Development of sensorless easy-to-use overhead crane system via simulation based control

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Abstract. This paper describes the newly developed overhead crane which has a sensorless vibration control system. Generally, loads which are carried by the overhead cranes are easy to vibrate and only skilled people can operate the cranes. Therefore, a lot of studies have been done to solve this problem by using feedback control with vibration sensors. However vibration sensors often break down in severe industrial environment and more reliable control systems are required. For this reason, we have been developing sensorless control system for overhead cranes. In this paper, we firstly introduce basic idea of simulation based control which is called IDCS, then overview and modeling of the overhead crane is presented. Next, the control system design of the overhead crane is discussed, and experimental results are shown for real overhead crane with 2 axes.

1. Introduction

Overhead cranes are widely used at various places in industrial environments. The purpose of the overhead crane is to carry heavy loads to the desired position as fast as possible. However, from nature of the overhead crane mechanism, the load which is carried by the overhead crane is easy to vibrate. Also natural frequency of the vibration changes with the wire length of the crane. Therefore, conventional systems are difficult to operate, and only skilled operators can manipulate well. For this reason, many studies have been done for vibration suppression of the cranes. These studies are categorized into two groups in terms of control strategy, that is, feedback control and feedback control. In feedback control, although high performance is expected [1], [2], vibration measurement sensors are required and this causes faults of the crane systems especially in severe industrial environments. On the other hand, sensors are not required in feedforward control. However, in most of studies using feed forward control, information of the final position of the crane has to be known in advance [3], [4] and this process extremely deteriorates usability of the crane system. In order to overcome these problems, we have been studying sensorless easy-to-use vibration control system of the overhead cranes via “simulation based control (IDCS)”. IDCS (Inverse Dynamics Compensation via ‘Simulation of feedback control’) is a method to calculate approximate inverse dynamics by carrying out the feedback control simulation [5]. Authors already showed effectiveness of the method experimentally with a small size crane model [6]. The goal of this study is to develop sensorless easy-to-use crane systems in real scale, which have no load vibration and easy-to-use performance.

In this paper, we firstly introduce basic idea of simulation based control (IDCS), then overview and modeling of the overhead crane is presented. Next, the control system design of the overhead crane is

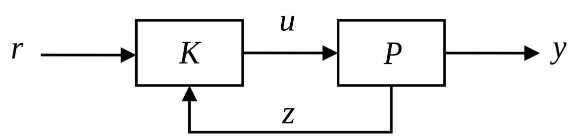


Figure 1. Feedback control

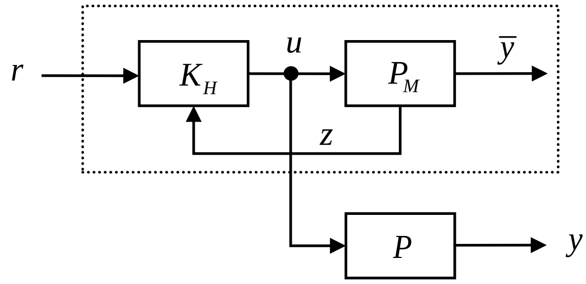


Figure 2. Principle concept of "IDCS"

discussed, and then experimental results using real overhead crane with 2 axes are shown. Finally the conclusions are presented.

2. Simulation based control

Figure 1 shows a block diagram of general feedback control system. In the figure, P is a controlled system, K is a controller which generally consists of feedback and feedforward terms, r is a reference input, y is a controlled variable and z is a measured variable. Thus, z consists of the controlled variable, y, plus any other measured variables. In general, the main purpose of the feedback control is:

(1) Stabilization of the controlled system, P.
(2) Good tracking performance, so that y accurately follows r.

However, in reality, many control systems have the following undesirable features:

(i) Unknown dynamics in the controlled system.
(ii) Model parameter errors in the controlled system.
(iii) Unexpected disturbances of the controlled system.
(iv) Signal noise from sensors, actuators, amplifiers, *etc*.

These undesirable factors degrade the control performance in achieving objectives (1) and (2). In order to overcome the problems caused by (i)-(iv), many control solutions have been proposed (e.g. references [7]). Even if advanced controllers are used, control performance will still be limited by the above factors, so that performance degradation is inevitable.
However, in control simulations, we can often obtain near-perfect results, since the simulation environment can be made completely free from the above undesirable factors. Therefore, numerical simulation can be considered to be an ideal environment for feedback control, where we can obtain the best possible performance from a controller.

