2010 IEEE International Conference on Control Applications
Part of 2010 IEEE Multi-Conference on Systems and Control
Yokohama, Japan, September 8-10, 2010

Innovative Integrated Simulator for Agile Control Design on Shipboard Crane Considering Ship and Load Sway

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Abstract— **In this paper, the integrated computer simulator tool of rotary crane with ship behavior in consideration of ship sway and load sway is newly built in order to systemize the state analysis of a shipboard crane. The integrated simulator of shipboard crane was realized by corporating an external force interface routine of a component with Fluid analysis software. The transfer control system is conducted by HSA (Hybrid Shape Approach) using STT (Straight Transfer Transformation) method. The proposal method was confirmed to be effective in order to reduce both the sway of a ship and a load by the simulation analysis.**

I. Introduction

Since Japan is an island encircled by sea, ship transfer is one of important transportation. So, shipboard crane with crane on the ship is often used for the transportation on the ocean, because loading work can be applied on the harbor without crane, and it is utilized while building the facilities on the sea. However, because the load of the shipboard crane generates the composite sway motion due to the motion of crane and ship, then, the development of the transfer system to carry the load with faster speed and safe without the sway of shipboard is highly expected.

Fig. 1. Shipboard crane

Among the previous research on shipboard crane, Shiraishi (see S. Shiraishi et al.[2000]) manufactured pilot ship of crane barge, and showed the effectiveness of sway-damping by two-pronged arm in model experiments. Tsutsui (see A. Tsutsui et al.[2006]) showed a method suppressing both of a load and ship sway while falling down a load on the ground, by controlling the luffing velocity of boom and the loading velocity. Akiyama (see S. Akiyama et al.[2004]) showed that their restoring force of ship gave large influence on the sway of a load using the proper mathematical model. However, the present control design on the shipboard crane has been experimentally conducted by trial and error method using actual shipboard crane. Because, a lot of cost and time have been then spent, alternate system for the design is highly demanded to be exploited.

On the other hand, numerous researches on rotary crane have been reported Terashima et al. (see Y.Shen et al.[2003] and K. Terashima et al.[2007]) have proposed the Straight Transfer Transformation (STT) method by transferring a load along a straight path using simultaneous movements of rotation, luffing and hoisting to avoid the exaggerated swaying of the load owing to the centrifugal force caused by rotation demonstrated the effectiveness of the proposed control method obtained by applying the nonlinear optimization technique. Sawodny (see O. Sawoddy et al.[2002]) built the nonlinear model of gantry crane, and showed the effectiveness the flat-base nonlinear control using real gantry crane. Furthermore, research on ship has been studied. Stefano et al. (see B. Stefano et al.[2006]) reported modeling of ship using numerical fluid dynamics with respect to the influence of wind on large ship. Ema (see Ema Muk-Pavic et al.[2006]) studied the influence of ship body on the free surface of fluid, using the software of computer fluid dynamics. But, the integrated research of rotary crane and ship using computer simulation has been not found up to the present, and therefore, its development is strongly expected as the innovation method, which can reduce the time and the cost spent by real experimental machine.

Then, in this paper, we present a virtual plant of shipboard crane combined Computational Fluid Dynamics (CFD) with Mechanical Dynamics. In order to conduct the state analysis of shipboard crane and realize the control design, we also propose a method to obtain a brief model. The purpose of this paper is then to present a method with the high efficient and cost reduction in terms of the systematic integrated method shown in this paper.

II. Computational Simulator of Shipboard crane

A. Construction of virtual plant

Parameter of shipboard crane is shown in Table 1. The form of the ship is represented by a rectangular parallelepiped. The rotational center of shipboard is the gravity center of shipboard, the direction of translation movement of shipboard is only z-direction, and the rotational direction is assumed to be around X-axis and Y-axis. The absolute coordinate system Σ is an X-Y-Z coordinate system fixed in space, and the crane coordinate system Σ' is an X'-Y'-Z' coordinate system fixed to the rotary crane.

A virtual plant built in this paper is comprised of Computational Fluid Dynamics Software (Flow 3D, Flow Science Inc.) to analyze the fluid behavior, in which the moving

