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Optimal Control Design for Automatic Ship Berthing by Using Bow and Stern Thrusters

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KEY WORDS: Berthing, Ship motion model, System identification, Optimal control, Tunnel thruster, 2DOF servosystem.

ABSTRACT: *Conventionally, because it is difficult to control a ship in shallow water and because attempting to do so creates unwanted environmental effects, maneuvering ships in the harbor area for berthing is usually done with the assistance of tugboats. In this paper, we propose a new method for berthing ships automatically by using bow and stern thrusters. Specifically, a steering motion model of a ship is considered, and parameters in the equation are evaluated by the system identification technique. An optimal controller based on observations was designed from the linearization of the non-linear ship motion in the horizontal plane. It is used to reduce the uncertainty about the ship's dynamics and reduce measurement requirements. The performance of the controller was also analyzed for its robustness relative to avoiding disturbing the environment due to winds, currents, and wave-drift forces. Experiments were conducted to estimate the potential for identifying result and the design of the controller. Specifically, in this paper, the system modeling and tracking control approach are discussed based on a two-degree-of-freedom (2DOF) servo-system design.*

1. Introduction

Nowadays, to reduce labor cost and time consuming by fully manned operation, the application control in autonomous marine vehicle is considerably growing, especially in surface marine vessel field. Introduction of automatic ship control started with the pioneering work of Sperry and Minorsky. By using gyrocompass for measuring the heading angle, Sperry constructed the first automatic ship steering with simple proportional gain in 1911 (Bennet, 1979). Later, Minorsky (1922) presented a detail analysis of the position feedback control system with PID controller. In order to prevent rudder saturation, the classical PID controller was extended with inclusion of limiter while a dead band and a filter were used to smooth the control effort preventing calls from not compensable disturbance, caused by high frequency yaw motion due to waves. More recently, with development of robust, adaptive and nonlinear control theory, the control of ship achieved significant researches by a large number of authors Koyama (1967), Van Amerongen and Udink (1975), Grimble and Patton (1980) and Fossen (1994). These researches center on course keeping, course changing, way point tracking, trajectory tracking, path-following control, dynamic ship positioning system for marine vessel. Together with, fuzzy and neural network algorithms, with independent of the mathematical ship motion model, are received more and more concern.

However, modern control theory has just been applied to ship maneuvering for berthing at early 1990's. It may be said that, ship berthing is one of the most sophisticated procedure for both human operation and automatic control .Firstly, with requirement for berthing at low speed, the controllability of ship reduced significantly with the change of ship hydrodynamic between deep and shallow water, whereas the disturbance from environment as wind, wave and current maybe become large relatively. Secondly, by using the main propeller and adjustment of the rudder, the motion of ship becomes unpredictable. Finally, with the interaction of ships located on the harbor, the ship handing is so more and more sophisticated (Zhang et al., 1997). For these reason, automatic ship berthing is still challenge in the marine cybernetic.

Commonly, automatic ship berthing control procedure can be separated into two phase as shown in Fig. 1. The first is called the ballistic phase and the second is the final phase. In each phase, two main purposes have been considered: optimal trajectory planning with description of ship dynamic system, environment disturbance, constraints on steering etc, and trajectory tracking, which ensure the accurate tracking in face of model uncertainty and disturbance rejected.

For the first purpose, ship berthing trajectory planning was introduced through the optimization of time – energy criterion taking into account constraints on the steering system,

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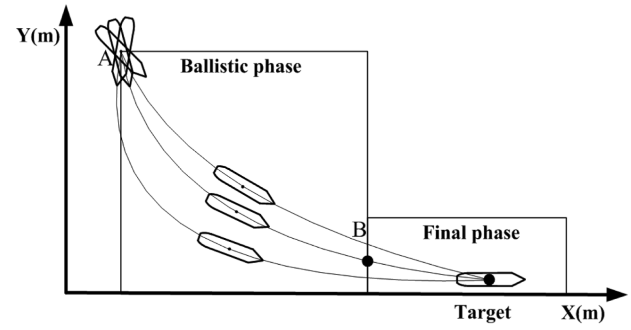

