Thesis for the Degree of Master of Engineering

A Study on Automatic Ship Berthing System Design with Side Thrusters

by

Van Phuoc Bui

Department of Control and Mechanical Engineering

The Graduate School
Pukyong National University

February 2010

A Study on Automatic Ship Berthing System Design with Side Thrusters

사이드스러스트를 갖는 선박의 자동접안시스템구축에 관한 연구

Advisor: Prof. Young Bok Kim

by

Van Phuoc Bui

A thesis submitted in partial fulfillment of the requirements
for the degree of

Master of Engineering

in Department of Control and Mechanical Engineering
The Graduate School
Pukyong National University

February 2010

A Study on Automatic Ship Berthing System Design with Side Thrusters

A thesis

by

Van Phuoc Bui

Approved as to style and content by:

____

Chairman Prof. Joo Ho Yang

______________________________ ______________________________

Member Prof. Ji Seong Jang Member Prof.Young Bok Kim

February 2010

Acknowledgements

Two years for master education program is not so long but it is one of the challenging and greatest times in my life. I am indebted to many people. Without their help, this thesis would not have been possible.

Deep in my heart, sincere appreciation is intended to my advisor Prof. Young Bok Kim. His kindness makes me warm when I live overseas. His knowledge and dedication in research impart me invaluable lessons. His patient makes me feel confident in study. I am eternally grateful for his support during my study.

I wish to express my gratitude to Prof. Joo Ho Yang and Prof. Ji Seong Jang for your devotion and valuable suggestion during the courses they lectured.

I also want to thanks Lab Marine Cybernetic members. They make me feel our lab to be closed family. Thank you for every helping.

Last but not least, I owned a lot my family. I want to dedicate the achievement to my parents. Your confident, encouragement and passion for education help me overcome impediments in study and life.

Van Phuoc Bui

Contents

Nomenclatures

Variable	**Description**
$Oxyz$	earth fixed coordinate frame
$Cx_by_bz_b$	moving coordinate frame
u	surge velocity of ship
v	sway velocity of ship
$\dot{\varphi}$	yaw rate velocity of ship
x_g	distance from O to G measured along x axis
I_z	inertia moment around z axis
q^{-1}	backward shift operator
T	kinetic energy of system
V	potential energy of system
$\mathbf{A}$	state matrix of system
A	polynomial A of system in discrete time form
$\mathbf{B}$	input matrix of system
B	polynomial B of measurable input signal in discrete time form
$\mathbf{C}$	output matrix of system
C	polynomial C of random disturbance signal in

	discrete time form
D	control matrix of system
D	polynomial D of measurable disturbance signal in discrete time form
J	quadratic cost function which represents weighted sum of energy of state and control
J	sum of error square

A Study on Automatic Ship Berthing System Design with Side Thrusters

Van Phuoc Bui

Department of Control and Mechanical Engineering, The Graduate School, Pukyong National University

Abstract

This thesis contains some analyses and new results on the problem of automatic ship berthing system design. The main motivation driving this work is to propose a new approach for ship berthing automatically by using only bow and stern thrusters.

In this thesis, the ship steering model is considered and simplified to suit the proposed system. Prediction Error Method, one of System identification techniques, is used to estimate the hydrodynamic coefficients of ship motion model. The two-degree-of-freedom servosystem incorporating observer is described. It satisfies two purposes:

- Optimal tracking response to step reference by using linear optimal regulator
- Robust stability with the uncertainty of model and effect of environmental disturbances

In order to evaluate the efficiency of proposed steering model and designed controller, the ship control experiments are performed in model basin. Motion of ship is measured and controlled based on SIMTOOL program through DAQ board. Experimental results show good performances with reduced overshoot and steady state error as well as robustness against environmental disturbances.

1. Introduction

1.1. History of Marine Vessel Control

Automatic ship control has been studied since early 20th century. Introduction of marine control started with pioneering work of Elmer Speery and Nicholas Minorsky. In 1911, by using gyrocompass for measuring heading angle, Speery constructed the first automatic ship steering mechanism with simple proportional gain in feedback control loop called “Metal Mike”. After that, in 1922, Minorsky presented a detail analysis of a position feedback control system with *Proportional-Integral-Derivative* (PID) control. The both autopilot systems of Speery and Minorsky are just single-input single-output (SISO) systems. Along with development of control theory and computer aided control, ship control applications have covered a huge diversity of vehicle. Dynamic positioning system (DPS), way point tracking control, course keeping and roll stabilization using rudder and fins etc. become commercial products.

The development of control theory applied to marine vessel can be summarized in the Fig.1.1. The horizontal axis performs the complexity of requested system such as number of required dimensions and number of inputs/outputs. The vertical axis presents the grade of difficult of controlled system. The control system can be classified in map. It is noticed that the control system design can be divided into two parts: model based control design (robust, optimal, adaptive control .etc) and un-modeled control design (fuzzy and neural network). With given mathematical model, design method based on modeling is more effective.

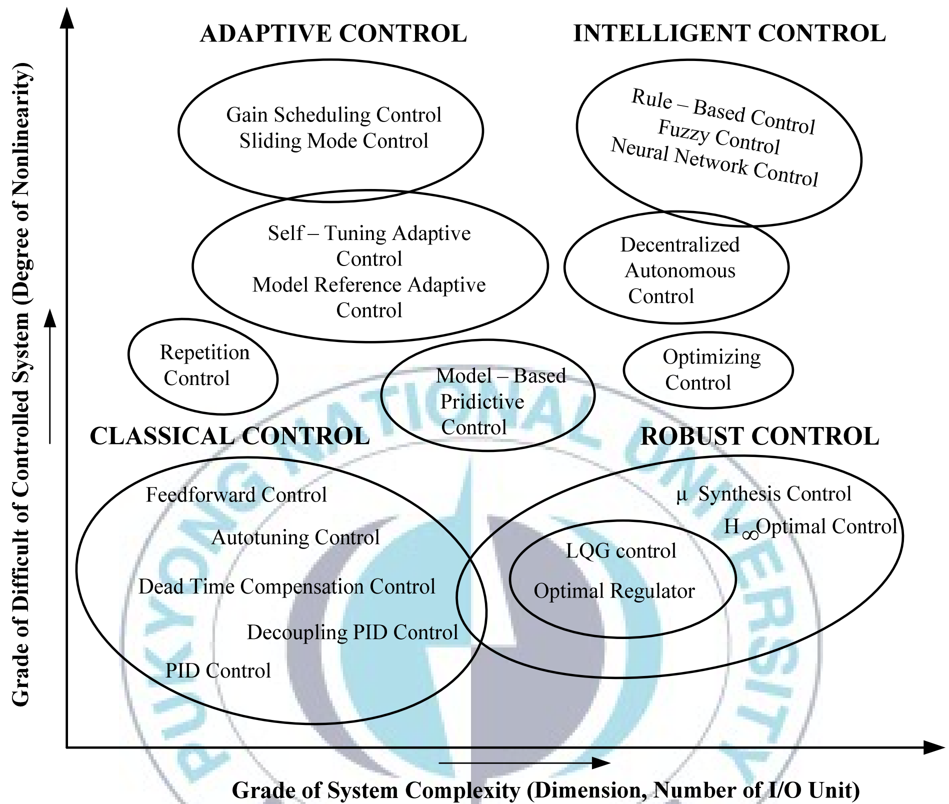

Fig.1.1. Map of the control system design applied marine vessel.

Normally, the solution of ship motion control problem depends on requirement of particular operations such as autopilot, path following, dynamic positioning, assisted position mooring and it is based on the interconnection of Guidance system, Control system and Navigation system as shown in Fig.1. 2.

- Guidance system continuously computes and updates the desired position, velocity and acceleration. According to information regarding mission and data collected from the motion sensors, amount of available power and weather condition (speed, direction of wind, current, height and slop of wave), trajectory generator establishes desired waypoints and then feeds results to ship's control system

- Control system processes information to infer the states of ship and generate an appropriate command for actuator (main propeller, rudder, tunnel thrusters) to reduce the different between the actual and desired trajectory. The controller can have the different operation modes such as autopilot mode, dynamic positioning mode, roll and pitch stabilization mode

- Navigation system provides reliable measurement about position, courses and distance traveled. The basic functions of this system are to collect the information from many sensors system equipped onboard (GPS, gyros-compass, speed log, accelerators), transform the measurements to a common coordinate reference frame, then transfer the quality signals to guidance and control system

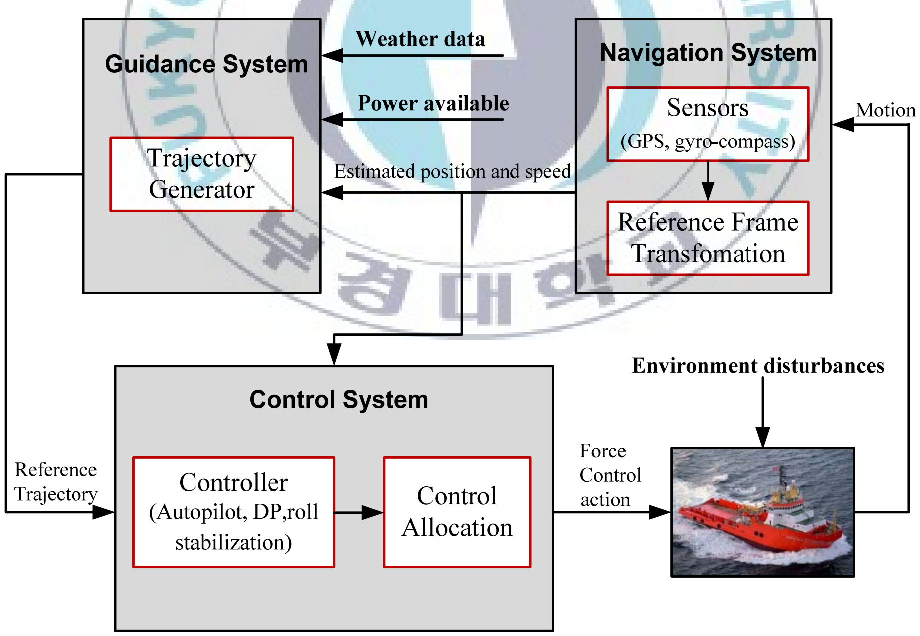

Fig.1.2. Ship motion control system.

1.2. Automatic Ship Berthing

Ship maneuvering in harbor area is maybe the first or final stage of helmsman during the passage. With change of hydrodynamic characteristics and reducing controllability significantly, berthing maneuvering is one of the most difficult and complexity mission. It requires experiment of senior helmsman and supporting from the harbor service center. The difficulties of ship berthing operation are summaried by the following facts:

- Due to low speed for berthing of heavy vessel, controllability of ship is considerably reduced, whereas the environment disturbances (wind, current and wave drift force) become relatively large
- Intensive rudder/propeller adjustments and large lateral movement of ship can intensify the non linear aspects of ship dynamics. Therefore, the behavior of ship motion is unpredictable
- Ship motion at low speed is difficult to present by using differential equation, thereby negating most control methods which depend on the exactly of ship dynamic model while the hydrodynamic characteristics between deep and shallow water are so difference
- The bank effect will add further adverse influence upon the ship handling.

Until now, with above difficulties, berthing maneuvering of heavy vessel is usually assisted by using tugboat as shown in Fig.1.3. Depend on the batch of ship two, four or more tugboats must be used. However, operating tugboats simultaneously is so complex, increase time consuming and labor cost. For these reasons, automatic ship berthing studies are more and more imperative and receive a lot of concern from the researchers.

Fig.1.3. Ship maneuvering for berthing with assistance of tugboats.

Studies on automatic ship berthing have been concerned from early 1990's. For safety purpose, ship berthing has to be considered as multiple input and multiple output parameters including data of environment disturbances such as amplitude and direction of wind, the effect of current and wave drift force, the interaction between moving ships in the harbor. Until now, many challenges are still overcome to develop a successful automatic ship berthing.

Normally, the ship control method considers two main purposes: optimal motion planning purpose and optimal trajectory tracking control purpose.

