A Ship Control System in the Berthing Phase

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ABSTRACT : *This paper addresses the trajectory tracking problem for ship berthing using sliding mode technique. With significant potential advantages: insensitivity to plant nonlinearities, parameter variations, remarkable stability and performance robustness with environmental disturbances, the multivariable sliding modes controller is proposed for solving trajectory tracking of ship in harbor area. In this study, the ship position and heading angle are simultaneously tracked to guarantees that the ship follows a given path (geometric task) with desired velocities (dynamic task). The stability of the proposed control law is proved based on Lyapunov theory. The proposed approach has been simulated on a computer model of a supply vessel with good results.*

KEY WORDS : *ship model, ship berthing, sliding mode control, trajectory tracking.*

1. Introduction

The trajectory tracking problem in the field of vessel maneuvering has been concerned from decades ago. Because of the nonlinear hydrodynamic properties of marine vessel, the control design tends to concentrate the nonlinear control. Nonlinear controllers overcome some limitation compare with linear control design. Example, conventional ship control systems are designed under the assumption that the kinematic and dynamic equation of motion can be linearised such that gain-scheduling techniques and optimal control theory can be applied [1,2]. It is not good in the condition that the surge, sway and yaw motion of ship are controlled simultaneously. Additionally, in the linear control design, the gain adjustment is a very complicated task with requires time consuming tests. Moreover, the controller performance varies with the environmental and loading conditions. Nonlinear controller has been applied to vessel maneuvering to overcome problems. Fossen and Strand [3] applied the nonlinear back steeping controller for global exponential tracking of marine vessel in the presence of actuator dynamics with very good results. Zhang [4] proposed using sliding mode control for path following of the surface ship in restricted water .

This paper proposes the multivariable nonlinear sliding mode control (SMC) for ship maneuvering in the harbor area. By using the SMC controller, we can capture the uncertainties such as the environmental disturbance forces and moment, modeling error and the change of hydrodynamic coefficients. In addition, to overcome the dead slow velocity phenomenon of main propellers in maneuvering condition at harbor area, we proposed using autonomous tugboats (Fig.1).

The remainder of this paper is structured as follows. In Section II, we express the dynamic system in the presence of environmental disturbance. The thrust configuration matrix is studied through force decomposition analysis. In section III, the multivariable nonlinear SMC is presented. In section IV, the efficiency of the proposed approach is evaluated through model ship control simulation. Conclusion and plans for future study are summarized and discussed in the Section V.

Fig. 1 Ship berthing by using tugboats

2. System Model

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2.1 Ship modeling

The low frequency motion of a large class of surface ship can be described by following model [5]

$$M\dot{\nu}+D\nu=\tau+R^T(\varphi)b,\qquad (1)$$
$$\dot{\eta}=R(\varphi)\nu$$

The inertia matrix $M\in R^{3\times 3}$ which includes hydrodynamic added inertia can be written:

$$M=\begin{bmatrix} m-X_{\dot{\upsilon}} & 0 & 0 \\ 0 & m-Y_{\dot{\nu}} & -Y_{\dot{\nu}} \\ & -N_{\dot{\nu}} & I_z-N_{\dot{\nu}} \end{bmatrix}\qquad (2)$$

where m is the vessel mass and I_Z is the moment of inertia about the vessel fixed z-axis. For control application, the motion of ship is restricted to low frequency. The wave frequency can be assumed independence from added inertia. This implies that $\dot{M}=0$.

For a straight-line stable ship, $D\in R^{3\times 3}$ will be a strictly positive damping matrix due to linear wave drift damping and laminar skin. The linear damping matrix is defined as

$$D=\begin{bmatrix} -X_{\upsilon} & 0 & 0 \\ 0 & -Y_{\nu} & -Y_{Y} \\ 0 & -N_{\nu} & -N_{Y} \end{bmatrix}\qquad (3)$$

$\eta=[x, y, \varphi]^T\in R^3$ represents the inertial position (x, y) and the heading angle φ in the earth fixed coordinate frame, $\nu=[u, \nu, r]^T\in R^3$ describes the surge, sway and yaw rate of ship motion in body fixed coordinate frame. The rotation matrix in yaw $R(\varphi)$ is used to described the kinematic equation of motion, that is

$$R(\varphi)=\begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}\qquad (4)$$

The slow varying external forces and moment due to winds, currents and waves are lumped together into a bias term $b\in R^3$.