Fig. 1 Planning route for ship berthing

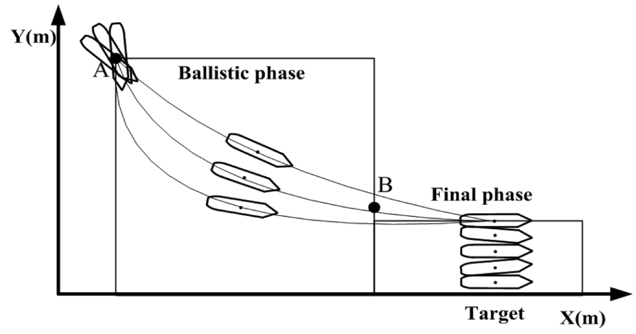

Fig. 2 Proposed planning route for ship berthing

environment, non-linearities (Djouani and Hamam, 1995). Ohtsu et al. (1996), Okazaki and Ohtsu (2008) presented minimum time ship berthing maneuvering control system by solving two-point boundary-value problem. Berthing trajectory tracking problem has been concerned considerably. Zhang et al. (1997) presented the multivariable neural controller for automatic ship berthing by using multi layer feed-forward neural network. This neural network controller was designed to adjust its parameters online for robustness performance under effect of environment disturbance. Kyun and Hasegawa (2002) proposed a motion identification method using the neural networks to overcome the lateral and longitudinal disturbance effects. Nguyen and Jung (2007) introduced a neural network method which is trained online by using adaptive technique to simulate the automatic berthing in the Busan bay.

However, these above researches may not be satisfied to apply in the final phase. The two main drawbacks in this phase are: firstly, with the low speed control, ship controllability reduces significantly, so using main propeller and rudder adjustment will increase the collision risk between the ship and the harbor. Secondly, by ship maneuvering from starting point B to the berth is easy to happen the contact between our ship and ships that were located in the harbor before, because we do not know exactly their position in tracking trajectory planning task while for safety maneuvering in harbor, the distance between ships are at least 3 [m] in both x and y directions. In our study, we propose a new approach as described in Fig. 2. In the ballistic phase, we can apply optimal trajectory tracking planning and trajectory tracking control as described above. In the final phase, for safety berthing, we propose the new approach for ship maneuvering by using only bow and stern thrusters. In this study, mathematical modeling of ship is described and parameters in this equation are estimated by system identification technique. The linear optimal controller is proposed to trade off the function cost between the state variables and the control signal supply to thrusters, also robust environment disturbance. The experimental results are presented to evaluate the efficiency of proposed approach.

2. Mathematical Modeling

To describe position and orientation of ship motion, it is necessary to using six independent coordinates. The first three term coordinates x, y, z axes determine the position while the other coordinates correspond to the orientation of ship. The six independent motion of ship are defined: surge, sway, heave, roll, pitch and yaw by SNAME as described in Table 1.

2.1 Coordinate frames

In analyzing the motion of most ships, it is common to reduce the six degree of freedom model to the motion in horizontal plane (surge sway and yaw motion). Two coordinate frames can be used to define the motion of ship as following figure:

Moving coordinate frame XYZ is fixed to the ship motion. It is called the body fixed frame. Its origin is usually chosen to coincide with the center of gravity (CG) of ship, while CG is often principle plane of symmetry, the body axes are chosen to coincide with the principle axes of inertia. The earth fixed coordinate frame $X_0Y_0Z_0$ can be considered to be inertial (the acceleration of the point on the surface of Earth can be neglected). Surge and sway velocities, which are the

Table 1 The notation of SNAME for marine vessel

DOF	Ship motion	Force	Linear/ angular velocity	Position/ euler angle
1	x-direction (surge)	X	u	x
2	y-direction (sway)	Y	v	y
3	z-direction (heave)	Z	w	z
4	x-axes (roll)	K	p	Φ
5	y-axes (pitch)	M	q	θ
6	z-axes (yaw)	N	r	ϕ

