that frequency modulation does not add any time delay.

A small residual jib velocity is observed, Fig. 4(a) and Fig. 5(a). This residual velocity causes a small drift in the jib position. This residual velocity is attributed to the fact that the feedback in the FM loop does not always integrate to zero.

This residual velocity can be eliminated by applying brakes at the end of the transfer maneuver. However, the

braking action may excite residual oscillations in the payload. To avoid exciting residual oscillations, the braking action applied is shaped according to the used input-shaping method, i.e., it is applied as a sequence of braking impulses. This split braking action is common in many applications. Fig. 6 and Fig. 7 show how braking eliminates the velocity drift which appears in Fig. 4(a) and Fig. 5(a), without compromising the performance of the FM system.

## V. SENSITIVITY ANALYSIS

In normal crane operations, payloads may vary in size and shape. Consequently, the location of the center of mass,  $r$ , and the radius of gyration,  $k$ , of the payload may vary significantly. Estimated values may include a large degree of uncertainty. Therefore, and since the FM gain,  $a$ , and the design frequency,  $\omega_c$ , of the modulated system depend mainly on those parameters, it is essential that a sensitivity analysis is carried out to determine the extent of the impact of uncertainties in the payload parameters on the performance stability and robustness of the proposed FM input-shaping strategy.

In this section, residual oscillations in the payload and hoisting cable angles are studied for a wide range of uncertainties in  $r$  and  $k$ . Errors are introduced in the estimated values of  $r$  and  $k$  up to  $\pm 50\%$  of the design values that are used to determine the FM parameters. The cable length is varied from one to ten times the value of  $r$ .



The ZV input-shaping technique is known to be the least robust of the input-shaping techniques. Nevertheless, residual oscillations in both the hoisting cable and the payload angles using the proposed FM input-shaping strategy remain below  $1^\circ$  across the complete range of the introduced errors and for all cable lengths used, as shown in Fig. 8. Residual oscillations are most sensitive to uncertainties for short cable lengths. It is also observed that the residual oscillations are less sensitive to variations in the radius of gyration,  $k$ , than they are to the location of the center of mass,  $r$ , even beyond the shown  $\pm 50\%$  uncertainty range. This property of the FM input-shaping strategy is most convenient since determining an accurate estimate for the value of  $k$  requires more calculations than those required to determine the value of  $r$ . As a matter of fact, the model is tolerant to uncertainties in  $r$  and  $k$  that the load can be treated as a rod regardless of its shape. Alternatively, the parameters  $r$  and  $k$  of the load can be determined through many ways including, visual inspection or a camera system among other methods.

Using a ZVD input-shaper, the FM input-shaping strategy produces even lower residual oscillations than those in the case of a ZV shaper. This result was expected since the ZVD is a more robust input-shaping technique than the ZV shaper. Residual oscillations in both the hoisting cable and the payload angles remain below  $0.75^\circ$  across the complete range of introduced errors and for all cable lengths used, as shown in Fig. 9.

Fig. 10 shows a reduction of more than 90% in residual oscillation for the complete  $\pm 50\%$  error range, and more than 95% reduction in an error range of  $\pm 35\%$ , in both oscillation angles and for both payload parameters  $k$  and  $r$ . As for the case of a ZVD input-shaper, a reduction of more than 95% in residual oscillation for the complete  $\pm 50\%$  error range, as shown in Fig. 11.

## VI. CONCLUSION

Eliminating residual oscillations in multimode systems using input-shaping techniques requires the use of complex multimode techniques. Multimode input-shaping techniques are designed to eliminate residual oscillation at a predetermined set of discrete frequencies. The problem becomes more complicated when the frequencies of the multimode system are time-dependent as in the case of a double-pendulum crane with varying cable length presented in this work.

Single-mode input-shapers can be used to eliminate vibrations in multimode systems provided that there exists a design frequency such that all ratios of the component mode frequencies to that design frequency are odd and coprime. However, there are no guarantees that such a frequency exists. Using frequency-modulation, the system frequencies are modulated to the point where such a frequency is guaranteed to exist.