- Optimal motion planning based on the description of ship motion model is linear or nonlinear. The system is under-actuated system which has the dimension of the space spanned by the control vector is less than the dimension of the configuration space or fully actuated system. Additionally, it considers the effect from environmental disturbance. Optimal motion planning solution will generates the set of way points on sea with prescribed position, tangent and time. This data is fed to the tracking control purpose.

- Trajectory tracking control solves the problem of difference between the reference trajectory generated from motion planning and actual trajectory of ship. This problem is so complicated by the nature of the system to be controlled. The controller must ensure accurate tracking in face of parameter uncertainty and must be insensitive to disturbances.

Automatic ship berthing studies normally separate planning route into two phases as shown in Fig.1.4. The first is called ballistic phase where only propeller and rudder are used and the second is the final phase with addition of tunnel thrusters to ensure final maneuver without collision with quay.

In each phase, motion control problems of ship are concerned. Optimal motion planning was introduced through the optimization of time-energy criterion taking into account constraints on the steering system, environment and non-linearities of ship dynamic model by Djouani. Ohtsu et al. (1996), Okazaki and Ohtsu(2008) presented minimum time ship berthing maneuvering control system

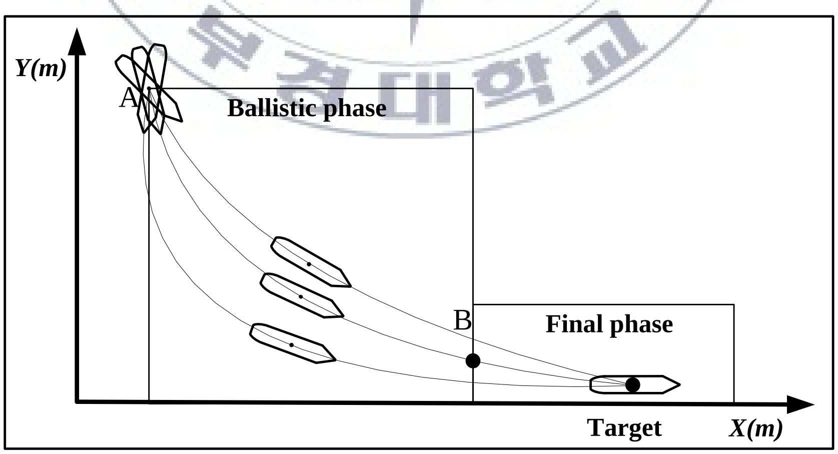

Fig.1.4. Planning route for ship berthing.

by solving two point boundary value problem and etc. Trajectory tracking control problems for berthing have been concerned considerably and most of studies were concentrated on develop the control methods without mathematical model of ship. 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 another kind of neural network, which combines with adaptive technique to trained online and it is simulated the berthing of vessel based on the characteristic of Busan bay.

However, these researches may not reasonable for maneuvering in the final phase. The two main drawbacks are:

- Firstly, with low speed control, ship controllability reduces significantly. Using main propeller and rudder adjustment can lead to unpredicted motion of ship. It is very dangerous with increasing the collision risk between the ship and harbor
- Secondly, by automatic ship maneuvering from starting point B in the final phase, it is easy to happen the contact between our ship and ships which were located in the harbor before, because we do not know exactly their location in our way points schedule generated from solving optimal motion planning, whereas the distance between ships are at least 3 [m] in both x and y direction for safety berthing

With stated difficulties of automatic berthing in final phase, in this thesis, a new approach for ship berthing by using only bow and stern thrusters is proposed to overcome the unpredicted ship motion. Additionally, to prevent the collision

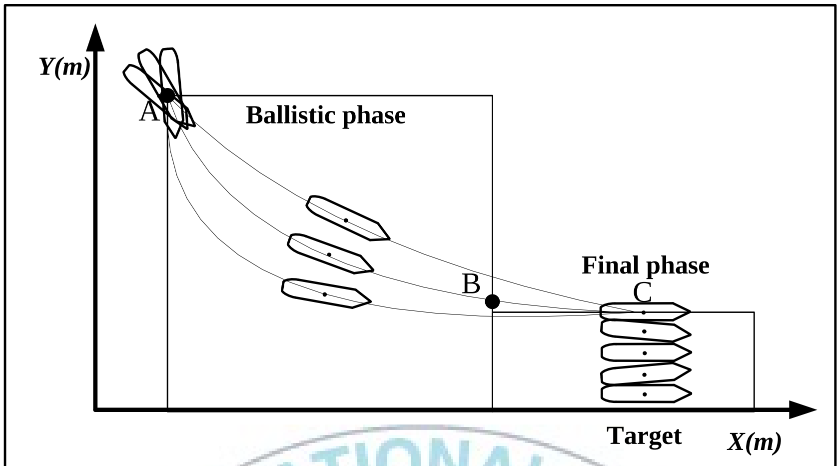

Fig.1.5. Proposed planning route for ship berthing automatically.

between ships, the starting point of the final phase will be moved to C as shown in Fig.1.5.

1.3. Outline of Thesis

In this thesis, a new approach for ship berthing is proposed. Based on this approach, hydrodynamic coefficients of ship berthing model are estimated as well as the controller design is presented and discussed. The thesis contains five main chapters. In Chapter 1, the history of control theory applied to ship control and its applications are reviewed. The problem of automatic ship berthing system are introduced and discussed. Based on these analyses, a new approach for ship berthing by using only bow and stern thrusters is proposed. Chapter 2 presents mathematical model of ship motion in horizontal plane. Steering model by using bow and stern thrusters which just contains main physical property is proposed by using Lagrange mechanics. Chapter 3 describes hydrodynamic coefficient estimation approach. The discrete time steering model is introduced, and all hydrodynamic parameters are estimated from Prediction Error Method which is one of the system identification techniques. The Chapter 4 deals with the controller design. Linear optimal approach is applied to design two-degree-of-freedom servosystem. The controller is optimal the tracking response to step reference and robust stability with the uncertainty of model and effect of environmental disturbance. Experiment results, which are received from the model basin test, are shown to illustrate the efficiency of controller. The last Chapter of thesis highlights some conclusion and some prospective ideas.

2. Mathematical Modeling

2.1 Coordinate Frame

To describe position and orientation of ship motion, it is necessary to use six independent coordinates. The first three terms determine the position and the others correspond to the orientation of ship. The six independent motions of ship are defined: surge, sway, heave, roll, pitch and yaw motion by SNAME (1950) as shown in Fig. 2.1 and in the Table 2.1.

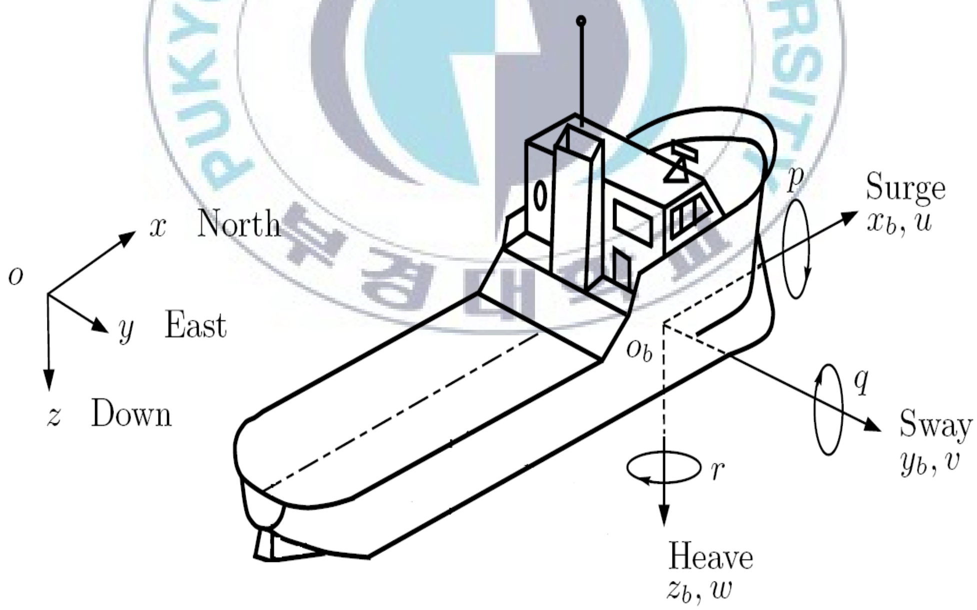

Fig.2.1 Motion variable for a marine vessel.

Table 2.1: The notation of SNAME for marine vessel

DOF	Ship Motion	Force/ Moment	Linear/ Angular Velocity	Position/ Euler angle
1	motion in x direction(surge)	X	u	x
2	motion in y direction(sway)	Y	v	y
3	motion in z direction(heave)	Z	w	z
4	rotation about the x axis (roll)	K	p	Φ
5	rotation about the y axis (pitch)	M	q	θ
6	rotation about the z axis (yaw)	N	r	φ

When analyzing the ship motion in the horizontal plane, we often concern 3 independent motions: surge, sway and yaw. Heave, pitch and roll motions can be ignored and it is conventional to define two coordinate frames as indicated in Fig.2.2.

Moving coordinate frame is fixed to motion of ship. It is called the body fixed frame. Its origin is located at the mid length rather than at the longitudinal position of the center of gravity (CG). This choice satisfies two purposes: one is to simplify computation in ship dynamic and the other is that the location of center of gravity is not constant but change with the condition of loading. The body axes $Cx_by_bz_b$ are chosen to coincide with the principle axes of inertia.

The earth fixed coordinate frame $Oxyz$ is North-East-Down (NED) frame. The positive x axis is towards the North, the positive y axis towards the East and the positive z axis towards the center of the Earth. This frame is considered inertial (the acceleration of the point on the surface of Earth can be neglected). This is the reasonable assumption because the velocity of ship is small enough for

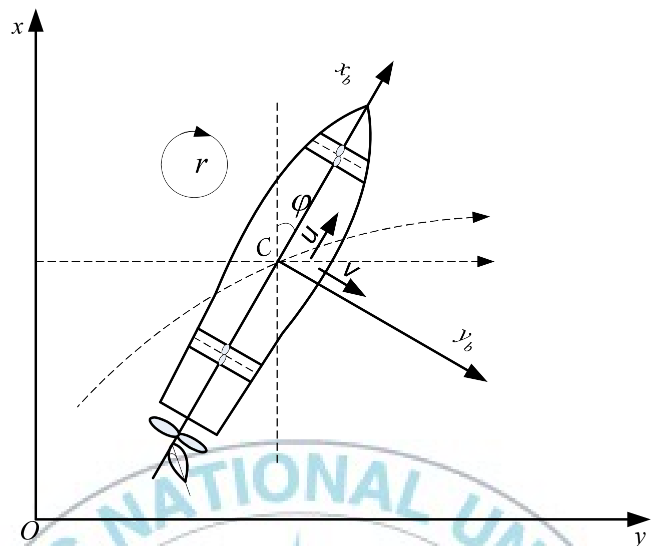

Fig.2.2. Coordinates frame of marine vessel.

the force induced from the Earth rotating being negligible compared to the hydrodynamic force action on the hull.

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 following:

$$\begin{aligned} &m(\dot{u} - vr - x_g r^2) = X_r + X_w + X_E \\ &m(\dot{v} + ur + x_g \dot{r}) = Y_r + Y_w + Y_E \\ &I_z \dot{r} + m x_g (\dot{v} + ur) = N_r + N_w + N_E \end{aligned} \tag{2.1}$$

Above equation describes the couple surge, sway and yaw motion of ship in fixed coordinate 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 identified by three components:

- Added mass due to the inertia of the surrounding fluid.
- Radiation-induced potential damping due to the energy carried away by generated surface waves.
- Restoring force due to Archimedes (weight and buoyancy).

The environmental forces and moments 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 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. The wave force can be separated by wave frequency motion (1st-order effects) and wave drift force (2nd –order effects). From the control system design perspective, the effect of wave drift force is counteracted by propulsion of ship whereas the high frequency waves should be prevented by using wave filtering.

X_E, Y_E and N_E describe the external force induced by main propellers, rudders, tunnel thrusters and tugboats.

