연구논문

J Korean Soc Fluid Power Constr Equip Vol.11 No.3 pp.7-13 Sep. 2014
ISSN(print) 2234-8328 ISSN(online) 2287-6146
http://dx.doi.org/10.7839/ksfc.2014.11.3.007

터그보트와 댐퍼 협조제어를 통한 선박접안시스템 설계에 관한 연구
A Ship Berthing System Design by Cooperating with Tugboats and Dampers

안민트란[1] · 지상원[2] · 김영복[2*]

Anh-Minh D. Tran, S. W. Ji and Y. B. Kim

Received: 24 May. 2014, Revised: 15 Jul. 2014, Accepted: 17 Jul. 2014

Key Words : Optimal Control(최적제어), Slow Speed Maneuvering(저속운항), Ship Berthing(선박접안), Tug Boat (터그보트), Damper(댐퍼)

Abstract: Everyday about 90% of cargos are delivered by ships, and thousands of vessels enter and depart the international container harbors such as Shanghai, Singapore, Hong Kong, Busan, Rotterdam, etc. Maneuvering at harbor is known as the most sophisticated and difficult procedure, because the effectiveness of actuators during low speed berthing is reduced. In this paper, a new berthing method is discussed. Tugboats are combined with damper systems to ensure safe berthing. A mathematical model describing the interaction between unactuated ship, tugboats and damper systems is presented. An optimal controller is designed to maneuver the ship without oscillation and overshoot. MCL (Marine Cybernetics Lab) model ship is used to evaluate the efficiency of the proposed approach through MatLab simulation.

1. Introduction

Compared with other ship maneuvers such as autopilot for steering, trajectory tracking, path following, dynamic positioning of station keeping, ship berthing maneuver is the most complicated procedure which involves both human experience and intensive control operations. In this process, the ship has to follow the given path at low speed to prevent collisions. Moving in confined waters with dead slow velocity significantly reduces the controllability of actuators such as main propeller, rudder, etc. The hydrodynamic coefficients of the ship also change. Besides the relatively large effect of environment disturbance also has an effect on the ship.

Hence, since the early 1990’s, automatic berthing approaches have been studied by many researchers[1-3]. Because the hydrodynamic coefficients change a lot when the ship moves from open sea into harbor, a number of authors have sought to develop intelligent control strategies independent of the dynamic model. These include fuzzy[4,5] and artificial neural network[6-9] control theory, etc[10,11]. The other studies for ship berthing use optimal[12-15] and adaptive control theory[16]. However, these methods do not guarantee stability analysis, especially for critical safety berthing system. To overcome these drawbacks and achieve automation solution, we propose a new approach to ship berthing by using

---

* Corresponding author: kpjiwoo@pknu.ac.kr

[1] Department of Control & Mechanical Engineering, the Graduate School, Pukyong National University, Busan 608-739, Korea

[2] Department of Mechanical System Engineering, Pukyong National University, Busan 608-739, Korea

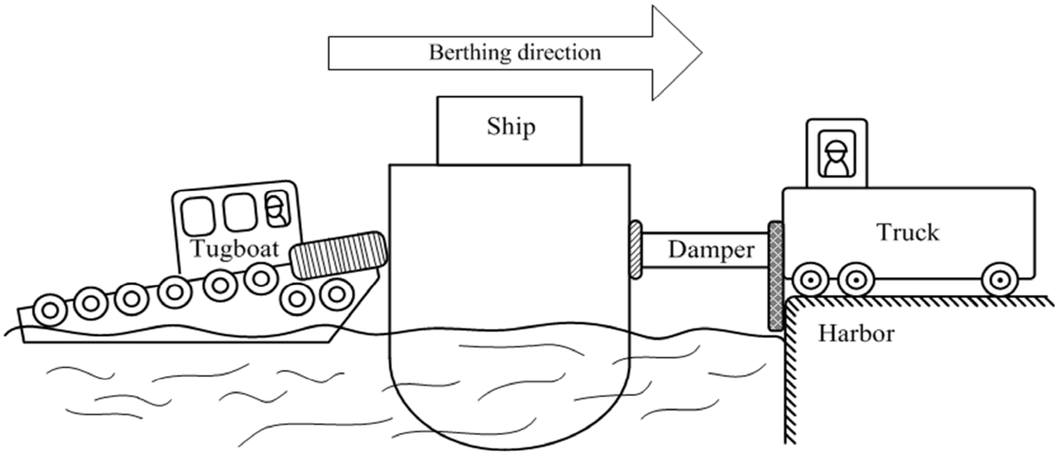

Fig. 1 Ship berthing system

tugboats and damper systems.

