Journal of the Korean Society of Marine Environment & Safety
Vol. 25, No. 3, pp. 306-312, May 31, 2019, ISSN 1229-3431(Print) / ISSN 2287-3341(Online)

Research Paper

https://doi.org/10.7837/kosomes.2019.25.3.306

Adaptive Sliding Mode Control Synthesis of Maritime Autonomous Surface Ship

Sang-Do Lee* · Xiao Xu** · Hwan-Seong Kim** · Sam-Sang You***†

* Korea e-Navi Information Technology Co. LTD., Busan, Korea
** Department of Logistics Engineering, Korea Maritime and Ocean University, Busan, Korea
*** Division of Mechanical Engineering, Korea Maritime and Ocean University, Busan, Korea

Abstract : *This paper investigates to design a controller for maritime autonomous surface ship (MASS) by means of adaptive super-twisting algorithm (ASTA). A input-out feedback linearization method is considered for multi-input multi-output (MIMO) system. Sliding Mode Controller (SMC) is suitable for MASS subject to ocean environments due to its robustness against parameter uncertainties and disturbances. However, conventional SMC has inherent disadvantages so-called, chattering phenomenon, which resulted from the high frequency of switching terms. Chattering may cause harmful failure of actuators such as propeller and rudder of ships. The main contribution of this work is to address an appropriate controller for MASS, simultaneously controls surge and yaw motion in severe step inputs. Proposed control mechanism well provides convergence bewildered by external disturbances in the middle of steady-state responses as well as chattering attenuation. Also, the adaptive algorithm is contributed to reducing non-overestimated value of control gains. Control inputs of surge and yaw motion are displayed by smoother curves without excessive control activities of actuators. Finally, no overshoot can be seen in transient responses.*

Key Words : *Maritime autonomous surface ship (MASS), Adaptive super-twisting algorithm (ASTA), Control synthesis, 3 DOF, Disturbances, Robustness*

1. Introduction

Recently, maritime autonomous surface ships (MASS) are in the spotlight in many countries due to the advent of the fourth industrial revolution. Especially, MASS has obviously launched to a new stage in the marine industry, which centers on European countries. The emergence of MASS has changed the concept of a conventional vessel. For instance, Det Norske Veritas (DNV) Germanischer Lloyd (GL) has developed a revolutionary concept for an unmanned, zero-emission, short-sea vessel.

Autonomous vehicles are already state-of-the-art in many land-based transport modes such as automated subways, self-driving intra-logistics vehicles or automated guided vehicles on modern container terminals. MASS has the potential to redefine the marine industry and the roles of the players in it.

Motion control scenarios of MASS are usually divided into three main categories, such as point stabilization, trajectory tracking, and path following. Li et al. (2008) studied point-to-point navigation of underactuated ships using a general back-stepping method, containing the concise and clear physical meaning of tracking errors. Practically, the sway speed of the ship is bounded to satisfy the passive bounded condition in case all other variables in its dynamics are bounded. Point-to-point navigation concept is similar to path following. Do et al. (2004) investigated parking and point-to-point navigation of a real ship using the Lyapunov's direct method and back-stepping technique. They showed good results path-following parts, convergence to a non-zero value and surge control, while it still has some breaking points such as over-estimating control gains, chattering in yaw control and lack of yaw angle information. It was found that such a classical controller may result in chattering for the case of practical environments and real ship. In order to overcome the previous threshold, sliding mode controller (SMC) with adaptive super-twisting algorithm (ASTA) was applied to the real ship.

SMC is widely used due to its advantages of robustness against parametric uncertainty and disturbances. Since it uses discontinuous function and high control gain, the property of finite-time convergence in the closed-loop system is noticeable (Plestan et al., 2010). In spite of remarkable strengths, SMC has the inherent characteristics of chattering, which resulted from the high frequency of switching functions. Since the chattering may results

---

* First Author: oksangdo@naver.com

† Corresponding Author: ssyou@kmou.ac.kr, 051-410-4366

※ A Study on the Nonlinear Dynamical Control of Maritime Autonomous Surface Ship, Autumn Annual Conference 2018, Korea Institute of Maritime and Fisheries Technology, November 29.

in a breakdown of actuators, there was a big effort to solve this problem in many ways. One of the important factors to distinguish superior controller is disturbances. As previously mentioned, conventional controllers hardly reduce chattering, especially in the case of disturbances.

