

SPECIFICATION

Title of the Invention

Method and device for controlling a jib crane

Technical Field

This invention relates to a method for controlling a jib crane and a device therefor and, more particularly, to such method and device which are capable of preventing swaying of a hanging load and vibration of a mast of a crane while eliminating a delay in actual operation to an operation command by an operator.

Background Art

In the field of jib cranes, many proposals have been made for mainly reducing swaying of a load caused by operation of a jib and these proposals include one using a feedback control and one based on an operation pattern. For example, Japanese Patent Application Laid-open Publication No. 09-315765 discloses a proposal which detects length of hanging portion of a rope, a rotation angle of a jib from present position to a target position, and an angle of swaying and swaying speed of a load and causes the load to stop at a target position by controlling angular velocity of rotation of the jib so that the angle of rotation, the swaying angle and swaying speed of the load will come within a permissible error range. Japanese Patent Application Laid-open Publication No. 05-85698 discloses a proposal which prevents swaying of a load by using an operation pattern using 2-stage acceleration timings which are optimum to length of a rope at the time of starting and at the time of finishing.

However, in jib cranes, particularly tower cranes used for construction of a building or a dam, it is considered difficult to build a mast (tower portion) which constitutes a base of the crane

with a rigid material and a flexible material is used for the mast. For this reason, movement of a crane causes vibration of the mast and remaining vibration of the mast added to swaying of the load imparts unpleasant feeling resembling sea-sick to the operator and this results in reduction in the work efficiency. Particularly in a tower crane, the range of variation in the length of load-rope is large and, therefore, swaying prevention efficiency has to be reduced when the length of load-rope is controlled to a limited range. Further, swaying caused by strong wind and earthquake must also be reduced. For this purpose, provision of swaying prevention devices using a pendulum or a gimbal (or jiroscope) is also proposed. For example, Japanese Patent Application Laid-open Nos. 03-200693 and 03-200694 disclose a swaying prevention device which has a pendulum in the main body of a crane. Japanese Patent Application Laid-open Publication No. 07-233854 discloses a device which detects rotation angle of a gimbal and detects vibration of a tower crane and computes these detection signals to drive the gimbal and thereby prevent vibration of the tower crane.

Japanese Patent Application Laid-open Publication No. 2005-67747 provides a method and device for controlling a jib crane which can achieve both position control of a load while swaying of load is prevented and prevention of vibration of a main body of a crane caused by crane work and also caused by disturbance caused by outer factors such as wind and earthquake by only operating a conventional motor of the jib crane in response to a desired command of the operator using a two-degree-of-freedom control system in which feedback control and feed-forward control are combined.

Summary of the Invention

The prior art crane control was limited to the control of load as shown in the above cited Japanese Patent Application Laid-open Publication No, 09-315765 or No. 05-85698 or the control of sway of

the mast as shown in the above cited Japanese Patent Application Laid-open Publication No.03-200693 or No. 03-200694. Such control of either one of load and mast only, however, leaves sway or vibration of the other of load and mast unremoved with the result that unpleasant feeling is imparted to the operator.

For controlling sway of a load and vibration of a mast simultaneously, therefore, it is necessary to provide, as shown in Japanese Patent Application Laid-open Publication No. 07-233854, not only a control function for preventing sway of the load but also a vibration prevention device such as a gimbal for preventing vibration of the mast. However, provision of such vibration control device in an existing crane necessitates a large-scale reforming work.

As an example of a method for simultaneously controlling both load and mast, Japanese Patent Application Laid-open Publication No. 2005-67747 has been cited above. However, in this proposed control, priority is given to prevention of sway of a load and vibration of a mast rather than to the positioning control of the load. Hence, prompt positioning control of the load in response to an operator's command cannot be achieved and, as a result, delay is caused in actual operation to the operator's command and this imparts unpleasant feeling to the operator in his operation.

This invention has been made for solving the above described problems of the prior art. It is an object of the invention to provide a method and a device for controlling a jib crane which are capable of preventing swaying of a hanging load and vibration of a mast of a crane while eliminating a delay in actual operation to an operation command given by an operator.