$\tau\in R^3$ is the control of forces and moment provided by the propulsion system, that is main propellers of ship, bow and stern thrusters. In this paper, to prevent ship collisions, the propulsion system is replaced by tugboats. The vector forces and moment τ is the result of combined efforts of four tugboats as shown in Fig. 2. Vector τ is defined as follows:

$$\tau=B(\alpha)f\qquad (5)$$

where the vector $f=[f_1\ f_2\ f_3\ f_4]^T\in F$ presents thrusts produced by tugboats. The set of F is described as $0\le f_i\le f_{\max},\ \forall i\in(1,\ldots,4)$.

The geometric configuration matrix $B(\alpha)\in R^{3\times 3}$ captures relationship between all four tugboats and ship. The i-th column of matrix $B(\alpha)$ is defined as follows:

$$B_i(\alpha)=\begin{bmatrix} \cos(\alpha_i) \\ \sin(\alpha_i) \\ -l_{yi}\cos(\alpha_i)+l_{xi}\sin(\alpha_i) \end{bmatrix}\qquad (6)$$

where the angle α_i defines the force direction of the $i-th$ tugboat. It is measured clockwise and is relative to x-axis of body fixed coordinate frame. The location of the $i-th$ contact point in the body fixed coordinate system is at (l_{ξ}, l_{yi}). So the control input vector τ can thus be expressed in the form of the geometric configuration matrix $B(\alpha)$ and thrust vector f by :

$$\tau=\begin{bmatrix} c\alpha_1 & s\alpha_1 & -l_{y1}c\alpha_1+l_{x1}s\alpha_1 \\ c\alpha_2 & s\alpha_2 & -l_{y2}c\alpha_2+l_{x2}s\alpha_2 \\ c\alpha_3 & s\alpha_3 & -l_{y3}c\alpha_3+l_{x3}s\alpha_3 \\ c\alpha_4 & s\alpha_4 & -l_{y4}c\alpha_4+l_{x4}s\alpha_4 \end{bmatrix}^T \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \end{bmatrix}\qquad (7)$$

where $s\alpha_i=\sin(\alpha_i)$ and $c\alpha_i=\cos(\alpha_i)$.

In this paper, we assume that the contact positions between ship and tugboats are fixed. The adequate set (α_i, f_i) will be solved by control allocation approach.

2.2 Environmental disturbance model

The effect of environmental disturbances is the sum of the low frequency motion components and wave frequency motion components. The wave frequency components describe the oscillatoric motion of the ship and should be neglected in the control design. The forces and moment due to slow varying wind, current and waves are lumped together in to Earth-fixed bias term $b\in R^3$. A frequently used bias model for marine control application is the first-order Markov process

$$\dot{b}=-T^{-1}b+\psi n\qquad (8)$$

where $b \in R^3$ is the vector of bias forces and moment, $n \in R^3$ is the vector of zero-mean Gaussian white noise. $T \in R^{3\times 3}$ is the diagonal positive bias time constants matrix and $\psi \in R^{3\times 3}$ is the diagonal matrix scaling the amplitude of white noise disturbance n.

This model can be used to described slow varying environmental forces and moment due to

- second order wave drift,
- ocean current,
- wind,
- unmodelled dynamics.

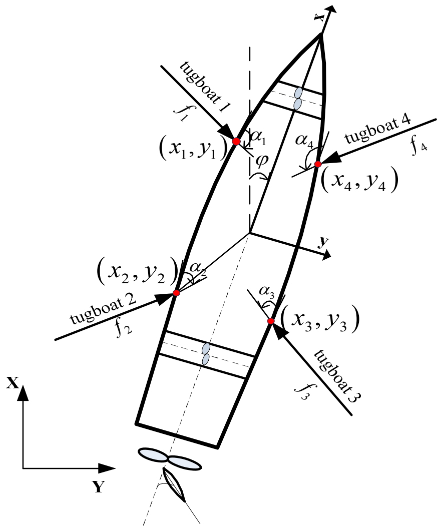

Fig. 2 Ship motion by manipulation of 4 tugboats

3. Sliding Mode Control Design

In this section, the SMC method is developed to design the controller. With significant potential advantages: insensitivity to plant nonlinearities, parameter variations, remarkable stability and performance robustness with environmental disturbances, this method satisfies the trajectory tracking requirements in the harbor area. The design of SMC includes two steps:

- First, choosing a set of switching surfaces that represent some sort of a desired motion
- Second, designing a discontinuous control law that guarantees the attractiveness of the switching surfaces and ensure convergence to the switching surfaces.