TABLE I

PARAMETERS OF THE SHIPBOARD CRANE

Symbol	Appellation	Value
m_L	Mass of the load	17000 [kg]
L_B	Length of the boom	37 [m]
H_c	Height of the turn table	3.0 [m]
l	Length of the rope	30 [m]
m_S	Mass of the ship	1500000 [kg]
L_S	Length of the shipboard	52 [m]
B_S	Width of the shipboard	19 [m]
H_S	Height of the shipboard	3.3 [m]
D_l	Distance from center of the ship to the crane	20 [m]

obstacle (shipboard) is floated, and crane simulation to analyze the behavior of the crane. Here, Flow 3D adapted in this paper is very famous software to analyze the sloshing and the filling behavior of fluid into cavity. As environmental conditions of fluid, it is possible to easily assign obstacle transfer in the liquid tank, the approaching state of ship to gulf and the condition of its transfer. However, it is impossible to calculate the obstacle (shipboard) in the fluid in real time. Then, the present virtual plant integrated Flow-3D with crane dynamics is insufficient. Hence, we newly developed an external interface routine to give the external force into a moving obstacle (shipboard). Flow chart is shown in Fig.3. And, schematic diagram of swing angle model of rotary crane is also shown in Fig.4. Here, θ [rad] : rotational angle, ϕ [rad] : luffing angle, l [m] : rope length, α [rad] : swing angle of a load in X-direction, β [rad] : swing angle of a load in Y-direction, $(\tilde{x}, \tilde{y}, \tilde{z})$ [m] : tip position of boom, (x, y, z) [m] : load position.

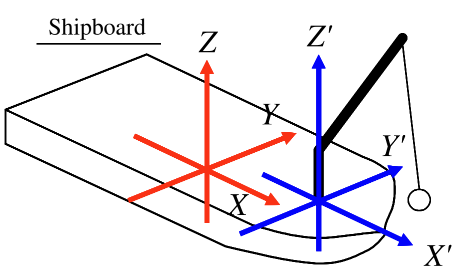

Fig. 2. The definition of a coordinate system

Using flow chart in Fig.3, let us explain the procedure of calculation with respect to the virtual plant. First, as shown in Step 1 of Fig.3, both the analysis of initial state of the obstacle objects and the fluid analysis by Flow 3-D are executed. Here, the fluid analysis by Flow 3-D solves a Navier-Stokes equation based on finite-difference method by control volume method. Next, following the step 2, rotational input, luffing input, and loading and unloading input of rotary crane are loaded from input file. Following to Step 3, the tip position $(\tilde{x}', \tilde{y}', \tilde{z}')$ of a boom are calculated for Eqs.(1)-(3).

$$\tilde{x}' = L_B \cos\phi \cos\theta \qquad (1)$$

$$\tilde{y}' = L_B \cos\phi \sin\theta \qquad (2)$$

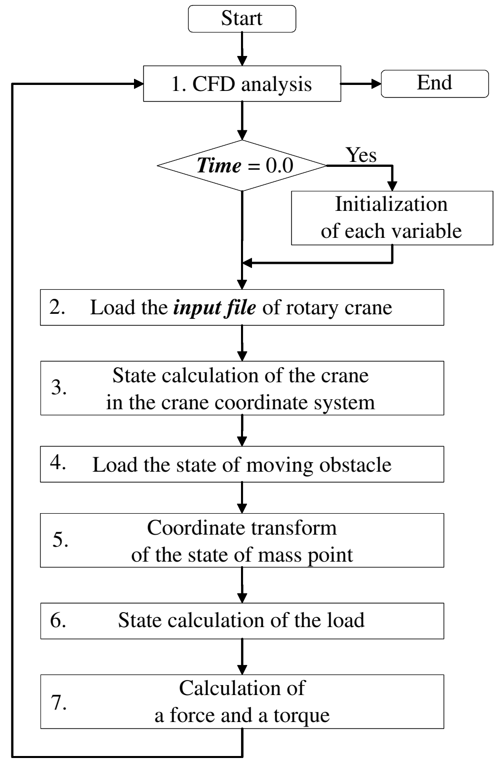

Fig. 3. Flow chart of virtual plant of shipbord crane

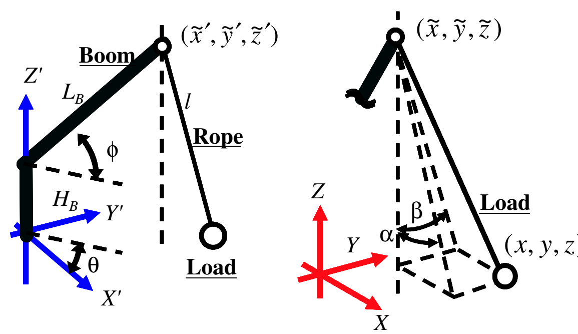

Fig. 4. Swing Angle Model

$$\tilde{z}' = H_C + L_B \sin\phi \qquad (3)$$

Following to Step 4, rotational value (ρ_x, ρ_y, ρ_z) of the moving obstacle and translation value $(\delta_x, \delta_y, \delta_z)$ are read from the data calculated by Flow 3-D. Following to Step 5, coordination transformation from Σ' to Σ is done.