In order to understand the impact of various features of forces and moments which affect on the controllability of ship, it is necessary to describe the ship motion model, which is familiar with the linear motion equation.

If we just consider the part of forces and moments in the right hand side of Eq. (2.1) which are function of the velocities and accelerations of ship, it is described as following:

$$\begin{aligned} X &= F_x(u, v, \dot{u}, \dot{v}, \dot{\varphi}, \ddot{\varphi}) \\ Y &= F_y(u, v, \dot{u}, \dot{v}, \dot{\varphi}, \ddot{\varphi}) \\ N &= F_\varphi(u, v, \dot{u}, \dot{v}, \dot{\varphi}, \ddot{\varphi}) \end{aligned} \tag{2.2}$$

In above equation, we do not concern the effect of environmental force due to wind, wave and current also external force. Its expressions should be reduced to useful mathematical form by using Taylor expansion of a function of several variables as following:

$$X = \frac{\partial X}{\partial \dot{u}}\dot{u} + \frac{\partial X}{\partial \dot{u}}\delta u + \frac{\partial X}{\partial v}v + \frac{\partial X}{\partial \dot{v}}\dot{v} + \frac{\partial X}{\partial \dot{\varphi}}\dot{\varphi} + \frac{\partial X}{\partial \ddot{\varphi}}\ddot{\varphi}$$
$$Y = \frac{\partial Y}{\partial v}v + \frac{\partial Y}{\partial \dot{v}}\dot{v} + \frac{\partial Y}{\partial \dot{\varphi}}\dot{\varphi} + \frac{\partial Y}{\partial \ddot{\varphi}}\ddot{\varphi} \tag{2.3}$$
$$N = \frac{\partial N}{\partial v}v + \frac{\partial N}{\partial \dot{v}}\dot{v} + \frac{\partial N}{\partial \dot{\varphi}}\dot{\varphi} + \frac{\partial N}{\partial \ddot{\varphi}}\ddot{\varphi}$$

Because of symmetry about the *xz* plane of ship and it is maneuvered at low speed, the terms $\frac{\partial X}{\partial v}$, $\frac{\partial X}{\partial \dot{v}}$, $\frac{\partial X}{\partial \dot{\varphi}}$, $\frac{\partial X}{\partial \ddot{\varphi}}$ are zero. So the linear equation of ship motion in the horizontal plane can be described in the vector form:

$$\begin{aligned} \boldsymbol{M}\dot{\mathrm{v}} + \boldsymbol{D}\mathrm{v} &= \boldsymbol{B}u \\ \dot{\eta} &= \boldsymbol{R}(\psi)\mathrm{v} \end{aligned} \tag{2.4}$$

where:

$$\boldsymbol{M} = \begin{bmatrix} m - \frac{\partial X}{\partial \dot{u}} & 0 & 0 \\ 0 & m - \frac{\partial Y}{\partial \dot{v}} & -\frac{\partial Y}{\partial \ddot{\varphi}} \\ 0 & -\frac{\partial N}{\partial \dot{v}} & I_z - \frac{\partial N}{\partial \ddot{\varphi}} \end{bmatrix} \tag{2.5}$$

is the system inertia matrix including add mass.

$$
\boldsymbol{D} = \begin{bmatrix} -\frac{\partial X}{\partial u} & 0 & 0 \\ 0 & -\frac{\partial Y}{\partial v} & -\frac{\partial Y}{\partial \dot{\varphi}} \\ 0 & -\frac{\partial N}{\partial v} & -\frac{\partial N}{\partial \dot{\varphi}} \end{bmatrix} \tag{2.6}
$$

is the damping matrix.

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

$$
\boldsymbol{R}(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{2.7}
$$

is the transformation matrix between the body fixed coordinate frame and inertia coordinate frame, while $\text{v} = [u, v, r]^T$ and $\eta = [x, y, \varphi]^T$ denote the motion of ship in the moving and earth fixed coordinate frame.

2.3 Proposed Steering Model for Ship Berthing

In this thesis, for ship berthing controller design by using bow and stern thrusters, the dynamic model of ship should be considered as steering model (the X equation of Eq. (2.4) is ignored and we only concern sway and yaw motion).

Conventionally, by using main propeller and rudder for course keeping or course changing, the transfer function relating yaw rate to rudder angle can be given from Eq. (2.4) as following:

$$
G_{r\delta}(s) = K\frac{(s + 1/T_3)}{(s + 1/T_1)(s + 1/T_2)} \tag{2.8}
$$

The transfer function relating sway velocity to rudder angle is:

$$G_{v\delta}(s) = K_v \frac{(s + 1/T_{3v})}{(s + 1/T_1)(s + 1/T_2)} \tag{2.9}$$

Nomoto and co-worker proposed the following approximation of Eq. (2.8):

- In time domain:

$$T'\dot{r} + r = K\delta \tag{2.10}$$

- Transfer function:

$$G_{r\delta} = \frac{K}{s + 1/T'} \tag{2.11}$$

where $T' = T_1 + T_2 - T_3$ and this model is call the Nomoto's 1st order model for ship steering.

As stated, for reducing the collision risk between ship and quay of harbor also ship and ships located in the harbor which caused by using main propeller and intensive of rudder, we just use bow and stern thrusters, so the steering model as shown in Eqs. (2.9) and (2.11) should be written to suit this purpose. In this study, the Lagrange mechanics approach is applied to describe the new steering model for ship berthing and the proposed steering model is shown in Fig.2.3

The Lagrange approach involves three basic. Firstly, we need to formulate a suitable expression for ship's kinetic and potential energy, denoted *T* and *V*, respectively. Then we compute the Lagrangian L according to formulate:

$$L = T - V \tag{2.12}$$

Finally, we apply the Lagrange equation:

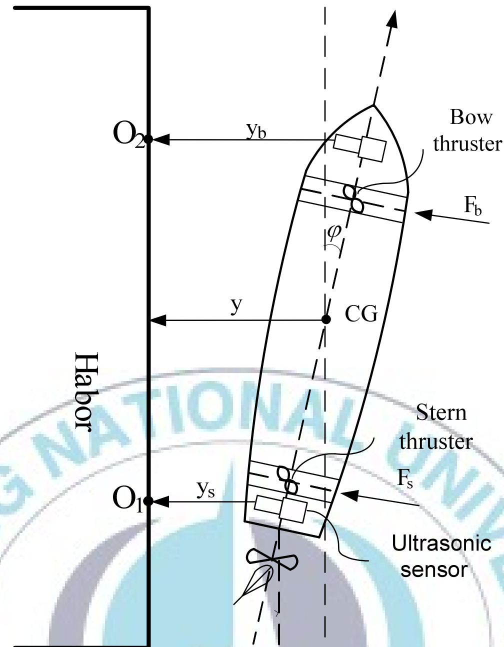

Fig.2.3. Proposed Steering Model.

$$\frac{d}{dt}(\frac{\partial L}{\partial \dot{q}_i}) - \frac{\partial L}{\partial q_i} + \frac{\partial D}{\partial \dot{q}_i} = u_i \tag{2.13}$$

For berthing purpose, the ship moves with low speed in horizontal plane. The potential energy V can be ignored and kinetic energy has just been considered as the sum of rigid body kinetic energy T_{RB} and fluid kinetic energy T_A:

$$L = T_{RB} + T_A = \frac{1}{2}(m - \frac{\partial Y}{\partial \dot{v}})\dot{y}^2 + \frac{1}{2}(I_z - \frac{\partial N}{\partial \ddot{\varphi}})\dot{\varphi}^2 \tag{2.14}$$

The dissipative energy is expressed as following:

$$D = \frac{1}{2}D_v\dot{y}^2 + \frac{1}{2}D_z\dot{\varphi}^2 \tag{2.15}$$

and the generalized coordinates q_i (i=1-2) are position of ship in y direction and heading angle φ , u_i describe the forces and moments induced by bow and stern thrusters.

From Eqs. (2.13), (2.14) and (2.15) the steering model is formulated:

$$\begin{aligned} &\left(m-\frac{\partial Y}{\partial \dot{v}}\right)\ddot{y}+D_v\dot{y}=(F_s+F_b)\cos\varphi \\ &(I_z-\frac{\partial N}{\partial \ddot{\varphi}})\ddot{\varphi}+D_z\dot{\varphi}=F_b l_b-F_s l_s \end{aligned} \tag{2.16}$$

With small value of yaw angle φ , Eq. (2.16) is rewritten as follows:

$$\begin{aligned} &\left(m-\frac{\partial Y}{\partial \dot{v}}\right)\ddot{y}+D_v\dot{y}=(F_s+F_b) \\ &(I_z-\frac{\partial N}{\partial \ddot{\varphi}})\ddot{\varphi}+D_z\dot{\varphi}=F_b l_b-F_s l_s \end{aligned} \tag{2.17}$$

The hydrodynamic coefficients in Eq. (2.17) will be estimated by using system identification which is described in Chapter 3 and it will be used as the model for controller design in Chapter 4. Commonly, position of ship in horizontal plane is measured by using Global Positioning System (GPS) or Inertial Navigation System (INS) while its orientation is obtained by gyroscope. However, with high accuracy requirement in measuring for ship berthing purpose, using GPS or INS to determine ship position maybe impossible because the accuracy range of these systems is about 0.5 ~ 3 m, so it should be replaced by vision system for measuring. In this thesis, to simplify and reduce the cost consuming for measuring system, two ultrasonic sensors with high accuracy (1 mm) and preserved from the noise, are mounted at fore and aft of ship. They are used to measure the distance from ship to quay during ship berthing.

3. Hydrodynamic Coefficients Estimation

3.1 Determination of Hydrodynamic Coefficients

The hydrodynamic forces and moments acting on the ship are normally determined by experimental methods using the scale model experiments with special test equipments. Typical approaches are the rotating arm, the free oscillator, the curved flow tunnel and the curved model in a straight flow facility. One successful technique has been developed by a research team at the David Taylor Model Basin 1957. By using a device called the Planar Motion Mechanism (PMM) system, all hydrodynamic coefficients in 6 degree of freedom ship motion can be determined. These include static stability coefficients, rotary stability coefficients and acceleration derivatives.

Besides this, some hydrodynamic coefficients can be determined by theoretical and semi empirical methods. For ships, the strip theory has been successfully applied. The other promising approach is system identification (SI) technique. SI technique provides the more direct answer from the cumulative error of measuring many coefficients individually. The disadvantage of SI approach is the high requirement of persistent excitation of the control input sequence.

In this Chapter, the hydrodynamic coefficients in the steering model of ship are estimated by using SI technique. It offers a way of determining ship steering dynamics directly by recording how the ship reacts to changes in the thrust supplied to bow or stern thruster.

3.2 Discrete Time Model of Ship

Ship model is considered a system which has input signals and output signals. If the system is referred to as a single input and single output system (SISO), the input *u(t)* is a control variable which can be thrust supplied to bow or stern thruster and the output *y(t)* is the yaw angle of ship. This concept can be shown in Fig 3.1.

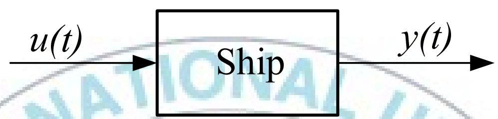

Fig.3.1 Ship model as an SISO system.

The ship in Fig.3.1 is assumed to be a discrete time linear model. In this situation, the control input *u(t)* can be related to the output response *y(t)* through the linear difference equation:

$$y(t)+a_1y(t-1)+...+a_ny(t-n)=b_0u(t)+b_1u(t-1)+...+b_mu(t-m) \quad (3.1)$$

By using the unit backward shift operator q^{-1} defined by

$$q^{-1}y(t)=y(t-1) \quad (3.2)$$

The ship model described by Eq. (3.1) can be expressed in the discrete time transfer function form:

$$y(t)=\frac{B}{A}u(t) \quad (3.3)$$

where *B* and *A* are the polynomials in the ship operator q^{-1}, given by

$$A = 1 + a_1 q^{-1} + a_2 q^{-2} + ... + a_n q^{-n} \quad (3.4)$$

$$B = b_0 + b_1 q^{-1} + b_2 q^{-2} + ... + b_m q^{-m} \quad (3.5)$$

The difference equation of ship model in Eq. (3.1) or discrete time transfer function form in Eq. (3.3) is call the linear difference equation without considering disturbance.