Means for Solving the Problem

For solving the above described problems, a method of claim 1

for controlling a jib crane by calculating a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in load-rope length of the jib crane and performing a feedback control using gain-scheduled control which uses the calculated linear fractional transformation (LTF) expression is characterized by steps of performing linear combination of a feedback control command for performing the feedback control with an operation command from an operation lever and changing ratio between the feedback control command and the operation command so as to prevent variation in the position of load notwithstanding variation in the load-rope length and thereby enable the load to be moved to a target position.

Claim 2 provides a method for controlling a jib crane wherein, in addition to items defined in claim 1, the ratio between the feedback control command and the operation command is changed between an operation area where the operation command from the operation lever is applied and an area outside of the operation area where the operation command is not applied.

Claim 3 provides a jib crane control device comprising rotation driving means for rotating a jib of the jib crane and derricking driving means for derricking (i.e., hoisting and lowering) the jib of the jib crane characterized by comprising

jib state detection means for detecting at least a rotation angle of the jib, a derricking angle of the jib, an angle of load, and displacement of crane main body;

an operation lever for performing rotation and derricking of the jib, and hoisting and lowering of the load;

lever detection means capable of detecting rotation and derricking of the jib and hoisting and lowering of the load performed by operation of the operation lever; and

a controller comprising a feedback control system performing gain-scheduled control which uses a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in previously input load-rope length,

and a linear combination control section which performs linear combination of a feedback control command from the feedback control system with an operation command from the lever detection means and changes the ratio between the feedback control command and the operation command:

said jib crane control device being capable of preventing variation in the position of the load notwithstanding variation in the load-rope length and thereby enabling the load to be moved to a target position.

Advantageous Results of the Invention

According to the method of claim 1, in a method for controlling a jib crane by calculating a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in load-rope length of the jib crane and performing a feedback control using gain-scheduled control which uses the calculated linear fractional transformation (LTF) expression, there are provided steps of performing linear combination of a feedback control command for performing the feedback control with an operation command from an operation lever and changing ratio between the feedback control command and the operation command so as to prevent variation in the position of load notwithstanding variation in the load-rope length and thereby enable the load to be moved to a target position. Therefore, by making and using a command of the control system by changing the ratio between the feedback control command and the operator's operation command in the command obtained by linear combination of the feedback control command and the operation command, said feedback control being performed for preventing sway of the load and preventing vibration of the mast by controlling an existing motor which performs rotation and derricking of the jib having regard to the load-rope length, control can be made following the operator's operation command and, as a result, positioning of the load can be made with pleasant feeling of operation while preventing vibration of the jib crane. Since

vibration of a jib crane can be prevented without imparting unpleasant feeling to the operator, conveying of load can be made quickly regardless of skill of the operator whereby work efficiency can be increased. Further, prevention of vibration can be made also against disturbance caused by outside factors such as strong wind and earthquake. It is unnecessary to provide a new vibration prevention device and the device of the present invention can be applied easily to an existing jib crane.

According to the method for controlling a jib crane of claim 2, the ratio between the feedback control command and the operation command is changed between an operation area where the operation command from the operation lever is applied and an area outside of the operation area where the operation command is not applied. Accordingly, the operator can make operation with further improved pleasant feeling of operation.

According to the jib crane control device of claim 3, the jib crane control device comprises rotation driving means for rotating a jib of the jib crane and derricking driving means for derricking the jib of the jib crane, and further comprises

jib state detection means for detecting at least a rotation angle of the jib, a derricking angle of the jib, an angle of load, and displacement of crane main body;

an operation lever for performing rotation and derricking of the jib, and hoisting and lowering of the load;

lever detection means capable of detecting rotation and derricking of the jib and hoisting and lowering of the load performed by operation of the operation lever; and

a controller comprising a feedback control system performing gain-scheduled control which uses a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in previously input load-rope length, and a linear combination control section which linearly performs linear combination of a feedback control command from the feedback control system with an operation command from the lever

detection means and changes the ratio between the feedback control command and the operation command:

said jib crane control device being capable of preventing variation in the position of the load notwithstanding variation in the load-rope length and thereby enabling the load to be moved to a target position. Therefore, by making and using a command of the control system by changing the ratio between the feedback control command and the operation command by the operator's operation of the operation lever in the command obtained by linear combination of the feedback control command and the operation command, said feedback control being performed for preventing sway of the load and preventing vibration of the mast by controlling an existing motor which performs rotation and derricking of the jib having regard to the load-rope length, control can be made following the operation command by the operator's operation of the operation lever and, as a result, positioning of the load can be made with pleasant feeling of operation while preventing vibration of the jib crane. Since vibration of a jib crane can be prevented without imparting unpleasant feeling to the operator, conveying of load can be made quickly regardless of skill of the operator whereby work efficiency can be increased. Further, prevention of vibration can be made also against disturbance caused by outside factors such as strong wind and earthquake. It is unnecessary to provide a new vibration prevention device and the device of the present invention can be applied easily to an existing jib crane.