Definition 1: The measure of tracking is defined as:

$$s = \dot{\tilde{\eta}} + \Lambda\tilde{\eta} \tag{9}$$

where $\Lambda \in R^{3\times 3}$ is diagonal positive design matrix, $\tilde{\eta} = \eta - \eta_d$ is the Earth-fixed tracking error. The desired trajectory in the Earth fixed coordinated frame is denoted by vector $\eta_d = [x_d, y_d, \varphi_d]$. Without any lose of generality, the selected trajectory is assumed to be both sufficiently smooth and bounded $\eta_d, \dot{\eta}_d, \ddot{\eta}_d \in L_\infty$. It can be seen that the convergence of s to zero implies that the tracking error $\tilde{\eta}$ converges to zero.

Definition 2: The virtual reference trajectory in body fixed and Earth-fixed coordinates are defined as

$$\dot{\eta}_\gamma = \dot{\eta}_d - \Lambda\tilde{\eta} \tag{10}$$

From Eqs. (9) and (10), s can be rewritten as following

$$s = \dot{\eta} - \dot{\eta}_\gamma \tag{11}$$

To simplify the development of controller design, the system model represented in Eq. (1) is rewritten as follows

$$M^*\ddot{\eta} + D^*\dot{\eta} = \tau^* \tag{12}$$

Notice that the bias term can be deal as uncertain disturbances and it is ignored in SMC design. The transformed system matrices $M^* \in R^{3\times 3}$, $D^* \in R^{3\times 3}$ and $\tau^* \in R^3$ are calculated as follows

$$\begin{aligned} M^* &= R(\varphi)MR^T(\varphi), \\ D^* &= R(\varphi)(DR^T(\varphi) - MS(\dot{\varphi})R^T(\varphi)), \\ \tau^* &= R(\varphi)\tau \end{aligned} \tag{13}$$

where, the skew symmetric matrix $S(\dot{\varphi}) \in R^{3\times 3}$ is defined as follows:

$$S(\dot{\varphi}) = \begin{bmatrix} 0 & -\dot{\varphi} & 0 \\ \dot{\varphi} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{14}$$

The differential equation of the sliding mode is derived as following:

$$M^*\dot{s} = -D^*s + (\tau^* - M^*\ddot{\eta}_\gamma - D^*\dot{\eta}_\gamma) \tag{15}$$

Let $\dot{s} = 0$, then the equivalent control can be obtained as

$$\tau_{eq} = D^*s + M^*\ddot{\eta}_\gamma + D^*\dot{\eta}_\gamma \tag{16}$$

The control input of SMC is defined as

$$\tau^* = \tau_{eq} + \tau_{sw} \tag{17}$$

where $W \in R^{3\times 3}$ and $K \in R^{3\times 3}$ are the designed diagonal positive matrices. Based on Eq. (18), the τ_{sw} can be chosen as

$$\dot{s} = -Ws - Ksgn(s) \tag{18}$$

Totally, the control input is designed as

$$\tau_{sw} = -M^*(Ws + Ksgn(s)) \tag{19}$$

The non-negative control Lyapunov function is chosen to analyze the stability of system:

$$\tau^* = D^* s + M^* \ddot{\eta}_\gamma + D^* \dot{\eta} - M^*(Ws + Ksgn(s)) \tag{20}$$

The derivative of V along the trajectory of system is

$$V = \frac{1}{2} s^T s \tag{21}$$

Substituting the control input τ^* in Eq. (20) to (21), we have

$$\dot{V} = -s^T Ws - s^T Ksgn(s) \leq 0 \tag{22}$$

Equation (22) gives the non-positive time derivative of the Lyapunov function candidate. Based on the Lyapunov stability, it is possible to conclude that the control system is asymptotically stable. Therefore, the tracking error and its derivative will converge to zero in a finite amount of time.

