Development of simple operation crane system for the real application

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Abstract. In each industry, the weight of the transportation work and quantity of the load has increased. Thus, now the crane equipment is introduced than ever. For overhead crane used in factories and warehouses, efficient operation which suppresses the swaying of the suspended load during transport is strongly demanded. In particular, it is necessary to suppress the initial shaking or disturbance due to the shift of the center of gravity and the hanging point position at the time of raising the suspended load. Therefore, we need to develop the simple operation crane system that enables the operation of the same level as the person skilled in the crane operation in order to improve the safety and efficiency. The author have investigated the control using Dual Model Matching method based on characteristic transfer function matrix to a configuration of the controller. By implementing feedback control on an actual overhead crane in practical use, the efficacy and operability of the system and the method were discussed. The purpose of this study, by developing the simple operation crane system that allows the same operation as the skilled operator, is to improve the safety and efficiency of the crane operation.

1. Introduction

Today’s cranes are used as transporters in a diverse range of industries such as construction, physical distribution and manufacturing. Among the different types, overhead traveling cranes are often used for transporting heavy loads in factories. An overhead traveling crane is capable of performing traveling motions to move along traveling rails installed along the walls on both sides of the building, as well as traversing motions to move along the girder that spans the traveling rails and hoisting and lowering motions to move the hanging load up and down by changing the wire length. By combining these motions, the crane is able to transport a heavy load to the target position. A crane is required to transport the hanging load to the target position with a high degree of accuracy and without swinging the hanging load during these motions. However, a load swing does arise due to the inertia force of the hanging load when a motion such as traveling or traversing is executed. In this case, it takes a few minutes before the load rests, resulting in a work delay. Furthermore, interference with surrounding equipment may occur during transport in a narrow area. When load swing arises, the natural frequency of vibration changes with the varying wire length of the crane, requiring a skilled operator to handle the crane. However, a shortage of skilled operators is anticipated in Japan in the future due to the declining birthrate and the growing unpopularity of skilled trade work. In addition, cases where operators with no experience in overhead traveling cranes are engaged in transporting work in the field.
are likely to accompany the increase in export of infrastructure to Southeast Asia. Although there are several examples of applied technologies for anti-vibration control of crane loads, they are applicable to limited conditions with a fixed movement locus.

The purpose of this study was to develop an overhead traveling crane control system that permits unskilled operators to work in a manner equivalent to that of skilled operators from the viewpoint of safety and working efficiency. Specifically, the aim is to establish a control system for an overhead traveling crane that adds automatic anti-vibration control to the conventional load positioning work by an operator. It is necessary in this case to maintain safety and suppress the hanging load vibration and residual vibration during the transient period at high velocity and with high accuracy.

2. Overview of overhead traveling crane

Fig. 1 shows an image of an overhead traveling crane in operation. Table 1 lists the specifications for the overhead traveling crane in this study. Incremental encoders were used to measure the traversing/traveling distance of the trolley of the overhead traveling crane, the wire swing angle and the wire length. During the measurement of the wire swing angle, the arm inclination was detected as the wire swing angle $\theta$ [rad] by the provision of guide arms along the rotary shaft of the encoder in such a form that they nip at the wire, as shown in Fig. 2. The inverter, which is the power unit for the overhead traveling crane, is a VF control inverter that outputs a voltage corresponding to the frequency (V/f characteristic). Furthermore, pushbutton operating switches (pendant switches) are directly connected to the crane. Wire hoisting/lowering and trolley traversing/traveling are commanded from these switches.

