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An improved input shaping design for an efficient sway control of a nonlinear 3D overhead crane with friction

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ABSTRACT

This paper proposes an improved input shaping scheme for an efficient sway control of a nonlinear three dimensional (3D) overhead crane with friction using the particle swarm optimization (PSO) algorithm. Using this approach, a higher payload sway reduction is obtained as the input shaper is designed based on a complete nonlinear model, as compared to the analytical-based input shaping scheme derived using a linear second order model. Zero Vibration (ZV) and Distributed Zero Vibration (DZV) shapers are designed using both analytical and PSO approaches for sway control of rail and trolley movements. To test the effectiveness of the proposed approach, MATLAB simulations and experiments on a laboratory 3D overhead crane are performed under various conditions involving different cable lengths and sway frequencies. Their performances are studied based on a maximum residual of payload sway and Integrated Absolute Error (IAE) values which indicate total payload sway of the crane. With experiments, the superiority of the proposed approach over the analytical-based is shown by 30–50% reductions of the IAE values for rail and trolley movements, for both ZV and DZV shapers. In addition, simulations results show higher sway reductions with the proposed approach. It is revealed that the proposed PSO-based input shaping design provides higher payload sway reductions of a 3D overhead crane with friction as compared to the commonly designed input shapers.

1. Introduction

An overhead crane is one of the mostly used types of industrial crane in industries, factories and ware houses [1]. Shipping yards and nuclear facilities are the other places where heavy loads must be transferred by overhead cranes. One of the significant factors affecting productivity and efficiency of the industrial systems is speed. However, fast manoeuvres of an overhead crane resulted in a significant payload oscillation and considerable residual sway, which negatively affects performance of the system. At higher speeds, these sway angles prevent the payload to settle down during movement and unloading. This problem will be crucial particularly for industrial applications where operators should manipulate the cranes [2]. Vast applications of overhead cranes encourage many researchers to work on control of these structures. Several controllers have been investigated that include an energy based technique [3], a sensorless approach to control the sway [4] and fuzzy

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logic controllers to reduce the motion-induced oscillation of crane systems [5]. Adaptive tracking control and error tracking control for an overhead crane with parametric uncertainties and external disturbances were proposed recently [6,7]. In addition, a command smoothing approach was also designed for sway control of a crane system with a distributed-mass payload [8].

One of the most useful approaches to reduce the motion-induced oscillations of oscillatory systems is an input shaping technique [9]. The technique was introduced by Singer and Seering [10] and has been applied for control of various oscillatory systems. For example, Zero Vibration (ZV) and Zero Vibration Derivative (ZVD) shapers [11] have been utilized to control a flexible robot manipulator [12] and crane systems [13,14]. Recently, several other input shapers have been proposed and implemented on a crane system. These include a Distributed Zero Vibration (DZV) shaper designed by using a distributed type delay [15,16] and an output-based command shaper [17].

Input shaping technique involves convolving a desired command with a sequence of impulses. Design objectives are to determine the amplitudes and time locations of the impulses that yields low system vibration. In designing input shapers, researchers often use analytical approaches that solve related mathematical equations derived based on a linear second order model. In this case, system damping ratios and natural frequencies are required to solve the equations. For a nonlinear system, an improved input shaper that gives higher sway reduction could be designed based on a nonlinear model. A few researchers have investigated heuristic approaches for designing input shapers [18,19]. Particle swarm optimization (PSO) is one of the heuristic approaches, which has been successfully used to improve several controllers for sway control of various crane systems [20,21]. It is envisaged that the PSO approach can be utilized to achieve higher sway reduction for a three dimensional (3D) overhead crane which is a nonlinear system with friction. Moreover, no direct comparison between both approaches has been presented in designing input shaper for sway control.

In this paper, ZV and DZV shapers are designed for sway control of a 3D crane by using the PSO algorithm based on a nonlinear model with friction, which is obtained using Newtonian techniques. Analytical-based input shapers are also designed for comparative assessments. The PSO is utilized to obtain parameters of the ZV and DZV shapers whereas mathematical formulations of ZV shaper [11] and DZV shaper [15] are used in the analytical design. MATLAB simulations and experiments on a laboratory overhead crane are performed to investigate the performance of the input shapers in payload sway reduction for rail and trolley movements of the 3D overhead crane. In addition, various operating conditions involving different cable lengths and natural frequencies are investigated. The performances are examined based on a maximum residual of payload sway response and Integrated Absolute Error (IAE) values which indicate total payload sway of the crane.

2. A 3D overhead crane system

Fig. 1 shows a laboratory crane used in this study. The overhead crane is capable of transferring a load from any location to a desired place in a restricted 3D space. The system hardware consists of three main components: a cart, a rail and a pendulum. The mathematical model is obtained based on the given characteristics of the crane by the manufacturer and the study by Pauluk et al. [22].

The obtained model is simulated using Simulink to investigate dynamic behaviour of the system. A schematic diagram of the 3D overhead crane system is shown in Fig. 2 with *XYZ* as the coordinate system. m_p, m_t and m_r are the payload mass, trolley mass (including gear box, encoders and DC motor) and moving rail respectively. l represents the length of the lift-line, α represents the angle of lift-line with Y axis and β represents angle between negative part of Z axis and projection of the payload cable onto the XZ plane. Table 1 shows the crane's parameters used for simulation and experiments in this study.

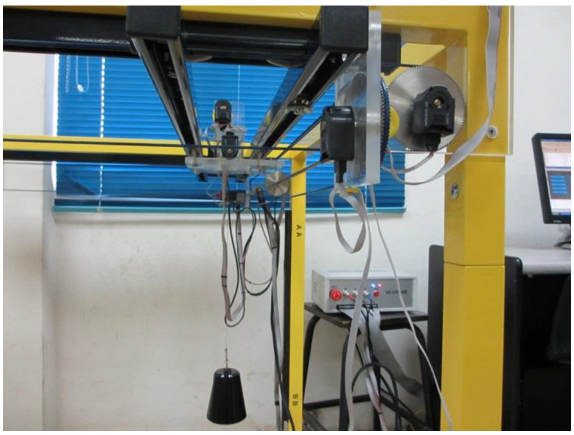

Fig. 1. A laboratory 3D overhead crane.