The control input of SMC controller presented by Eq. (20) contents the discontinuous signum function and generates the chattering on the surface vector s=0. In order to eliminate this chattering phenomenon, the signum function should be replaced by the saturation function. The control law can be represented as follows

$$\tau^* = D^* s + M^* \ddot{\eta}_\gamma + D^* \dot{\eta}_\gamma - M^*(Ws + Ksat(s/\delta)) \tag{23}$$

where δ is a boundary layer thickness and the saturation function is defined as:

$$\begin{cases} sat(\gamma) = \gamma & \text{if} |\gamma| < 1 \\ sat(\gamma) = sgn(\gamma) & otherwise \end{cases} \tag{24}$$

4. Simulation Results

Computer simulations have been used to evaluate the performance and robustness of the controlled system. Both ship motion and tugboats dynamic during berthing in the condition of environmental disturbances have been shown.

We have used the CybershipI [6], which is the model of an offshore supply vessel scale 1:70, shown in Fig. 3. In this study, ship actuators are not used. The motion of ship is maneuvered by four tugboats. The model ship has the mass of 17.6[kg] and a length of 1.19[m].The center of gravity is located at x_g=-0.04[m]. It is chosen as the body fixed coordinate original. Hydrodynamic coefficients of model are described as follows:

$$\begin{aligned} M &= [19[kg]\ 0\ 0; 0\ 35.2[kg] - 0.7[kg.m^2] \\ &\quad ;0\ -0.7[kg]\ 1.98[kgm^2]] \\ D &= diag4[kg/s], 6[kg/s], 1[kg.m^2/s]; \end{aligned} \tag{25}$$

The tugboats configuration are described as

$$\begin{aligned} &(l_{1x}, l_{1y}) = (0.41, -0.15),\ (l_{2x}, l_{2y}) = (-0.41, -0.15), \\ &(l_{3x}, l_{3y}) = (-0.41, 0.15),\ (l_{4x}, l_{4y}) = (0.41, 0.15) \end{aligned} \tag{26}$$

Constraints about limitation of thrust, contact angle as well as slowly varying direction are chosen as follows

$$\begin{aligned} &f_{\min} = 0, \quad f_{\max} = 0.5[N] \\ &\alpha_{1\min} = \frac{\pi}{2}, \quad \alpha_{1\max} = \frac{5\pi}{6} \\ &\alpha_{2\min} = \frac{\pi}{6}, \quad \alpha_{2\max} = \frac{\pi}{2} \\ &\alpha_{3\min} = \frac{-\pi}{2}, \quad \alpha_{3\max} = \frac{-\pi}{6} \\ &\alpha_{4\min} = \frac{-5\pi}{6}, \quad \alpha_{4\max} = \frac{-\pi}{2} \\ &\dot{\alpha} = \frac{\pi}{18}[rad/s] \end{aligned} \tag{27}$$

Fig. 3 Cybership I : scale 1:70 of a supply vessel

The SMC control law is simulated with $\Lambda = diag0.1,\ 1,\ 1,\ \ W = diag1,\ 1,\ 1,\ K = diag1,\ 1,\ 1\times 10^{-3}$.

For safety berthing, the trajectory for ship tracking should be separated into two phase as shown in Fig. 4. The first is called approaching phase and the second is berthing phase.

In this simulation, ship is maneuvered on the straight line from point A (0, 0) where the initial heading angle is $\pi/3$ to point B (10,10) with $\pi/4$ on the desired heading angle. After that, the ship is maneuvered from point B to final target C (10, 15) with 0 degree on the desired heading angle (the ship and the jetty are parallel to each other).

To evaluate the robustness of controlled system, slow varying disturbances is considered in both phases. The bias matrix T and scale amplitude matrix Ψ are defined as following:

$$T = diag\{100, 100, 100\}, \psi = diag\{0.1, 0.1, 0.03\} \qquad (28)$$

Fig. 5 and Fig. 6 display the motion of ship under the proposed SMC controller and control allocation strategy. It is clearly seen that the ship follows the reference trajectory with high accuracy. Dynamic behavior of ship is also satisfied. Based on ship performance, it is ensured that, the ship can move to the berth without collision between ship and the others located in the harbor as well as between ship and the jetty.