$$\tilde{X} = T_{xyz}\tilde{X}' \qquad (4)$$

$$\frac{d\tilde{X}}{dt} = \frac{dT_{xyz}}{dt}\tilde{X} + T_{xyz}\frac{d\tilde{X}'}{dt} \qquad (5)$$

$$\frac{d^2\tilde{X}}{dt^2} = \frac{d^2T_{xyz}}{dt^2}\tilde{X}' + 2\frac{dT_{xyz}}{dt}\frac{d\tilde{X}'}{dt} + T_{xyz}\frac{d^2\tilde{X}'}{dt^2} \qquad (6)$$

where,

$$\tilde{X} = [\ \tilde{x} \quad \tilde{y} \quad \tilde{z} \quad 1\ ]^T, \quad \tilde{X}' = [\ \tilde{x}' \quad \tilde{y}' \quad \tilde{z}' \quad 1\ ]^T$$

Here, coordination transform matrix T_{xyz} is a matrix comprised of $(\sigma_x, \sigma_y, \sigma_z)$ and (ρ_x, ρ_y, ρ_z) calculated by Flow 3-D. Following to Step 6, load position is calculated from Eqs.(9)-(11) using to load swing model of Eqs.(7)-(8).

$$\ddot{\alpha} = f_1\left(\ddot{\tilde{x}},\ \ddot{\tilde{y}},\ \ddot{\tilde{z}},\ \dot{\alpha},\ \alpha,\ \dot{\beta},\ \beta\right) \tag{7}$$

$$\ddot{\beta} = f_2\left(\ddot{\tilde{x}},\ \ddot{\tilde{y}},\ \ddot{\tilde{z}},\ \dot{\alpha},\ \alpha,\ \dot{\beta},\ \beta\right) \tag{8}$$

$$x = \tilde{x} + l\sin\alpha\cos\beta \tag{9}$$

$$y = \tilde{y} + l\cos\alpha\sin\beta \tag{10}$$

$$z = \tilde{z} - l\cos\alpha\cos\beta \tag{11}$$

Equations (7)-(11) are called a swing angle model of shipboard crane, and the detailed is described in the literature (see R. Ito et al.[2008]). The validity of this model is guaranteed by conducting many experiments using the experimental devices of author's laboratory. Finally, following to Step 7, force and torque added to shipboard is calculated from the current state of rotary crane and load. Then, return to Step 1, and the procedure is repeated. These calculation is repeated every sampling time. The originality of this paper is to have presented a virtual plant comprised of fluid model of shipboard using CFD and rotary crane model based on the mechanical dynamics.

B. Transfer simulation

Using a virtual plant of shipboard crane, transfer simulation of a load is done, and motion characteristics of shipboard crane is studied. Assumption on transfer environment is given as follows; wind and wave does not exist, and there exists a shipboard crane in the static water on the large sea, and Sommerfelt condition as the fluid boundary condition of virtual plant is adopted such that transfer phenomena at constant speed is assumed to generate around the boundary between shipboard and fluid. The region of the fluid is given as length 180 [m], width 120 [m], and water depth 10 [m], where mesh width is given as 0.4 [m], because the fluid region must be given as the finite region. Initial rotation angle π [rad] and initial luffing angle $\pi/3$ [rad] are given as the crane condition. Then, rotational transfer of $\pi/2$ [rad] is simulated in the clockwise direction. Two kinds of transfer pattern is chosen as shown in Table2. Simulation results are shown in Fig.5 and Fig.6.

TABLE II
VELOCITY INPUT OF ROTARY TRANSFER

	Rotary acceleration [rad/s^2]	Rotary velocity [rad/s]
Transfer1	0.1	0.05
Transfer2	0.1	0.08

As seen from Fig.5 (b), a load is apart from the center of shipboard by transferring a load, and shipboard is gradually tilting due to the increase of torque added to the shipboard. Because the trajectory of boom tip position exists outside of reference, it is assured that boom tip motion is influenced by the tilt and movement of shipboard. As seem from Fig.5 and

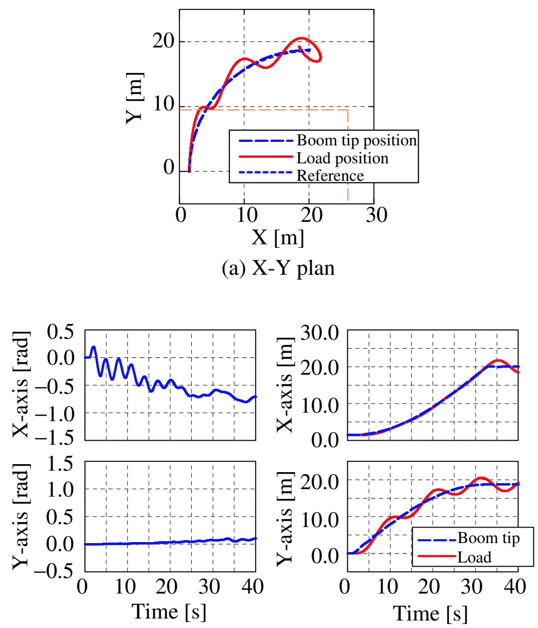

Fig. 5. Simulation results of Transfer1 using virtual plant

Fig.6 (a), it is checked that a load of transfer 2 is largely swayed outside due to the influence of centrifugal force stronger than the case of transfer 1, because the rotational angular velocity of transfer 1 is faster than that of transfer 2. Then, since torque added to the shipboard is increased, it is assured that shipboard is largely vibrated. The reason why shipboard is continuously vibrated after the transfer end time of transfer 1 and 2, is considered that the force is transmitted to shipboard, because of residual vibration of a load.