Our damper system is designed as semi-active fender. It includes a damper mounted on a truck as described in figure 1. The damper is powered via hydraulics. This design method provides the mobility for this type of fender. It can move to any place on the harbor, start up and operate rapidly. The damper systems contact the ship from the beginning to the end of the berthing phase and are combined with tugboats to maneuver the ship to the harbor safely.

In this paper, we assume that none of the ship's actuators are used. It means that the ship is considered as an unactuated system. Tugboats and damper systems control the movement of the ship. The mathematical model of the system is presented. An optimal controller is designed to undertake the performance of the ship and avoid overshoot which can damage the ship as well as the harbor.

The remainder of this paper is structured as follows. In section II, we provide the dynamic system of the ship considered in the horizontal plane. And the ship model is reduced to 2DOF linear maneuvering model (sway-yaw subsystem). In section III, an optimal state feedback control with an integrator is presented. In section IV, the effectiveness of the proposed approach is evaluated through the model ship simulations.

Conclusions and future studies are summarized and discussed in section V.

2. System Description

With the assumptions that the ship has homogeneous mass distribution as well as the center of gravity coincides with center of geometry, $y_g = 0$; the speed and ship steering equations of motion in surge, sway and yaw[17) are described as follows:

$$\begin{cases} m\left(\dot{u} - \upsilon r - x_g r^2\right) = X \\ m\left(\dot{\upsilon} + ur + x_g \dot{r}\right) = Y \\ I_z \dot{r} + m x_g \left(\dot{\upsilon} + ur\right) = N \end{cases} \tag{1}$$

where m is the mass of the ship, I_z is the inertia moment around z axis, x_g is the center of gravity. X, Y, N are external forces in surge, sway and external moment in yaw. u, υ, r are surge, sway velocity and yaw rate.

Based on additional assumptions that the sway velocity u, the yaw rate υ and the rudder angle δ are small, the nonlinear ship equations of motion can be expressed as speed and steering equation as described as:

$$m\dot{u} = X$$

$$\begin{cases} m\left(\dot{\upsilon} + u_0 r + x_g \dot{r}\right) = Y \\ I_z \dot{r} + m x_g \left(\dot{\upsilon} + u_0 r\right) = N \end{cases} \tag{2}$$

where u_0 is the mean forward speed.

With considering of low speed maneuvering (the ship from the starting point to the desired final point in Y_e direction), the linear steering equations are used and the surge velocity is assumed to be small such that $u_0 \approx 0$. The system equations are rewritten as follows:

$$\begin{cases} m\left(\dot{\upsilon}+x_g\dot{r}\right)=Y \\ I_z\dot{r}+mx_g\dot{\upsilon}=N \end{cases} \tag{3}$$

In this paper, the propulsion(main) system is replaced by tugboats and damper systems to prevent ship collision (see figure 2).

By using the linear theory[18], the hydrodynamic force and moment can be described as:

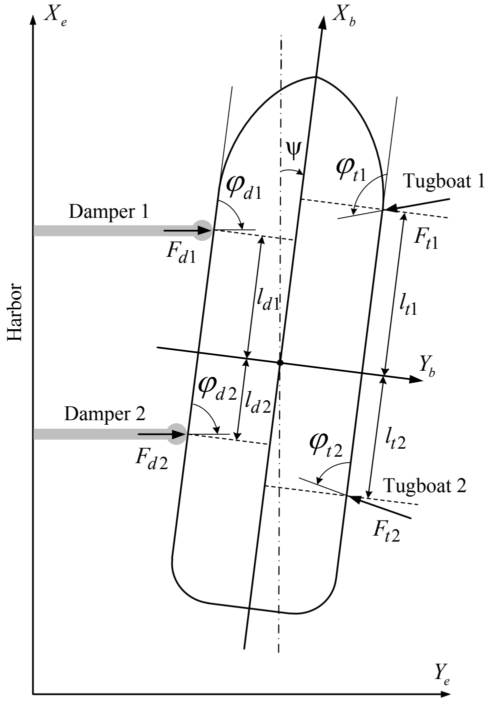

Fig. 2 Ship motion with the assistance of tugboat and damper system

$$\begin{aligned} Y &= Y_{\dot{v}}\dot{v}+Y_{\dot{r}}\dot{r}+Y_v v+Y_r r+\tau_y \\ N &= N_{\dot{v}}\dot{v}+N_{\dot{r}}\dot{r}+N_v v+N_r r+\tau_n \end{aligned} \tag{4}$$

where $Y_{\dot{v}}, Y_{\dot{r}}, N_{\dot{v}}, N_{\dot{r}}$ are added mass terms, $Y_v, Y_r,$ N_v, N_r are radiation induced forces and moments, τ_y, τ_n are vector control force and moment in y and z direction.