Lee and Utkin (2007) reduced the chattering problem in the system with unmodeled dynamics based on state-dependent or equivalent-control-dependent gain method. Davila et al. (2010) applied variable gain to the super-twisting algorithm (STA) to guarantee the global finite time convergence to the sliding surface and chattering mitigation. STA is a second order SMC. It also shows robustness without any information about derivatives of sliding constraints. However, this approach may cause over-estimation of the value of control gains.

Recently, high-order SMC combined with the adaptive algorithm is considered as an effective method to solve the chattering problem and over-estimation of control parameters. Some papers have been reported to lower the gains. Plestan et al. (2010) studied the adaptive technique for an electro-pneumatic actuator without over-estimation of the gain. Shtessel et al. (2012) developed the adaptive algorithm based on the STA that does not allows not-overestimation of the control gains. Similar research has been completed without information of disturbance bounds by Edwards and Shtessel (2016). Han and Pan (2016) applied an idea of gain-scheduling to the ASTA for the uncertain nonlinear system without the information of upper bounds.

In this paper, ASTA was implemented to produce high performance in controlling surge and yaw motion for MASS. A input-output feedback linearization method is employed for multi-input multi-output (MIMO) system. The sliding surface of surge control is affected by two controllers. The patrol boat of Australian Customs bay class is used to show the effectiveness of the proposed controller. Severe step inputs are taken into account to ensure control performance. The contribution of this work is to present chattering mitigation as well as non-estimating control gains.

2. Ship Dynamics and Control Synthesis

2.1 Ship Dynamical Model

The horizontal motion of a surface ship is represented by the motion components in surge, sway and yaw. Fig. 1 shows the motion variables in this case. Two reference frames are considered such as body-fixed frame $O_bX_bY_bZ_b$ and earth-fixed frame $O_EX_EY_EZ_E$. The origin O_b of the body-fixed frame is located at the center of gravity (CG). For marine ships, the body axes X_b, Y_b and Z_b are chosen to coincide with the principal axes of inertia and they are commonly defined as follows.

X_b - longitudinal axis (directed from aft to fore)

Y_b - transverse axis (directed to starboard)

Z_b - normal axis (directed to top to bottom)

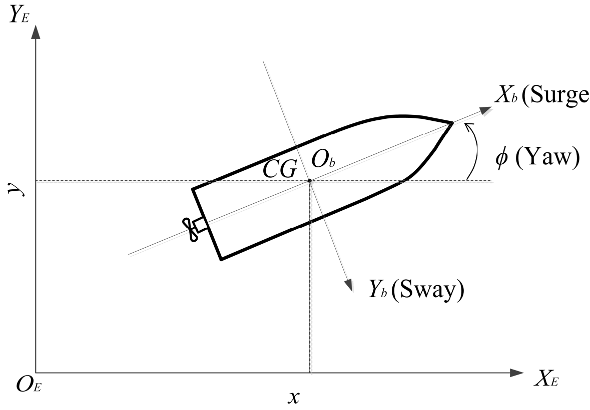

Fig. 1. Simplified horizontal ship model with its coordinate system.