Preferred Embodiments of the Invention

Description will now be made about preferred embodiments of the invention with reference to the accompanying drawings.

FIG. 1 is a block diagram of a control system of one embodiment of the method and apparatus for controlling a jib crane according to the invention.

This jib crane control system is made of a feedback control system using gain-scheduled control having regard to variation in load-rope length. This feedback system has a function of preventing sway and vibration due to disturbance caused by outside factors. A feedback control command is linearly combined with an operation command by an operator's operation of an operation lever. A linear combination operation section changes the ratio between these two commands (i.e., the feedback control command and the operator's operation command) in accordance with state of operation of the operation lever. By this arrangement, a control is made following the operator's operation command and positioning of the jib can be carried out without delay and with pleasant feeling of operation imparted to the operator.

In this embodiment, since it is necessary to realize the feedback control system as a gain-scheduled decentralized control system for derricking and rotational directions, a simple and convenient control system is designed by using, in each direction, a scheduling model (hereinafter referred to as "LFT model") based on linear fractional transformation (LFT) which was formulated by Packards et al (see the above cited Japanese Patent Application Laid-open Publication No. No. 2005-67747).

Such control of a jib crane can be achieved by modeling, design of the control system and verification based on actual moving by an operator (see the above cited Publication No. 2005-67747).

Outline of modeling based on LFT expression having regard to load-rope length will be described below.

Properties of the object of control vary depending upon variation in load-rope length and such variation in the properties is expressed by a model using linear fractional transformation. This modeling is made with respect to each or both of derricking

and rotation having regard to variation in load-rope length and thereby modeling a tower crane by LFT expression. By this modeling, discrete distribution of the control system is made only off line and it is not necessary to cause discrete distribution of the control system on line as in the case of modeling to a parameter variation system.

Outline of design of the feedback control (gain-scheduled control) system is as follows:

By adopting the gain-scheduled control system according to which the controller changes in accordance with variation in load-rope length, a feedback control having an excellent effect of preventing sway and vibration caused by disturbance caused by outside factors such as wind and earthquake and also an erroneous operation by an operator can be achieved regardless of load-rope length.

The above described modeling and manner of designing the control system will be described in detail below.

Modeling

(1 · 1) Derivation of three-dimensional model Q

. A three-dimensional model of a tower crane is shown in FIG. 2. In the figure, reference character 1 designates a mast, 2 a jib, 3 a load, and 4 a rope. Definitions of main symbols will be given below.

X_1 : absolute displacement of each portion of the mast in x-direction, y_1 : absolute displacement of each portion of the mast in y-direction, ν : derricking angle of the jib, θ : sway up angle of the load in the derricking direction, ζ : angle of rotation, ψ : sway up angle of the load in the rotational direction, L : length of the jib, l : length of the load-rope, L_1 : length of the mast,

W_b : mass of the jib, W_o : mass of the load, M_d : mass of the rotation frame including motors for derricking and rotation and gantry, κ : equivalent spring constant of a lower dimension model, c_1 : equivalent attenuation constant of the lower dimension model, x_r : displacement of the highest portion of the mast in derricking direction, y_r : displacement of the highest portion of the mast in derricking direction and right angle direction, ν_n : angle of derricking of the jib with counter-clockwise direction from the x-axis being assumed to be positive direction, u_s : input torque in rotational direction, u : input torque in derricking direction, g : gravitational acceleration

The origin of x-y-z coordinates is assumed to be located at the highest portion of the mast and the following assumptions are made.

- a) The mass of the rope is disregarded.
- b) Torshional vibration of the mast which is considered to be very small is disregarded.
- c) The mast is assumed to be based on 4-particle model in only parallel direction in the x-y plane.
- d) The jib is assumed to be a rigid body.
- e) Dynamic characteristics of the jib supporting rope is disregarded and it is assumed that input torque only is applied directly to the tip of the jib.