Fig. 3 shows the configuration of the control system for the entire overhead traveling crane. Controllers are mounted by designing and constructing programs and controllers that generate velocity command values in real time using MATLAB Simulink on a PC and by loading these programs in the digital signal processor (DSP), manipulated variables are output and a velocity command signal is input to the inverter through the programmable logic controller (PLC). Upon receiving a signal from the inverter, the trolley motor of the crane starts up and the values of the trolley displacement, wire swing angle and wire length are fed back from the encoders to the DSP. In the DSP, the displacement of the hanging load in the horizontal direction is calculated from the measurement results for the wire angle, trolley displacement and wire length. Furthermore, the velocity of the hanging load is calculated by pseudo-differentiation of the hanging load displacement, and the trolley velocity is controlled.
3. Modeling

Fig. 4 shows the control model of an overhead traveling crane, which is the control object. The overhead traveling crane is composed of a trolley that moves in the traversing and traveling directions in the horizontal uniaxial direction and a hoisting device for changing the rope length. The parameters of the control model are set as trolley displacement $u$, rope length $l$, hanging load displacement $y$, rope swing angle $\theta$, and hanging load mass $m$. The transfer function from trolley displacement to hanging load displacement is derived from the equation of motion as a pendulum that is attached to the trolley that moves in such a manner in the uniaxial direction. It is assumed that the response of the trolley is free from lag and that the trolley displacement changes with the reference.

From Newton’s equation of motion, the equation of motion of the pendulum using the rotating system of coordinates of the trolley is:

$$ml^2\ddot{\theta} + 2ml\dot{\theta} + mgl\sin{\theta} + ml\dot{u}\cos{\theta} = 0 \quad (1)$$

Assuming that the wire rigidity is high and the wire swing angle is minor, the following is obtained:

Table 1. Crane specification

| Parameter           | Value               |
|---------------------|---------------------|
| Supply voltage      | 0-200V              |
| Power frequency     | 50Hz                |
| Rated velocity      | 0.167 m/s (Hoisting) |
|                     | 0.350 m/s (Traversing, Traveling) |
| Wire length         | 20 m                |
| Capacity            | 20 ton              |
\[ \ddot{\theta} + 2 \frac{l}{l} \dot{\theta} + \frac{g}{l} \theta + \frac{1}{l} \dot{u} = 0 \]  
(2)

where it is assumed that wire length \( l \) and wire length velocity \( \dot{l} \), which is a derivative of wire length, are constant. Performing Laplace transform with the initial value 0 using this process gives:

\[ \left( s^2 + 2 \frac{l}{l} s + \frac{g}{l} \right) \Theta(s) = -\frac{1}{l} s^2 U(s) \]  
(3)

Furthermore, the wire swing angle in the model shown in Fig. 4 is given by.

\[ \theta = \sin \theta = \frac{y-u}{l} \]  
(4)

Upon Laplace transform of Eq. (3) with the initial value 0, the transfer function \( P_{uy} \) from trolley displacement to hanging load displacement is as shown in Eq. (5). Furthermore, Fig. 5 shows a Bode diagram.

\[ P_{uy} = \frac{y}{u} = \frac{2 l^2 + g l}{s^2 + 2 \frac{l}{l} s + \frac{g}{l}} \]  
(5)

In addition, from the transfer function, the natural frequency \( \omega_n [\text{rad/s}] \) and damping ratio \( \zeta \) of the hanging load model are given by:

\[ \omega_n = \frac{\sqrt{gl}}{l}, \zeta = \frac{\dot{l}}{\sqrt{gl}} \]  
(6)

From Fig. 5 and Eq. (6), the natural frequency and damping ratio change with the wire length, and the damping ratio also changes with the wire winding velocity. Thus, the hanging load model of the overhead traveling crane can be expressed as a linear parameter-varying system related to the wire length and wire winding velocity.

**Fig. 4** Analysts model of the overhead traveling crane

**Fig. 5** Bode diagram of Crane model
4. Overview of Dual Model Matching (DMM) method

In similar studies related to crane vibration control, various control system design techniques that take into account variation of the wire rope length are proposed, including nonlinear control [1] that grips the wire rope length as a time-varying system, gain schedule control [2][3] that uses $H^\infty$ control, feedback control [4][5] that uses optimum regulators and so forth. These techniques, however, use the state-space form or a combination of state-space and transfer-function forms, making it difficult to understand the complex structure of the entire control system. Consequently, we decided to adopt a control technique that applies hanging load anti-vibration measures through control of the crane’s traversing trolley using the dual model matching method (hereinafter called "DMM method") which is based on the characteristic transfer function matrix (CTFM)[6] in the composition of controllers.

