Swing free Control of silo-crane for UNLOADING Radioactive waste containers

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1. INTRODUCTION

The natural sway of crane payloads is detrimental to safe and efficient operation. Most crane control research has focused on oscillation induced by motion of the overhead trolley that perpendicular to the vertical suspension cables. Little consideration has been given to bouncing oscillation in the hoist direction and pitching oscillation with respect to mass center of the payload. These dynamic effects arise in cases when the suspension cables are very long and the suspended payload weight is very heavy, even a cable made of thick steel wire must be considered as a flexible spring. This flexibility causes a bouncing oscillation in the hoist direction. Furthermore, if the payload is bulky withlarge dimensions and if the mass center of the payload is not located on the center line of hoist cables (unbalanced), then this bouncing motion results in an additional pitching motion of the payload. These motions cause difficulty in accurate positioning during unloading operations. One such example can be found in nuclear waste storage facilities, where radiological waste containers are regularly stacked in tight matrix formations inside silos, requiring positioning accuracy less than 1 cm. This paper presents a result of applying ZV input shaper which is designed to suppress payload oscillations of bouncing and pitching[1]. Theoretical models are used to develop and evaluate the input-shaping control algorithm.

2. CRANE HOIST DYNAMICS

Figure 1 shows a schematic representation of a crane suspending a payload that has unbalanced mass distribution. The payload is hoisted by applying a hoisting force, F_L, to the cables. Two cables with same spring constant k support the mass, M, below the trolley. The vertical displacement (ΔL) of the center of the gravity is measured from the equilibrium position in the absence of any motions when the suspension cable length is $L = L_0$. The hoist dynamics is given as:

$$\ddot{\Delta L} + {\omega_L}^2 \Delta L - {\omega_L}^2 \delta\theta = g - \frac{F_L}{M}, \quad \ddot{\theta} + {\omega_\theta}^2 (1 + \frac{\delta^2}{D^2})\theta - {\omega_\theta}^2 \frac{\delta \Delta L}{D^2} = 0 \quad \text{where } \omega_L = \sqrt{2k/M} \text{ and } \omega_\theta = \sqrt{2kD^2/J} \quad (1)$$

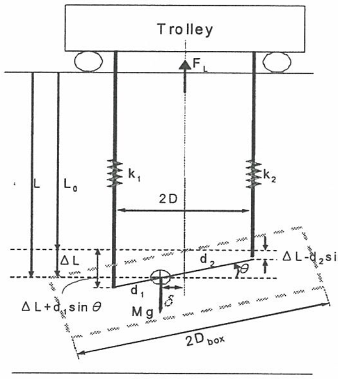


Figure 1. Crane payload with unbalanced mass distribution.

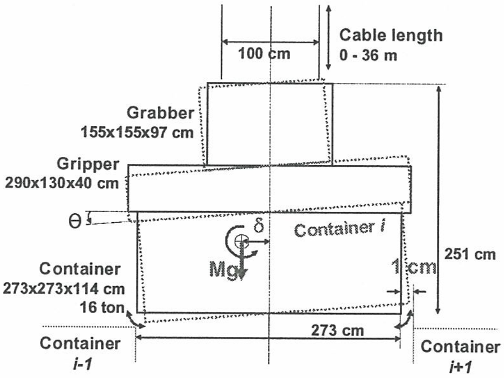


Figure 2. Pitching motion generated by mass center deviation

3. PROBLEM DEFINITION

Figure 2 shows the pitching motion of the radiologicalwaste container which is to be unloaded in the space between two other containers. The container is packed with 16 drums inside. Each drum contains various radiological wastes including metal, liquid, epoxy, filters, etc. Thus, the weight of the drums depends heavily on the type of waste contents. The typical weight of solid waste drums is in the range of 270±150 kg [15]. Some drums are compacted and repackaged into new drums to reduce the volume of the waste. Also, some drums are filled with concrete to shield high radiation. These repackaged drums typically weigh in the range of 400±100 kg [2].