Let $\tau=\begin{bmatrix}\tau_y & \tau_n\end{bmatrix}^T$. Vector control force and moment τ is the result of combined efforts of two tugboats and two damper systems. Vector τ is defined as follows:

$$\tau=T(\varphi)f \tag{5}$$

where the vector $f=[F_{t1} \quad F_{t2} \quad F_{d1} \quad F_{d2}]^T$ presents thrusts produced by tugboats and damper systems. The geometrical configuration matrix $T(\varphi)$ is defined as follows:

$$T(\varphi)=\begin{bmatrix} \sin(\varphi_{t1}) & \sin(\varphi_{t2}) & \cdots \\ \cdots & \sin(\varphi_{d1}) & \sin(\varphi_{d2}) \\ l_{t1}\sin(\varphi_{t1}) & -l_{t2}\sin(\varphi_{t2}) & \cdots \\ \cdots & l_{d1}\sin(\varphi_{d1}) & -l_{d2}\sin(\varphi_{d2}) \end{bmatrix} \tag{6}$$

where angles $\varphi_{t1}, \varphi_{t2}, \varphi_{d1}, \varphi_{d2}$ define the force direction of tugboats and damper systems. These are measured clockwise and relative to x axis of the body fixed coordinate frame.

Distances $l_{t1}, l_{t2}, l_{d1}, l_{d2}$ are x location of the contact points between tugboats, damper systems and the ship in the body fixed coordinate frame. From equations (3) and (4), we can write the equation of motion according to:

$$M\dot{v}+Dv=\tau \tag{7}$$

where

$$v=[\upsilon,\ r]^T \tag{8}$$

$$M=\begin{bmatrix} m-Y_{\dot{\upsilon}} & mx_g-Y_{\dot{r}} \\ mx_g-Y_{\dot{r}} & I_z-N_{\dot{r}} \end{bmatrix} \tag{9}$$

is the system inertia matrix, and $M \neq M^T$.

$$D = \begin{bmatrix} -Y_{\upsilon} & -Y_{r} \\ -N_{\upsilon} & -N_{r} \end{bmatrix} \tag{10}$$

is the damping matrix of ship.

3. Control System Design

Equation (7) can be rewritten as:

$$\dot{\nu} = A\nu + B\tau \tag{11}$$

where

$$A = -M^{-1}D = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}, \quad B = M^{-1} = \begin{bmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{bmatrix}. \tag{12}$$

Based on an assumption that heading angle ψ is sufficiently small, $\dot{\eta} = \nu$ or $[\dot{y} \quad \dot{\psi}]^T \approx [\upsilon \quad r]^T$, where y and $\dot{y}$ denote the center position and its derivative of ship in y direction, ψ and $\dot{\psi}$ denote the heading angle and yaw rate.

Let $x = [y \quad \upsilon \quad \psi \quad r]^T$ or $x = [y \quad \dot{y} \quad \psi \quad \dot{\psi}]^T$ is the state vector, then the corresponding state-space model is obtained as follows:

$$\begin{cases} \dot{x} = A_c x + B_c u_c \\ y = C_c x \end{cases} \tag{13}$$

where

$$A_c = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & a_{11} & 0 & a_{12} \\ 0 & 0 & 0 & 1 \\ 0 & a_{21} & 0 & a_{22} \end{bmatrix}, \quad B_c = \begin{bmatrix} 0 & 0 \\ b_{11} & b_{12} \\ 0 & 0 \\ b_{21} & b_{22} \end{bmatrix}, \tag{14}$$

$$C_c = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}.$$

$$u_c = \tau . \tag{15}$$

To keep the ship berthing without overshoot and oscillation, an optimal state-feedback control with an integrator is designed based on LQ control theory[19].