The DMM method is described here. This technique is used to design controllers for developing a control system from transfer functions by directly setting the closed loop transfer functions from noise to control input and the closed loop transfer functions from reference to control input as two closed loop transfer functions while satisfying certain conditions.

Fig. 6 shows a block diagram of DMM control. $W_{vy}$ is related to robust stability. $W_{ry}$ is related to the reference tracking performance. Therefore, $W_{vy}$ and $W_{ry}$ are important transfer function matrixes that determine the basic characteristics of a closed loop system, such as robust stability, sensitivity reduction and reference tracking.

From Fig. 6, the relationship shown in Eq. (7) can be derived for $W_{vy}$ and $W_{ry}$:

$$W_{vy} = P_{uy}\ W_{vu}$$
$$W_{ry} = P_{uy}\ W_{ru}$$

(7)

controller transfer functions $C_{rw}(s)$ and $C_{hw}(s)$ can be expressed as:

$$C_{hw} = W_{qu}\ W^{-1}_{ru}$$
$$C_{rw} = W_{qu}\ W^{-1}_{ru}$$

(8)

This is the basic concept of the DMM method, and we call the transfer function matrix $[W_{vu} \ W_{ru}]$ a dual model. Furthermore, by setting $W_{vu}$ and $W_{ru}$ it is also possible to determine $W_{qu}$. For this reason, the DMM method permits simultaneous consideration of three factors, that is, reference tracking, robust stability and disturbance suppression. By using this concept of the DMM method, it is possible to express a controller by algebraic symbol notation.

![Fig. 6 DMM based LPV control system](image-url)

$r$ : Reference  
$y$ : Output  
$z$ : Measured variable  
$q$ : External disturbance  
$v$ : Sensor noise from  
$u$ : Input to the plant function from  
$h$ : Input to the controller  
$w$ : Output from the controller

$P_{uy}$ : Plant transfer function from $u$ to $y$  
$C_{rw}$ : Controller transfer function $r$ to $w$  
$C_{hw}$ : Controller transfer $h$ to $w$  
$W_{ry}$ : Closed loop transfer function from reference $r$ to output $y$  
$W_{vy}$ : closed loop transfer function from noise $v$ to output $y$
5. Design of crane control system via the DMM method

This section describes the development of controllers based on the control model and DMM control method described in Sections 3 and 4. From Eq. (5), a control system plant is expressed by transfer function \( P_{uy} \) from trolley displacement to hanging load displacement. From Eq. (8), the controllers can be expressed by:

\[
C_{hw} = (1 + W_{ru}P_{uy})^{-1}W_{ru} \\
C_{rw} = (1 + W_{ru}P_{uy})^{-1}W_{ru}
\]

(9)

The controllers designed this time are intended to provide the following three points as characteristics of the whole closed loop system:

- Continually good reference tracking performance and relatively high damping ratio regardless of the wire length
- Suppression of disturbance in the low-frequency band
- Noise elimination and robust stability in the high-frequency band

For determining the order of a controller, the following three points are required for a controller to cause the closed loop system to provide the above characteristics:

- Order for setting reference tracking
- Order for adjustment of disturbance suppression
- Order for providing a low-pass filter

Fig. 7 and 8 show Bode diagrams of controllers \( C_{hw} \) and \( C_{rw} \). Wire length \( l \) was set at 2m, 6m and 10 m, and rope length change velocity \( v_l \) was set at 0.10 m/s. Controllers \( C_{hw} \) and \( C_{rw} \) change with the rope length by sequentially acquiring varying parameters and substituting them in the controllers. Fig. 9 show Bode diagrams of controllers \( W_{ry} \).