Figure 2 shows the basic concept of IDCS, which merges the ideal control simulation performance with the real world, using the principle of inverse dynamics. In the figure, the dotted box encloses the simulation environment. As indicated above, a high-performance controller K_H (typically, a high-gain controller) can be used in the simulation, so that the output $\bar{y}$ from P_M will be close to the reference value, r. Since P_M is assumed to be an accurate model of the real system, when u is input to P, the corresponding output, y, will be close to $\bar{y}$. Therefore, the output y from P will also closely follow the target value, r. The dotted frame in figure 2. corresponds to the block P_M^{-1}. This implies the principle concept behind IDCS: i.e. the system within the dotted frame (feedback control simulation) has the same function as the inverse dynamics of P. Since the IDCS controller is considered to be a kind of feedforward controller, the error between the output $\bar{y}$ of the system model P_M and the output

y of the actual model P doesn't necessarily converge to zero. However, in the same way that numbers of feedforward controllers work well without asymptotically stable condition in various actual systems, IDCS can be applied to various kinds of practical systems.

3. Overhead crane

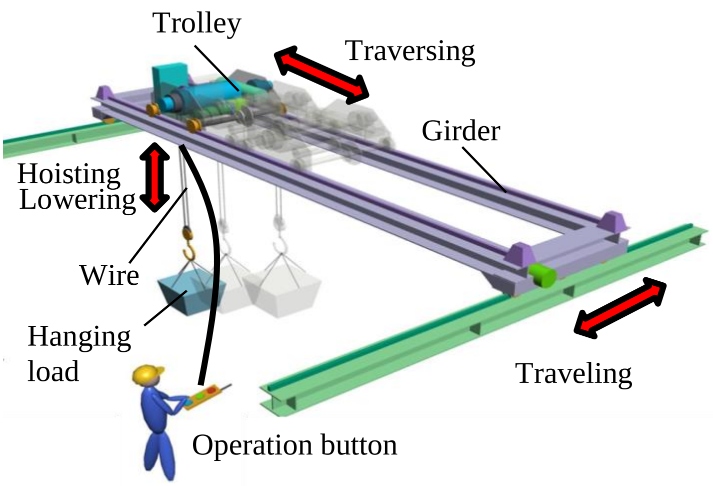


Figure 3. Overview of overhead crane

3.1. *Overview of overhead crane*

Figure 3 shows an image of an overhead crane in operation. Generally, overhead cranes have 3 kinds of motion, that is, traveling, traversing and hoisting (lowering). Traveling is a girder motion along two rails on the walls. Traversing is a trolley motion along the girder. Hoisting and lowering is a wind up and down motion of the hanging load, respectively. The overhead crane can carry the hanging load in any position through combination of these 2 horizontal and 1 vertical motions.

3.2. *Modeling of overhead crane*

Figure 4 shows an analytical model of a typical overhead crane system. In the figure, x is load displacement, u is trolley displacement, l is length of wire, θ is angle of wire, and m is load mass. Equation of motion of the crane system is given as follows:

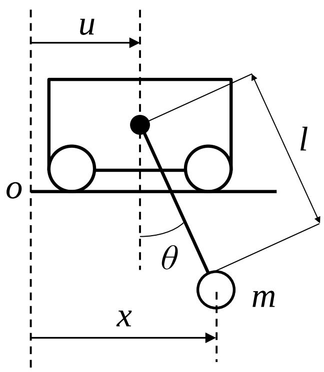


Figure 4. Analytical model

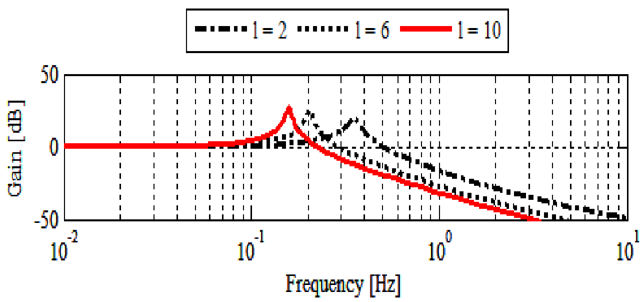


Figure 5. Frequency response (gain)

$$ml^2\ddot{\theta} = -2ml\dot{l}\dot{\theta} - mgl\sin\theta - m\ddot{u}l\cos\theta \tag{1}$$

From geometric relation in the figure, the following equation is obtained:

$$\sin\theta = \frac{x-u}{l} \tag{2}$$

Substitute equation (2) into equation (1) and assuming $\sin\theta \approx \theta$ and $\cos\theta \approx 1$, then following equation is obtained:

$$\ddot{\theta} + 2\frac{v_l}{l}\dot{\theta} + \frac{g}{l}\theta + \frac{1}{l}\ddot{u} = 0, \tag{3}$$