The state vectors are chosen as $\eta = [x,\, y,\, \psi]^T$ and $\nu = [u,\, v,\, r]^T$. It means that the dynamics associated with the motion in heave, roll and pitch are ignored, that is $w = p = q = 0$. The kinematic equations of motion can be reduced from the general 6 DOF (degrees of freedom) expression. In addition, it is assumed that the vessel has homogeneous mass distribution and xz-plane of symmetry such that $I_{xy} = I_{yz} = 0$ (Fossen, 2011). Under the assumptions, the dynamics of a surface ship moving in a horizontal plane is simplified as

$$M\dot{\nu} + C(\nu)\nu + D\nu = \tau \tag{1}$$

$$\dot{\eta} = J(\eta)\nu \tag{2}$$

where the matrices M, $C(\nu)$, D and $J(\eta)$ are given by

$$M = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & 0 \\ 0 & 0 & m_{33} \end{bmatrix} \tag{3}$$

$$C(\nu)=\begin{bmatrix}0 & 0 & -m_{22}v\\ 0 & 0 & m_{11}u\\ m_{22}v & -m_{11}u & 0\end{bmatrix} \tag{4}$$

$$D=\begin{bmatrix}d_{11} & 0 & 0\\ 0 & d_{22} & 0\\ 0 & 0 & d_{33}\end{bmatrix} \tag{5}$$

$$J(\eta)=\begin{bmatrix}\cos(\phi) & -\sin(\phi) & 0\\ \sin(\phi) & \cos(\phi) & 0\\ 0 & 0 & 1\end{bmatrix} \tag{6}$$

with $m_{11}=m-X_{\dot{u}}$, $m_{22}=m-Y_{\dot{v}}$, $m_{33}=I_z-N_{\dot{r}}$, $d_{11}=-X_u$, $d_{22}=-Y_v$ and $d_{33}=-N_r$. The vector τ for propulsion force and yaw moment is given as $\tau=\left[\tau_u\ 0\ \tau_r\right]^T$. The mathematical model of underactuated ship moving in surge, sway and yaw can be reformed as

$$\dot{x}=u\cos(\psi)-v\sin(\psi) \tag{7}$$

$$\dot{y}=u\sin(\psi)+v\cos(\psi) \tag{8}$$

$$\dot{\psi}=r \tag{9}$$

$$\dot{u}=\frac{m_{22}}{m_{11}}vr-\frac{d_{11}}{m_{11}}u+\frac{1}{m_{11}}\tau_u \tag{10}$$

$$\dot{v}=-\frac{m_{11}}{m_{22}}ur-\frac{d_{22}}{m_{22}}v \tag{11}$$

$$\dot{r}=\frac{m_{11}-m_{22}}{m_{33}}uv-\frac{d_{33}}{m_{33}}r+\frac{1}{m_{33}}\tau_r \tag{12}$$

The control inputs are the surge force τ_u and the yaw moment τ_r. Since the sway control force is not considered, the above system is underactuated. In these equations, environmental disturbances such as wind, waves and currents are not included (Do and Pan, 2009).

Let $x_1=x$, $x_2=y$, $x_3=\psi$, $x_4=u$, $x_5=v$ and $x_6=r$. Then the state space model of MASS can be changed to

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\\ \dot{x}_3\\ \dot{x}_4\\ \dot{x}_5\\ \dot{x}_6\end{bmatrix}=\begin{bmatrix}x_4\cos(x_3)-x_5\sin(x_3)\\ x_4\sin(x_3)+x_5\cos(x_3)\\ x_6\\ (\frac{m_{22}}{m_{11}})x_5x_6-(\frac{d_{11}}{m_{11}})x_4+(\frac{1}{m_{11}})\tau_u\\ -(\frac{m_{11}}{m_{22}})x_4x_6-(\frac{d_{22}}{m_{22}})x_5\\ (\frac{m_{11}-m_{22}}{m_{33}})x_4x_5-(\frac{d_{33}}{m_{33}})x_6+(\frac{1}{m_{33}})\tau_r\end{bmatrix} \tag{13}$$

The goal of design is to make appropriate controls that guarantee robust performance. The surge displacement $x_1=x$ and yaw angle $x_3=\psi$ must track a reference position x_{1ref} and reference angle x_{3ref}.

2.2 Adaptive Control Synthesis

In this section, ASTA is considered to control surge and yaw motion. Adaptive algorithm is applied to STA. ASTA scheme guarantees the appearance of a 2-sliding mode $\sigma=\dot{\sigma}=0$, which attracts the trajectories in finite time (Shtessel et al., 2017). Fig. 2 shows the block diagram of ASTA for 3 DOF vessel system.