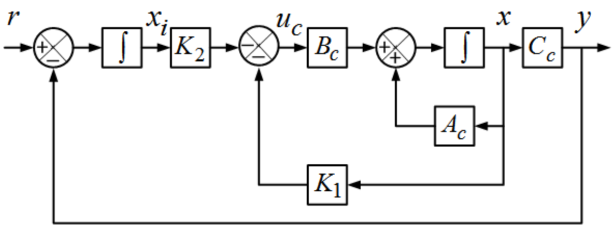

Fig. 3 Ship berthing system with optimal control

The controller is formulated as shown in figure 3.

Let $z = [x \quad x_i]^T$, where x_i is the integrator output. State space system with the plant and augmented integrator is described as follows:

$$\begin{cases} \dot{z} = A_i z + B_i u_c \\ y = C_i z \end{cases} \tag{16}$$

where

$$A_i = \begin{bmatrix} A_c & 0 \\ -C_c & 0 \end{bmatrix}, \; B_i = \begin{bmatrix} B_c \\ 0 \end{bmatrix}, \; C_i = [C_c \quad 0]. \tag{17}$$

With given weighting matrices Q and R, the solution of the LQR set point regulation problem is:

$$u_c = -R^{-1} B_i^{\,T} P z \tag{18}$$

where P is obtained by solving the Algebraic Riccati equation. Then this forms the state feedback law:

$$u_c = -Kz = -[K_1 \quad K_2][x \quad x_i]^T . \tag{19}$$

4. Simulation Results

Computer simulations have been done to evaluate the performance of the ship motion control with tugboats and damper systems and the optimal state feedback controller.

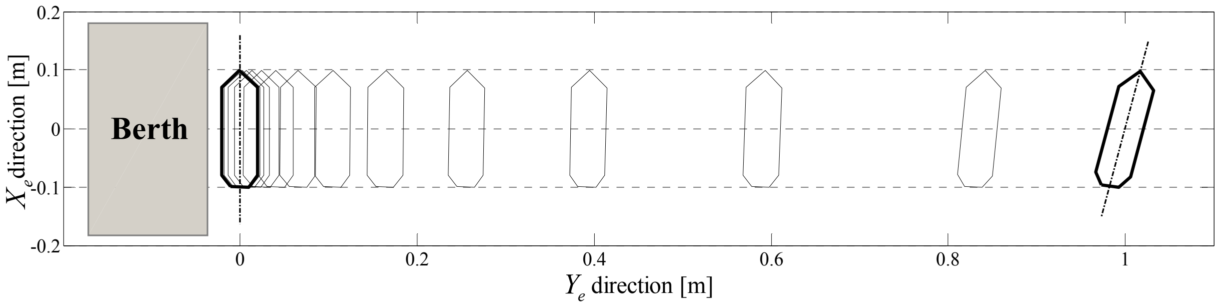

Fig. 4 Ship berthing motion

A model ship in our laboratory (MCL: Marine Cybernetics Lab) is used in simulation. The ship has a mass of 21.5[kg], a length of 2[m] and a breath of 0.4[m]. It is assumed that the center of gravity coincides with the origin. At low speed maneuvering, the model parameters are given as following. The inertia matrix, including hydrodynamic added inertia is

$$M = \begin{bmatrix} m - Y_{\dot{\upsilon}} & mx_g - Y_{\dot{r}} \\ mx_g - Y_{\dot{r}} & I_z - N_{\dot{r}} \end{bmatrix} \tag{20}$$

where

$$m - Y_{\dot{\upsilon}} = 41.7, \quad mx_g - Y_{\dot{r}} = 0.65, \quad I_z - N_{\dot{r}} = 5.26. \tag{21}$$

The linear low-frequency damping matrix is assumed to be symmetrical

$$D = \begin{bmatrix} \text{-}Y_{\upsilon} & \text{-}Y_r \\ \text{-}N_{\upsilon} & \text{-}N_r \end{bmatrix} \tag{22}$$

where $\text{-}Y_{\upsilon} = 6.7$, $\text{-}N_{\upsilon} \approx \text{-}Y_r = 0.5$ and $\text{-}N_r = 1.78$.

In the berthing phase, the ship moves along the Y_e direction from the starting point (0,1) with 10[deg] initial heading angle on the right to the desired final point (0,0) with 0[deg] in yaw angle near the harbor on the left. The tugboats are attached on the right side of the ship. The damper systems on the left side of the ship are used to avoid the collision between the ship and harbor.

The moment arms in yaw of tugboats and damper systems are $l_{t1} = 0.6$[m], $l_{t2} = 0.6$[m], $l_{d1} = 0.4$[m], $l_{d2} = 0.4$[m].