Figure 7 shows the comparison between the shipboard crane, and the ground crane by assuming sway free shipboard. In order to compare the shipboard crane with the ground crane, the coordination of shipboard crane is given as the coordination of crane installed on shipboard. Figure 8 is the enlarged figure of Y-axis graph in Fig.7 (c). Here, A_s and A_r is representing the amplitude of a load in shipboard crane and the ground crane. The average of each amplitude is as follows; A_s=6.489 [m] and A_r=5.329 [m]. Because the amplitude A_s is 1.16 [m] larger than that of A_r, the movement of crane's load is largely influenced by the side sway of shipboard. Through the above results, it is thought that simulation well explains the actual phenomena of shipboard crane, and the present integrated simulator proposed in this paper is adopted as a virtual plant in what follows.

III. A BRIEF MODEL FOR CONTROL DESIGN

Procedure for control design considered in this paper is shown in Fig.9. In this paper, control design is not conducted using a virtual plant, because a virtual plant is a very complex model and it needs an enormous time to compute.

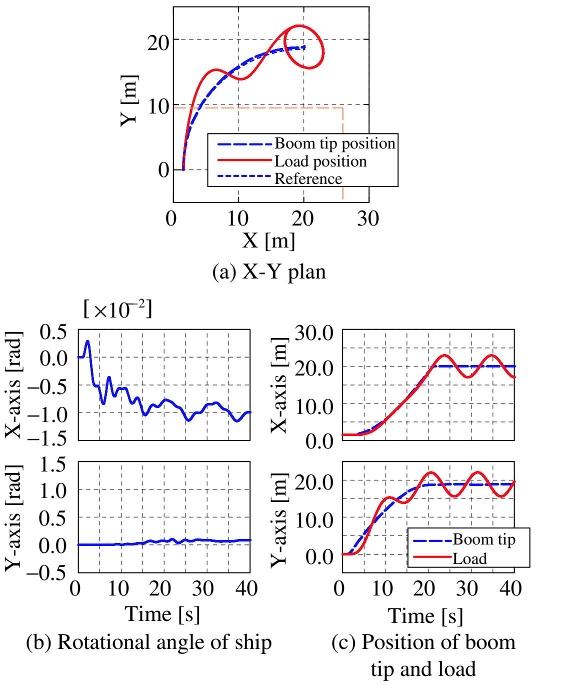

Fig. 6. Simulation results of Transfer2 using virtual plant

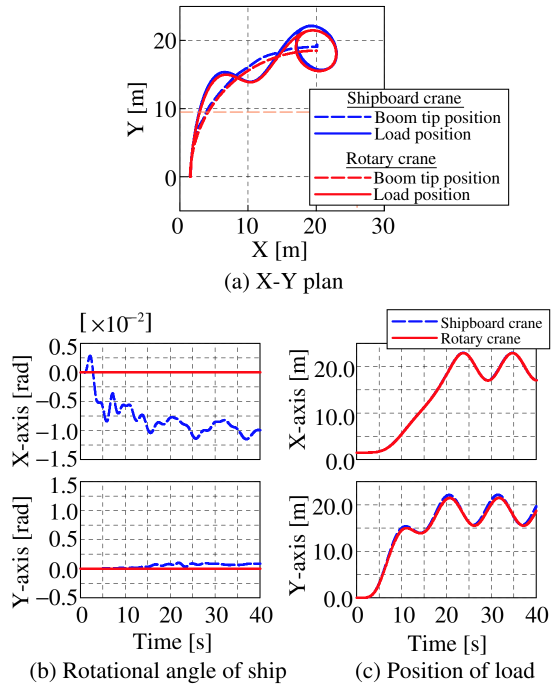

Fig. 7. Simulation results of Transfer2 using virtual plant

Alternatively, we build a simplified brief model for control design.

