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Vibration controller for overhead cranes considering limited horizontal acceleration

Yoshihito Mori, Yasutaka Tagawa [*]

Tokyo University of Agriculture and Technology, Department of Mechanical System Engineering, 2-24-16 Nakacho Koganei-shi, Tokyo, Japan

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ABSTRACT

This paper proposes a vibration controller for overhead cranes considering limited horizontal acceleration. Our previous article proposes a transfer-function-based vibration controller that suppresses the vibration of a lifted load regardless of wire length. However, this controller does not consider the nonlinear acceleration limitation of the crane. Thus, to consider the limited acceleration with a transfer-function-based controller, a linear parameter varying (LPV) acceleration-limitation model is developed. Moreover, the proposed controller is designed by using a dynamic model of the crane and the LPV limited-acceleration model. Experiments verify that the proposed controller suppresses the vibration and does not exceed the acceleration limits.

1. Introduction

1.1. Background and fundamental purpose

Overhead cranes are currently used in a wide variety of industrial fields and contribute significantly to the rationalization and labor of carrying tasks. However, when a lifted load is moved horizontally by an overhead crane, the lifted load is easily vibrated because of the mechanical features of the overhead crane. To reduce this vibration, skillful operation by a skilled operator is indispensable; novice operators cannot reduce the vibration completely. For this reason, it is imperative to have a vibration control system that suppresses the vibration of the lifted load without depending on the skill of operators.

1.2. State of art

Various control methods have been studied to realize a vibration control system for cranes. These control methods are of two main classes: feedback control measuring the vibration of the lifted load, and feedforward control without measuring. As examples of feedback control, Nishikawa, Shimoda, Nishimura, and Tanida (2010) implemented gain-scheduled control for a tower crane that adapts itself to a variable wire length of the crane. Ito and Suzuki (2006) proposed vibration control that considers the coupled vibration of a lifted load by detecting the states of the hook and lifted load via still pictures. Hajdu and Gasper (2016) presented a LPV controller design method which can handle the effect of varying lifted load magnitude and position of a stacker crane and performed time domain simulations. Gonzalez, Hoffmann, Radisch, and Werner (2013) presented an LPV controller for the damping of the vibration of a lifted load and conducted a posteriori analysis that verified closed-loop guarantees for stability and performance for the LPV controller. As examples of feedforward control, Mizota, Kondou, Matsuzaki, Sowa, and Mori (2015) proposed a method of focusing the external force that does not include the natural frequency of the overhead crane and does not generate a residual vibration. Also, an input shaping technique that generates control commands to reduce vibration by convolving a sequence of impulses (known as an input shaper) with a reference command is implemented in several types of crane (Kim & Singhose, 2010; Singhose, Porter, Kenison, & Kriikku, 2000). Furthermore, the combined method of feedback control and feedforward control (Takagi, Nishimura, & Uchida, 2001) and the combined method of PID control and input shaping (Maghsoudi, Mohamed, Husain, & Tokhi, 2016; Sorensen, Singhose, & Dickerson, 2007) have been reported.

1.3. Present approaches and tasks

In various industrial fields, a carrying task in which the wire length is varied is a standard operation for moving a lifted load at height. Therefore, it is essential to design the controller gain to accommodate a variable wire length.

To consider a variable wire length, our research team proposed a transfer-function-based controller (Wada, Mori, Tagawa, Kawajiri, & Nouzuka, 2016). This controller was based on the dual-model-matching (DMM) method (Tagawa, Tagawa, & Stoten, 2009) and DMM method has following features:

(1) DMM is possible to take into account robust stability and disturbance suppression performance explicitly in controller design.

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[*] Corresponding author.
E-mail addresses: my.zgmf.x10a@gmail.com (Y. Mori), tagawa@cc.tuat.ac.jp (Y. Tagawa).

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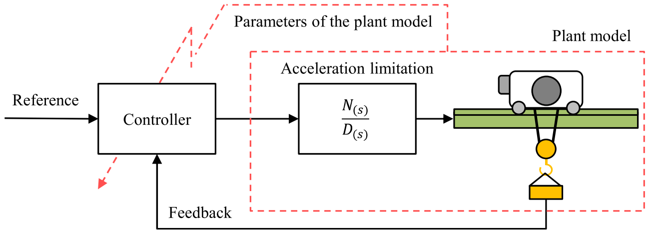

Fig. 1. Control diagram of the proposed system.

(2) Since DMM-based controllers can include the parameters of plant models in symbolic forms, DMM is possible to design controllers for LPV plants in the same manner as LTI plants.

(3) When DMM is applied to vibration control of overhead cranes, the following performances are obtained:

(a) Utilizing feature (1), vibration can be damped not only for reference input but also for any disturbances such as wind force, unbalanced force arising at load lifting off the ground.