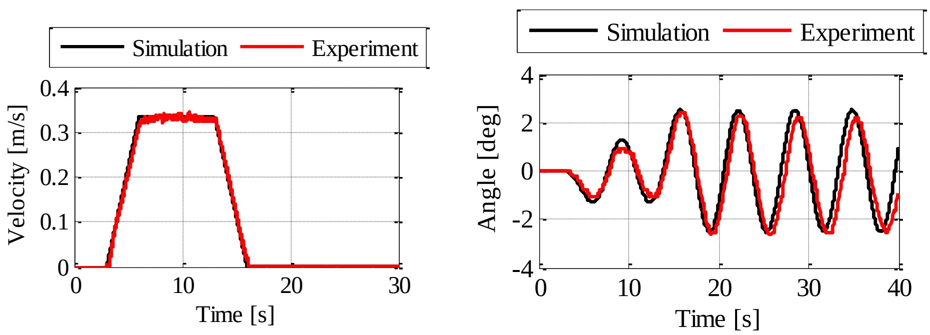
where $v_l = \dot{l}$, then the transfer function from the trolley displacement u to the hanging load displacement x is given as follows:

$$\frac{X}{U} = \frac{2\frac{v_l}{l}s + \frac{g}{l}}{s^2 + 2\frac{v_l}{l}s + \frac{g}{l}} \tag{4}$$

From equation (4), a state space expression of the system is given as follows:

$$\begin{aligned} \begin{bmatrix} \ddot{x} \\ \dot{x} \end{bmatrix} &= \begin{bmatrix} 0 & -g/l \\ 1 & -2v_l/l \end{bmatrix} \begin{bmatrix} \dot{x} \\ x \end{bmatrix} + \begin{bmatrix} g/l \\ 2v_l/l \end{bmatrix} u \\ y &= \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{x} \\ x \end{bmatrix} \end{aligned}, \tag{5}$$

where, the system output y denotes the load displacement x. In equation (5), it is seen that A and B matrices of the state equation include varying parameters (l and v_l). Such system is called "Linear Parameter Varying (LPV) system" and generally the LPV systems are difficult objects for control ,



(a) Velocity of trolley (b) Wire angle

Figure 6. Comparison between simulation and experiment

compare to Linear Time Invariant (LTI) systems. Figure 5 shows frequency response from u to y (load displacement). It is seen that the natural frequency changes with wire length.

In figure 6, simulation results using equation (5) is compared with experimental results, when trapezoidal shape velocity command is given to the crane in traversing direction (wire length: 10m). Figure 6(a) shows velocity of the trolley $\dot{u}$ and figure 6(b) shows wire angle θ. Considerably good agreements between simulation and experiment are seen in both figures, and almost the same results are obtained in traveling direction. Therefore feedback controller in IDCS, that is, K_H in figure 2 is designed using this model.

4. Control system

4.1. Feedback controller in simulation

Since feedback control simulation is the essential part of IDCS, the feedback controller design for the simulation is important. In this study, Dual Model Matching (DMM) [8] is chosen for the feedback controller design in IDCS. DMM is a transfer function based 2 degrees of freedom control design method. The reason we have chosen DMM is as follows:

1) Since DMM is a transfer function based method, it has intuitive and easily understandable nature
2) DMM is possible to take into account robust stability and disturbance suppression performance in controller design
3) DMM is possible to design controllers without any difference between LTI plants and LPV plants
4) We have several successful experiences using DMM in practical systems [9]-[11]

In this study, the closed loop poles are adjusted in the following ways:
a) The corresponding closed loop poles follow varying natural frequency of the crane
b) The same damping ratio is given for any wire length
c) The same reference following performance is given for any wire length

4.2. Sensorless IDCS controller

Figure 7 shows a block diagram of the sensorless IDCS controller for the crane system. In figure 7, input to the plant model is trolley/girder velocity command signal, and output from the plant model is load velocity. Since the transfer function between "trolley and load displacement" is the same as the transfer function between "trolley and load velocity", the plant model in figure 7 is expressed as equation (4). Also, as shown in the figure, the DMM feedback controller discussed in 4.1 is used in feedback simulation. The trolley/girder velocity command signal is input to the actual overhead crane.