6. Verification of anti-vibration control via DMM control

An analysis was made using the controllers designed in Section 5. The controllers were mounted on the overhead traveling crane described in Section 2 and experiments were conducted. The results are described below. As analysis conditions, the hanging load was set in the traversing direction or traveling direction, the wire length was fixed at 10 m, and the trolley velocity, wire swing angle and hanging load displacement were analyzed under the conditions of without control and with DMM control, respectively, with the acceleration/deceleration time set at 3 second and the stationary velocity set at 0.35 m/s. The hanging load displacement was calculated from the wire swing angle, wire length and trolley displacement at this time. DMM control was considered to be effective, even after termination of the command, until the velocity dropped to 5% (0.018 m/s) of the stationary velocity of the trolley. Fig. 10(a) shows the trolley velocity, Fig. 10(b) shows the wire swing angle and Fig. 10(c) is an overlap view of the hanging load displacement without control and with DMM control. It is learned from Fig. 10(a) that in the case of DMM control, the trolley velocity returns the swing of the load caused by the inertia at the time of motion of the hanging load by driving the trolley in a notch.
form at the time of acceleration (4–9 s) and rapid acceleration/deceleration is made again in a notch form so as to suppress the overrun of the hanging load caused by inertia at the time of deceleration (14–18 s). From Fig. 10(b) and Fig. 10(c), while the vibration amplitude of the hanging load caused by the residual vibration at the time of termination of control (in the vicinity of about 18 s) was about 0.4 m and the wire swing angle was about 3.5deg in the case without control, it is learned that the vibration amplitude is reduced and vibration deadening is achieved under DMM control.

Fig. 11(a), Fig. 11(b) and Fig. 11(c) show the experimental results for the trolley velocity, wire swing angle and hanging load displacement by traversing with a hanging load mass of 240 kg under the same conditions as for the above analysis. From Fig. 11(a), the trolley velocity exhibits similar behavior to that in the analysis(Fig. 10(a)), and concerning the swing angle shown in Fig. 11(b) and the hanging load displacement shown in Fig. 11(c), good vibration deadening effect is produced similarly to that in the analysis(Fig. 10(b), Fig. 10(c)). A comparison of the experimental results and the analysis shows that the results of the experiments without control and with DMM control are also equivalent. The adequacy of the analysis model was confirmed from these results and the effectiveness of DMM control could be verified. In addition, equivalent experimental results were also obtained in the traveling direction.

Next, the results are shown for DMM control under the following experimental conditions: a stationary hanging load was swung in the traversing direction until the wire swing angle became 1.5deg, the wire length was fixed at 10 m in the state where disturbance was intentionally applied and the hanging load was moved at an acceleration/deceleration time of 3 s and a stationary velocity of 0.35 m/s. Fig. 12(a) shows the trolley velocity, Fig. 12(b) shows the wire swing angle and Fig. 12(c) shows the hanging load displacement. When the trolley velocity is compared between the case without disturbance (Fig. 11(a),with control) and the case with disturbance (Fig. 12(a)), it is learned that the width and height of notching for deadening the swing caused by the disturbance are larger in the case with disturbance. Furthermore, even at a stationary velocity (6–14 s), it is learned that DMM control
performed gradual acceleration/deceleration to suppress the disturbance. Due to the suppression, the trolley stationary time lagged by about 1 second. Furthermore, when the position of the hanging load is compared between with disturbance and without disturbance (Fig. 11(c) and Fig. 12(c)), while the stop position was about 3.3 m in the case without disturbance (Fig. 11(c), With Control), the stop position was about 2.8 m in the case with disturbance (Fig. 12(c)), and the distance was shortened, due to the suppression of disturbance, by about 0.5 m, which is approximately equivalent to the vibration amplitude portion of the disturbance (0.5 m when the hanging load moving distance is calculated from the conditions for disturbance, i.e., wire swing angle 1.5 deg, wire length 10 m). From Fig. 12(b), however, it is learned that the wire swing angle and the residual vibration at the position of the hanging load have decreased even in the case with disturbance. It is learned from these facts that feedback control is effectively working against the disturbance.