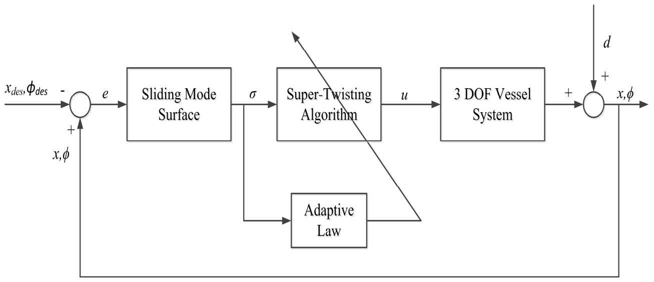

Fig. 2. Control block diagram for MASS.

The tracking error vector is defined with $e=x-x_{des}$ where x is a state vector, and x_{des} for the desired state vector. The sliding surface σ is selected as

$$\sigma_i(t)=p_1\dot{e}_i+p_2e_i,\ (i=1,2) \tag{14}$$

where p_1 and p_2 are positive constants that define the convergence rate of the vessel system. A first sliding variable σ for surge position x_1 towards its equilibrium point x_{1ref} is proposed as

$$\sigma_1 = x_1 - x_{1ref} \tag{15}$$

Derivative of σ_1, the relative degree of sliding mode variable σ_1 equals 2 can be seen as

$$\begin{aligned} \dot{\sigma}_1 &= \dot{x}_1 - \dot{x}_{1ref} \\ \ddot{\sigma}_1 &= \dot{x}_4 \cos(x_3) - x_4 \sin(x_3) - \dot{x}_5 \sin(x_3) - x_5 \cos(x_3) \end{aligned} \tag{16}$$

Above equation control input u_1 appears in the 2 order derivative of σ_1. Similarly, denoting x_{3ref} the desired yaw angle, following form can be written as

$$\sigma_2 = x_3 - x_{3ref} \tag{17}$$

Derivative of σ_2, the relative degree of sliding mode variable σ_2 equals 1 can be chosen as

$$\dot{\sigma}_2 = \dot{x}_6 - \dot{x}_{6ref} \tag{18}$$

Then the space state expression can be described by considering sliding mode variable $\sigma = \left[\ddot{\sigma}_1, \dot{\sigma}_2\right]^T$.

$$\begin{bmatrix} \ddot{\sigma}_1 \\ \dot{\sigma}_2 \end{bmatrix} = A + B\tau = \begin{bmatrix} A_1 \\ A_2 \end{bmatrix} + \begin{bmatrix} B_{11} & 0 \\ B_{21} & B_{22} \end{bmatrix} \begin{bmatrix} \tau_u \\ \tau_r \end{bmatrix} \tag{19}$$

The outputs of the above multi-input multi-output (MIMO) system are coupled because two control inputs influence $\ddot{\sigma}_2$. Therefore, an input-output feedback linearization method motivated by Yi-geng (2010) can be employed as

$$\tau = B^{-1} \cdot [-A + s_w] \tag{20}$$

In the above new dynamics, the term of $-B_0^{-1} A_0$ is the equivalent control part and $s_w = \left[s_{w1}, s_{w2}\right]^T$ is the switching part in the sliding context. For the switching part, the following STA control is designed to reach sliding mode. Control input is composed by two parts. One is the differentiation of discontinuous item and the other is continuous function of sliding mode variable. It can be simplified as

$$s_{wi}(t) = -\lambda_i \sqrt{|\sigma_i|}\, sgn(\sigma_i) + \theta_i \tag{21}$$

$$\dot{\theta}_i(t) = -\frac{W_i}{2} sgn(\sigma_i) \tag{22}$$

where λ_i, W_i $(i = 1,2)$ are the control gains to be designed, $\dot{\theta}_i$ describes the leakage term of STA; it is a second-order sliding mode algorithm. Also, the adaptive gains can be given as

