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Performance studies of human operators driving double-pendulum bridge cranes

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ABSTRACT

Oscillation of crane payloads makes it challenging to manipulate payloads quickly, accurately, and safely. The problem is compounded when the payload creates a double-pendulum effect. This paper evaluates an input-shaping control method for reducing double-pendulum oscillations. Human operator performance testing on a 10-ton industrial bridge crane is used to verify the effectiveness and robustness of the method. Fifty operators drove the crane with a standard control pendent, as well as a wireless touchscreen interface. Data from these experiments show that human operators drive the crane much faster and safer with the input-shaping control scheme. Furthermore, considerably less operator effort is required when input shaping is used to limit the oscillation. Additional tests required the operators to drive the crane numerous times over a period of eight days. These experiments show that significant learning occurred when operators did not have the aid of input shaping. However, the performance never approached that achieved by untrained operators using input shaping.

1. Introduction

Manipulation of heavy objects at nuclear plants, warehouses, construction sites, and shipyards (Zrnić, Petković, & Bošnjak, 2005) is often accomplished with gantry or bridge cranes, such as the one shown in Fig. 1. Human-controlled cranes are large, complex, and powerful systems whose performance is critical to the success of many industries. Furthermore, cranes routinely operate in dangerous environments that require great skill and care by the human operator.

Experienced crane operators can eliminate much of the residual payload swing by properly shaping the commands they issue to the crane. The success of this approach depends on the skill and diligence of the operator. However, when the system behaves like a double pendulum, the manual method of shaping commands to reduce vibration becomes very difficult. An auxiliary control scheme can be added to ensure cranes perform low-sway motions regardless of what actions the operator performs. However, any such secondary control scheme must modify the operator's intended commands. This has the potential to confuse or annoy an operator, possibly resulting in poorer overall performance.

Cranes are often driven by pressing on-off buttons that issue constant-velocity commands to the crane. On-off inputs tend to induce substantial payload oscillations. Therefore, a practical real-time oscillation controller must filter out unwanted excitations from the human-generated command signal. This can be accomplished by convolving the human-generated command with a sequence of impulses (Singer & Seering, 1990; Singhose, 2009; Smith, 1958, 1957). This input-shaping process is demonstrated in Fig. 2 with a velocity pulse command and an input shaper containing four impulses. The positive and negative step functions that form the pulse have been converted into staircases. The proper timing and scaling of these steps (impulses) ensures that the payload oscillation is suppressed.

Input-shaping techniques were first developed in the 1950s (Smith, 1958, 1957). The "posicast" control method developed by Smith modifies inputs by breaking them into two smaller magnitude components, one of which is delayed by one half period of the natural frequency. The primary constraint equation used to calculate the command components ensures there will be zero residual vibration when the system model is perfect. Therefore, posicast control is now commonly referred to as zero vibration (ZV) input shaping. Although input-shaping techniques were developed in the 1950s, strong evidence that they would work on cranes first appeared only in 1985 (Starr, 1985).

Input shaping has been implemented on several large bridge cranes at nuclear facilities (Singer, Singhose, & Kriikku, 1997; Singhose, Porter, Kenison, & Kriikku, 2000), a boom crane (Lewis, Parker, Driessen, & Robinett, 1998; Parker et al., 1999), a 10-ton

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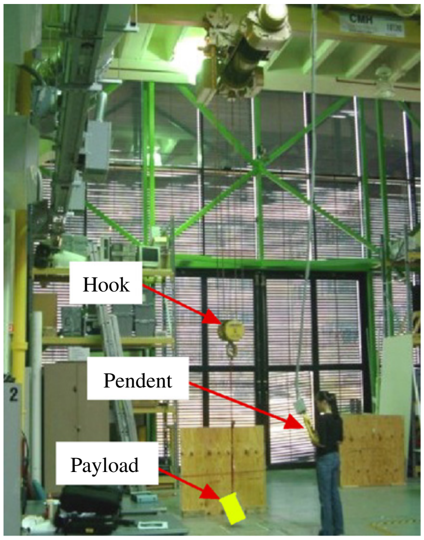

Fig. 1. Industrial bridge crane at Georgia tech.

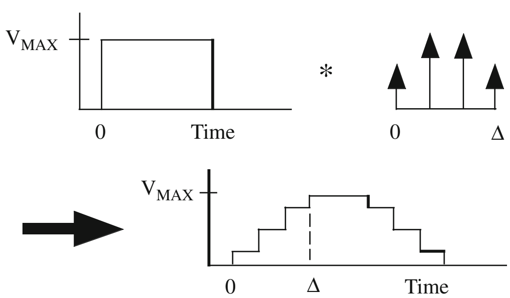

Fig. 2. Input shaping a velocity pulse command.