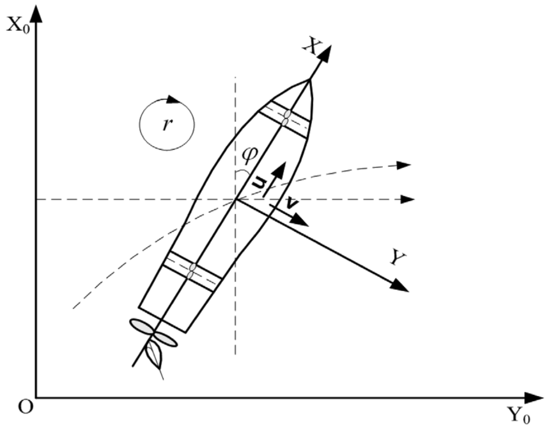

Fig. 3 Coordinate frames

components of ship in the moving coordinate frame are *u*, *v* respectively, while *r* and *φ* denote the turning rate and heading angle of ship.

2.2 Ship dynamic model

The nonlinear equation of ship motion in the horizontal plane can be deduced by the Newton's Second Law for rigid body as follow:

$$\begin{aligned} m(\dot{u}-vr-x_G r^2) &= X_r+X_w+X \\ m(\dot{u}+ur+x_G\dot{r}) &= Y_r+Y_w+Y \\ I_z\dot{r}+mx_G &= N_r+N_w+N \end{aligned} \tag{1}$$

Above equation describes the couple surge sway and yaw motions in the coordinate fixed frame, where m is the mass of ship, x_G is the center of gravity, and I_z is the inertia moment around *Z* axis.

X_r, Y_r and N_r are the radiation induced force and moment. They can be determined by three components:

- Added mass due to the inertia of surrounding fluid.
- Radiation-induced potential damping.
- Restoring force due to Archimedes.

The environmental forces deduced by wind wave and current, are represented by X_w, Y_w and N_w. Such terms will be highly nonlinear and they are generally difficult to be characterized by the mathematical modeling. The effect of current force is considered in the relative velocity between ship and current. The wind force is unsteady and will be time dependent and the wave force can be separated by first order and second order wave drift. We are often concerned the effect of the last wave force more than the first kind in the control design.

X, *Y* and *N* are the external force deduced by the main propeller, rudder, tunnel thrusters and the tugboat.

By consideration to low speed maneuvering and under hypothesis that : the ship is symmetry by the *XZ* plane and center of gravity coincides with the center of geometry, the motion of ship can be linearized and vectorized by following form (Fossen, 1994).

$$\begin{aligned} M\dot{v}+Dv &= Bu \\ \dot{\eta} &= R(\psi)v \end{aligned} \tag{2}$$

Where, $M=\begin{bmatrix} m-X_{\dot{u}} & 0 & 0 \\ 0 & m-Y_{\dot{v}} & -Y_{\dot{r}} \\ 0 & -N_{\dot{v}} & I_z-N_{\dot{r}} \end{bmatrix}$ is the system inertia matrix.

$D=\begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix}$ is the damping matrix of ship.

B is the control matrix describing the thruster configuration and *u* is the control input.

$R(\varphi)=\begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}$ is the transformation matrix between the body fixed coordinate frame and inertia coordinate frame, while $v=[\mathrm{i}, v, r]^T$ and $\mathrm{h}=[x, y, \phi]^T$ denote the motion of ship in the moving and earth fixed coordinate frame.

By using bow and stern thrusters to maneuver ship from the starting point of the final phase to the berth as described above, also reducing the complex in the coefficients estimation procedure, we should simplify the mathematical model in the Eq. (2). The simplified model should contain only the main physical property of system. The new equation has just described yaw and sway motion (steering equation) and neglected the surge motion as shown in Fig. 4. It is described by the following equation.