When it comes to dealing with time-dependent multimode systems, the proposed FM input-shaping strategy presented in this work shows two major advantages over traditional stand-alone multimode input-shaping techniques. The first advantage is that only a single-mode input-shaping technique

is required to eliminate oscillations in both modes of the double-pendulum crane. The second is that the FM system parameters are time-independent and do not have to be changed when the system frequencies change. This was demonstrated by simulations involving simultaneous travel and large and fast hoist maneuvers. Such advantages make the FM system simple to design and implement. Further, the fixed parameters advantage allows systems using input-shaping techniques to function seamlessly with operator in the loop.

The FM input-shaping strategy is independent of whichever primary input-shaping technique used. As a matter of fact, the response of the system is as robust as the primary input-shaping technique used. Thorough robustness analysis revealed very low sensitivity to uncertainties in the system parameters, namely payload size and shape.

Although the model presented in this paper is a double-pendulum crane system, the method can be extended to most time-dependent underactuated multimode systems. The model presented is, merely, an illustrative example of how the FM input-shaping method can be applied to such systems.

## REFERENCES

- [1] Z. Zrnić, P. Zoran, and S. Bošnjak, "Automation of ship-to-shore container cranes: A review of state-of-the-art," *FME Trans.*, vol. 33, no. 3, pp. 111–121, 2005.
- [2] E. M. Abdel-Rahman, A. H. Nayfeh, and Z. N. Masoud, "Dynamics and control of cranes: A review," *J. Vib. Control*, vol. 9, no. 7, pp. 863–908, Jul. 2003.
- [3] Z. Masoud, A. Nayfeh, and A. Al-Mousa, "Delayed position-feedback controller for the reduction of payload pendulations of rotary crane," *J. Vib. Control*, vol. 9, pp. 257–277, Jan. 2003.
- [4] Z. N. Masoud, A. H. Nayfeh, and D. T. Mook, "Cargo pendulation reduction of ship-mounted cranes," *Nonlinear Dyn.*, vol. 35, no. 3, pp. 299–311, 2004.
- [5] Z. N. Masoud, M. F. Daqaq, and N. A. Nayfeh, "Pendulation reduction on small ship-mounted telescopic cranes," *J. Vib. Control*, vol. 10, no. 8, pp. 1167–1179, Aug. 2004.
- [6] Z. N. Masoud, A. H. Nayfeh, and N. A. Nayfeh, "Sway reduction on quay-side container cranes using delayed feedback controller: Simulations and experiments," *J. Vib. Control*, vol. 11, no. 8, pp. 1103–1122, Aug. 2005.
- [7] M. Kenison and W. Singhose, "Input shaper design for double-pendulum planar gantry cranes," in *Proc. IEEE Int. Conf. Control Appl.*, Kohala Coast, HI, USA, Aug. 1999, pp. 539–544.
- [8] T. H. Hsu, "Control of a chaotic double pendulum model for a ship mounted crane," Ph.D. dissertation, Dept. Eng. Mech., Virginia Polytech. Inst. State Univ., Blacksburg, VA, USA, 2000.
- [9] D. Liu, W. Guo, and J. Yi, "GA-based composite sliding mode fuzzy control for double-pendulum-type overhead crane," in *Proc. 2nd Int. Conf. Fuzzy Syst. Knowl. Discovery*, Changsha, China, 2005, pp. 792–801.
- [10] D. Kim and W. Singhose, "Reduction of double-pendulum bridge crane oscillations," in *Proc. 8th Int. Conf. Motion Vib. Control*, Daejeon, South Korea, 2006, pp. 300–305.
- [11] M. A. Ahmad, R. M. T. Raja Ismail, M. S. Ramli, and N. Hambali, "Investigations of NCTF with input shaping for sway control of a double-pendulum-type overhead crane," in *Proc. 2nd Int. Conf. Adv. Comput. Control ((ICACC))*, Shenyang, China, 2010, pp. 456–461.
- [12] Z. Masoud, K. Alhazza, E. Abu-Nada, and M. Majeed, "A hybrid command-shaper for double-pendulum overhead cranes," *J. Vib. Control*, vol. 20, no. 1, pp. 24–37, Jan. 2014.
- [13] Z. N. Masoud and K. A. Alhazza, "Frequency-modulation input shaping control of double-pendulum overhead cranes," *J. Dyn. Syst., Meas., Control*, vol. 136, no. 2, Mar. 2014, Art. no. 021005.
- [14] W. Singhose, D. Kim, and M. Kenison, "Input shaping control of double-pendulum bridge crane oscillations," *J. Dyn. Syst., Meas., Control*, vol. 130, no. 3, May 2008, Art. no. 034504.

