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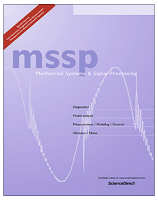

Model reference command shaping for vibration control of multimode flexible systems with application to a double-pendulum overhead crane

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ABSTRACT

This paper proposes a Model Reference Command Shaping (MRCS) approach for an effective vibration and oscillation control of multimode flexible systems. The proposed MRCS is designed based on a reference model and avoids the need for measurement or estimation of several modes of frequency and damping ratio as in the case of other input shaping and command shaping approaches. To test the effectiveness and robustness, the designed MRCS is implemented for oscillation control of a double-pendulum overhead crane. Simulations on a nonlinear crane model and experiments using a laboratory overhead crane are carried out under two cases, without and with payload hoisting. Without a prior knowledge of the system frequency and damping ratio, the MRCS is shown to provide the highest reductions in the overall hook and payload oscillations when compared to the multimode Zero Vibration and Zero Vibration Derivative shapers designed based on the Average Travel Length approach. In addition, the MRCS is more robust towards changes in the frequency during payload hoisting and changes in the payload mass. It is envisaged that the proposed method can be useful in designing effective vibration control of multimode flexible systems.

1. Introduction

Flexible dynamic systems ranging from nano-positioning devices to large industrial cranes are widely used for various applications. However, these systems suffer from residual vibration and unwanted transient deflection that significantly affect the positioning accuracy, effectiveness and safety during their operations [1]. Vibration and oscillation control of these systems has been an active research, and the control challenges increase for systems with two or more vibration modes, known as multimode systems. Examples of multimode system are flexible robot manipulators and double-pendulum cranes. For single and multi-link flexible manipulators, the end-point vibrates with several modes of frequencies during motion [2–5]. On the other hand, operations of the double-pendulum cranes involve oscillations in the hook and payload which are coupled [6–8]. For an effective control of such systems, all the vibration modes need to be considered in controller design.

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A significant amount of researches has been devoted to dynamic modelling and control of crane systems, and a comprehensive review on these issues was given in [9]. In modelling, several approaches were proposed and investigated which include the Lagrangian [8,10], the Kane [11,12] and the discrete time transfer matrix methods [13–15]. On the other hand, the crane control can be categorised into feedforward (open-loop) and feedback (closed-loop) control strategies. Recently, several feedback control strategies were investigated for accurate trolley positioning and anti-swing control of double-pendulum cranes. These include adaptive tracking control [16], nonlinear stabilising control [17] and nonlinear anti-swing control [18,19].

Besides, feedforward control strategies have been widely utilised by numerous researchers for vibration and oscillation control of flexible systems [1,9]. Within the feedforward control scheme, input shaping technique is one of the mostly used strategies that can be applied for real-time applications. The system's vibration is reduced by convolving a command input signal with a sequence of impulses designed based upon natural frequencies and damping ratios of the system. In handling multimode effects, a convolution of multiple single-mode input shapers is required to cater for the system oscillations [20]. The first implementation of input shaping for a double-pendulum crane system was reported in [21]. Since then, many researchers investigated various multimode input shaping techniques including a two-mode specified-insensitivity shaper [22–24], a two-mode Zero Vibration (ZV) shaper [25], a convolution of ZV and Zero Vibration Derivative (ZVD) shaper [26] and a two-mode specified negative amplitude shaper [27] to achieve zero vibration at the modelled natural frequencies and damping ratios. In [28], a frequency-modulation input shaping technique for a two-mode system was also presented.

Command shaping is another open-loop technique with difference design approaches as compared to the input shaping technique. In [29], a smooth multimode waveform command shaping control with selectable command length for a multimode system was proposed. The shaped command was designed based on the resonant frequencies of the system to eliminate residual vibrations. In another work, a command smoother technique was designed for a flexible system by depending only on the first mode frequency [30]. In [31], a command smoother was implemented on double-pendulum crane systems and was successful in suppressing the oscillations. The technique was also combined with a wind-rejection command to suppress operator-induced oscillations and to reject the wind disturbance of a bridge crane with a distributed-mass payload [12].

However, all the previously proposed open-loop control strategies in input shaping and command shaping require either first mode, second mode or both frequency modes for controller designs. In the literature, the frequencies were obtained through measurements using various types of sensor or estimations using several techniques. In addition, the damping ratio is also needed in several controller designs. However, obtaining accurate vibration/oscillation frequencies and damping ratios of a system is challenging. In addition, small measurement or estimation errors could lead to an inefficient controller and may also result in a higher system vibration and oscillation. In solving this issue, a successful design of an open-loop control without a prior knowledge of the multimode frequencies will be an advantage and desirable.

This paper proposes Model Reference Command Shaping (MRCS) for vibration and oscillation control of multimode flexible systems. The main contribution of this paper lies on the MRCS design approach for multimode systems which is based on a reference model and does not require system natural frequency and damping ratio. This is in contrast to the existing input or command shaping design approaches. For multimode systems, the MRCS approach has a clear advantage as measurements or estimations to obtain accurate values of the required parameters are difficult. Although the concept was applied to a single mode system [32–34], control of multimode systems with a higher system order involving several modes of frequencies and damping ratios is more challenging. In addition, to the best of authors' knowledge, this work is the first implementation of the proposed approach to multimode flexible systems. To examine the effectiveness of the controller, the application of MRCS on a double-pendulum overhead crane with payload hoisting for minimising the hook and payload oscillations is considered. Simulations using a nonlinear model and experiments on a laboratory double-pendulum crane are carried out to investigate the performance and robustness of the controller in two cases, without and with payload hoisting, and with different payload masses. The maximum and overall hook and payload oscillations are measured and used for assessment of the controller. For comparisons, multimode ZV and ZVD input shapers designed with the Average Travel Length (ATL) technique are also implemented.

2. A double-pendulum overhead crane

The most popular technique for modelling of a double-pendulum crane system was the Lagrangian method [9]. In this section, dynamic equations representing a double-pendulum overhead crane with constant and hoisting cables are given.

2.1. Nonlinear dynamic model

A schematic diagram of a double-pendulum overhead crane system with a constant cable length is illustrated in Fig. 1. The crane consists of three independent generalised coordinates namely the trolley position, x, the hook angle, θ_1, and the payload angle, θ_2. m, m_1, m_2, l_1, l_2, f_x and g represent the trolley mass, the hook mass, the payload mass, the massless cable length between the trolley and the hook, the massless cable length between the hook and the payload, the viscous damping coefficients of trolley and the gravitational acceleration constant respectively. F_x is an external force applied to the crane,