Because the container is packed with drums of differentweight, the mass center of the container will not be located on the center axis of the two suspension cables. Assuming the above range of drum weights and an empty container weight of approximately 8,000 kg, the maximum deviations of mass center ($\delta_{\max}$) from the center axis are 16 cm and 7 cm for a solid waste container and repackaged waste container, respectively. Note that this value is very small compared with the width of the container (273 cm). However, this small deviation causes a pitching motion of the container as mentioned previously. This pitching motion makes it difficult for the crane operators to accurately unload the payload. In this application, with positioning accuracy of 1 cm, the tolerable level of peak-to-peak amplitude of pitching angle, θ, must be less than 0.2°.

4. INPUT-SHAPING CONTROL

The crane hoist dynamics given by equation (1) has two-mode frequencies, pitching and bouncing frequencies. These frequencies can be derived as:

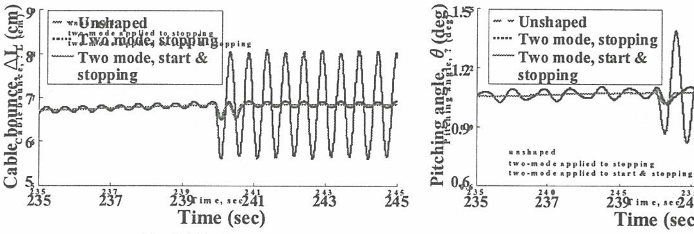
$$(\omega_{p,b})^2 = \frac{\left[\left(\omega_L^2+\omega_{\theta d}^2\right)\mp\sqrt{\left(\omega_L^2+\omega_{\theta d}^2\right)^2-4\omega_L^2\omega_\theta^2}\right]}{2} \qquad \text{where } \omega_{\theta d}=\omega_\theta\sqrt{1+(\delta/D)^2} \tag{2}$$

Using Equation (2), a Two-mode Zero Vibration (ZV) input-shaper[3] formed by convolving two single-mode ZV shapers for the bouncing and pitching frequencies is given as:

$$\begin{bmatrix} A_i \\ t_i \end{bmatrix}_{at\ starting} = \begin{bmatrix} 0.250 & 0.250 & 0.250 & 0.250 \\ 0 & 0.043 & 0.068 & 0.111 \end{bmatrix} \qquad \begin{bmatrix} A_i \\ t_i \end{bmatrix}_{at\ stopping} = \begin{bmatrix} 0.250 & 0.250 & 0.250 & 0.250 \\ 0 & 0.259 & 0.410 & 0.669 \end{bmatrix} \tag{3}$$

Figure 3 shows the responses with two-mode ZV shaping. The dotted lines represent the response when the two-mode ZV shaper is applied only during the stopping motion. As shown in the figure, residual oscillation of the pitchingmotions is reduced to only 0.07 °, well below the tolerable level. The residual oscillation of the bouncing and pitching motion is greatly reduced when comparedto that of the unshaped bouncing response(dashed line). However, small oscillations still remain. These oscillations are generated by forces that occurduring the start of the lowering motion. Because a two-mode input-shaper was applied only at the stopping motion of the hoist, only the oscillations generated by the stopping decelerationwere removed.

To remove these oscillations, two-mode input-shapers are applied to both the start and stopping motions of the hoist. The solid lines represent these responses. As shown in the figure, the bouncing and pitching oscillations are virtually eliminated during the travel and the residual oscillation is eliminated.



(a) Cable bounce (b) Pitching angle

Figure 3. Comparison of unshaped and two-mode ZV shaped responses($\delta/D = 0.14$).

5. CONCLUSION

When a crane payload is bulky and heavy and/or the hoist travel is far, the suspension cable of the hoist must be regarded as a flexible spring. This causes a bouncing motion. Ifthe payload has unbalanced weight distribution, then the bouncing motion causes a pitching motion of the payload. Ultimately, these motions make it difficult for the crane operators to accurately unload the payload. In this paper, input shaping was shown to significantly reduce the bouncing and pitching motions of a payload when it is hoisted. It was shown that two-mode input-shapers should be designed for the frequencies at both the start and stopping motions of the hoist.

6. REFERENCES

[1] Yoon, J.S., Singhose, W., "Dynamics and Control of Crane Payloads that Bounce and Pitch during Hoisting," Proceedings of the ASME 2009 International Design Engineering Technical Conferences, pp.1-10. San Diego, California.

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