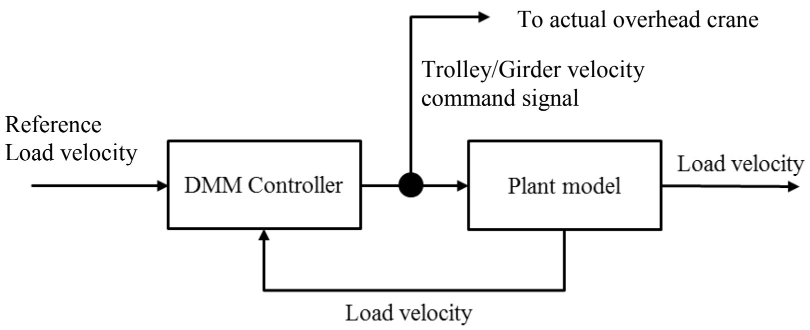


Figure 7. Block diagram of sensorless IDCS controller

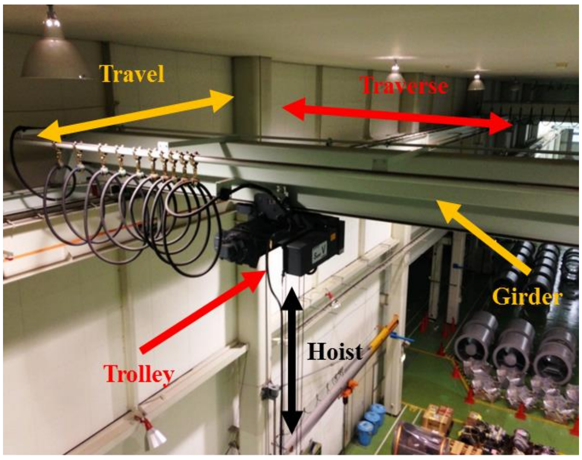


Figure 8. Overhead crane for experiment

Table 1. Crane specification

	Hoisting	Traversing Traveling
Supply voltage	0-200V	
Power frequency	50 Hz	
Rated speed	0.167 m/s	0.350 m/s
Lift	12 m	—
Capacity	2.0ton	—

4.3. Experimental set-up

Figure 8 shows a photo of the overhead crane which is used in the experiments, and table 1 lists its specifications. Figure 9 shows a signal flow of the experimental set-up. In the experiments, the control program is downloaded from PC to DSP (digital signal processor). The overhead crane is driven by push button switches. The push button switches are categorized into 3 groups, that is, groups for traveling motion, traversing motion, and hoisting/lowering motion. Each group has two switches (forward and backward switches for traveling and traversing motion, up and down switches for hoisting/lowering motion). In traveling and traversing motion, the DSP implements the feedback

