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Control of bridge cranes with distributed-mass payloads under windy conditions

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ABSTRACT

Operating cranes is challenging because payloads experience large and dangerous oscillations, especially when the system is suffering from wind disturbances and the large-size payload is modeled as a distributed-mass model. The payload oscillations induced by both intentional motions commanded by the human operator and by the external wind disturbances make the dynamics more complicated. This paper presents a novel combined control architecture to limit oscillations of the distributed-mass payload caused by both human-operator commands and wind disturbances. While a smoothed command suppressed operator-induced oscillations, a wind-rejection command eliminated the payload swing resulting from the wind gusts. Through simulations, a large range of system parameters and motions are analyzed to investigate the dynamic behavior of bridge cranes with distributed-mass beams and wind disturbances by using the new control scheme. Experimental results obtained from a small-scale bridge crane validate the simulated dynamic behavior and the effectiveness of the proposed method.

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1. Introduction

Cranes provide essential material-handling services throughout the world. However, the flexible nature of their physical structures degrades their effectiveness and safety. Payload oscillations induced by both intentional motions commanded by the human operator and by external disturbances are a major limitation [1]. Therefore, it is critical to design a controller that can effectively limit payload oscillations under the influence of human-operator commands and external disturbances, such as wind.

Numerous scientists have provided solutions to damp the payload swing of the crane by using feedback control, such as proportional-integral-derivative control [2–6], sliding-mode control [7,8], adaptive control [9,10], optimal iterative learning control [11], H_∞ control [12] and fuzzy control [13,14]. However, there are some obstacles toward the application of the feedback controllers, including the difficulty of accurately sensing the payload and its velocity. In addition, the conflict between computer-based feedback controller and the actions of human operator is also a drawback [15]. Some schemes of reducing crane payload oscillations are open-loop control, including inverse kinematics [16–18], input shaping [19–26] and command smoothing [27,28]. But the existed open-loop techniques can only reduce the vibrations induced by human-operator commands. They cannot reject the influence of external wind disturbances [29]. Another method has combined input shaping with feedback control to eliminate the crane payload oscillations caused by human-operator commands and

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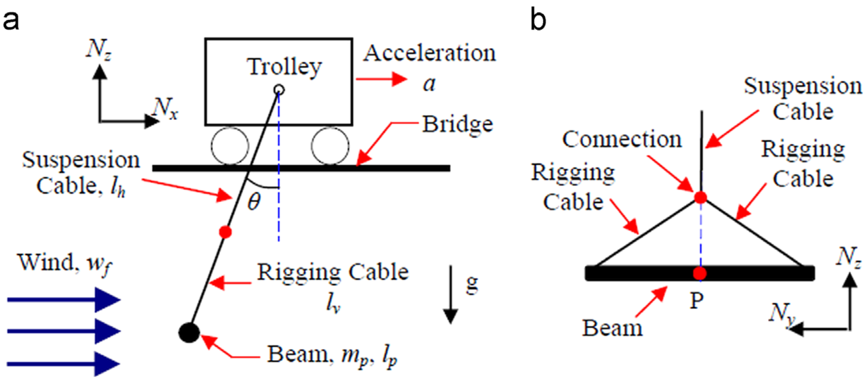

Fig. 1. Model of a bridge crane with distributed-mass beams and wind gusts: (a) model and (b) configuration of hoisting mechanism.

external disturbances [1,30]. Input shaping eliminated payload swing resulting from human-operator commands, and a low-authority feedback controller eliminated payload oscillations caused by wind disturbances.

Significant progress has been achieved by using feedback control and open-loop control schemes to eliminate payload oscillations. But the difficulty of accurately sensing the payload states is the obstacle toward the application of the feedback controllers, and the difficulty of rejecting the external disturbance is the barrier for the previous presented open-loop control scheme. Thus, the study is essential for a new method to control payload oscillations caused by both human-operator commands and wind disturbances without measuring the payload states on-the-fly. Furthermore, the new technique will also benefit vibration reduction for other types of flexible machines including space manipulators [31] and magnetic bearing [32].

The rest of this paper is organized as follows. The modeling of a bridge crane with distributed-mass beams and wind gusts is derived in Section 2. A novel combined control scheme for limiting payload oscillations induced by both the human-operator commands and wind disturbances is investigated in Section 3. The effectiveness and robustness of the proposed method are also verified through numerous simulations in this section. Experiments on a bridge crane transporting a distributed-mass beam are performed to verify dynamics behavior of the system and the effectiveness of the presented method in Section 4. Finally, the conclusions are drawn in Section 5.

2. Model of a bridge crane with distributed-mass beams and wind gusts

Fig. 1(a) shows a schematic representation of a bridge crane with distributed-mass beams and wind gusts. The trolley slides along the bridge in the x direction. A massless suspension cable of length, l_h, hangs below the trolley. A uniformly distributed-mass beam of mass, m_p and length, l_p, is attached to the suspension cable by two massless rigging cables of length, l_v, as shown in Fig. 1(b). The centroid of the payload is P. The wind is modeled as a force, w_f, acting on the payload in the x direction. Note that the wind travels perpendicular to the initial direction of the edge of the payload length and parallel to the bridge.

The crane dynamics will become much more complicated when the payload twisting occurs. The wind direction has large impacts on the payload twisting. The model shown in Fig. 1 cannot cause the payload twisting because the initial direction of the payload length is perpendicular to the wind direction and the bridge. The specified direction simplifies the dynamic model.

The inputs to the model shown in Fig. 1 are the acceleration of the trolley, a, the suspension cable length, l_h, and the wind force, w_f. The output is the swing angle of the suspension cable, θ. It is assumed that the motion of the trolley is unaffected by motion of the payload due to the large mechanical impedance in the drive system. The model also assumes that damping ratio is approximately zero. Using the Kane's method, the equation of motion for the model shown in Fig. 1 is derived. The nonlinear equation of motion relating the swing angle to the trolley acceleration, suspension cable length and the wind force is:

$$(l_h+\sqrt{l_v^2-0.25l_p^2})\cdot\ddot{\theta}+2\dot{l}_h\dot{\theta}+g\ \sin\ \theta=(a-\frac{w_f}{m_p})\cdot\ \cos\ \theta \tag{1}$$

where g is the gravitational constant. The limited cable swing of crane systems allows one to assume a small angle approximation. Then from (1), the linearized natural frequency is given by:

$$\omega=\sqrt{g/(l_h+\sqrt{l_v^2-0.25l_p^2})} \tag{2}$$

Thus, the natural frequency depends on the suspension cable length, rigging cable length and payload length. Fig. 2 shows the natural frequency as a function of suspension cable length and payload length when the rigging cable length was

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