![Fig. 12 Response of experiment (With disturbance)](image)

(a) Trolley velocity  
(b) Wire angle  
(c) Load displacement

Also shown are the results for traversing at an acceleration/deceleration time of 3 second and a stationary velocity of 0.35 m/s performed while the hanging load is hoisted (rope length is reduced from 10 m to 8 m). Fig. 13(a) shows the trolley velocity, Fig. 13(b) shows the wire swing angle and Fig. 13(c) shows the hanging load displacement. Good vibration deadening effect of DMM control could thus be verified even under the condition when the rope length was varied. It is learned from these results that while sequential changes occur with the functions of wire rope length \( l \) and velocity \( v_l \) in plant model \( P_y \) expressed by Eq. (5), the vibration deadening at each wire rope length is expressed by the tracking changes of controllers \( C_{rw} \) (Fig. 7) and \( C_{hw} \) (Fig. 8).

![Fig. 13 Response of experiment (Rope length is reduced from 10 m to 8 m)](image)

(a) Trolley velocity  
(b) Wire angle  
(c) Load displacement

Shown below are the experimental results for traversing at an acceleration/deceleration time of 3 second and a stationary velocity of 0.35 m/s without control and with DMM control in the case where the hanging load mass is 500 kg and 1000 kg, respectively. Fig. 14(a) shows the trolley velocity under the condition of a hanging load mass of 500 kg and 1000 kg. Fig. 14(b) shows the wire swing angle and Fig. 14(c) shows the hanging load displacement under the condition of a hanging load mass of 500 kg and 1000 kg. As a result of comparing these values with those under the condition of a hanging load mass of 240 kg (Fig. 11(b), Fig. 11(c)), it is learned that an almost equivalent vibration deadening
effect is obtained. Thus, it is learned that with plant model $P_{dy}$, the control object is not dependent on the mass.

![Image](71x719)\(P\)uy

![Image](331x717)\(P\)

Next, a comparison was made between the case without control and the case with DMM control when the trolley is traversed under the conditions of wire rope length 10m, acceleration/deceleration time of 3 second and stationary velocity of 0.35 m/s using controllers $C_{rw}$ and $C_{hw}$ for a wire length of 9 m, 7m and 5m. Fig. 15(a) shows the trolley velocity, Fig. 15(b) shows the wire swing angle and Fig. 15(c) shows the hanging load displacement. As the vibration deadening effect was observed even in the case where the rope length differs by 50%, the robustness of the controllers for this control system was verified.

![Image](71x415)(a)Trolley velocity

![Image](195x542)(b)Wire angle

![Image](148x529)(c)Load displacement

**Fig. 14 Response of experiment (Hanging load mass of 500kg,1000kg)**

**Fig. 15 Response of experiment (Controllers for a wire length of 9 m,7m and 5m)**

7. **Conclusion**

With the goal of developing an overhead traveling crane control system that permits unskilled overhead traveling crane operators to perform in a manner equivalent to skilled operators from the viewpoint of safety and working efficiency, we adopted a control technique to execute anti-vibration of the hanging load by controlling the traversing and traveling trolley of the crane by following the dual model matching method. The following conclusions were reached by mounting this control technique on a crane:

- An actual crane simulation model was produced by combining a trolley model and a moving pendulum model, a velocity control system that corresponds to an actual crane was constructed, and the effectiveness of the control system was verified through simulation analysis.
- It was verified that the swing of the hanging load can be suppressed by DMM control under such conditions that the trolley travels and traverses in a state where the wire length of the overhead
traveling crane is constant. Furthermore, the effectiveness of the control model could be verified because the control model and experimental results were equivalent. In the controlled state, the swing of the hanging load can be almost completely suppressed while the trolley velocity is at the set maximum velocity level.

- It was learned that vibration deadening is effective in the case of a control system that sequentially updates the controllers so as to match the conditions of traversing/traveling while the wire length varies.
- Even with a disturbance that causes the hanging load to swing, the hanging load displacement can be suppressed by controlling the trolley of the overhead traveling crane by acceleration/deceleration such as a notch.
- Almost the equivalent vibration deadening effect was verified in the case where the hanging load mass changes, and the controllers are not dependent on the mass.
- Robustness of the controllers was verified, as the vibration deadening effect was observed under the condition where the rope length differs by 50%.

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