$$\lambda_i = \lambda_i(\sigma, \dot{\sigma}, t) \tag{23}$$

$$W_i = W_i(\sigma, \dot{\sigma}, t) \tag{24}$$

The control design problem (21, 22) is to drive the sliding variable σ and its derivative $\dot{\sigma}$ to zero in finite time in the presence of the bounded perturbation with the unknown boundaries using continuous control. The idea of designing ASTA is to dynamically increase the control gains until the 2-sliding mode establishes. Any initial conditions, the sliding surface will be reached in finite time using STA control with the following adaptive gains (Shtessel et al., 2012)

$$\dot{\lambda}_i = \begin{cases} \omega_i \sqrt{\dfrac{\gamma_i}{2}}\, sgn(|\sigma_i| - \mu_i) & \text{, if } \lambda_i > \lambda_m \\ \zeta_i & \text{, if } \lambda_i \le \lambda_m \end{cases} \tag{25}$$

$$W_i = 2\epsilon_i \lambda_i \tag{26}$$

where ω_i, γ_i, ζ_i, ϵ_i, μ_i $(i = 1,2)$ are arbitrary positive constants.

3. Simulation Tests

The proposed ASTA was employed to control surge and yaw motion of the underactuated ship. Some simulation results can be illustrated to show the effectiveness of the controller. The specification of a model ship is given in Table 1. This ship is a patrol boat owned by Australian Customs service (Fig. 3). The ship has a single rudder and a single propeller. Table 1 shows added mass and damping matrices calculated by the commercial program (MARINTEK) (Do et al., 2004).

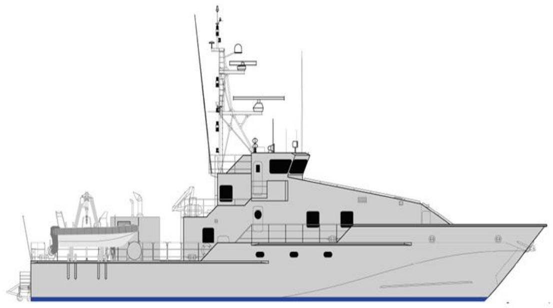

Fig. 3. Model ship (Patrol Boat of Australian Customs). Picture courtesy of Austal, Australia.

Table 1. Specifications of model ship

Parameters	Values
L_{OA}	38.2 m
Beam (moulded)	7.2 m
Depth (moulded)	4.5 m
Hull draft (maximum)	4.5 m
Speed (maximum)	24.0 knots
Maximum surge force	5.2×10^9 kg
Maximum yaw moment	8.5×10^8 Nm
Minimum turning circle (radius)	150 m
Mass	118×10^3 kg
m_{11}	120×10^3 kg
m_{22}	177.9×10^3 kg
m_{33}	636×10^3 kg
d_{11}	215×10^2 kgs^{-1}
d_{22}	147×10^3 kgs^{-1}
d_{33}	802×10^4 kgm^{2}s^{-1}

Assume the initial condition of the system is $[x(0),y(0),\phi(0),u(0),v(0),r(0)]=[-1,1,-0.15,0,0,0]$. The parameters of ASTA are listed in Table 2. In order to find optimum parameter values, the understanding of its property is helpful for control designers. The value of one parameter affects each surge and yaw control since MIMO system is coupled. As you can see in Table 2, control gains are not over-estimated. However, results show good performance without chattering even in a real ship model.

Table 2. Control parameters of ASTA

Surge controller		Yaw controller	
Parameters	Values	Parameters	Values
λ_1	10	λ_2	2
λ_m	0.01	λ_m	0.01
ω_1	20	ω_2	0.5
γ_1	1	γ_2	1
μ_1	0.01	μ_2	0.01
ζ_1	0.02	ζ_2	0.02
ϵ_1	1	ϵ_2	1

In addition, ASTA shows the high performance of convergence as well as chattering mitigation, even the disturbances acting on the system severely. In many papers related to trajectory tracking and path following, surge speed is set to constant. This paper focuses on controlling the two directions simultaneously. Disturbances are usually set at the beginning of simulation as the initial condition, such as control of single-degree-of-freedom (SDOF) dynamics (Lee et al., 2018). However, in this paper, severe step inputs are given after reaching the desired points. Such a process is applied to the interaction situation of two ships in close proximity. Interaction forces from bank and other ships can be regarded as disturbances after reaching the state-state responses.