Generally, by considering a discrete time transfer function model of marine vehicle with control input signal *u(t)* which can be rudder angle or thruster control signal and output signal *y(t)* which can be yaw angle or yaw rate signal , subject to disturbance such as wind and current from the measurable source, drift and random noise, the ship model can be written in the following form

$$Ay(t) = Bu(t) + Dv(t) + R(t) + Ce(t) \quad (3.6)$$

where

$$\begin{aligned} A &= 1 + a_1 q^{-1} + a_2 q^{-2} + ... + a_n q^{-n} \\ B &= b_0 + b_1 q^{-1} + b_2 q^{-2} + ... + b_m q^{-m} \\ D &= d_0 + d_1 q^{-1} + d_2 q^{-2} + ... + d_p q^{-p} \\ R &= d_0 + d_1 t^1 + d_2 t^2 + ... + d_p t^p \\ C &= 1 + c_1 q^{-1} + c_2 q^{-2} + ... + c_l q^{-l} \end{aligned} \quad (3.7)$$

Some definitions are summarized as follows:

- **Offset**

The simplest kind of signal is a constant value d. A system with offset d can be represented by the equation.

$$s(t) = d \quad (3.8)$$

- **Drift**

A generalization of the constant offset is the drift signal where the offset becomes a function of time. In many situations, drift can be modeled by a polynomial function of time

$$s(t) = R(t) = d_0 + d_1 t^1 + d_2 t^2 + ... + d_p t^p \qquad (3.9)$$

- **Measurable disturbance signal sources**

A measurable disturbance can be represented by

$$s(t) = \frac{D}{A} v(t) \qquad (3.10)$$

- **Random signals**

An important class of random signals is that associated with small unpredictable changes in the system and unobservable noise-like disturbances. Such disturbance can be aggregated and modeled by a single noise source which is often assumed to be a stationary. Gaussian noise sequence which can be represented by a white noise sequence *e(t)* with zero mean and variance σ. In general, a stationary signal source can be represented by the transfer function model

$$s(t) = \frac{C}{A} e(t) \qquad (3.11)$$

- **Overall model**

The representation of deterministic, random and measurable disturbance can be drawn together in form of overall model which will meet most signal representation situations as shown in Fig.3.2.

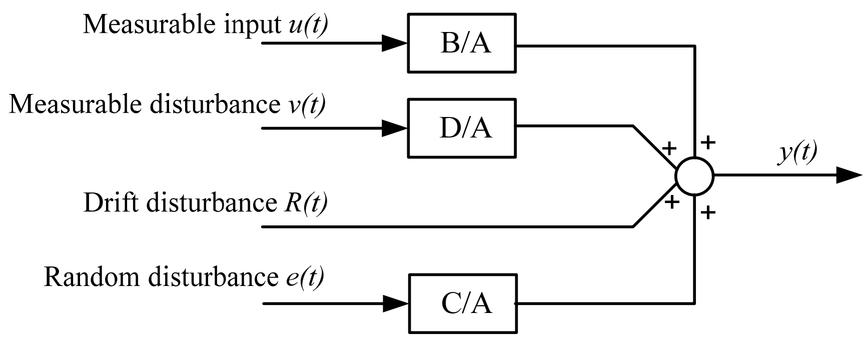

Fig.3.2 Discrete time model of ship including all possible input and disturbance components.

In this thesis, for simplifying without loss of generalization, it is assuming that there are no measurable and drift disturbance signal in the ship model, we only consider random disturbance, so that the ship model can be depicted in the following form:

$$Ay(t) = Bu(t) + Ce(t) \tag{3.12}$$

The Eq. (3.12) is referred to as an ARMAX (Auto-Regressive Moving Average eXogenous) model. In which *Ay(t)* is an Auto_Regressive (AR) part, *Ce(t)* is Moving Average (MA) part and *Bu(t)* is eXogenous part. For more simplify the term *C* will be equal 1 and the model is known as ARX model and written in the form

$$\mathrm{A}y(t) = Bu(t) + e(t) \tag{3.13}$$

3.3 Prediction Error Method

Prediction error methods are a broad family of parameter estimation methods that can be applied to quite arbitrary model parameterizations.

Let $Z^N = \{u(1), y(1), u(2), y(2), ..., u(N), y(N)\}$ collect all data up to time N, where *u(t)* is the control input vector supplied to ship and *y(t)* is the output vector of yaw rate response during testing and this measured data have been sampled at discrete time points.

The idea behind the prediction error approach is that if we describe the model as a predictor of the next output:

$$\hat{y}_m(t/t-1) = f(Z^{t-1}) \tag{3.14}$$

here $\hat{y}_m(t/t-1)$ denotes the one step ahead prediction of the output and *f* is an arbitrary function of past, observed data.

Parameterize the predictor in terms of a finite dimensional parameter vector θ

$$\hat{y}(t/\theta) = f(Z^{t-1}, \theta) \tag{3.15}$$

We can estimate the θ from the model parameterization and the observed data set Z^N so that the distance between $\hat{y}(1/\theta), ..., \hat{y}(N/\theta)$ and $y(1), ..., y(N)$ is the minimized in a suitable norm.

- **Least Square Method**

In this study, we use the special case of Prediction Error Method- Least Squares Method (LSM) to estimate the hydrodynamic coefficients in the yaw motion of ship.

For the purpose of establishing an estimation algorithm by using LSM, the ARX model described in Eq. (3.13) can be rewritten in the matrix form as following

$$y(t) = \phi^T(t)\theta + e(t) \tag{3.16}$$

where $\phi^T(t)$ is a regression vector that consists measured input/output data which are referred to as thrust supplied to bow or stern thruster and yaw rate. It can be described as

$$\phi^T(t) = [y(t-1),...,y(t-n),u(t-1),...,u(t-m)] \tag{3.17}$$

and θ is the vector of unknown parameters, defined by

$$\theta^T = [-a_1,...,-a_n,b_0,...,b_m] \tag{3.18}$$

With the system described in Eq. (3.16), our task is to determine the vector of unknown parameter θ from the available data. To do this, a model of the system in correct structure can be assumed

$$y(t) = \phi^T(t)\hat{\theta} + \hat{e}(t) \tag{3.19}$$

where $\hat{\theta}$ is a vector of adjustable model parameters and $\hat{e}(t)$ is the corresponding modeling error at time *t*. With the idea behind the Prediction error method, our aim is to select the $\hat{\theta}$ so that overall modeling error is minimized, it is implied that

$$\hat{e}(t) = e(t) + \phi^T(t)(\theta - \hat{\theta}) \tag{3.20}$$

So that $\hat{e}(t)$ depends on $\hat{\theta}$ and, in some cases, the "minimized" modeling errors will be equal to the white noise sequence corrupting the system output data. The input/output data can be expressed in the vector form from Eq. (3.19)

$$\begin{bmatrix} y(1) \\ y(2) \\ . \\ . \\ . \\ y(N) \end{bmatrix} = \begin{bmatrix} \phi^T(1) \\ \phi^T(2) \\ . \\ . \\ . \\ \phi^T(N) \end{bmatrix} \hat{\theta} + \begin{bmatrix} \hat{e}(1) \\ \hat{e}(2) \\ . \\ . \\ . \\ \hat{e}(N) \end{bmatrix} \tag{3.21}$$

So by rearranging Eq. (3.21), we can have the form of estimated error $\hat{e}$

$$\hat{e} = y - \phi\hat{\theta} \tag{3.22}$$

And with selecting an estimate $\hat{\theta}$ of the true vector of parameters which minimizes *J*, the sum of squares of error will be

$$J = \sum_{t=1}^{N} \hat{e}^2(t) = \hat{e}^T \hat{e} \tag{3.23}$$

Rewrite above equation in term of the data vectors and parameter vector

$$J = (y - \phi\hat{\theta})^T (y - \phi\hat{\theta}) = y^T y - \hat{\theta}^T \phi^T y - y^T \phi\hat{\theta} + \hat{\theta}^T \phi^T \theta\hat{\phi} \tag{3.24}$$

If the derivative of *J* is set to zero

$$\frac{\partial J}{\partial \hat{\theta}} = -2\phi^T y + 2\phi^T \phi\hat{\theta} = 0 \tag{3.25}$$

Hence, the least squares estimator for the parameter vector is

$$\hat{\theta} = [\phi^T \phi]^{-1} [\phi^T y] \tag{3.26}$$

3.4. Hydrodynamic Coefficients Estimation

From the proposed steering model described in Eq. (2.17), the relation between the thrust supplied to bow or stern thruster and the yaw rate of ship can be depicted as

$$(I_z - \frac{\partial N}{\partial \ddot{\varphi}})\ddot{\varphi} + D_z\dot{\varphi} = kf_i \tag{3.27}$$

where k is the torque coefficient and f_i is the current supplied to bow or stern thruster.

The Eq. (3.27) is rewritten in form of Eq. (3.16) with $\phi = [\dot{\varphi}(k-1)\ f_i(k-1)]^T$ and $\theta = [-a_1\ \mathrm{b}_0]^T$. By using the least square method described in the Eq. (3.26), the hydrodynamic $(I_z - \frac{\partial N}{\partial \ddot{\varphi}})$ and D_z are estimated.

The hydrodynamic coefficients estimation results in the yaw motion test by using bow and stern thrusters are respectively shown from Fig.3.3 ~3.6. The first two figures appear the experimental results by using bow thruster with different amplitude of supplied thrust and the other describe the results by using stern thruster. Based on these figures, we can conclude that the PEM method suitable with hydrodynamic coefficient estimation in this test. These parameters will be shown later in the Table 3.1

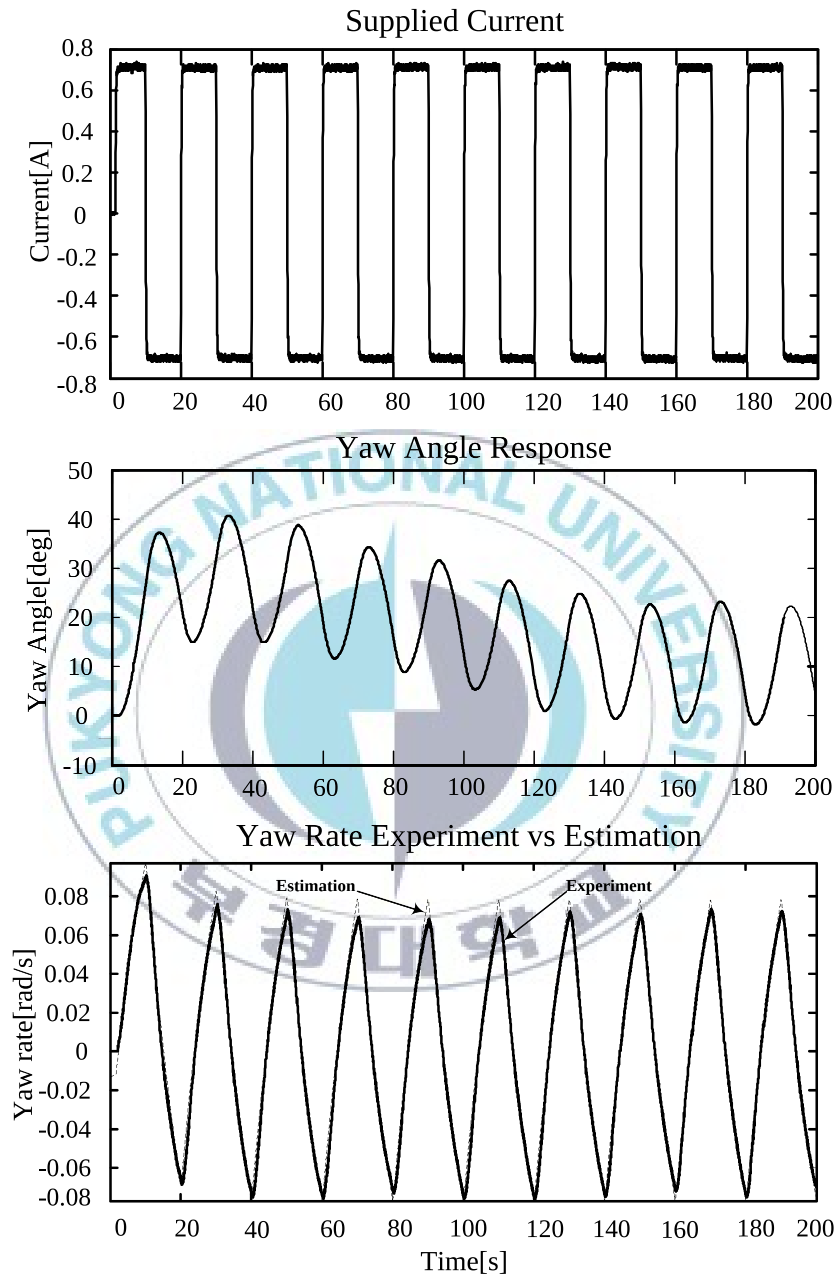

Fig.3.3. Yaw angle response of ship by 0.7[A] supplied to bow thruster and compared yaw rate experiment and estimation result.