Then, first, we conduct control design based on a simplified brief model of shipboard, and evaluate control performance on it. Next, we evaluate control performance using a virtual plant if its performance using a simplified brief model satisfies the requested specification. This procedure simplifies a control design and reduce the time to design, and hence this design procedure, comprised of a complicated and exact virtual plant, and a simplified brief model, is considered to be a reasonable and effective method. A brief model is a mathematical model which represent the behavior of shipboard, and this model is made from a virtual plant. Then, a mathematical model of shipboard is firstly built. Motion equation of shipboard is derived from the balance equation on inertia force (or torque) of shipboard $F_I(t)$, radiation fluid force (or torque) $F_R(t)$, viscous fluid force (or torque) $F_V(t)$, restoring force (or torque) based on static water $F_S(t)$, and external force (or torque) added to shipboard $F(t)$. Generally, a ship performs six degree of freedom motion. However, while shipping and discharging the load by transfer work using a shipboard crane, rolling and pitching motion are important. It is assumed that the heaving, the surging, the swaying and yawing motion is small. Thus, the mathematical model of ship sway took into consider the rolling and pitching among the six degree of freedom as follows;

$$(I_x + m_x)\ddot{\rho}_x + N_x\dot{\rho}_x + C_x\rho_x = T_x \tag{12}$$
$$(I_y + m_y)\ddot{\rho}_y + N_y\dot{\rho}_y + C_y\rho_y = T_y \tag{13}$$

Here, ρ_i: inclination angle of shipboard, I_i inertial moment, m_i mass quantity of added water, N_i: wave making damping coefficient, C_i: coefficient of restitution (displacement × metacentric height), T_i: Torque added to shipboard, and i=x, y.

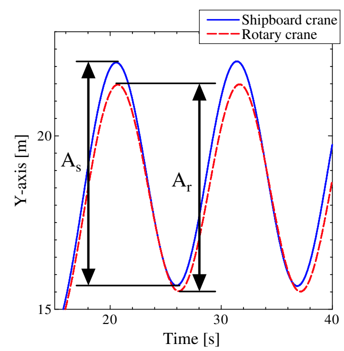

Fig. 8. Simulation results of Transfer2 using virtual plant

Equations (12) and (13) of rolling and pitching motion are represented using damping ration ζ and natural frequency ω_n as follows;

$$\ddot{\rho}_x + 2\zeta_x\omega_{nx}\dot{\rho}_x + {\omega_{nx}}^2\rho_x = \frac{T_x}{I_x + m_x} \tag{14}$$
$$\ddot{\rho}_y + 2\zeta_y\omega_{ny}\dot{\rho}_y + {\omega_{ny}}^2\rho_y = \frac{T_y}{I_y + m_y} \tag{15}$$

, where

$$\zeta_x = \frac{N_x}{2\sqrt{C_x(I_x + m_x)}}, \quad \omega_{nx} = \sqrt{\frac{C_x}{I_x + m_x}}, \quad K_x = \frac{1}{C_x}$$

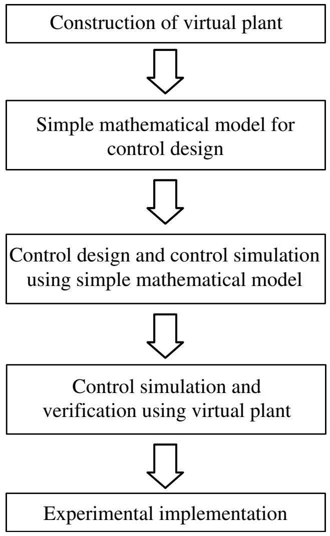

Fig. 9. Concept of the control design

$$\zeta_y = \frac{N_y}{2\sqrt{C_y(I_y+m_y)}}, \quad \omega_{ny} = \sqrt{\frac{C_y}{I_y+m_y}}, \quad K_y = \frac{1}{C_y}$$

Furthermore, when ρ_i is output and T_i is input, each transfer function $G_{px}(s)$ and $G_{py}(s)$ becomes from Eqs. (14) and (15) as follows;

$$G_{\rho_x}(s) = \frac{K_x\omega_{nx}}{s^2+2\zeta_x\omega_{nx}s+{\omega_{nx}}^2} \tag{16}$$

$$G_{\rho_y}(s) = \frac{K_y\omega_{ny}}{s^2+2\zeta_y\omega_{ny}s+{\omega_{nx}}^2} \tag{17}$$

Now, damping ratio ζ_i, national frequency ω_{ni} [rad/s], and gain K_i must be identified. Conventionally, these parameters must be identified by experiments, but in this research, parameters can be identified by computer simulation using a virtual plant comprised of CFD model (Flow 3-D) and rotary crane model. This is a large advantage in this research. Concretely, while transfer of rotary crane is executed using a virtual plant, inclination angle of shipboard is calculated. Parameter identification is carried out by Least Square Method using Simplex Method such that inclination angle of shipboard by brief model matches with that of a virtual plant. The parameter values obtained by this method are as follows;

$$K_x = 2.177\times10^{-9}, \quad \zeta_x = 0.0677, \quad \omega_{nx} = 2.597$$
$$K_y = 2.364\times10^{-10}, \quad \zeta_y = 0.0764, \quad \omega_{ny} = 1.964$$

Figure 10 shows model identification results which compares between virtual plant and a brief simplified model. As seem from Fig.10, the response of virtual plant well agrees with the response of a brief model, and therefore the validity of a brief model derived has been proved. Now, computation time using a virtual plant is about 20 [h] for the transfer time 40 [s] of a load, while we utilize personal computer (Intel Xeon CPU 3.80 GHz, Memory 4.0 GB) and CFD software (Flow 3-D; Single Processor License). On the other hand, computation time is about 2 [s] under the same condition with a virtual plant, while we use a brief model. Hence, it is clear that this brief model of shipboard is extremely effective as mathematical model for control design.