Kinetic energy T_b and potential energy V_b which the jib has, kinetic energy T_o and potential energy V_o which the load has and kinetic energy T_1 which the rotation frame has are respectively calculated and then equation of motion of the crane portion including the rotation frame is calculated by using the following Lagrange's equation

$$\begin{aligned}
\frac{d}{dt} \left(\frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial T}{\partial q_i} + \frac{\partial V}{\partial q_i} &= Q_i \quad i = 1, \dots, 6 \quad (1) \\
T &= T_b + T_o + T_t, \quad V = V_b + V_o \\
q &= [q_1, \dots, q_6]^T = [x_1, y_1, \nu, \theta, \zeta, \psi]^T \\
Q &= [Q_x, Q_y, Q_u u, 0, u_s, 0]^T
\end{aligned}$$

In this equation, Q_u is a coefficient which arises geometrically with respect to the supporting rope. The moments M_x , and M_y about the axis y_r and x_r of the crane portion are converted by modification of straight beam to equivalent outside forces Q_x and Q_y which are applied to the highest portion of the mast as

$$Q_x = \frac{3}{2L_t} M_x, \quad Q_y = \frac{3}{2L_t} M_y \quad (2)$$

Further, mass, attenuation, rigid elements which are common to the equation of motion of the mast based on the 4-particle spring-mass-damper system are added and combined. Further, considering that the sway angle of the load-rope is small,

$$\sin \theta \simeq \theta, \quad \cos \theta \simeq 1, \quad \sin \psi \simeq \psi, \quad \cos \psi \simeq 1 \quad (3)$$

By converting this to

$$\begin{aligned}
\sin \nu &= \frac{\sin \nu}{\nu} \cdot \nu, \quad \cos \nu = \frac{\cos \nu}{\nu} \cdot \nu \\
(20 \leq \nu \leq 70 \quad (\text{deg})) &
\end{aligned} \quad (4)$$

the following state equation is obtained:

$$\begin{aligned}\dot{x}_{td} = & A_{td}(\nu, \dot{\nu}, \theta, \dot{\theta}, \zeta, \dot{\zeta}, \psi, \dot{\psi}, l, \dot{l}, \ddot{l})x_{td} \\ & + B_{td}(\nu, \dot{\nu}, \theta, \dot{\theta}, \zeta, \dot{\zeta}, \psi, \dot{\psi}, l, \dot{l}, \ddot{l}) [u \ u_s]^T\end{aligned}\quad (5)$$

where

$$\begin{aligned}x_{td} = & [x_1, y_1, \nu, \theta, \zeta, \psi, x_2, x_3, x_4, y_2, y_3, y_4, \\ & \dot{x}_1, \dot{y}_1, \dot{\nu}, \dot{\theta}, \dot{\zeta}, \dot{\psi}, \dot{x}_2, \dot{x}_3, \dot{x}_4, \dot{y}_2, \dot{y}_3, \dot{y}_4]^T\end{aligned}$$

The amount of observation y_{td} is expressed by the following output equation:

$$y_{td} = [x_1, y_1, \nu, \theta, \zeta, \psi]^T = C_{td}x_{td}\quad (6)$$

(1 · 2) Derivation of the control system design model

For performing a decentralized control in derricking and rotational directions, a lower dimension model for designing a controller in derricking and rotational directions is derived in the following manner. FIG. 2(a) shows a lower dimension model in derricking direction and FIG. 2(b) shows a lower dimension model in rotational direction. These models are made on the following assumptions:

- a) The tower portion is assumed to be an equivalent 1 particle system and each direction only is considered.
- b) Sway of the load is considered in each direction only.

The equation of motion is calculated by Lagrange's equation (2). As regards the lower dimension model in the derricking direction, linearization is made by designating input which balances with gravitation acting on the jib and load when the jib derricking angle is a target angle $\bar{\nu}$ as $\bar{u}$, deviation between the jib derricking angle ν and $\bar{\nu}$ as small angle δ_ν , and a control

input which compensates it as δu . As a result, the state equation, amount of observation and output equation become

$$\begin{aligned}\dot{x}_r = & A_r(\bar{\nu}, \delta\nu, \dot{\delta\nu}, \theta, \dot{\theta}, l, \dot{l}, \ddot{l})x_r \\ & + B_r(\bar{\nu}, \delta\nu, \dot{\delta\nu}, \theta, \dot{\theta}, l, \dot{l}, \ddot{l})\delta u\end{aligned}\quad (7)$$