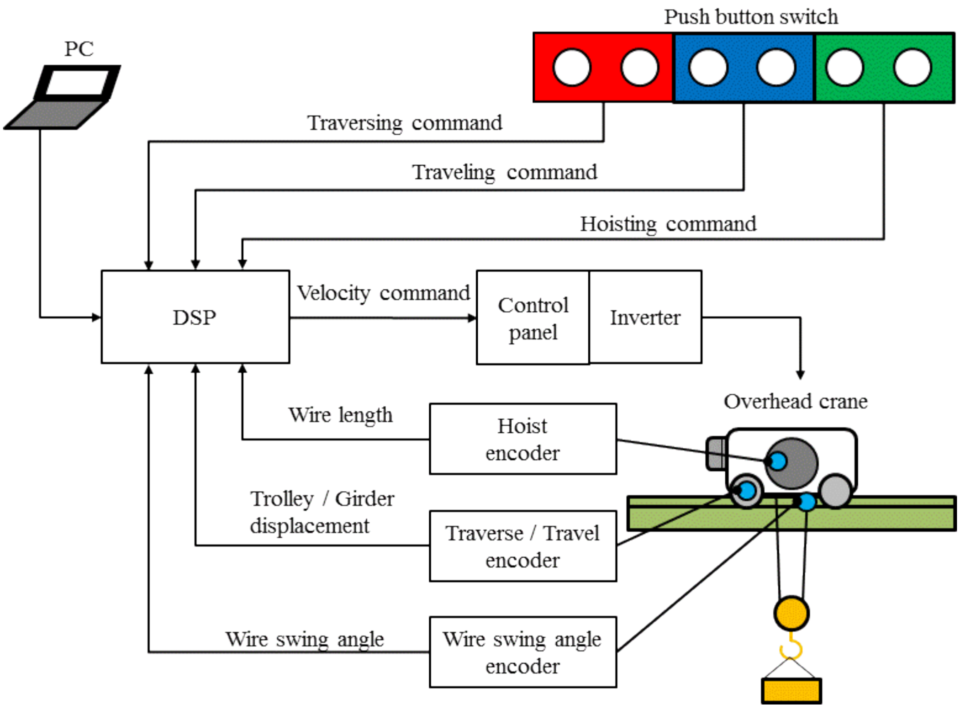


Figure 9. Signal flow of the overhead crane experiment

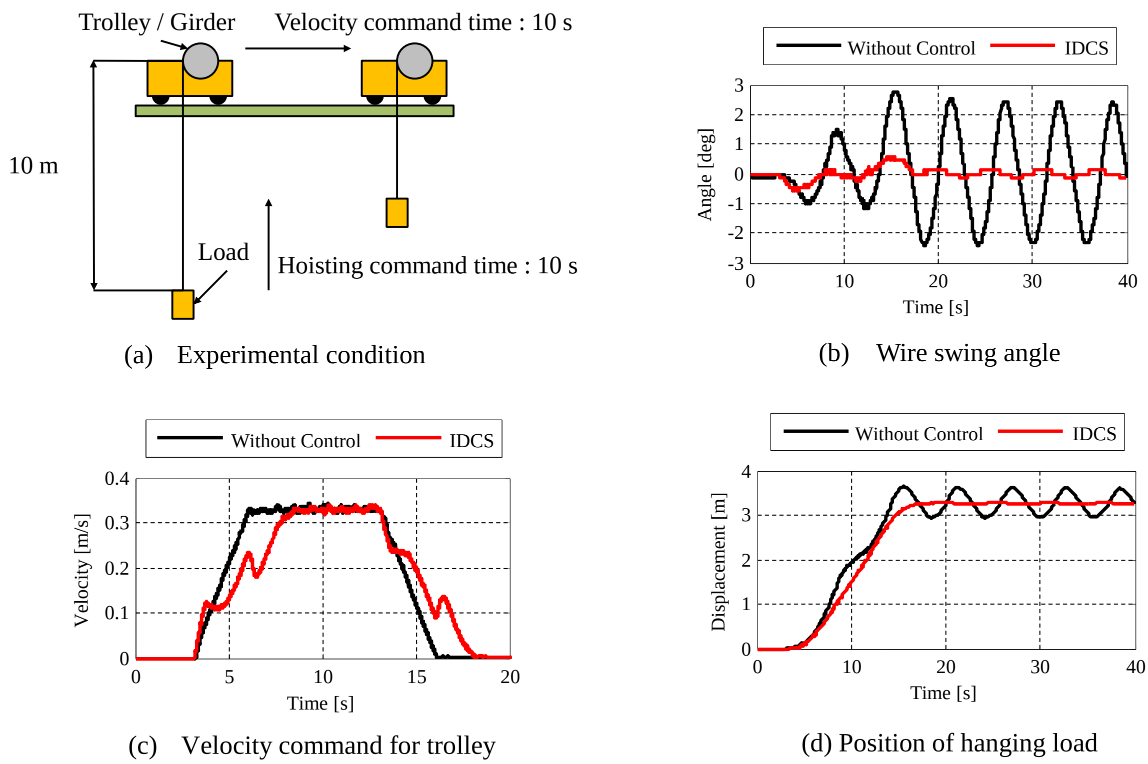


Figure 10. Traverse motion control with varying wire length

control simulation which is shown in figure 7, and calculates the trolley/girder velocity command signal. This command signal is input to the inverter and the trolley/girder is driven respectively. The trolley/girder displacement and wire swing angle in each horizontal axis are measured by encoders for monitoring.

5. Experimental results

In this section, performance of the control system is evaluated by experiments under several conditions.

5.1. Single axis motion control with varying wire length

Figure 10 shows vibration suppression performance in traversing direction. As shown in figure 10(a), the trolley moves for 10 seconds with trapezoidal velocity shape (figure 6), at the same time, the hanging load is hoisting at 0.35m/s. Figure 10(b), 10(c), and 10(d) show the wire swing angle, velocity command for the girder, and position of the hanging load, respectively. Remarkable vibration suppression performance can be seen from the figures. Similar control performance is obtained in

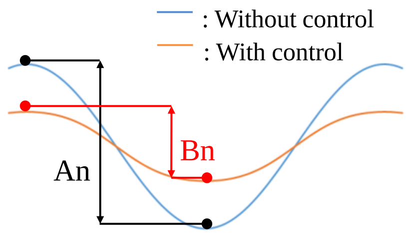


Figure 11. Control performance index

experiments for traveling direction. In order to evaluate vibration control performance quantitatively, the following performance index ε is introduced.