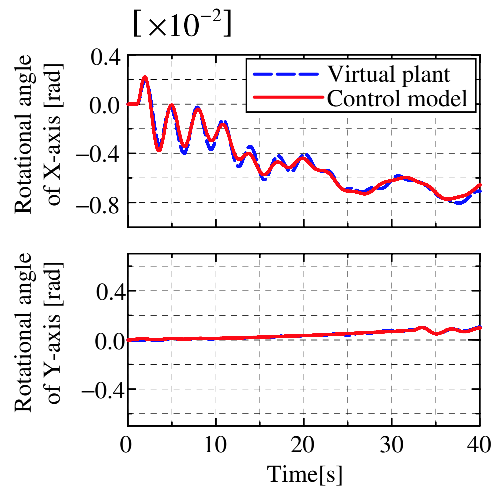

Fig. 10. Model identification

IV. TRANSFER CONTROL

Shipboard crane system considered in this paper is shown in Fig.11. This system is comprised of gyro sensor to measure rolling, pitching and heaving motion, and encoder to measure rotary angle, luffing angle, rope length, and load's sway angle. Hence, a load's position is detectable using these sensing system.

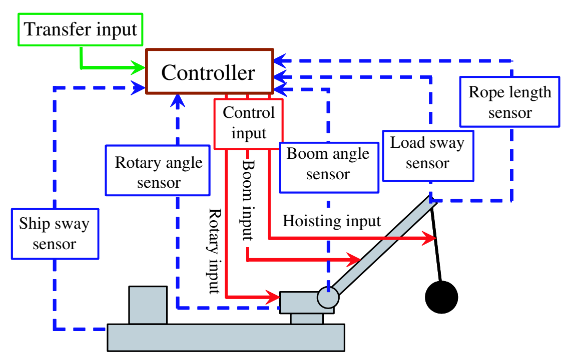

Fig. 11. Shipboard crane system

A. Straight transfer transformation (STT) method

The present transfer using a rotary crane in actual sites mainly uses rotary motion. However, because centrifugal force is generated due to the rotary motion, a load is largely swayed, and it takes a long time to suppresses the load's sway. On the other hand, by using simultaneous control of rotary and luffing motion, there exists a straight transfer transformation method (see K. Terashima, et al.[2007] and Y. Shen et al.[2004]) such as a load is carried out straightly on X-Y plane from a start point to end. By using this transfer method, a load's sway is restricted in only the straight direction which is a transfer direction, and therefore it enables us to easily design anti-sway control for transfer. Then, in this paper, the STT method is adopted.

Now, control velocity reference for STT is calculated along the straight transfer from start to end. Then, its reference on straight line is decomposed to each velocity reference of X-axis direction and Y-axis direction. Furthermore, using Jacobi Matrix which is derived from the relation between tip position of boom, and rotary and luffing angle of crane, each velocity is transformed into rotary velocity and luffing velocity of rotary crane, which is finally control input of rotary crane. The detail is described in the literature (see Y. Shen et al.[2003] , K. Terashima, et al.[2007] and Y. Shen et al.[2004]), and omitted due to the paper limitation.

B. Hybrid shape approach

In this paper, centrifugal force is excluded by STT method, and anti-sway control system is designed by applying Hybrid Shape Approach (HSA) proposed previously by authors. HSA (see K. Yano et al.[2001]) enables us to satisfy the specifications given by both of frequency domain (vibration characteristic, gain and phase characteristic) and time domain (transient characteristic, settling time, overshoot, input constraints) by placing the both design specification as penalty functions for optimization. Furthermore, HSA is a control design method using notch filter corresponding to natural frequency by vibration elements of controlled object.

The present control system is comprised of PI controller to progress the tracking and the responsibility, low pass filter to cut the higher order dynamics and noise, and notch filter to possibly suppress the sway of crane's load and shipboard.

$$K_{(s)} = \frac{K_P s + K_I}{s} \frac{1}{T_L s + 1} \prod_{i=1}^{3} \frac{s^2 + 2\zeta\omega_i s + \omega_i^2}{s^2 + \omega_i s + \omega_i^2} \tag{18}$$

Here, ζ is set as 0.0001, in order to reduce the gain at the natural frequency drastically. Vibration elements of shipboard crane are sway of crane's load, and rolling sway and pitching sway of ship. Notch filter is respectively compensated corresponding to each elements, where natural frequency ω_l of crane's load is ω_l=0.5717 [rad/s]. Unknown parameter K_P, K_I and T_L are optimally determined by means of Simplex Method of Nelder such as satisfies both specifications of frequency and time domain. However, a solution obtained by Simplex Method is not always globally optimum one, and then trial using another initial simplex value has been repeated until the values to satisfy the requested specification is obtained. The obtained control value is given as follows, and gain diagram of the obtained controller is shown in Fig.12.

$$K_P = 0.42523, \quad K_I = 0.22908, \quad T_L = 0.27908$$

Good characteristics of controller has been obtained.