- [15] D. Kim and W. E. Singhose, "Performance studies of human operators driving double-pendulum bridge cranes," *Control Eng. Pract.*, vol. 18, no. 6, pp. 567–576, Jun. 2010.
- [16] M. A. Ahmad, R. M. T. R. Ismail, M. S. Ramli, A. N. K. Nasir, N. A. Ghani, and N. H. Noordin, "Comparison of input shaping techniques for sway suppression in a double-pendulum-type overhead crane," in *Proc. 3rd UKSim Eur. Symp. Comput. Modeling Simulation*, 2009, pp. 321–326.
- [17] J. Vaughan, D. Kim, and W. Singhose, "Control of tower cranes with double-pendulum payload dynamics," *IEEE Trans. Control Syst. Technol.*, vol. 18, no. 6, pp. 1345–1358, Nov. 2010.
- [18] H. I. Jaafar, Z. Mohamed, N. A. Mohd Subha, A. R. Husain, F. S. Ismail, L. Ramli, M. O. Tokhi, and M. A. Shamsudin, "Efficient control of a non-linear double-pendulum overhead crane with sensorless payload motion using an improved PSO-tuned PID controller," *J. Vib. Control*, vol. 25, no. 4, pp. 907–921, Feb. 2019.
- [19] S. Tanaka and S. Kouno, "Automatic measurement and control of the attitude of crane lifters: Lifter-attitude measurement and control," *Control Eng. Pract.*, vol. 6, no. 9, pp. 1099–1107, 1998.
- [20] S. Lahres, H. Aschemann, O. Sawodny, and E. P. Hofer, "Crane automation by decoupling control of a double pendulum using two translational actuators," in *Proc. Amer. Control Conf.*, vol. 2, 2000, pp. 1052–1056.
- [21] R. Mar, A. Goyal, V. Nguyen, T. Yang, and W. Singhose, "Combined input shaping and feedback control for double-pendulum systems," *Mech. Syst. Signal Process.*, vol. 85, pp. 267–277, Feb. 2017.
- [22] M. Zhang, X. Ma, X. Rong, X. Tian, and Y. Li, "Adaptive tracking control for double-pendulum overhead cranes subject to tracking error limitation, parametric uncertainties and external disturbances," *Mech. Syst. Signal Process.*, vols. 76–77, pp. 15–32, Aug. 2016.
- [23] N. Singer and W. Seering, "Preshaping command inputs to reduce system vibration," *ASME J. Dyn. Syst., Meas., Control*, vol. 112, no. 1, pp. 76–82, 1990.
- [24] O. J. M. Smith, "Posicast control of damped oscillatory systems," *Proc. IRE*, vol. 45, no. 9, pp. 1249–1255, Sep. 1957.
- [25] O. J. M. Smith, *Feedback Control Systems*. New York, NY, USA: McGraw-Hill, 1958.
- [26] K. A. Alhazza and Z. N. Masoud, "A novel wave-form command-shaping control with application on overhead cranes," in *Proc. ASME Dyn. Syst. Control Conf.*, Cambridge, MA, USA, Jan. 2010, pp. 331–336.
- [27] K. A. Alhazza, "Experimental and numerical validation on a continuous modulated wave-form command shaping control considering the effect of hoisting," in *Proc. ASME Int. Design Eng. Tech. Conf. (IDETC) Comput. Inf. Eng. Conf. (CIE)*, Aug. 2013, Art. no. V07AT10A057.
- [28] Z. N. Masoud and K. A. Alhazza, "A smooth multimode waveform command shaping control with selectable command length," *J. Sound Vib.*, vol. 397, pp. 1–16, Jun. 2017.