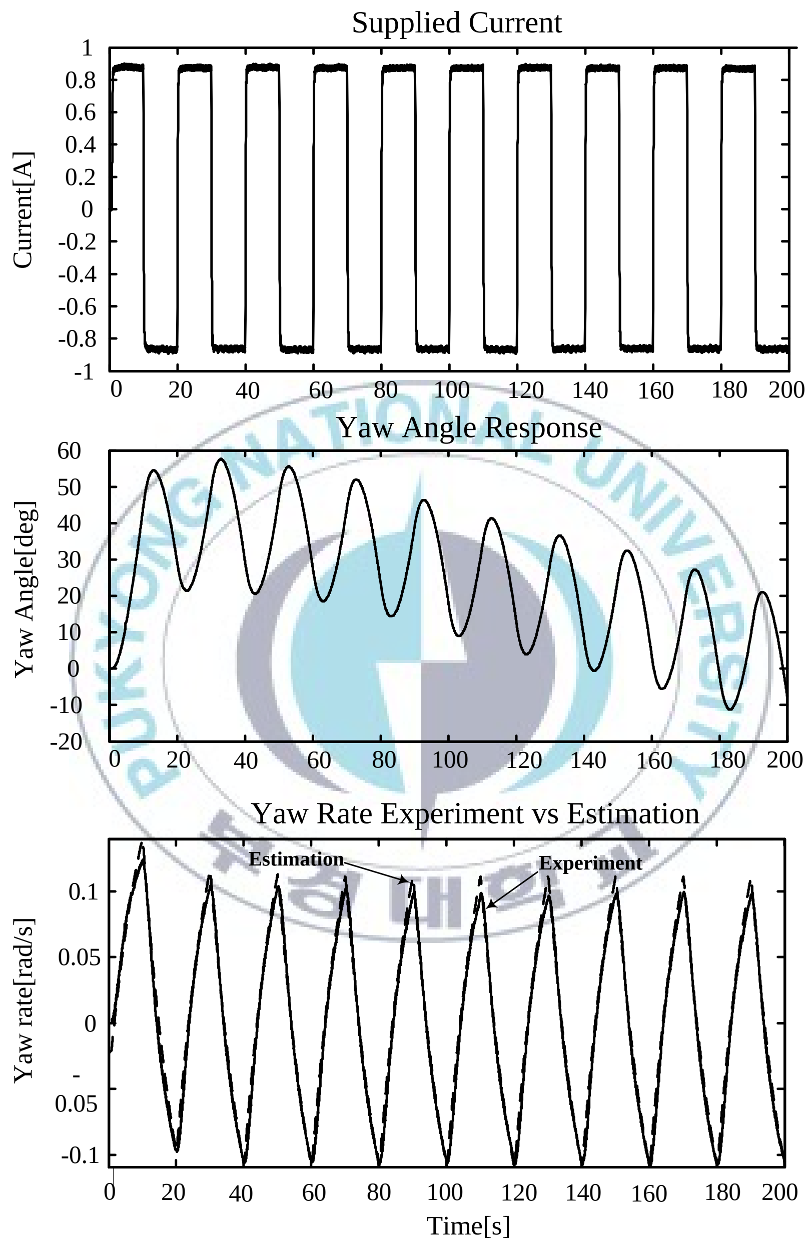

Fig.3.4. Yaw angle response of ship by using 0.9[A] supplied to bow thruster and compared yaw rate experiment and estimation result.

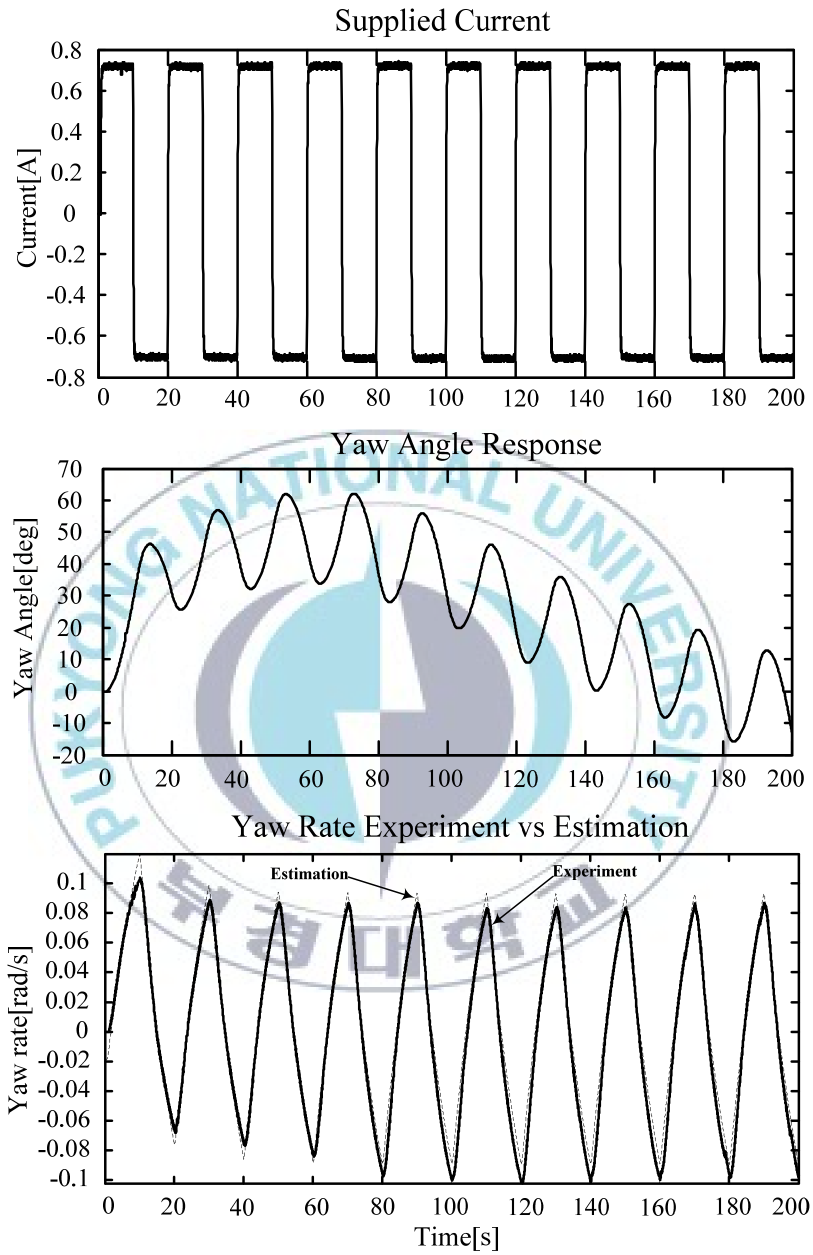

Fig.3.5. Yaw angle response of ship by 0.7[A] supplied to stern thruster and compared yaw rate experiment and estimation result.

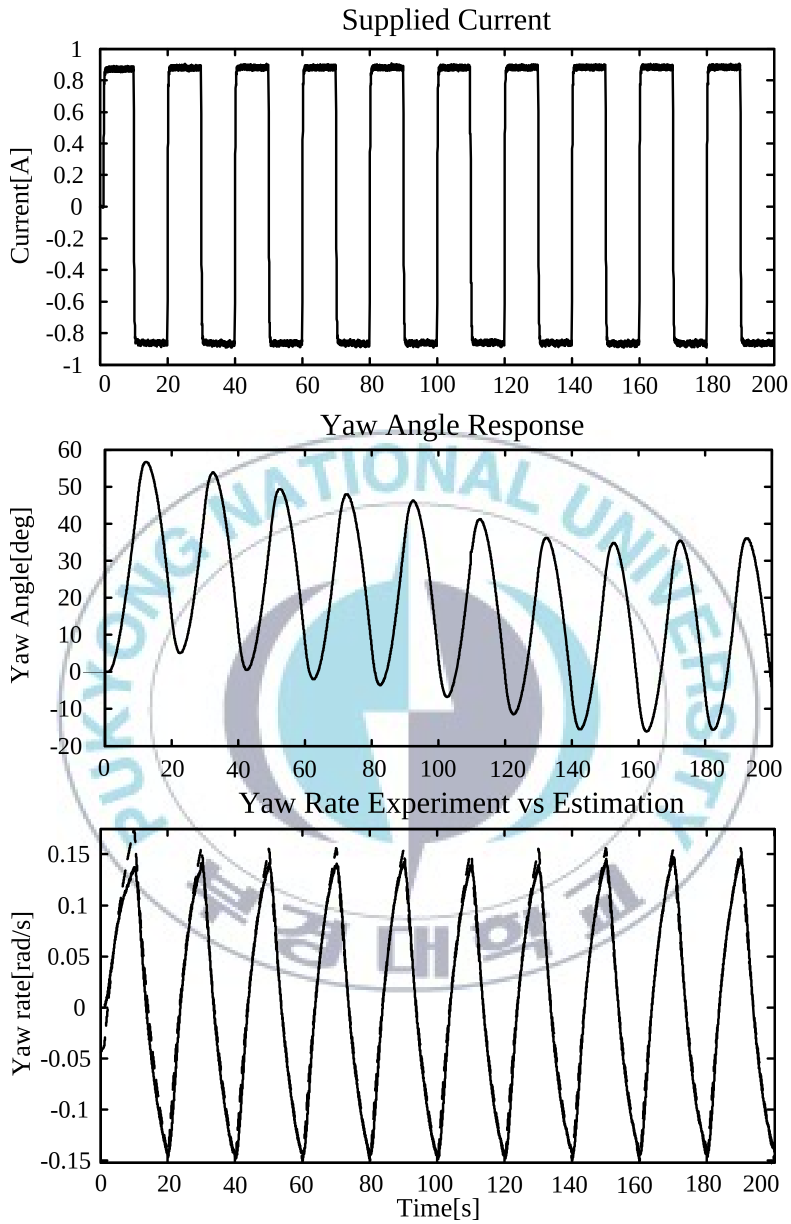

Fig.3.6. Yaw angle response of ship by 0.9[A] supplied to stern thruster and compared yaw rate experiment and estimation result.

Similarly, hydrodynamic coefficients in the sway motion equation can be estimated by using above approach. However, in this study, we do not have enough data acquisition equipments to get available data for identification. Specifically, by using two ultrasonic sensors, we cannot supervise sway and yaw motions of ship simultaneously. So these parameters are evaluated from the curve fitting of step response. Fig.3.7 shows the result between the response of ship in the sway motion by using bow and stern thrusters and estimation.