$$\varepsilon = \frac{B_{mean}}{A_{mean}} \times 100 \ \ [\%] \, , \tag{6}$$

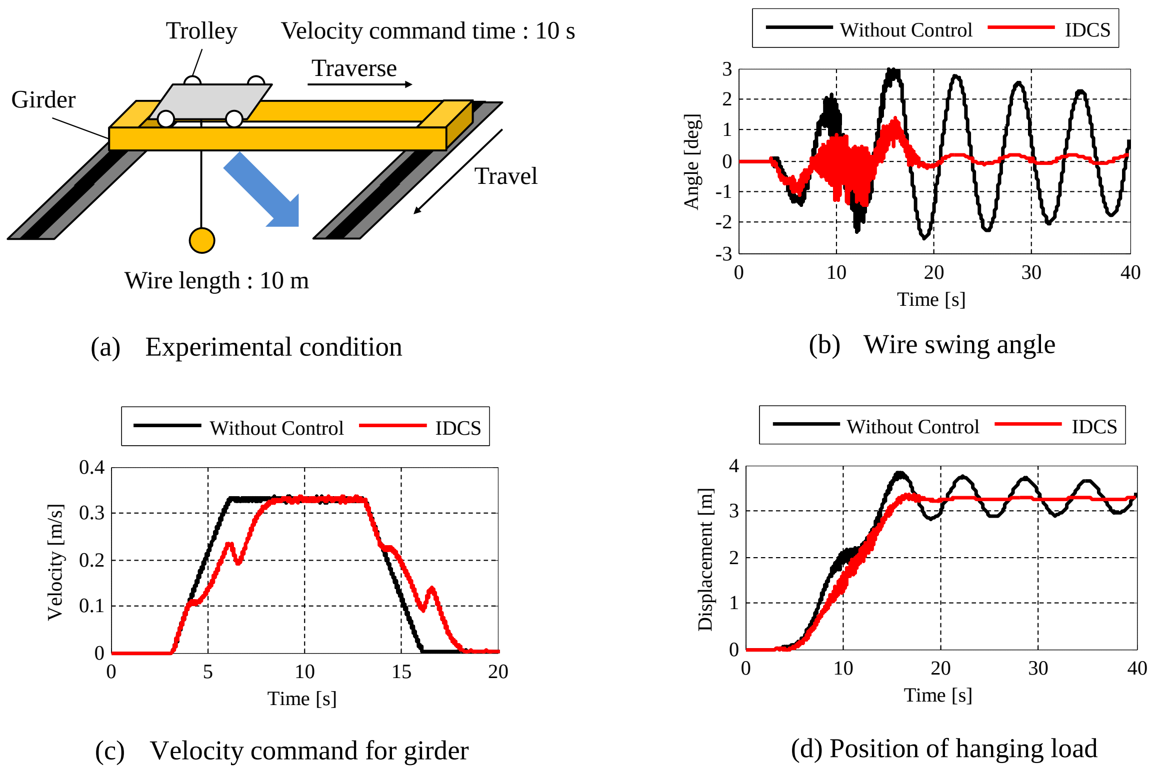
where, B_{mean} expresses the average of 5 wire swing angle amplitude B_n shown in figure 11 after the trapezoidal velocity command input. Also, A_{mean} is obtained by similar manner using A_n in figure 11. Table 2 shows vibration reduction rates using this index. In both directions, the wire swing angles are suppressed about 1/20 compared to without control case.

Table 2. Reduction rate of wire swing angle with IDCS

Traverse	Travel
4.9 %	5.3 %

5.2. Double axes motion control

Figure 12 and figure 13 show vibration suppression performance when the crane is simultaneously controlled in both traversing and traveling directions. The performance in traveling direction is shown in figure 12, and the performance in traversing motion is shown in figure 13. In the experiments, the same trapezoidal velocity shape is used as reference velocity. From these figures, it is seen that wire swing angle is suppressed considerably well in both directions. Table 3 shows performance index which is calculated by equation (6). Almost the same performance as single motion control is obtained in double axis motion control.