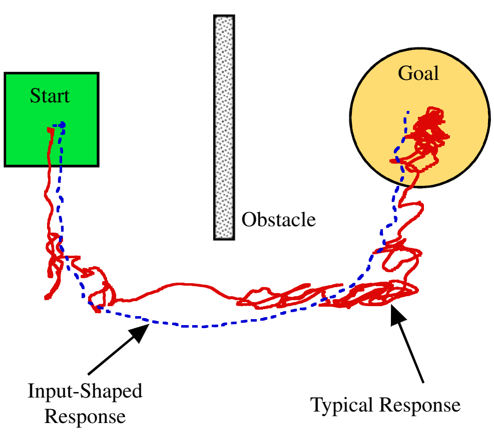

Fig. 3. Typical double-pendulum hook responses.

bridge crane at Georgia Tech (Khalid, Huey, Singhose, & Lawrence, 2006; Sorensen, Singhose, & Dickerson, 2007), a 35-ton crane at Logan Aluminum (Sorensen, Danielson, & Singhose, 2008), a 100-ton crane at Bandon Cranes, as well as portable cranes (Lawrence & Singhose, 2005; Lawrence, Singhose, Weiss, Erb, & Glauser, 2006). The bridge crane at Georgia Tech has an overhead vision system that can track the motion of the hook. Fig. 3 shows the double-pendulum responses of the crane hook for a manipulation task under standard operation and also when input shaping is enabled. The two responses are from the same human operator. Input shaping virtually eliminates the dangerous and detrimental oscillations. Studies of numerous human operators driving a simple, single-pendulum crane demonstrated that input shaping greatly improved throughput and safety (Khalid et al., 2006). A different type of command filtering was also experimentally validated on a scale model of a ship boom crane (Parker et al., 1999).

When input shaping was implemented on a 15-ton bridge crane at the Savannah River Technology Center (SRTC), the oscillations were greatly reduced (Singer et al., 1997), even when the payload was hoisted (Singhose et al., 2000). 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. A large hook mass (or a relatively small-mass payload) can lead to double-pendulum effects that can degrade the effectiveness of input shaping, if the input shaper is designed only for single-mode oscillations.

This paper investigates the performance of human-operated cranes that exhibit double-pendulum dynamics. The goal of these studies is to quantitatively measure the performance of the operators both with and without input shaping. Furthermore, the effect of operator learning is also quantified. Section 2 briefly illustrates the double-pendulum dynamics problem. An input-shaping scheme to mitigate the double-pendulum effects is then presented. Section 3 presents a study of the effects of input shaping on human operators driving an industrial bridge crane. Section 4 presents a study of learning effects when human operators drive the crane multiple times. The results of these studies clearly demonstrate the advantages of input shaping.

2. Double-pendulum dynamics

Fig. 4 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. The rigging and payload are modeled as a second 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

$$\ddot{\theta}_1(t) = -\left(\frac{g}{L_1}\right)\theta_1 + \left(\frac{gR}{L_1}\right)\theta_2 - \frac{u(t)}{L_1}$$

$$\ddot{\theta}_2(t) = \left(\frac{g}{L_1}\right)\theta_1 - \left(\frac{g}{L_2} + \frac{gR}{L_2} + \frac{gR}{L_1}\right)\theta_2 + \frac{u(t)}{L_1} \tag{1}$$

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.

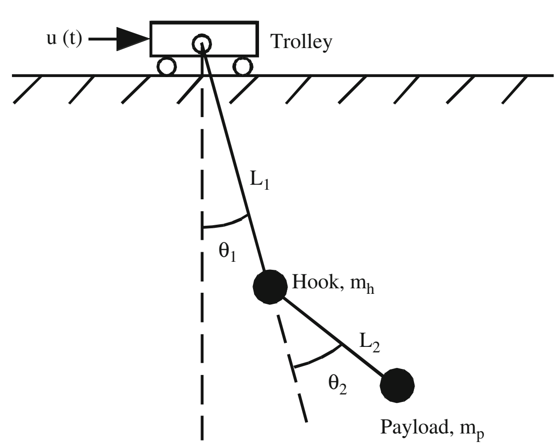

Fig. 4. Double-pendulum crane.