- [29] J. Vaughan, A. Yano, and W. E. Singhose, "Comparison of robust input shapers," *J. Sound Vib.*, vol. 315, nos. 4–5, pp. 797–815, Sep. 2008.
- [30] W. Singhose, "Command shaping for flexible systems: A review of the first 50 years," *Int. J. Precis. Eng. Manuf.*, vol. 10, no. 4, pp. 153–168, Oct. 2009.
- [31] W. Singhose, E. Crain, and W. Seering, "Convolved and simultaneous two-mode input shapers," *IEE Proc., Control Theory Appl.*, vol. 144, no. 6, pp. 515–520, Nov. 1997.
- [32] T. Singh and G. R. Heppler, "Shaped input control of a system with multiple modes," *J. Dyn. Syst., Meas., Control*, vol. 115, no. 3, pp. 341–347, Sep. 1993.
- [33] W. Singhose, L. Porter, M. Kenison, and E. Krikkku, "Effects of hoisting on the input shaping control of gantry cranes," *Control Eng. Pract.*, vol. 8, no. 10, pp. 1159–1165, 2000.
- [34] Z. N. Masoud and M. F. Daqaq, "A graphical approach to input-shaping control design for container cranes with hoist," *IEEE Trans. Control Syst. Technol.*, vol. 14, no. 6, pp. 1070–1077, Nov. 2006.
- [35] H. Park, D. Chwa, and K. Hong, "A feedback linearization control of container cranes: Varying rope length," *Int. J. Control Autom. Syst.*, vol. 5, no. 4, p. 379, 2007.
- [36] A. T. Le, S.-G. Lee, and S.-C. Moon, "Partial feedback linearization and sliding mode techniques for 2D crane control," *Trans. Inst. Meas. Control*, vol. 36, no. 1, pp. 78–87, 2014.
- [37] K. A. Alhazza, A. M. Hasan, K. A. Alghanim, and Z. N. Masoud, "An iterative learning control technique for point-to-point maneuvers applied on an overhead crane," *Shock Vib.*, vol. 2014, pp. 1–11, May 2014.
- [38] K. A. Alghanim, K. A. Alhazza, and Z. N. Masoud, "Discrete-time command profile for simultaneous travel and hoist maneuvers of overhead cranes," *J. Sound Vib.*, vol. 345, pp. 47–57, Jun. 2015.
- [39] A. M. Abdullahi, Z. Mohamed, M. Z. Abidin, S. Buyamin, and A. A. Bature, "Output-based command shaping technique for an effective payload sway control of a 3D crane with hoisting," *Trans. Inst. Meas. Control*, vol. 39, no. 10, pp. 1443–1453, Oct. 2017.
- [40] Y. Zhou, X. Zhang, Z. Yu, D. Schott, and G. Lodewijks, "An improved zero vibration method and parameter sensitivity analysis for the swing control of bridge-type grab ship unloader," *Proc. Inst. Mech. Eng. C, J. Mech. Eng. Sci.*, vol. 230, no. 14, pp. 2463–2472, Aug. 2016.
- [41] J. Kim, B. Kiss, D. Kim, and D. Lee, "Tracking control of overhead crane using output feedback with adaptive unscented Kalman filter and condition-based selective scaling," *IEEE Access*, vol. 9, pp. 108628–108639, 2021.
- [42] S. Arabasi and Z. Masoud, "Simultaneous travel and hoist maneuver input shaping control using frequency modulation," *Shock Vib.*, vol. 2017, pp. 1–12, Jun. 2017.



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