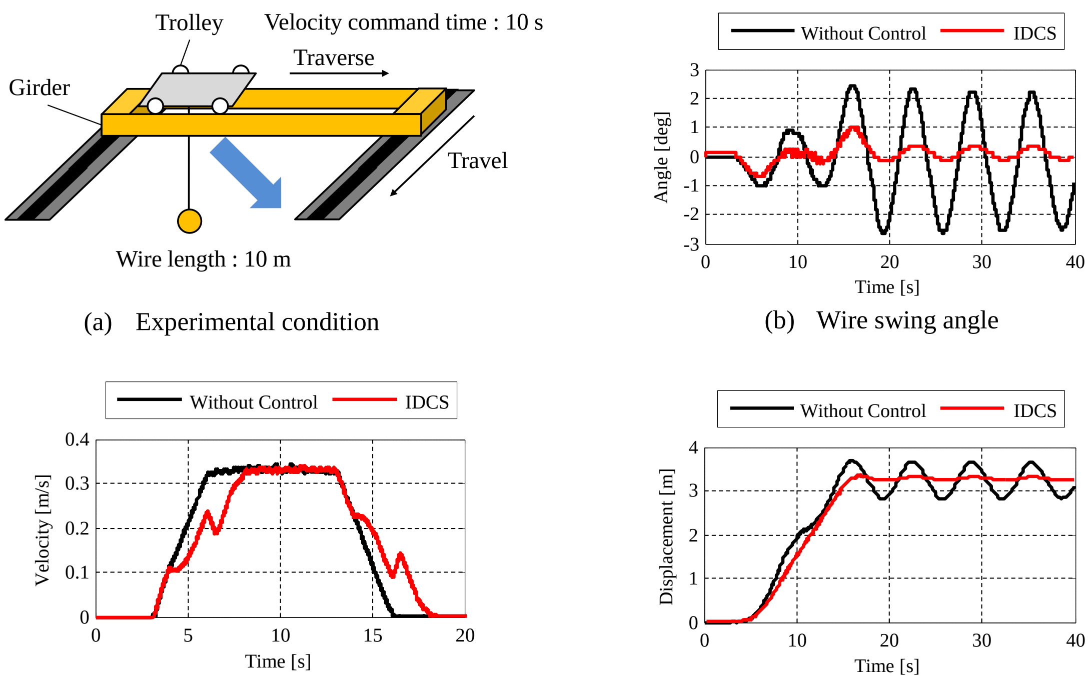
(a) Experimental condition (b) Wire swing angle

(c) Velocity command for girder (d) Position of hanging load

Figure 12. Traveling motion control

Table 3. Reduction rate of wire swing angles with IDCS

Traverse	Travel
9.8 %	5.1 %



(a) Experimental condition (b) Wire swing angle

(c) Velocity command for trolley (d) Position of hanging load

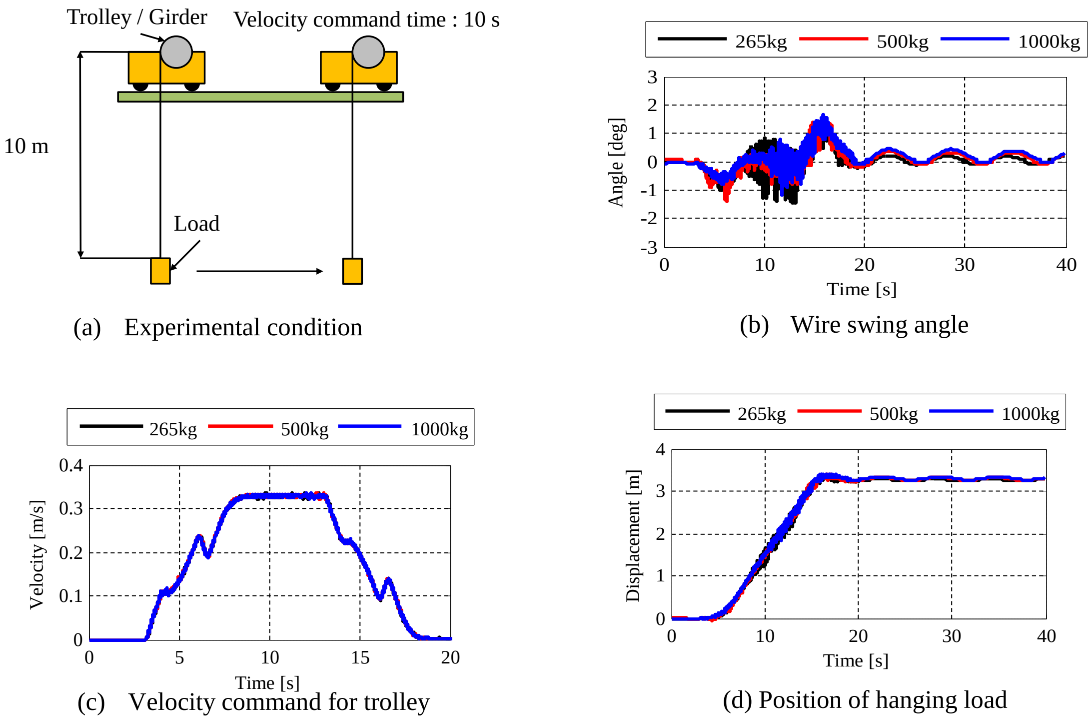
Figure 13. Traversing motion control

5.3. Robustness

Since IDCS is basically a kind of feedforward control method, model errors may cause control performance deterioration. Therefore, several experiments regarding robustness are implemented in this section.