$$y_r = [x_r, \delta\nu, \theta]^T = C_r x_r \quad (8)$$

where

$$x_r = [x_r, \delta\nu, \theta, \dot{x}_r, \dot{\delta\nu}, \dot{\theta}]^T$$

As regards the lower dimension model in rotational direction, linearization similar to the equation (3) leads to

$$\begin{aligned}\dot{x}_s = & A_s(y_r, \zeta, \dot{\zeta}, \psi, \dot{\psi}, l, \dot{l}, \ddot{l})x_s \\ & + B_s(y_r, \zeta, \dot{\zeta}, \psi, \dot{\psi}, l, \dot{l}, \ddot{l})u_s\end{aligned}\quad (9)$$

$$y_s = [y_r, \zeta, \psi]^T = C_s x_s \quad (10)$$

where

$$x_s = [y_r, \zeta, \psi, \dot{y}_r, \dot{\zeta}, \dot{\psi}]^T$$

In these equations, x_r and y_r are relative coordinates regarding angle of rotation ζ of displacement x_1 and y_1 of the highest portion of the mast and can be obtained by

$$x_r = \sqrt{x_1^2 + y_1^2} \cos(\zeta - \rho) \quad (11)$$

$$y_r = -\sqrt{x_1^2 + y_1^2} \sin(\zeta - \rho) \quad (12)$$

$$(\rho = \tan^{-1} \frac{y_1}{x_1})$$

(1 · 3) Derivation of LFT expression to variation in the load-rope length

For designing the gain-scheduled control system using LFT, an LFT expression of a lower dimension model using the load-rope length as perturbation is obtained. There is a method according to which model perturbation is taken out in the descriptor form and then is converted to an LFT expression. If such transformation is applied to the derricking direction model equation (7), perturbing parameter number becomes 2 and, for design of the gain-scheduled control system, a solution can be obtained more easily when the number of parameter is smaller. For this reason, derivation of LPV model will be first shown and transformation to an LFT expression will be made by using this model. In the following description, the upper side LFT of N and M will be expressed as

$$N \oplus M$$

Matrixes A_r and B_r of the equation (7) respectively become a function of $\bar{\nu}, \delta\nu, \dot{\delta\nu}, \theta, \dot{\theta}, l, \dot{l}, \ddot{l}$. When $\bar{\nu}$ is fixed to a specific angle ν_0 of a jib, $\delta\nu, \dot{\delta\nu}, \theta, \dot{\theta}, \dot{l}, \ddot{l}$ are respectively made 0, and only the load-rope length l is considered, a factor including the term of l in the matrixes A_r and B_r varies by variation of the

load-rope length l but, in the present case, only variation of eight factors which vary largely is considered. When the (6, 1) element of the matrix is designated Z , the other varying elements can all be expressed by a fixed number of times of Z as shown in the following equation (13):

$$A(Z) = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & p_1 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & p_2 \\ Z & p_3 Z & p_4 Z & p_5 Z & \cdot & p_6 \sim p_7 Z \end{bmatrix}, \quad (13)$$

$$B(Z) = \begin{bmatrix} \cdot & \cdot & \cdot & \cdot & \cdot & p_8 Z \end{bmatrix}^T \quad (14)$$

$p_1, \dots, p_8 = \text{const.}$

In this manner, matrixes A and B in the case of variation in the load-rope length l can be expressed by the parameter Z only and the following LP model thereby can be obtained:

$$\dot{x} = \overbrace{(A_0 + ZA_Z)}^{A(Z)} x + \overbrace{(B_0 + ZB_Z)}^{B(Z)} u \quad (15)$$

where A_0 and B_0 are matrixes obtained by removing varying elements from the matrixes A and B , and A_z and B_z are matrixes which consist only of coefficients of Z .

Assuming that the jib angle ν_0 is

$$\nu_0 = 45^\circ \text{deg} \quad (16)$$

which is a middle point in the movable range of the jib and the varying range of the load-rope length l is

$$l \in [0.5, 1.6] \text{ m} \quad (17)$$

the range of Z will become

$$\begin{aligned} Z_{\min} &\leq Z \leq Z_{\max} \\ Z_{\min} &= 1.6729 \cdot 10^1, \quad Z_{\max} = 5.3533 \cdot 10^1 \end{aligned} \quad (18)$$

Z is calculated from

$$Z = 26.766 / l \quad (19)$$

by using the load-rope length l .