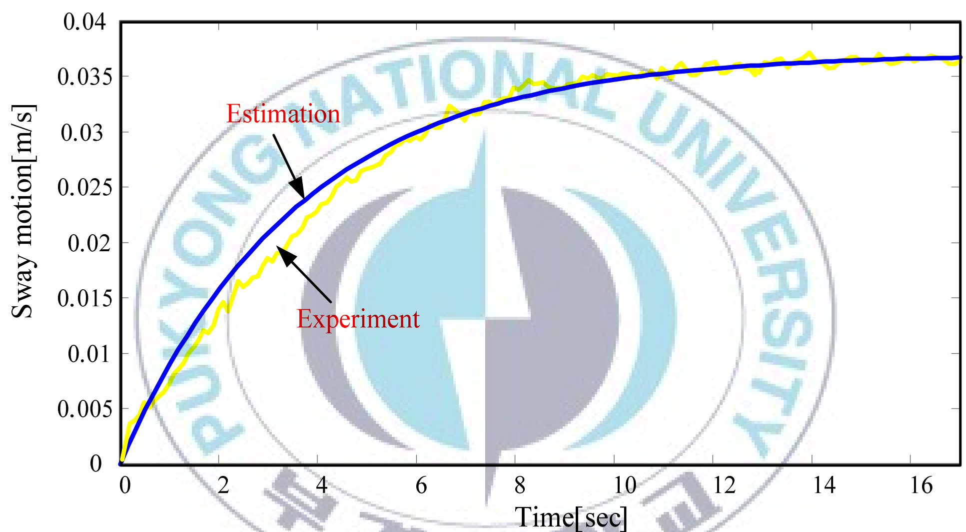

Fig.3.7 Sway response by using bow and stern thrusters simultaneously and estimation result.

With above results, the parameters in steering model described in Eq.(2. 17) and some model particular are summarized in Table 3.1.

Table.3.1 Model particular 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[kgm^2]
D_v	2.7[kg/s]
D_z	0.0826[kgm/s]

4. Optimal Controller Design

4.1 Linear Optimal Control Method

Linear optimal control is a special kind of optimal control. The plant that is controlled is assumed to be a linear system in state space form, and the objective function is a quadratic functional of the plant states and control inputs. The linear optimal control can be applied to both SISO model and MIMO model. It can be used to increase performance and to reduce fuel consumption.

For designing the controller for ship berthing by using linear optimal control method, the steering model of ship is described by a state space model as follows

$$\begin{aligned} \frac{dx}{dt} &= \boldsymbol{A}x(t) + \boldsymbol{B}u(t) \\ y(t) &= \boldsymbol{C}x(t) \end{aligned} \tag{4.1}$$

where vector $x(t) = [y_C \; \dot{y}_C \;\; \varphi \;\; \dot{\varphi}]$ denotes the center position and its derivative in y direction as well as heading angle and yaw rate. Vector control input $u(t) = [I_b \; I_s]^T$ is the currents supplied to bow and stern thruster respectively. Output matrix $\boldsymbol{C}$, state matrix $\boldsymbol{A}$, and input matrix $\boldsymbol{B}$ are calculated from Eq. (2.17)

$$\boldsymbol{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \tag{4.2}$$

$$\boldsymbol{A} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{D_v}{m - \dfrac{\partial Y}{\partial \dot{v}}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\dfrac{D_z}{I_z - \dfrac{\partial N}{\partial \dot{r}}} \end{bmatrix} \tag{4.3}$$

$$\boldsymbol{B} = \begin{bmatrix} 0 & 0 \\ \dfrac{k_b}{l_b(m - \dfrac{\partial Y}{\partial \dot{v}})} & \dfrac{k_s}{l_s(m - \dfrac{\partial Y}{\partial \dot{v}})} \\ 0 & 0 \\ \dfrac{k_b}{(I_z - \dfrac{\partial N}{\partial \dot{r}})} & \dfrac{k_s}{(I_z - \dfrac{\partial N}{\partial \dot{r}})} \end{bmatrix} \tag{4.4}$$

In above matrixes, $l_b = 0.46\ [m]$ and $l_s = 0.46\ [m]$ are the distance from the thrusters to the center of ship, $k_b = 0.2757[N.m/A]$ and $k_s = 0.239[N.m/A]$ are thruster torque coefficients. Eq. (4.1) can be rewritten as follows

$$\begin{bmatrix} \dot{y} \\ \ddot{y} \\ \dot{\varphi} \\ \ddot{\varphi} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & -\dfrac{D_v}{m - \dfrac{\partial Y}{\partial \dot{v}}} & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & -\dfrac{D_z}{I_z - \dfrac{\partial N}{\partial \dot{r}}} \end{bmatrix} \begin{bmatrix} y \\ \dot{y} \\ \varphi \\ \dot{\varphi} \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ \dfrac{k_b}{l_b(m - \dfrac{\partial Y}{\partial \dot{v}})} & \dfrac{k_s}{l_s(m - \dfrac{\partial Y}{\partial \dot{v}})} \\ 0 & 0 \\ \dfrac{k_b}{(I_z - \dfrac{\partial N}{\partial \dot{r}})} & \dfrac{k_s}{(I_z - \dfrac{\partial N}{\partial \dot{r}})} \end{bmatrix} \begin{bmatrix} I_b \\ I_s \end{bmatrix} \tag{4.5}$$

$$y(t) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} x(t)$$

The linear optimal control law is to minimize the quadratic cost function which represents the weighted sum of energy of state and control:

$$\boldsymbol{J} = \frac{1}{2}\int_{0}^{T} (x(t)^{T} \boldsymbol{Q} x(t) + u(t)^{T} \boldsymbol{R} u(t))dt \tag{4.6}$$

where $\boldsymbol{Q}$, $\boldsymbol{R}$ are weighting matrices (symmetric and positive definite matrixes) which represent respective weights on different states and control channel. *x(t)* describes the sway position, yaw angle and their derivatives, *u(t)* presents thrust supplied to bow and stern thrusters.

The solution for this problem can be found by applying the R. Bellman's Principle of Optimality: "An optimal policy, or optimal control strategy, has the property that, whatever the initial state decision, the remaining decision must form an optimal control strategy with respect to the state resulting from the first decision"

Minimizing the cost function leads to solving the algebraic Riccacti equation:

$$\frac{\boldsymbol{-dP}}{\boldsymbol{dt}} = \boldsymbol{A'P + PA + Q - PBR^{-1}B'P} \tag{4.7}$$

The state feedback control gain can be obtained from the stationary of this Riccacti equation

$$u(t) = -\boldsymbol{R^{-1}B'P}x(t) \tag{4.8}$$

With in practical aspects of designing and implementing, the choice of design parameter for proper weightings matrices $\boldsymbol{Q}$ and $\boldsymbol{R}$ are very important so it should be considered carefully. Fig.4.1 shows the block diagram of the optimal control algorithm applied to design the ship berthing controller.

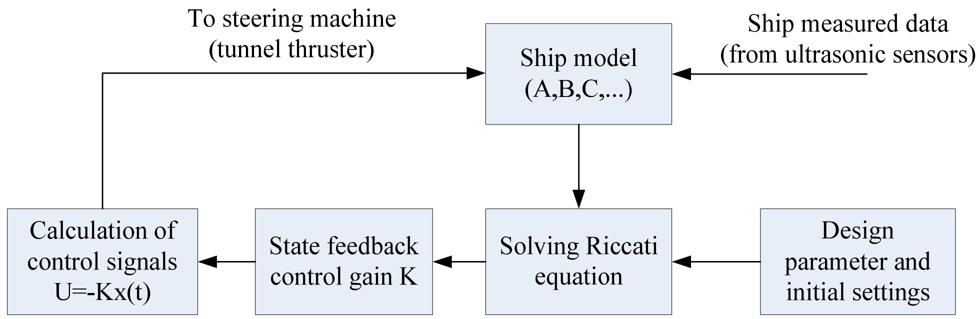

Fig.4.1 Block diagram of optimal control algorithm.

4.2 Two-Degree-of-Freedom Servosystem Design for Ship Berthing

Based on the linear quadratic optimal control theory presented in the previous section, in this study, the servo controller is designed for ship berthing with two purposes:

- Optimal tracking response to step reference by using linear optimal regulator
- Robust stability with the uncertainty of model and effect of environment disturbance

Actually, we can consider optimization of the transient tracking property to the reference signal by using the optimal regulator theory. Furthermore, the internal model principle said that to reject the steady state tracking error, we can include the integral compensator in servosystems for constant reference signals. Commonly, the optimal regulator theory is applied to augmented system composed of the plant and the integral compensator. In this case, the state of the integral compensator has to be included as well as the tracking error and control input in the quadratic performance index, otherwise the augmented system cannot be stabilized by this approach. Thus, it is not be suitable to the aim of optimizing the transient tracking behavior. So the optimization tracking property should be considered independently of the integral compensator and the integral compensator does not intend to treat the transient tracking behavior. From this point of view, a two-degree-of-freedom is proposed, in which the integral compensator is effective on the modeling error or disturbance input.

- Firstly, the optimal tracking problem for the plant is considered
- Secondly, the integral compensator is applied to cope with the modeling error and disturbance
- Finally, the complementary state feedback to cancel the effect of integral compensator in the ideal case (no modeling error and no disturbance input) is employed to preserving the optimal tracking property designed for the plant model

4.2.1 Optimal Tracking

If we consider the steering model of ship is a linear time invariant system as described in the Eq. (4.5), the pair (***A, B***) is stabilizable and (***C, A***) is detectable. In our case, we require the ship track a reference signal

$$r(t) = \begin{cases} r_+ & (0 \le t) \\ r_- & (t \le 0) \end{cases} \tag{4.9}$$

in the steady state with no error. Because of $\det(\begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{0} \end{bmatrix}) \neq 0$ so the controlled output can archive any r_+ and there exist a unique state x_∞ and a unique control input u_∞ for $y(t) = r_+$. They can be calculated as follow

$$\begin{bmatrix} x_\infty \\ u_\infty \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{0} \end{bmatrix}^{-1} \begin{bmatrix} 0 \\ r_+ \end{bmatrix} \tag{4.10}$$

If we denote the variation of the state *x(t)* and the control input *u(t)* from the x_∞, u_∞ and the tracking error of the controlled output *y(t)* by

$$\begin{aligned} \tilde{x}(t) &= x(t) - x_\infty \\ \tilde{u}(t) &= u(t) - u_\infty \\ e(t) &= r(t) - y(t) \end{aligned} \tag{4.11}$$

Using this notation, the variation of system can be defined by

$$\begin{aligned} \dot{\tilde{x}}(t) &= \boldsymbol{A}\tilde{x}(t) + \boldsymbol{B}\tilde{u}(t) \\ e(t) &= -\boldsymbol{C}\tilde{x}(t) \end{aligned} \tag{4.12}$$

We can applied the optimal regulator theory to the variation system described by above equation to obtain a good transient behavior of tracking to the reference signal *r(t)*. In this case, the quadratic cost function can be shown by

$$\boldsymbol{J} = \int_0^\infty \{e^T(t)\boldsymbol{Q}e(t) + \tilde{u}^T(t)\boldsymbol{R}\tilde{u}(t)\}dt \tag{4.13}$$

The constant matrix gain ***P*** can be calculated as the result of positive definite solution of the algebraic Riccati equation in a asymptotically stable closed loop system. The optimal control law is

$$\tilde{u}(t) = -\boldsymbol{R}^{-1}\boldsymbol{B}^{T}\boldsymbol{P}\tilde{x}(t) \tag{4.14}$$

Control input *u(t)* is calculated by rewritten the optimal control law in Eq. (4.14) in form of Eqs. (4.10) and (4.11)

$$u(t) = \boldsymbol{F_0}x(t) + \boldsymbol{H_0}r(t) \tag{4.15}$$

where

$$
\begin{aligned}
&\boldsymbol{F_0} = -\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P} \\
&\boldsymbol{H_0} = [-\boldsymbol{R}^{-1}\boldsymbol{B}^T\boldsymbol{P} \quad \boldsymbol{I}]\begin{bmatrix} \boldsymbol{A} & \boldsymbol{B} \\ \boldsymbol{C} & \boldsymbol{0} \end{bmatrix}^{-1}\begin{bmatrix} \boldsymbol{0} \\ \boldsymbol{I} \end{bmatrix} = \{-\boldsymbol{C}(\boldsymbol{A}+\boldsymbol{BF_0})^{-1}\boldsymbol{B}\}^{-1}
\end{aligned}
\tag{4.16}
$$

Fig.4.2 shows the result of optimal tracking closed loop system. It is composed the feedback from the state *x(t)* and the feed-forward from the reference signal *r(t)*. The state space of the control system is described by

$$
\begin{aligned}
&x(t) = (\boldsymbol{A} + \boldsymbol{BF_0})x(t) + \boldsymbol{BH_0}r(t) \\
&y(t) = \boldsymbol{C}x(t)
\end{aligned}
\tag{4.17}
$$

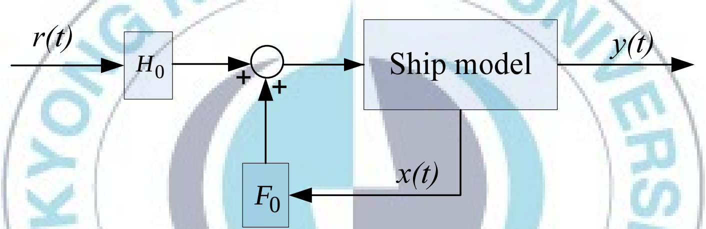

Fig.4.2 Linear quadratic servo system.