Fig. 7 and Fig. 8 depict the performance of four tugboats. The resulting thrust and directions of tugboats satisfy the constraint about limited pushing force and varying direction.

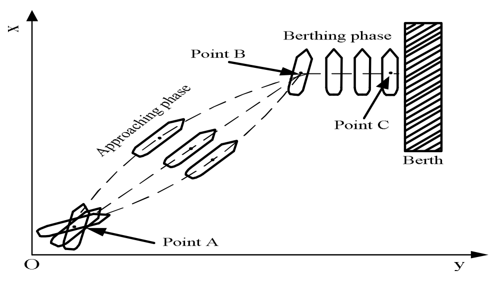

Fig. 4 Planning route for ship berthing

5. Conclusion

In this paper, we proposed the new approach for ship berthing with assistance of autonomous tugboats. The modeling of system was figured out. SMC controller showed good performance in the presence of environmental disturbance. The efficiency of proposed approach was evaluated through trajectory tracking simulation of the model ship in the presence of environmental disturbance. It exhibited good performance and revealed the possibility of extending these results to future studies. The combination of tunnel thrusters and the tugboats will be studied to determine suitable solution for various ship berthing situations.

References

[1] Holzhuter. T, "LQG approach for the high precision track control of ships," IEE Proc Control Theory Applications, pp. 121-127, 1997.

[2] Nomoto. K.T, Taguchi. K.H, and Hirano. S, "On the steering qualities of ships", Technical report, Int. Shipbuilding Progress, pp. 3554-370, 1957.

[3] Fossen. T.I and Berge. S.P, "Nonlinear vectorial backsteping design for global exponential tracking of marine vessels in the presence of actuator dynamics," Proc. 36th Conf. on Decision and Control, pp. 4237-4242, 1997 .

[4] Zhang. R. C, Sun. Z, Sun. F and Xu. H, "Path control of a surface ship in restricted waters using sliding mode," Proc. 37th IEEE Conf. on Decision and Control, pp 4237-4244, 1998.

[5] Thor. I.Fossen, Marine Control System- Guidance, Navigation, Rigs and Underwater Vehicle, Trondheim, Norway, Norwegian University of Science and Technology.

[6] J. P. Strand, "Nonlinear Position Control System Design for Marine Vessels," PhD. Thesis, Dept of Engineering Cybernetics, Norwegian University of Science and Technology, 1999.