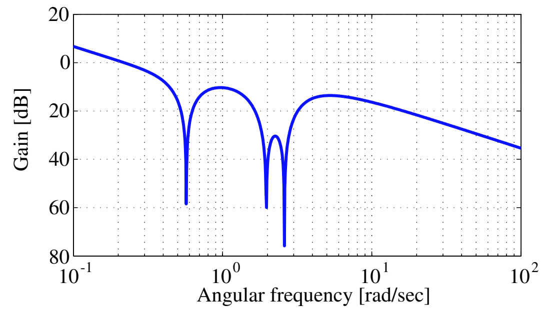

Fig. 12. Gain diagram of the proposed controller

C. Control simulation

Control simulation result is shown in Fig.13. Transfer environment and transfer distance are as the same as transfer simulation of crane's load conducted in section 2.2, where acceleration 2.0 [m/s^2] and velocity 1.0[m/s] are set for the straight transfer. In order to compare the present control system, straight transfer without using anti-sway control is also done, and it is shown in Fig.14.

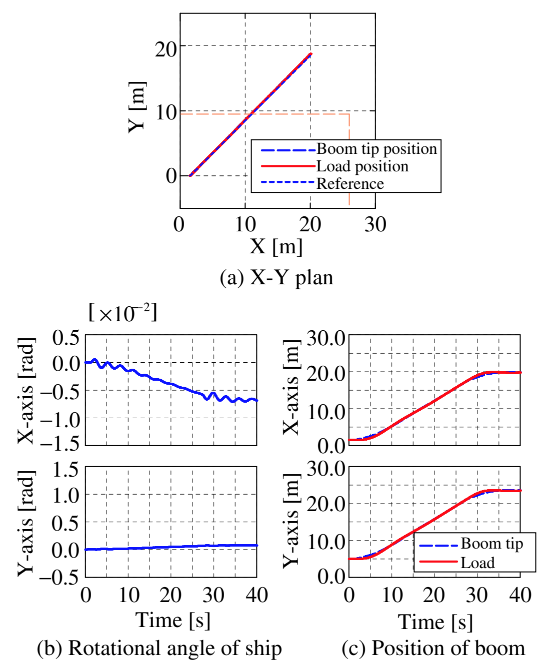

Fig. 13. Simulation results of HSA control using simple mathematical model

As seem from Fig.13 (a), it is assured that this control system excludes the centrifugal force by straight transfer, and their load is not swayed outside. Further, from Fig.13 (b) and (c), this system dose not excite the sway of ship and the sway of crane's load, and hence anti-sway transfer of load has been achieved. On the other hand, straight transfer case without sway control excites large sway of load along the straight transfer direction, and therefore it is said that the system without sway control is very dangerous. From