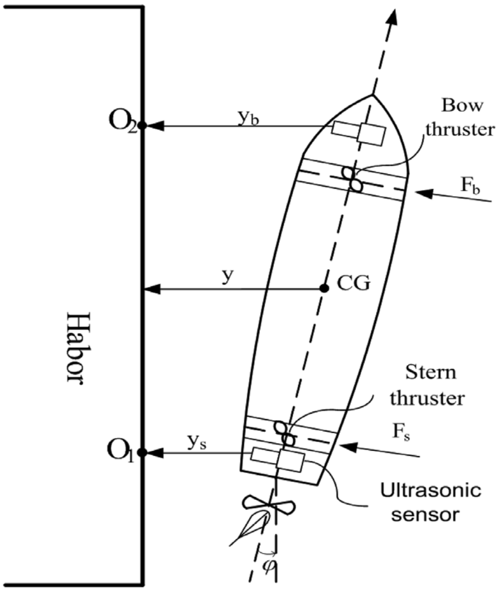

Fig. 4 Proposed steering model.

$$
\begin{aligned}
&(m-Y_{\dot{v}})\ddot{y}+D_v\dot{y}=(F_s+F_b)\cos\varphi \\
&(I_z-N_{\dot{r}})\ddot{\varphi}+D_z\dot{\varphi}=(T_b-T_s)
\end{aligned}
\tag{3}
$$

Equation (3) is obtained by using Lagrange mechanics as described following.

$$
\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right)-\frac{\partial T}{\partial q_i}+\frac{\partial D}{\partial \dot{q}_i}=u_i \tag{4}
$$

where $T=\frac{1}{2}(m-Y_{\dot{v}})\dot{y}^2+\frac{1}{2}(I_z-N_{\dot{r}})\dot{\varphi}^2$ is the kinetic energy and $D=\frac{1}{2}D_v\dot{y}^2+\frac{1}{2}D_z\dot{\varphi}^2$ depicts the dissipation function. The generalized coordinates $q_i(i=1-2)$ are chosen by position of ship in y direction and heading angle φ. F_s, F_b, T_s and T_b are forces and moments deduced from the bow and stern thrusters respectively.

3. Hydrodynamic Coefficients Estimation

The hydrodynamic coefficients are obtained from partial derivative of hydrodynamic forces as described in the previous section. As well-known, maneuvering capability of ship is strongly related to the accuracy in the determination of hydrodynamic coefficients, which specify the mathematical model of ship motion. These coefficients depend on linear and angular velocity and acceleration of ship. Additionally, these coefficients also change in the different sea water condition. They may be readily calculated in the condition of deep water, but are much more difficult to estimate them in the shallow water and inversely. So, accurate of hydrodynamic coefficients estimation are not easy to achieve.

Almost hydrodynamic coefficients can be found from the model basin test or free tuning test by various methods such as captive model test, slender body theory, simulation tool, computational fluid dynamic (CFD), or using empirical method. Each approach have some advantages and disadvantage, such that: the accuracy of estimation will be significantly improve by using captive model test (rotating arm or planar motion mechanics) but it will increase time consuming and expensive. It has to be equipped with highly accuracy equipment. Contrastingly, simulation tool will be cheaper than but it is just able to provide general information about the maneuverability performing without offering more detail information on the characteristic of the ship analysis. Another promising approaching is system identification. With the development of numerical analysis, System identification is more economical and provides more direct answer by measuring coefficients individually.

As well known, system identification can be divided by parametric model method and non parametric model method. The non parametric method does not require prior information on the structure of model, while parametric model method base on the mathematical model that describes the structure of the system. So using parametric model will be improved the accuracy and resolution of identification method. Many identification methods are developed to estimate parameter of such parametric model methods. Such that, least square estimation (LSE), maximum likelihood algorithm (MLA), subspace method, instrument variable method (IV), eigen-system realization (ERA), and prediction error minimization method (PEM).

In this paper, system identification technique based on PEM method is used to estimate the hydrodynamic coefficients. Generally, ship maneuvering model can be depicted as the multi-variable auto-regressive with exogenous (MARX) discrete time model.