(b) Utilizing feature (2), the same damping ratio and the same reference following performance are realized in any wire length by controller update at each sampling time.

In experiments on a two-axis commercial based overhead crane, the method was able to suppress the vibration of the lifted load by more than 80%.

However, these control methods did not consider the limitations of the crane's hardware when designing the controller. Especially, in the methods that control the overhead crane with velocity commands, the nonlinear horizontal-acceleration limitation affected the control performance. Generally, when high tracking performance is designed, the operation time becomes short whereas the vibration-suppression performance becomes poor because the acceleration limitation prevents high-acceleration responses to suppress the vibration. In particular, when inching commands (i.e., repeat move and stop to horizontal direction quickly) are issued to the crane and the tracking performance of the controller is designed to be high, the vibration-suppression performance becomes remarkably poor.

Thus, the novel purpose herein is to develop a control system that considers both high tracking performance and high vibration-suppression performance under limited acceleration.

1.4. *Contents of paper*

This paper is structured as follows. Section 2 introduces the proposed method to consider limited acceleration. Section 3 gives an overview of typical overhead cranes and an overhead crane at our laboratory. Section 4 explains how to derive a linear crane model and a LPV limited-acceleration model. Section 5 describes the basic concept of the DMM method and designs a controller based on this method. Section 6 presents the results of experiments using a one-axis overhead crane. Finally, Section 7 concludes the paper.

2. Proposed method

2.1. *Typical methods considering hardware limitations*

The typical methods that consider hardware limitations are model predictive control (MPC) and anti-windup control (AWC). MPC determines the control inputs by predicting the future behavior of real plants by considering plant models and solving optimization problems (constrained or unconstrained) sequentially (Maciejowski, 2005). Moreover, some studies have implemented MPC for experimental crane equipment (Chen, Fang, & Sun, 2016; Jolevski & Bego, 2015). However, MPC takes a long time to complete its calculations and does not ensure closed-loop stability. By contrast, AWC prevents the severe performance degradation known as windup. AWC is realized by adding an anti-windup compensator to the linear controller that performs the desired control over an unlimited region of control inputs. This design procedure is known as the two-step anti-windup scheme (Wada & Saeki, 2001). However, AWC cannot clarify how limitations affect the control performance because the controller and the anti-windup compensator are designed individually.

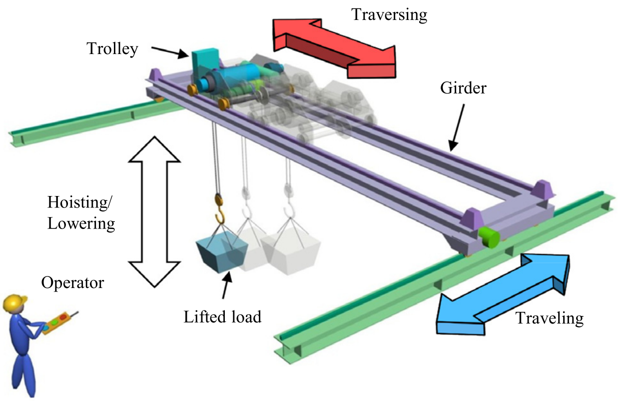

Fig. 2. Schematic of a typical overhead crane.

Table 1
Specifications of the overhead crane.

	Hoist		Traverse
Rated capacity		2800 kg	
Height		2.0 m	
Range		6.5 m	
Maximum velocity	0.167 m/s		0.417 m/s
Acceleration time	–		4 s

2.2. *Proposed method*

As noted in Section 1.3, the purpose of the present study is to develop a control system with both high tracking performance and high vibration-suppression performance under limited horizontal acceleration. In addition, MPC and AWC, the major methods that consider limitation, have several weaknesses.

For this purpose and academic background, this paper proposes a vibration control system for overhead cranes considering limited horizontal acceleration. Fig. 1 shows a control diagram of this system.

A vibration controller is designed by the DMM method to use the advantages of that method as noted in Section 1.3; it is therefore a transfer-function-based controller. Since a DMM-based controller is a linear controller, generally, it cannot consider a nonlinear horizontal-acceleration limitation. For this reason, the nonlinear limitation has to be approximated by some form of linear function.

Thus, hyperbolic functions and first-order delay systems are applied to build a LPV acceleration-limitation model. The controller was designed with a plant model described with the LPV acceleration-limitation model and the dynamic model of overhead crane. The major advantages of the proposed control system are (1) to ensure closed-loop stability and (2) to attain the desired control performance under a certain acceleration limitation of the control input.

3. Overhead crane

Fig. 2 shows a schematic of a typical overhead crane. Generally, an overhead crane has three types of motion: traveling, traversing, and hoisting (lowering). Traveling is the motion of a girder along two rails on the walls. Traversing is the motion of a trolley along the girder. Hoisting and lowering are the up and down motion, respectively, of a