Assuming here that

$$\begin{aligned} Z_n &= (Z_{\max} - Z_{\min}) / 2, \\ \delta_z &= Z_{\max} - Z_n \end{aligned} \quad (20)$$

$$\begin{aligned} A_n &= A_0 + Z_n A_z, \\ A_1 &= \delta_z A_z \end{aligned} \quad (21)$$

$$\begin{aligned} B_n &= B_0 + Z_n B_z, \\ B_1 &= \delta_z B_z \end{aligned} \quad (22)$$

the LPV model will be expressed as

$$\dot{x} = (A_n + \delta A_1)x + (B_n + \delta B_1)u, \quad |\delta| < 1 \quad (23)$$

Assuming that

$$L_1 \in \Re^{6 \times 1}, [R_1 \ W_1 \ Z_1] \in \Re^{1 \times 13}$$

according to the above cited Japanese Publication No. 2005-67747, reduction of

$$[O \ A_1 \ B_1] = [L_1] \times [R_1 \ W_1 \ Z_1] \quad (24)$$

is made and the following LFT expression can be obtained:

$$y = \delta \oplus G u \quad (25)$$

where

$$G := \left[\begin{array}{c|cc} A_n & L_1 & B_n \\ \hline W_1 - R_1 A_n & -R_1 L_1 & Z_1 - R_1 B_n \\ C_r & 0 & 0 \end{array} \right] \quad (26)$$

A similar transformation is applied to the lower dimension model in the rotational direction.

2. Design of the control system

Design of a gain-scheduled controller

Design of a gain-scheduled control system using LFT which can be carried out easily will now be described. Outline of a manner of derivation of a gain-scheduled controller using LFT will be explained on the basis of the Japanese Publication No. 2005-67747.

First, a generalized plant as shown in FIG. 4 including perturbation of the object of control is constructed. In the figure, δ designates perturbation of the object of control relating to the load-rope length and Δ_w designates hypothetic perturbation introduced into the path of performance. Then, as shown in FIG. 5(a), mutual connection in which the controller has a perturbation block similar to the object of control is performed. As shown in FIG. 5(b), the perturbation block of the controller is pulled up to the side of the object of control. Assuming that parameter data can be observed on line, a controller which is stable to all δ and

its $\mathcal{L}_2$ gain from $w_1 := [w_{11}, w_{12}]^Y$ to $z_1 := [z_{11}, z_{12}]^T$ satisfies

$$\sup_{0 \neq w_1 \in \mathcal{L}_2} \frac{\|z_1\|_{\mathcal{L}_2}}{\|w_1\|_{\mathcal{L}_2}} < \gamma \quad (27)$$

can be obtained by solving LMI (linear matrix inequality). Herein, $\gamma > 0$ is a given scalar. The gain-scheduled controller is expressed by LFT made of a perturbation block similar to that of an object of control.

If the range of perturbation is taken as in the equations (20), γ does not become smaller in the path of perturbation than in the path of performance resulting in a conservative controller. As variation in γ has been examined by making constant w_{11} , w_{12} and w_{13} which are weight functions to the mast, jib derricking angle and load and making the range of perturbation narrow, it has been found that the value of γ does not substantially vary when δ_z is smaller than

$$\hat{\delta}_z = 0.1\delta_z \quad (28)$$

From this, in designing a controller, width of variation is set to be $\hat{\delta}_z$ of the equation (28), though there is no security for stability of the entire range of variation of the parameter. The controller will be actually be made by varying the parameter within the range of $\hat{\delta}$ in the equation (20) and confirming that there will be no problem by e.g., numerical simulation.