A discrete time MARX model is presented as following.

$$
A(q)y(t)=B(q)u(t-k)+e(t) \tag{5}
$$

where $y(t)$ and $u(t)$ are the vector of measured output and input data, k is time delay, $e(t)$ presents Gaussian noise with zero mean. The matrix A and B the polynomials in the delay operator q^{-1}. They can be expressed as

$$
A(q)=I+a_1q^{-1}+\cdots\cdots\cdots\cdots\cdots+a_{na}q^{-na} \tag{6}
$$

$$
B(q)=b_0+b_1q^{-1}+\cdots\cdots\cdots\cdots\cdots+b_{nb}q^{-nb} \tag{7}
$$

It can be expressed as following.

$$
y(t)=\phi^T\theta+e(t) \tag{8}
$$

where matrix input and output measurement is $\phi=[-y^T(t-1),\ \cdots,\ -y^T(t-na),\ u^T(t-k),\ \cdots,\ u^T(t-k-nb)]$ and $\theta=[A\ B]=[a_1,\ a_2,\ \cdots,\ a_{na},\ b_0,\ b_1,\ \cdots,\ b_{nb}]$ is the unknown parameter matrix.

The idea behind the prediction error can be stated: if we want to described the model as the predictor of the next output:

$$
\hat{y}_m(t/t-1)=f(Z^{t-1}) \tag{9}
$$

with $\hat{y}_m(t/t-1)$ denotes the one step ahead prediction of the output and f is an arbitrary function of past and observed data (Ljung, 2002). Parameterize the predictor in terms of finite dimensional parameter vector θ.

$$
\hat{y}(t/\theta)=f(Z^{t-1},\theta) \tag{10}
$$

So the determination of estimate of θ is done to minimize the distance between $\hat{y}(1/\theta),\ldots,\hat{y}(N/\theta)$ and $y(1/\theta),\ldots,y(N/\theta)$ in a suitable norm. In this study, we using the least square criterion, then prediction error will be:

$$V_N(\theta, Z^N) = \frac{1}{N}\sum_{t=1}^{N}\frac{1}{2}[y(t)-\varphi^T(t)\theta]^2 \tag{11}$$

So, the parameter of model can be estimated by following equation:

$$\widehat{\theta_N^{LS}} = \left[\frac{1}{N}\sum_{t=1}^{N}\varphi(t)\varphi^T(t)\right]^{-1}\frac{1}{N}\sum_{t=1}^{N}\varphi(t)y(t) \tag{12}$$

For hydrodynamic coefficient estimation in steering equation described in Eq. (3), the ship is tested in the model basin as shown in Fig. 5. $Y_{\dot v}$ and D_v are obtained from the sway motion test, with two ultrasonic sensors mounted on fore and aft are used to calculate distance from ship to target. The $N_{\dot r}$ and D_z coefficients are estimated from yaw motion. In this case, high resolution encoder sensor is used to measure yaw angle, and two current sensors calculate current supply to bow and stern thruster during testing. Ship response during yaw motion test is shown in Fig. 6. With these responses, $N_{\dot r}$ and D_z coefficients are estimated base on the proposed prediction error method. The result from the identification and the experiment show good performance as shown in Fig. 7. Similarly, Fig. 8 compares experiment and estimation results in yaw motion by using stern thruster.