4.2.2 Two-Degree-of-Freedom-Servosystem

The controlled output *y(t)* of system (4.17) coincide to reference signal *r(t)* if the model of ship is accurate and no effect of disturbance. However, the hydrodynamic coefficients of ship maybe change during motion so the model of ship can be considered as the uncertainty system and the effect of wind and wave disturbances have to be concerned during the ship berthing. Based on the internal model principle, the integral compensator is applied to cope with the modeling error and disturbance input. With the original motivation that the integral compensator is effective only when there exits modeling error or disturbance and the control input *u(t)* has to achieve the optimal transient behavior of tracking as previous analysis even in case we introduce integral compensator, we develop the two-degree-of-freedom-servosystem. The open loop of augmented linear quadratic servo system is shown in Fig 4.3. Here *w(t)* is given by

$$w(t) = \int_0^t e(\tau)d\tau + w_0 \text{ where } w_0 \text{ is the intial value} \tag{4.18}$$

This system can be described by

$$\begin{bmatrix} \dot{x}(t) \\ \dot{w}(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} + \boldsymbol{BF_0} & \boldsymbol{0} \\ -\boldsymbol{C} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} + \begin{bmatrix} \boldsymbol{BH_0} \\ \boldsymbol{I} \end{bmatrix} r(t) + \begin{bmatrix} \boldsymbol{B} \\ \boldsymbol{0} \end{bmatrix} v(t)$$
$$y(t) = \begin{bmatrix} \boldsymbol{C} & \boldsymbol{0} \end{bmatrix} \begin{bmatrix} x(t) \\ w(t) \end{bmatrix} \tag{4.19}$$

If *v(t)*=0, the behavior of the *x(t)* can be calculated by

$$x(t) = (\boldsymbol{A} + \boldsymbol{BF_0})^{-1}\dot{x}(t) - (\boldsymbol{A} + \boldsymbol{BF_0})^{-1}\boldsymbol{BH_0}r(t) \tag{4.20}$$

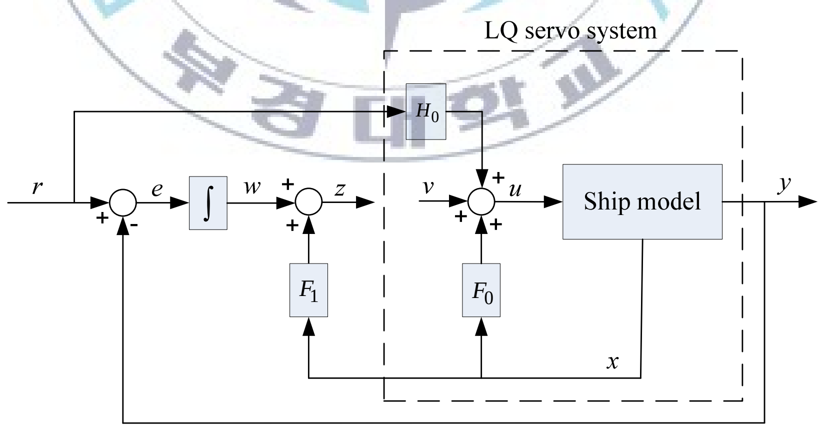

Fig.4.3 Augmented linear quadratic servo system.

By using this representation, the tracking error *e(t)* can be described as

$$\begin{aligned} e(t) &= r(t) - \boldsymbol{C}(\boldsymbol{A}+\boldsymbol{BF_0})^{\boldsymbol{-1}}\dot{x}(t) + \boldsymbol{C}(\boldsymbol{A}+\boldsymbol{BF_0})^{\boldsymbol{-1}}\boldsymbol{BH_0}r(t) \\ &= -\boldsymbol{C}(\boldsymbol{A}+\boldsymbol{BF_0})^{\boldsymbol{-1}}\dot{x}(t) \end{aligned} \tag{4.21}$$

So the integral *w(t)* can be represented by

$$w(t) = \int_0^t e(t)dt + w_0 = -\boldsymbol{F_1}x(t) + \boldsymbol{F_1}x_0 + w_0 \tag{4.22}$$

where

$$\boldsymbol{F_1} = \boldsymbol{C}(\boldsymbol{A}+\boldsymbol{BF_0})^{\boldsymbol{-1}} \tag{4.23}$$

Hence, if the model of the plant is exact, *w(t)* can be cancelled by a state feedback plus a constant signal. So the variable *z(t)* can be defined by

$$z(t) = w(t) + \boldsymbol{F_1}x(t) - \boldsymbol{F_1}x_0 - w_0 \tag{4.24}$$

Now the input *v(t)* can be connected to *z(t)* by matrix gain ***G*** as shown in Fig.4.4 to have the two-degree-of-freedom linear quadratic servo system.

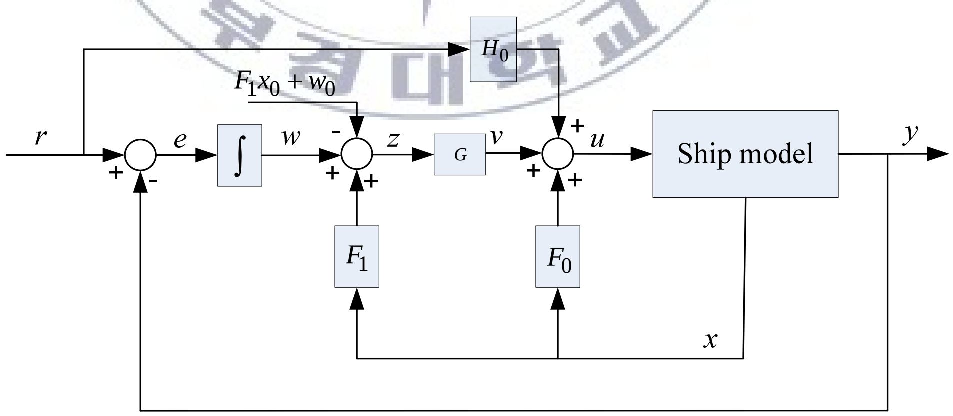

Fig.4.4 Two-degree-of-freedom linear quadratic servo system.

$$v(t) = \boldsymbol{G}z(t) = \boldsymbol{G}[\boldsymbol{F_1} \quad \boldsymbol{I}]\begin{bmatrix} x(t) \\ w(t) \end{bmatrix} - \boldsymbol{G}(\boldsymbol{F_1}x_0 + w_0) \tag{4.25}$$

To obtain the system with have to have the steady state tracking property robust to modeling errors and disturbance inputs, the matrix gain ***G*** has to be chosen so that the system is stable. For stability analysis, the system (4.19) can be represented

$$\begin{bmatrix} \dot{x}(t) \\ \dot{z}(t) \end{bmatrix} = \begin{bmatrix} \boldsymbol{A} + \boldsymbol{BF_0} & \boldsymbol{BG} \\ \boldsymbol{0} & \boldsymbol{F_1BG} \end{bmatrix}\begin{bmatrix} x(t) \\ z(t) \end{bmatrix} \tag{4.26}$$

So the stable of system implies that $\boldsymbol{F_1BG}$ is a stable matrix. A special choice of ***G*** will be

$$\boldsymbol{G} = -\boldsymbol{R}^{-1}(\boldsymbol{F_1B})^{\boldsymbol{T}}\boldsymbol{W} \tag{4.27}$$

where *W* is considers as the tuning gain.

Furthermore, for using the state feedback gain $\boldsymbol{F_0}$ and $\boldsymbol{F_1}$, all states of system are measured. However, the ship in this study is not equipped with enough sensors to estimate all states, and they are too sensitive with noise from the environment, so we use the full order observer technique to estimate all the states of system. Based on observability of steering model, the matrix gain ***L*** is calculated. It has to be chosen so that response of observer is faster than the response of close loop system and the matrix $\boldsymbol{A - LC}$ has to be stable matrix. Fig.4.5 shows the structure of two-degree-of-freedom servosystem incorporating full order observer.

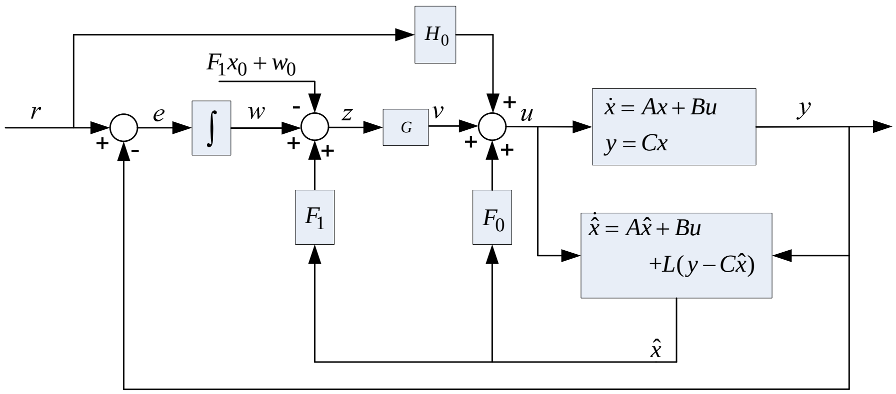

Fig.4.5 Two-degree-of-freedom Servosystem incorporating full order observer.

4.3 Experimental Results

In order to evaluate the efficiency of proposed controller, the ship is tested in the model basin. The motion of ship is controlled and measured based on SIMTOOL program through DAQ board. The experiment was performed in the Marine Cybernetic Laboratory with the ship model as shows in Fig.4.6.

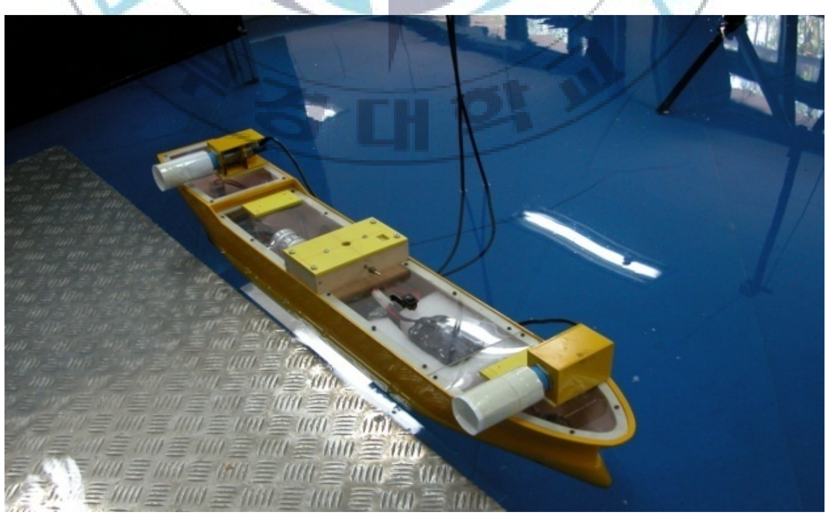

Fig.4.6 Photograph of ship model.