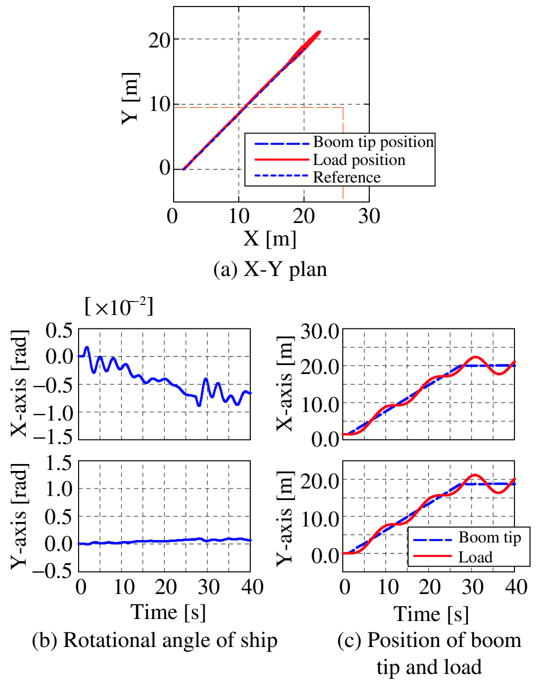

Fig. 14. Simulation results of STT control using simple mathematical model

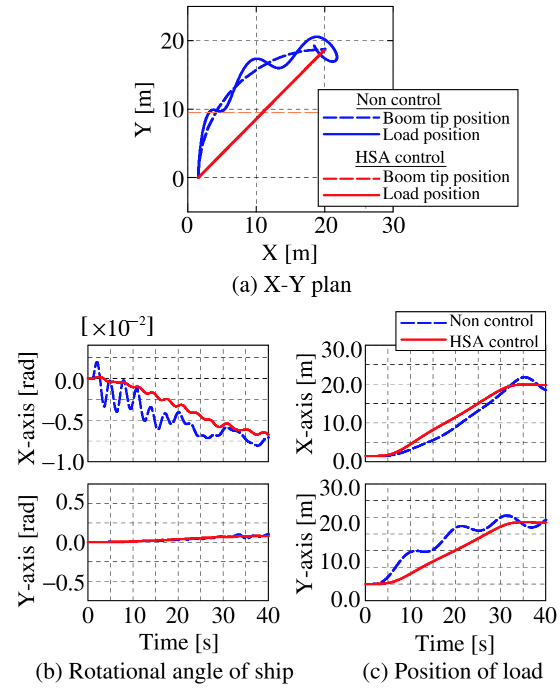

Fig. 15. Simulation results of HSA control using virtual plant

the above result, the proposed control system designed by considering the both sway of crane's load and ship showed good performance on the load's transfer of ship board crane.

V. Control Results Using a Virtual Plant Integrated by CFD and Rotary Crane Model

Finally, the effectiveness of the obtained control system is validated through the computer simulation using a virtual plant. The condition such as transfer environment and transfer distance is as the same as the case of section 2.2. Simulation result is shown in Fig.15.

As seem from Fig.15, load dose not sway outside by straight transfer to exclude the centrifugal force induced during the rotary transfer. Furthermore, the sway of load and ship are not excited at all by anti-sway control, and good transfer without sway has been achieved. Through this virtual simulation, it was made clear that the obtained control system is very effective. The results obtained by using a virtual plant is almost similar with the results obtained by using a brief model, although slight difference exists. However, when ship is inclined, tip position of boom deviates from the reference position. Furthermore, wind and wave exist in the actual place as disturbances. In order to solve these actual experimental problems, the building of the second degree of freedom controller comprised of feedforward and feedback controller will be required. It is written in the literature (see R. Ito et al.[2008]).

Figure 16 shows the feature of video animation obtained by simulation. The arrow painted by white color in Fig.16 (b), (c) is velocity vector of fluid. The virtual plant of shipboard crane can easily output as animation on the fluid behavior induced by load's transfer of rotary crane. Because the system built in this research can visualize not only as numerical value but also as animation, it is very effective tool for predicting the actual phenomenal and designing control system.

VI. Conlusion

In this paper, an integrated computer simulation of ship-board crane comprised of Flow 3-D simulation, a brief model of ship, rotary crane model and control design system is built, and a agile systematic control design with anti-sway of crane's load and ship can be achieved without actual experiments. Compared with control design using actual plants by trial and error method, because the proposed system can reduce the development period to design the control system, and simulate under the various environmental condition, the proposed system is considered to be very effective tool for control design of shipboard crane.

VII. Acknowledgments

We deeply acknowledge Mr. Y. Miyamoto and Mr. S. Baba of CFD Laboratory com. for supporting to develop the integrated virtual plant of shipboard cane.

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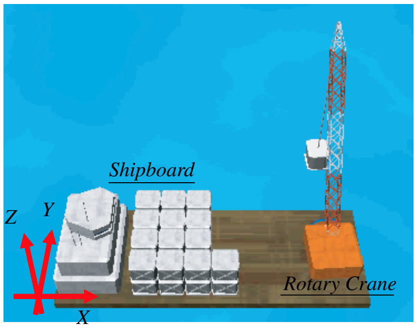
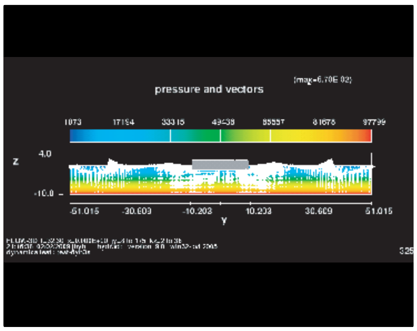
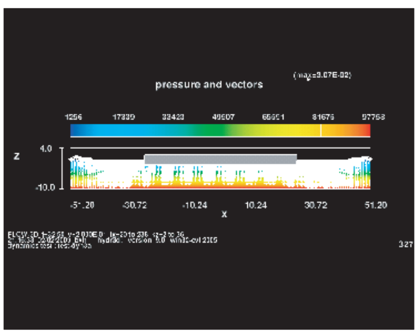


(a) Movie of transfer using Shpboard crane



(b) CFD analysis of movie in Y-Z plane



(b) CFD analysis of movie in X-Z plane

Fig. 16. Movie of virtual plant

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