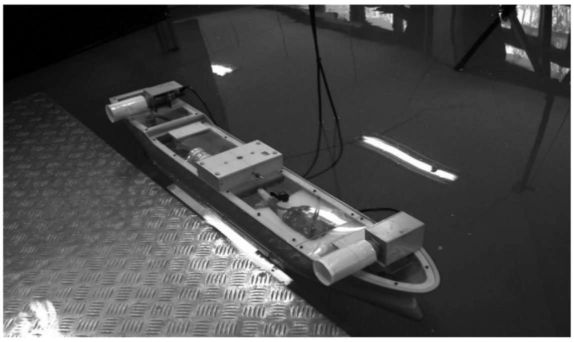

Fig. 5 Model test basin

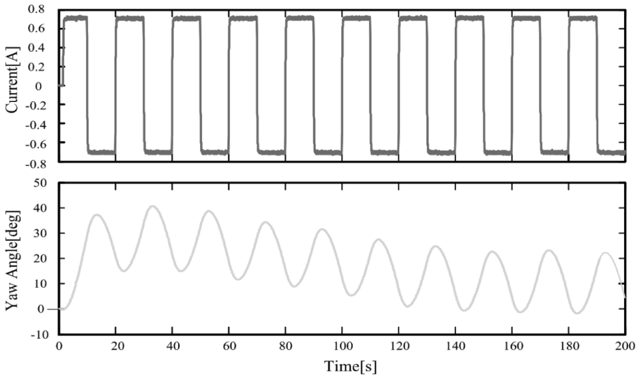

Fig. 6 Current supplied to bow thruster and yaw angle response

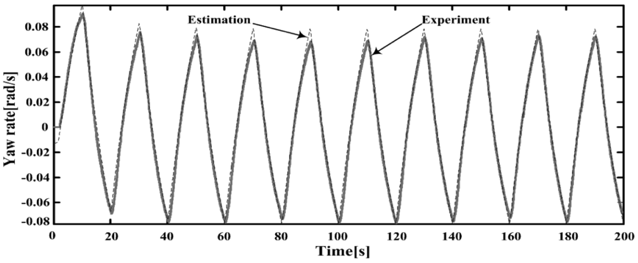

Fig. 7 Yaw rate response and estimation by using bow thruster

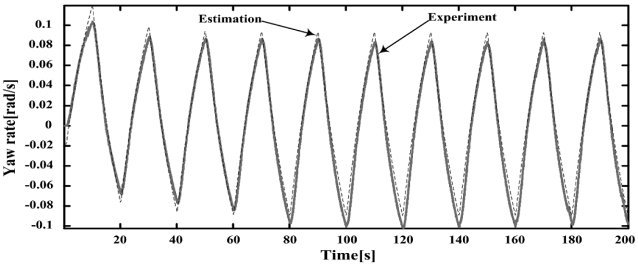

Fig. 8 Yaw rate response and estimation by using stern thruster

Table 2 Model particulars and hydrodynamic coefficients

Parameter	Value
Length overall	1.1 [m]
Breadth	0.15 [m]
Draft	0.05 [m]
Number of propellers	1
Number of tunnel thrusters	2
$m-Y_{\dot v}$	10 · 3 [kg]
$I_z-N_{\dot r}$	1.1925 [kg · m^2]
D_v	2.7 [kg/s]
D_Z	0.0826 [kg · m/s]

From Fig. 7 and Fig. 8, we can conclude that the proposed steering model is suitable for berthing purpose. Also predictor shows good relay on hydrodynamic coefficients estimation. Furthermore, by verifying the other parameters from sway moving test, all coefficients in the steering model are calculated. The main characteristics and hydrodynamic coefficients of ship are listed in the Table 2.

4. Automatic Berthing Control System

This section describes the controller designed for ship berthing automatically by only using bow and stern thruster. The main goal of the design is to maneuver the ship to stop at desired point near planned of berth with almost zero final speed and keep the ship moving without oscillation. For this purpose, linear optimal controller based on the observer is proposed.

The state equation of ship can be rewritten from the ship steering model:

$$\begin{aligned}\dot{x} &= Ax + Bu + v\\ y &= Cx + w\end{aligned} \tag{13}$$

The vector $x = [y_c \; \dot{y}_c \; \varphi \; \dot{\varphi}]^T$ denotes the center position and its derivative of ship in y direction also heading angle and yaw rate. Vector control input $u = [I_b \; I_s]^T$ is the current supplied to bow and stern thrusters. The system matrixes A, B, C are calculated as Eq. (14).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & \dfrac{-D_v}{m - Y_{\dot{v}}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & \dfrac{-D_z}{I_z - N_{\dot{r}}} \end{bmatrix},$$

$$B = \begin{bmatrix} 0 & 0 \\ \dfrac{K_b}{L_b(m - Y_{\dot{v}})} & \dfrac{K_s}{L_s(m - Y_{\dot{v}})} \\ 0 & 0 \\ \dfrac{K_b}{I_z - N_{\dot{r}}} & \dfrac{K_s}{I_z - N_{\dot{r}}} \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{14}$$

In above matrixes, parameters $L_b = 0.45$ [m] and $L_s = 0.46$ [m] are the distance from the thrusters to center of gravity, $K_b = 0.2757$ [N · m/A] and $K_s = 0.239$ [N · m/A] are thruster torque coefficients.