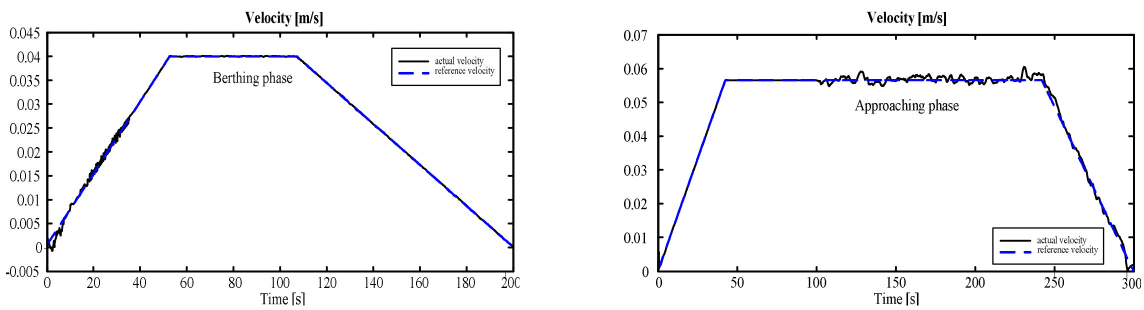

Fig. 5 Ship velocity during berthing

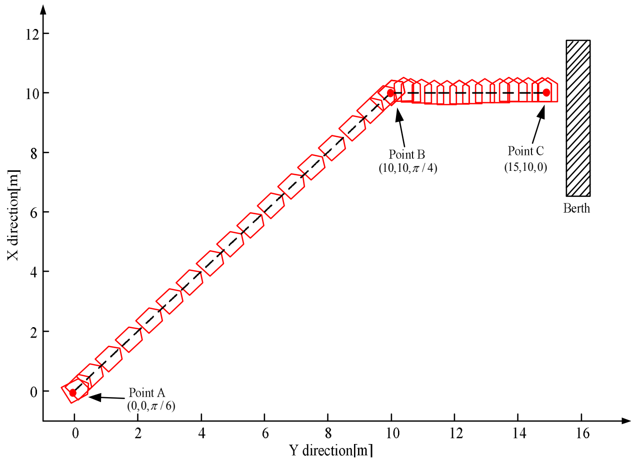

Fig. 6 Ship berthing motion

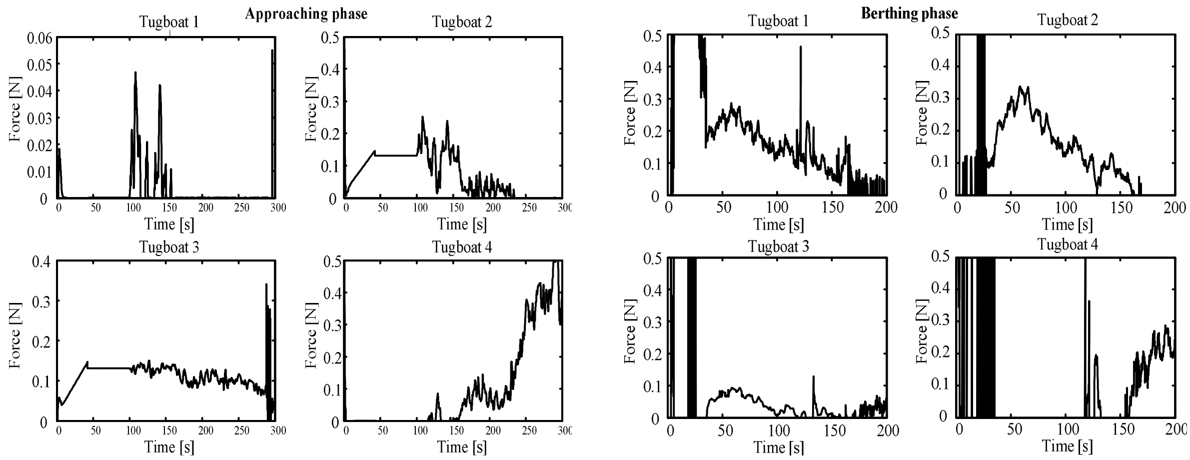

Fig. 7 Tugboat thrusts during berthing

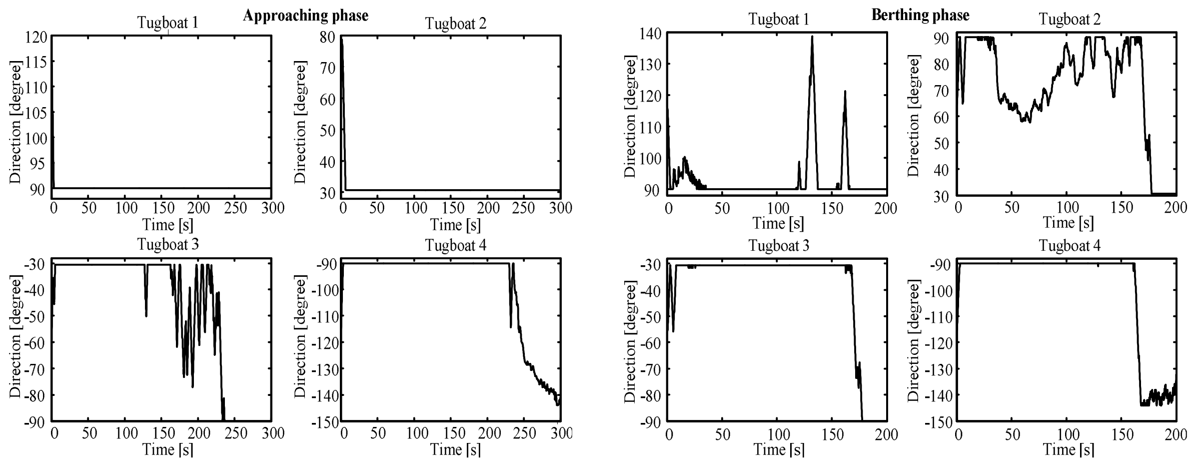

Fig. 8 Tugboats directions during berthing