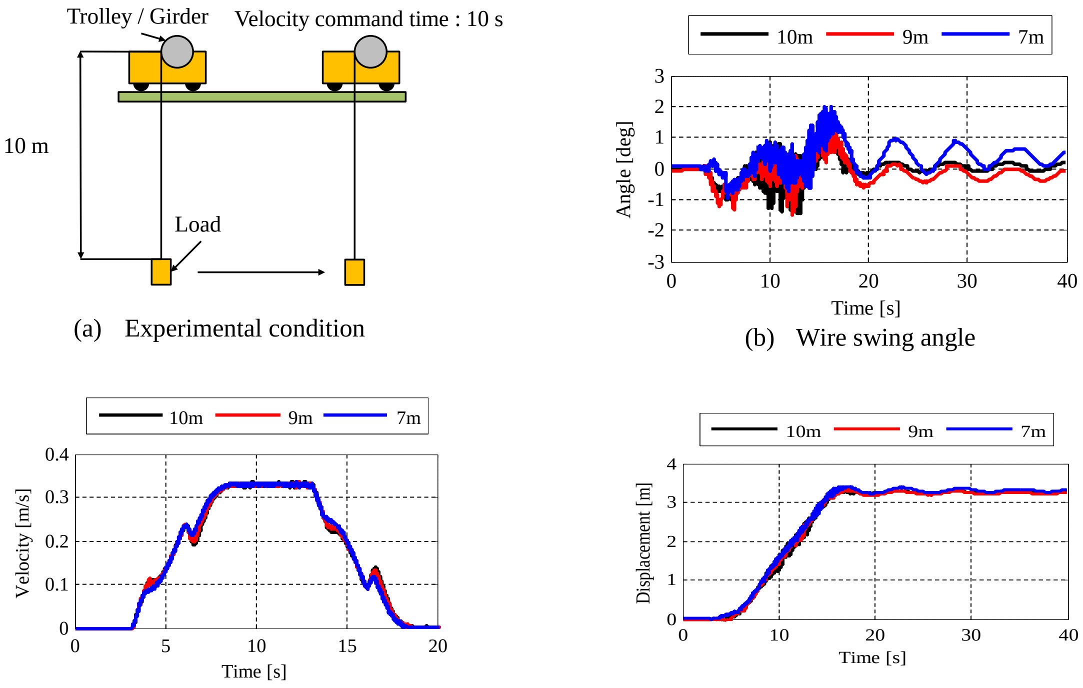
5.3.1. Robustness for load mass variation The purpose of the overhead crane is to carry many kinds of loads to the target position, and in almost all cases, accurate mass of the loads are unknown. Therefore, control system must be robust for load mass variation. In this study, the controller is designed using the plant model expressed by equation (4). Since equation (4) doesn't include mass of the load, the proposed control system should be robust for load mass variation. Figure 14 compares vibration control performances when 3 different masses are used for the hanging loads. The mass of the load is 265kg, 500kg, 1000kg respectively. Even though they have maximum 400% difference in mass, we confirmed experimentally that the control performance changes very few as we expected.

5.3.2. Robustness for wire length variation Generally, it is difficult to measure accurate wire length of the overhead crane in actual site where the crane is used. Therefore, robustness for wire length variation is important in the same way as mass variation. Figure 15 compares control performances with 3 different controllers which are designed with 3 wire length (10m, 9m, and 7m). In the experiments, the wire length of the actual overhead crane is kept with 10m, then above 3 controllers are applied. In every case, we could get better performance than no control case. Especially, the controllers for 10m and 9m have almost same performances (robust for 10% error). From this fact, it is seen that the proposed control system is sufficiently robust for wire length variation.



(a) Experimental condition
(b) Wire swing angle
(c) Velocity command for trolley
(d) Position of hanging load

Figure 14. Robustness for load mass variation (traveling motion)



(a) Experimental condition
(b) Wire swing angle
(c) Velocity command for trolley
(d) Position of hanging load

Figure 15. Robustness for wire length error (traveling motion)

6. Conclusion

In this paper, we firstly introduced basic idea of simulation based control (IDCS), then mechanism and modeling of the overhead crane was presented. Next, the control system design of the overhead crane was related, and then experimental results using real overhead crane with 2 axes are shown. The followings are summary of this article.

(1) For the first time, IDCS (simulation based control) is applied to the real overhead crane
(2) Considerably good vibration suppression performances are obtained for motion with varying wire length, and also simultaneous motion in 2 axes
(3) Robustness of the control system is confirmed for both load mass variation and wire length error
(4) IDCS (sensorless) experiments show almost the same performance as sensor feedback experiments

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