Noise signal v (process noise) is used to model the effect of random wind, wave drift force, current and the unmodelled phenomena. It is assumed as white noise signal with Gaussian disturbance. It should be reduced as much as possible by means of feedback controller. The noise signal which is present in the position measurement of ultrasonic sensor can be eliminates from the low pass filter. The structure of a controller based on observer design is shown in Fig. 9 which is a two-degree-of-freedom (2DOF) servosystem (Kim et al., 2006).

In Fig. 9, F_0 is a gain such that $A + BF_0$ is stable. Then, F_1, H_0 is calculated as following.

$$F_1 = C(A + BF_0)^{-1} \tag{15}$$

$$H_0 = [-C(A + BF_0)^{-1}B]^{-1} \tag{16}$$

where H_0 is a feedforward gain and G is a tuning gain to obtain good tracking performance for the target. The tuning gain G should be given such that the feedback system is stable. If we calculate the gain G based on LQ control theory, it may be given as following:

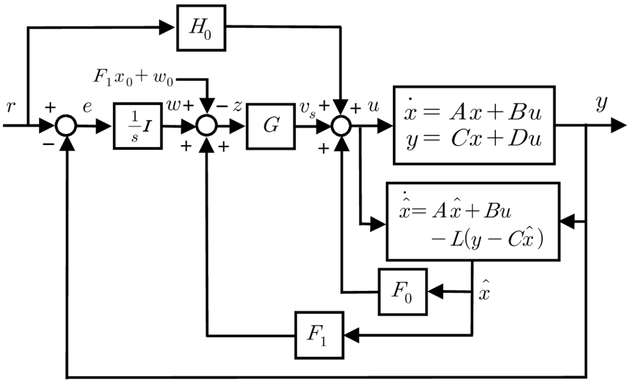

Fig. 9 2DOF servosystem incorporating an observer

$$G = -R^{-1}(F_{1s}B)^T W = G_0 W \tag{17}$$

Based on the fact mentioned before, the control gains are calculated as following.

$$F_0 = \begin{bmatrix} -0.943 & -2.399 & -1.053 & -2.178 \\ -1.053 & -2.735 & 0.943 & 2.043 \end{bmatrix} \tag{18}$$

$$F_1 = \begin{bmatrix} -4.974 & -9.239 & 0.067 & 0.277 \\ 0.067 & 0.157 & -2.271 & -2.318 \end{bmatrix} \tag{19}$$

$$H_0 = \begin{bmatrix} 0.943 & 1.053 \\ 1.054 & -0.943 \end{bmatrix} \tag{20}$$

$$G = \begin{bmatrix} 0.094 & 0.105 \\ 0.105 & -0.943 \end{bmatrix} \tag{21}$$

Because the ship is not equipped with enough sensors to estimate all states of system, and the derivative of bow, stern positions and yaw rate are so sensitive with noise, so full order observer technique is used to estimate all states. Based on observability of system, the gain L is calculated. It has to be chosen so that response of observer is faster than the response of close loop system and signal controls are not exceed the limit of actuators.

$$L = \begin{bmatrix} 1.273 & -0.022 \\ 0.252 & -0.009 \\ -0.025 & 1.448 \\ -0.016 & 0.472 \end{bmatrix} \tag{21}$$

In order to evaluate the efficiency of proposed ship steering model and controller designed, the ship is tested in the model basin. The motion of ship is controlled and measured based on SIMTOOL program through DAQ board (RealGain, 2009). Bow, aft positions and yaw angle of ship during testing is shown in the Fig. 10. From starting point at 1.4 [m] approximately for bow and stern, with 5 [deg] heading angle, the ship moved to the desired final point (0.5 [m] at bow and stern and zero heading angle) with small overshoot and oscillation as possible as. Notice that, to reduce the overshoot which is induced by inertia force of ship, the control inputs