3. Experiment for verification by actual movement by an operator using an experimental device

(3 · 1) Experimental device

An experimental device for a tower crane is schematically

shown in FIG. 3. A jib 2 is rotated by a rotating motor 5 in the form of a servo motor and is lifted and lowered by a derricking motor 6 in the form of a servo motor. The rope length of a load 3 is adjusted by a lifting and lowering motor 7 in the form of a DC motor. As to displacement of the crane main body, strain of the mast is detected by displacement sensors 8 and 9 in the form of a pair of strain gauges attached at the lowest portion of the mast in x direction and y direction and the detected strain is multiplied by a fixed number of times and used as displacement of the highest portion of the mast. As the displacement sensors 8 and 9, instead of using the strain gauges, an acceleration meter may be disposed in the upper portion of the mast and displacement of the upper portion of the mast may be measured on the basis of acceleration exhibited in the acceleration meter. Rotation angle ζ of the crane is detected by a rotation angle sensor 10 in the form of a rotary encoder incorporating a servo motor. Jib angle ν is detected by attaching a derricking angle sensor 11 in the form of a potentiometer on the rotation axis at the lower end portion of the jib. Sway angles θ and ϕ are detected by load angle sensors 12 and 13 in the form of potentiometers for derricking direction and rotational direction attached to the tip end portion of the jib, each of the potentiometers being fixed to a fork which holds the load-rope. A two-axis control lever 14 incorporating a potentiometer is used as an operation device. Inclination angles ρ_{UD} and ρ_{RD} of the control lever 14 are detected and used as command values for derricking acceleration and rotational acceleration. The load-rope length is controlled by operation on a key board of a controller 15 (a computer for controlling). Reference character 16 designates a linear combination operation section.

For mounting the control system on the jib crane, the control system is made discrete with sampling time of 4ms. K_{UD} and K_{RD} in the figure are gain-scheduled controllers in derricking direction and rotational direction. Reference characters r_{UD} and r_{RD} designate command values (operation commands) in derricking

direction and rotational direction and u_b and u_{sb} designate feedback signals in derricking direction and rotational direction.

Since the gain-scheduled controller of the LFT model uses LFT in which parameters Z and Y determined by the load-rope length constitute perturbation, it is provided as a minor loop concerning the controller.

(3·2) Response of a target value to variation of the load-rope length

A verification test of effectiveness of the gain-scheduled control system with respect to variation of the load-rope length has been made. As a result, it has been found that LFT enables control of the mast without deterioration in the efficiency by rising of the peak of gain of the controller (see the above cited Publication No. 2005-67747).

(3·3) Control with respect to a desired command by an operator

An experiment of control with respect to an operator's desired operation by a feedback control system has been conducted on the condition that ratio of feedback control command by the linear combination operation section 16 is 100% and ratio of operation command is 0%. As shown in FIG. 6 (b), since the operator conveys a load in such a manner that an obstacle is avoided by varying the load-rope length, when the operator who operates the crane gives a command to the rotational acceleration speed or the derricking acceleration speed by operating the operation lever while varying the load-rope length or even when the operator gives an abrupt change in his lever operation, sway of the mast and load is promptly reduced. By this arrangement, sway of the load is promptly attenuated and the operator can convey the load easily to a desired position without taking a particular sway stopping step for the load. Variation of the load-rope length is compensated by the gain-scheduled controller and, therefore, convergence of sway of the mast and load is almost the same regardless of the load-rope length.

It has also been found that, with respect to derricking angle of the jib, sway of the load in derricking direction and response of the load-rope length occurring when disturbance caused by an outside factor is applied to the load during operation, sway of the load due to such disturbance is promptly reduced by the gain-scheduled controller.

In the feedback control system in which the ratio between a feedback control command by the linear combination operation section 16 and an operation command is changed, the state equation of the object of control of the linear combination control system can be expressed by the above described equations (5) and (6).

This linear combination control can be applied by inputting u (or u_s), i.e., control command to the derricking motor and control command to the rotation motor which are input terms to the object of control of the equations (5) and (6) to the following equation:

$$u(\text{or } u_s) = (\alpha \times r) + (\beta \times u_{bk}) \quad (29)$$

where

$$\alpha = 0.85 - (f/2.5) \quad (0 \leq \alpha \leq 1)$$

$$\beta = 1 - \alpha$$

In this equation, α represents the ratio of operator's operation command and β the ratio of the feedback control command.

f represents a coefficient which is $f = 0$ in the operation area (i.e., when the operation lever is in an input state) and f increases momentarily in real time in the area outside of the operation area (i.e., when the operation lever is not in the input state). By way of an example, α , β and f may be $\alpha = 0.85$, $\beta = 0.15$ and $f/2.5$. These values can be changed freely depending upon factors such as characteristics of the jib crane and state of use and operation state

of the jib crane.