And using the assumptions $\varphi_{t1} \approx \varphi_{t2} = -90$[deg] and $\varphi_{d1} \approx \varphi_{d2} = 90$[deg], the geometrical configuration matrix is rewritten as follows:

$$T(\varphi) = \begin{bmatrix} -1 & -1 & 1 & 1 \\ -l_{t1} & l_{t2} & l_{d1} & -l_{d2} \end{bmatrix}. \tag{23}$$

Figures 4~7 show the time responses during berthing. The designed controller guarantees the

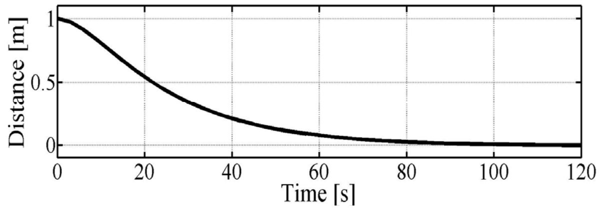

Fig. 5 Ship motion (distance to the berth)

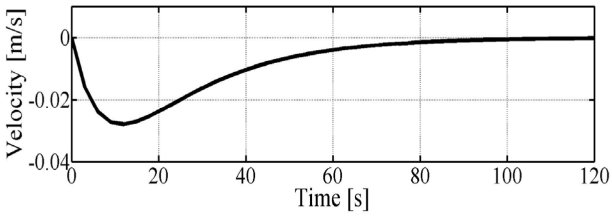

Fig. 6 Ship velocity during berthing

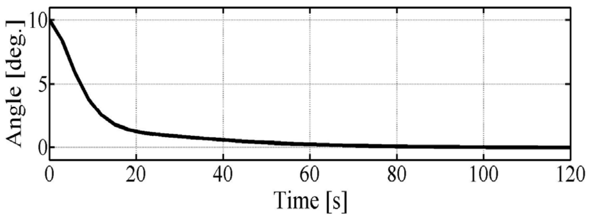

Fig. 7 Ship heading angle during berthing

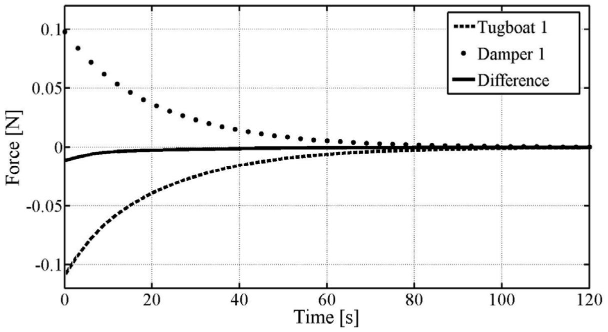

Fig. 8 Thrusts of tugboat #1 and damper system #1

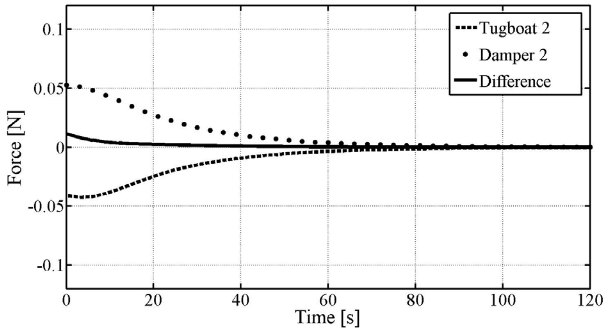

Fig. 9 Thrusts of tugboat #2 and damper system #2

good performance of ship motion without oscillation, overshoot and steady state error. The velocity is kept under limit 0.5[m/s] defined by us. Based on the ship performance, it is ensured that the ship can move to the berth without collision.

Figures 8 and 9 depict the performance of tugboats and damper systems during berthing. The resulting thrusts of tugboats satisfy the given constraint about limited pushing force.

5. Conclusions

In this paper, we proposed a new approach for ship berthing with the assistance of tugboats and damper systems. A linear quadratic integral controller was designed to maneuver the ship automatically. The efficiency of the proposed approach was evaluated through simulation of the model ship in Mat Lab environment. It showed good performance and revealed the possibility of testing the model in real condition. The combination of mooring systems and damper systems will be studied to find out suitable solution for various ship berthing situations.

Acknowledgement

This work was supported by the Basic Science Research Program funded by the Ministry of Education Science and Technology (2012R1A1A22039012).