This ship is equipped with one main propeller and two tunnel thruster at fore and aft to produce a sway and yaw motion. Two ultrasonic sensors are mounted on board to measure the distance from ship to harbor. The range of sensor is 0.4 to 3 [m]. The experimental apparatus used in this study is shown in Fig.4.7.

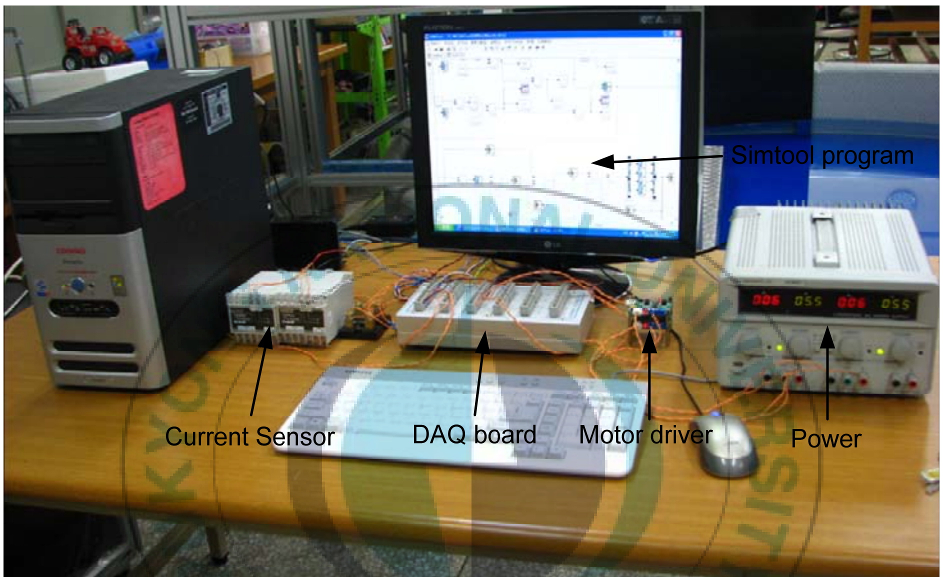

Fig4.7. Photograph of the experimental apparatus.

In this test, all matrixes of controller are calculated as following:

$$\boldsymbol{Q} = \mathrm{diag}\{10\ 5\ 10\ 5\},\ \boldsymbol{R} = \mathrm{diag}\{5\ 5\} \tag{4.28}$$

$$\boldsymbol{P} = \begin{bmatrix} 49.75 & 92.39 & -0.67 & -2.77 \\ 92.39 & 237.1 & -1.56 & -7.75 \\ -0.67 & -1.57 & 22.7 & 23.1 \\ -2.77 & -7.75 & 23.2 & 49.09 \end{bmatrix} \tag{4.29}$$

$$\boldsymbol{F_0} = \begin{bmatrix} -0.943 & -2.399 & -1.053 & -2.178 \\ -1.053 & -2.735 & 0.943 & 2.043 \end{bmatrix} \tag{4.30}$$

$$F_1 = \begin{bmatrix} -4.974 & -9.239 & 0.067 & 0.277 \\ 0.067 & 0.157 & -2.271 & -2.318 \end{bmatrix} \tag{4.31}$$

$$H_0 = \begin{bmatrix} 0.943 & 1.053 \\ 1.054 & -0.943 \end{bmatrix} \text{ and } G = \begin{bmatrix} 0.094 & 0.105 \\ 0.105 & -0.943 \end{bmatrix} W \tag{4.32}$$

Bow, aft positions and yaw angle of ship during testing are shown in the Fig.4.8. 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. Notice that, to reduce the overshoot which is induced by inertia force of ship, the control inputs of bow and stern thrusters change their direction around 10 to 20s as shown in Fig.4.9.

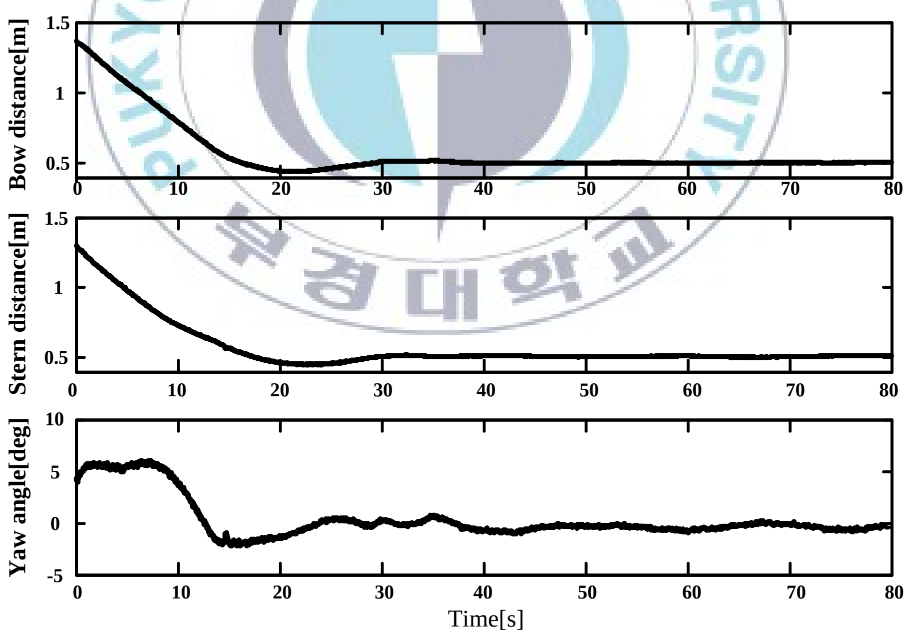

Fig.4.8 Position and yaw angle of ship during berthing.

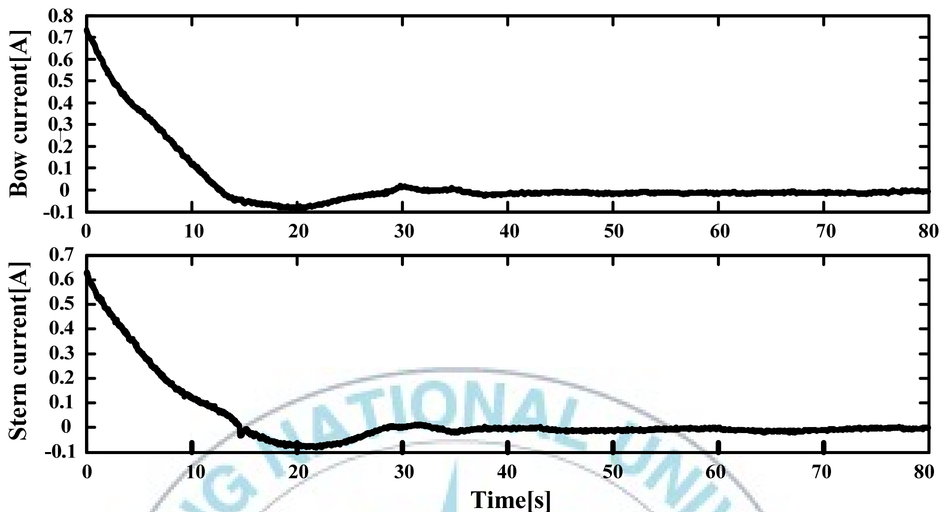

Fig.4.9 Currents supplied to bow and stern thrusters.

5. Conclusion and Future Development

5.1 Conclusion

Based on analyses of previous researches, they have limits for safety berthing automatically by combination of rudder adjustment and main propeller. In this thesis, we proposed the new approach by using only bow and stern thrusters.

Especially, a new and simple ship steering model was described. Hydrodynamic coefficients were estimated from system identification techniques by prediction error method. After that, the two-degree-of-freedom linear quadratic servo system incorporating 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 evaluation showed that good performance for automatic ship berthing by using bow and stern thrusters can be obtained.

5.2 Future Development

This thesis presented the study for automatic ship berthing system by using bow and stern thrusters. However some kind of heavy marine vessel in not equipped bow and stern thrusters simultaneously. So future work will concentrate on the following two parts:

- Combining assistance of tugboats and active fender for automatic ship berthing
- Develop the control algorithm for automatic ship berthing system by operation tugboats remotely

References

1. Astrom, K.J, Kallstrom, C.G. (1981). "Experiences of System Identification Applied to Ship Steering", Automatica, Vol 17, pp. 187-189.
2. Djouani, K and Hamam, Y. (1995). "Minimum Time Energy Trajectory Planning for Automatic Ship Berthing", IEEE Journal of Oceanic Engineering, Vol 20, No 1, pp. 4-11.
3. Fossen, T. I. (1994). "Guidance and Control of Ocean Vehicle", John Wiley and Sons Ltd.
4. Fujusaki, M, Ikeda, M. (1992). "A Two-degree-of-freedom Design of Optimal Servosystems", Proc. 31^{st} Conference on Decision & Control, pp. 3588-3589.
5. Grimble. M.J and Patton.R.J. (1979). "Use of Kalman Filtering Techniques in Dynamic Ship Positioning System", IEE Proceedings, Vol 127, No 3, pp. 93-102.
6. Hagiwara, T, Yamasaki, T. (1996). "Two-degree-of-freedom design method of LQI servo system: disturbance rejection by constant state feedback", International Journal of Control, Vol 63, No 4, pp. 703-719.
7. Kallstrom, C.G, Astrom, K.J. (1976). "Identification of Ship Steering Dynamic", Automatica, Vol 12, pp. 9-22.
8. Kim, Y.B, Ikeda, M and Fujusaki, Y. (1995). "Robust Stability and High-Gain Compensation of a Two-Degree-of-Freedom Servosystem", Proc. 34^{th} Conference on Decision & Control, pp. 1431-1436.
9. Kim, Y.B, Ikeda, M, Fujusaki, Y, Nakabo, M. (1997). "Robust Stability of a Two-Degree-of-Freedom Servosystem with Structured and Unstructured Uncertainties", Proc 2^{nd} Asian Control Conference, pp. 407-410.
10. Koyama, T. (1967). "All the Optimum Automatic Steering System of Ship at Sea", J.S.N.A, Vol 122.

11. Kyun, I.N and Hasegawa, K. (2002). "Motion Identification using Neural Networks and Its Application to Automatic Ship Berthing under Wind" SOTECH, Vol 6, No 1, pp. 16-26.

12. Ljung, L. (1987). " System Identification: Theory for the User", Prentice Hall, New Jersey, USA.

13. Ljung, L. (2002). "Prediction Error Estimation Methods", Circuits System Signal Processing, Vol 21, No 1, pp. 11-21.

14. Nguyen, H.P and Jung, C,Y. (2007). "Automatic Berthing Control of Ship Using Adaptive Neural Networks", International Journal of Navigation and Port Research, Vol 31, No 7, pp. 563-568.

15. Ohtsu, K, Shoju, K and Okazaki, T. (1996). "A Minimum Time Maneuvering of Ship with Wind Disturbances", Control Eng. Pratice Vol 4, No 3, pp. 385-392.

16. Okazaki, T and Ohtsu, K. (2008). "A Study on Ship Berthing Support System", IEEE International Conference on System, Man and Cybernetics, pp. 1522-1527.

17. Roberts, G.N, Sutton, R, Tiano, A. (2003). "Intelligent ship autopilots- A historical perspective" Mechatronics, Vol 13, pp. 1091-1103.

18. Roberts, G.N. (2008). "Trends in marine control system", Annual Reviews in Control, Vol 28, pp. 263-269.

19. Van Amerongen, J and Udink, T.C.J. (1975). "Model References Adaptive Autopilots for Ships", Automatica, Vol 11, pp. 441-449.

20. Yamamoto, I. (2001). "Robust and non-linear control of marine system", International Journal of Robust and Nonlinear Control, Vol 11, pp. 1285-1341.

21. Zhang, Z, Grant, E.H and Pratyush, S. (1997). "A Multivariable Neural Controller for Automatic Ship Berthing", IEEE Control System, Vol.17, pp. 31-34.