By changing the ratio between α and β , as shown in FIG. 7, the ratio between the feedback control command and the operation command is changed in accordance with state of operation in the operator's operation area where the operator's operation is given priority and the area outside of the operator's operation area.

The ratio of the feedback control command by the linear combination operation section 16 and the ratio of the operation command can be presupposed by estimating, by on-the-desk simulation using the state equations (5) and (6) of the object of control in which the equation (29) of the input term to the object of control is substituted, change in the amount of state of the object of control in accordance with change in the ratio β of the feedback control command and the ratio α of the operation command. Final determination of the ratio β of the feedback control command and the ratio α of the operation command should preferably be made by comparing verification by experiments with result of the on-the-disk simulation. In a case where sufficient conformity can be expected between the result of the on-the-desk simulation and the result of experiments, verification by experiments may be omitted.

An experiment has been made about the control to the operator's desired operation by the feedback control system which changes the ratio of the feedback control command by the linear combination operation section 16 and the ratio of the operation command. As a result, as shown in FIG. 6(a), delay in action to the operation command in the operation area has been improved. As to sway of the load, sway becomes large in the operator's operation area but it stays within a target range in the area outside of the operator's operation area when the sway prevention control becomes 100%.

By application of this control method, delay time to an

operation command caused by the feedback control system can be shortened and, as a result, positioning control corresponding to the operator's operation command can be achieved while performing a vibration prevention control and the operator's feeling of operation can thereby be improved.

The present invention is not limited to the above described embodiments but various modifications may be made within the spirit and scope of the invention.

Brief Description of the Drawings

FIG. 1 is a block diagram showing one embodiment of the jib crane control method and device according to the invention.

FIGs 2(a) and 2(b) are explanatory views showing a lower dimension model in derricking direction and a lower dimension model in rotational direction of a tower crane.

FIG. 3 is a schematic view showing an experiment device for a tower crane.

FIG. 4 is a block diagram showing a generalized plant including perturbation of the object of control.

FIG. 5(a) is a block diagram showing mutual connection in which the controller has a perturbation block similar to an object of control and FIG. 5(b) is a block diagram showing the perturbation block is pulled up to the side of the object of control.

FIGs.6(a) and 6(b) are graphs showing results of experiments about operation angle and sway of load to an operation command by the linear combination control in comparison with results of the feedback control only.

FIG. 7 is an explanatory view showing an example of timewise

change of the linear combination ratio.

Explanation of Reference Characters

1	mast
2	jib
3	load
4	rope
5	rotation motor
6	derricking motor
8	displacement sensor of crane main body (strain gauge)
9	displacement sensor of crane main body (strain gauge)
10	rotation angle sensor
11	derricking angle sensor
12 , 13	load angle sensors
14	operation lever
15	controller
16	linear combination operation section

Claims

1. A method for controlling a jib crane by calculating a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in load-rope length of the jib crane and performing a feedback control using gain-scheduled control which uses the calculated linear fractional transformation (LTF) expression

CHARACTERIZED BY steps of performing linear combination of a feedback control command for performing the feedback control with an operation command from an operation lever and changing ratio between the feedback control command and the operation command so as to prevent variation in the position of load notwithstanding variation in the load-rope length and thereby enable the load to be moved to a target position.

2. A method for controlling a jib crane as defined in claim 1 wherein the ratio between the feedback control command and the operation command is changed between an operation area where the operation command from the operation lever is applied and an area outside of the operation area where the operation command is not applied.

3. A jib crane control device comprising rotation driving means for rotating a jib of the jib crane and derricking driving means for derricking the jib of the jib crane

CHARACTERIZED BY comprising

jib state detection means for detecting at least a rotation angle of the jib, derricking angle of the jib, an angle of load, and displacement of crane main body;

an operation lever for performing rotation and derricking of the jib, and hoisting and lowering of the load;

lever detection means capable of detecting rotation and derricking of the jib and hoisting and lowering of the load performed by operation of the operation lever; and

a controller comprising a feedback control system performing

gain-scheduled control which uses a linear fractional transformation (LTF) expression of a lower dimension model having regard to variation in previously input load-rope length, and a linear combination control section which performs linear combination of a feedback control command from the feedback control system with an operation command from the lever detection means and changes the ratio between the feedback control command and the operation command:

said jib crane control device being capable of preventing variation in the position of the load notwithstanding variation in the load-rope length and thereby enabling the load to be moved to a target position.