Also, this work was a part of the project titled “The Development of Mooring Positioning Control System for Offshore Accommodation Barge” funded by the Ministry of Oceans and Fisheries.

References

1) K. Kose, J. Fujuto, K. Sugano, S. Akagi and M. Harada, “On a Computer Aided Maneuvering System in Harbors”, Journal of the Society of Naval of Architects of Japan, Vol.160, pp.103-110, 1986.
2) K. Kose, S. Hirao, K. Yoshikawa and Y. Nakagawa, “Study on Abilities of Harbor Tugboats”, Journal of the Society of Naval of Architects of Japan, Vol.162, pp.141-146, 1987.
3) K. Ohtsu, T. Takai and H. Yoshihisa, “A Fully Automatic Berthing Test Using the Training Ship Shioji Maru”, Journal of Navigation, Vol.44, pp.213-223, 1991.
4) T. Takai and H. Yoshihisa, “An Automatic Maneuvering System in Berthing”, Proceeding of 8th Ship Control Systems Symposium, Vol.3, pp.183-201, 1987.
5) Y. A. Kasabeh, M. M. A. Pourzanjani and M. J. Dove, 1993, “Automatic Berthing of Ships”, Proceeding of the Institute of Marine Engineer 3rd International Conference on Maritime Communications and Control, pp.10-17, 1993.
6) K. Hasegawa and K. Kitera, “Automatic Berthing Control System Using Neural Network and Knowledge-base”, Journal of Kansai Society of Naval Architects of Japan, Vol.220, pp.135-143, 1993.

7) K. Hasegawa and T. Fukutomi, "On Harbor Maneuvering and Neural Control System for Berthing with Tug Operation", Proceeding of 3rd IFAC Conference on Maneuvering and Control of Marine Craft (MCMC'94), pp.197-210, 1994.

8) Y. Zhang, G. E. Hearn and P. Sen, "A Multivariable Neural Controller for Automatic Ship Berthing", IEEE Journal of Control Systems, Vol.17, pp.31-45, 1997.

9) N. K. Im and K. Hasegawa, "Motion Identification Using Neural Networks and Its Application to Automatic Ship Berthing Under Wind", Journal of Ship and Ocean Technology, Vol.6, pp.16-26, 2002.

10) Y. B. Kim, "A Positioning Mooring System Design for Barge Ship Based on PID Control Approach", Journal of the Korea Society for Power System Engineering, Vol.17, No.5, pp.94-99, 2013.

11) Y. Mizuchi, T. Ogura, Y. Hagiwara, A. Suzuki, Y. B. Kim and Y. W. Choi, "Distance Measurement System Using a Stereo Camera and Radial Pattern Target for Automatic Berthing Control", Journal of the Korea Society for Power System Engineering, Vol.17, No.5, pp.121-127, 2013.

12) K. Shouji and K. Ohtsu, "A Study on the Optimization of Ship Maneuvering by Optimal Control Theory (1st Report)", Journal of the Society of Naval of Architects of Japan, Vol.172, pp.365-373, 1992.

13) K. Shouji, K. Ohtsu and T. Hotta, "A Study on the Optimization of Ship Maneuvering by Optimal Control Theory (2nd Report)", Journal of the Society of Naval of Architects of Japan, Vol.173, pp.221-229, 1993.

14) K. Shouji and K. Ohtsu, "A Study on the Optimization of Ship Maneuvering by Optimal Control Theory (3rd Report)", Journal of the Society of Naval of Architects of Japan, Vol.174, pp.339-344, 1993.

15) J. G. Hu and K. U. Yang, "Proposition of Automatic Ship Mooring Using Hydraulic Winch", Journal of the Korea Society of Fluid Power & Construction Equipments, Vol.10, No.4, pp.14-21, 2013.

16) Y. Liu and C. Guo, "Automatic Berthing Control of Underactuated Surface Ships in Restricted Waters Based on Nonlinear Adaptive Control Method", Proceeding of 32st Chinese Control Conference, pp. 939-944, 2012.

17) T. I. Fossen, Guidance and Control of Ocean Vehicles, John Wiley & Sons. Ltd. ISBN 0-471-94113-1, 1994.

18) K. S. M. Davidson and L. I. Schiff, "Turning and Course Keeping Qualities", Transactions of Society of Naval Architects and Marine Engineers, Vol.54, 1946.

19) P. C. Young and J. C. Willems, "An Approach to the Linear Multivariable Servomechanism Problem", International Journal of Control, Vol.15, pp.961-979, 1972.