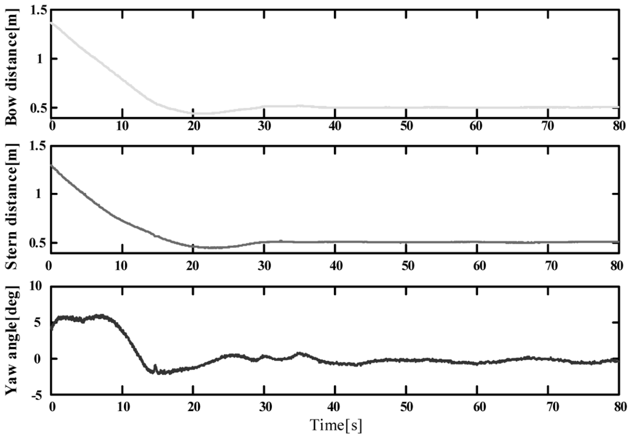

Fig. 10 Position and yaw angle of ship during berthing

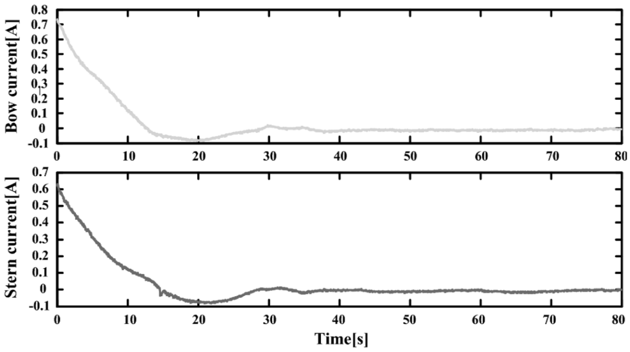

Fig. 11 Currents supplied to bow and stern thruster

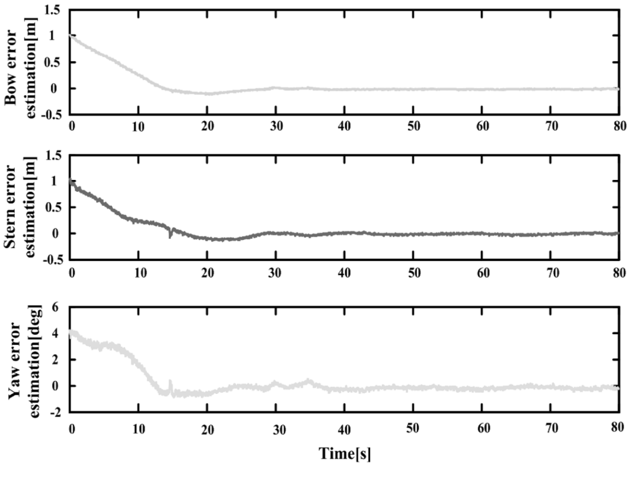

Fig. 12 Compared results between the real states and observer

of bow and stern thrusters change their direction around 10 to 20 [s] as shown in Fig. 11. Fig. 12 shows good control performance of the designed control system with observer.

5. Conclusion

In this paper, based on analysis of presented researches, there exist many limits about safety berthing automatically by combination of rudder adjustment and main propeller. We proposed the new approach by using only bow and stern thrusters. Especially, we proposed a new and simple method for ship steering. Hydrodynamic coefficients are estimated from system identification techniques by prediction error minimization method. After that, the optimal controller based on observer was designed to maneuver ship berthing automatically without oscillation, overshoot and steady state error due to effect of environment disturbance and uncertainty of model. Experiments were carried out to evaluate the effectiveness of the proposed steering model and control method in the bad environment conditions. The experimental evaluations showed that good performance for automatically berthing by using bow and stern thrusters can be obtained.

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