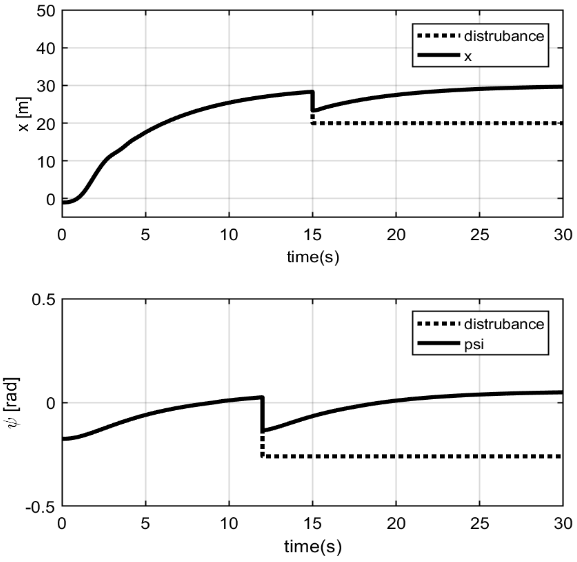

Fig. 4. Transient responses due to disturbance.

Fig. 4 depicts responses of surge and yaw motion using ASTA. The two state variables converge well to the desired point. Overshoot cannot be seen in both cases. In the case of overshoot value, a ship may collide with another ship and obstacles due to the ship's progress. The ship moves forward to the length of 30m in 15 seconds. Approximately 1L_{OA} of the ship is considered for testing the surge control. Although step inputs are given in opposite directions such as backward and portside direction, the system compensates for controlled steady-states conditions. The ship's heading turns to starboard side with the help of the controller and retains its straight direction despite the severe disturbances forced to return initial heading. As shown in Fig. 4, when step inputs start to act on the system, responses of surge and yaw motion directly return to the previous position and direction. Practically, ships hardly go back their previous points in a split second no matter what the disturbance condition. In this work, most egregious phenomenon is considered to represent the performance of ASTA.

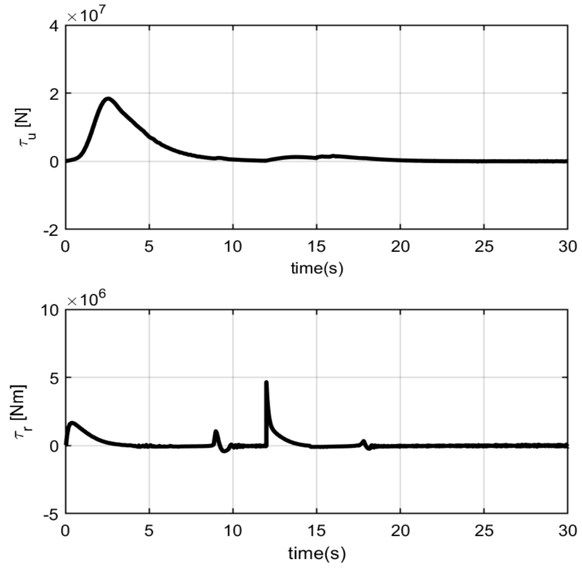

Fig. 5. Control inputs due to disturbance.

Fig. 5 demonstrates the control efforts of surge and yaw motion. The high magnitude of controls resulted from a real ship model and large disturbances. Chattering is greatly restrained in both cases. In a zoom case of yaw control, frequent control switching can be observed in short intervals. However, on the whole, ASTA gives a smoother curve without excessive control activities. High control activities may result in the destructive failure of actuators such as propeller and rudder. Fig. 6 illustrates the sliding surfaces of surge and yaw motions. The sliding surface is driven to zero within a finite time by the continuous ASTA.

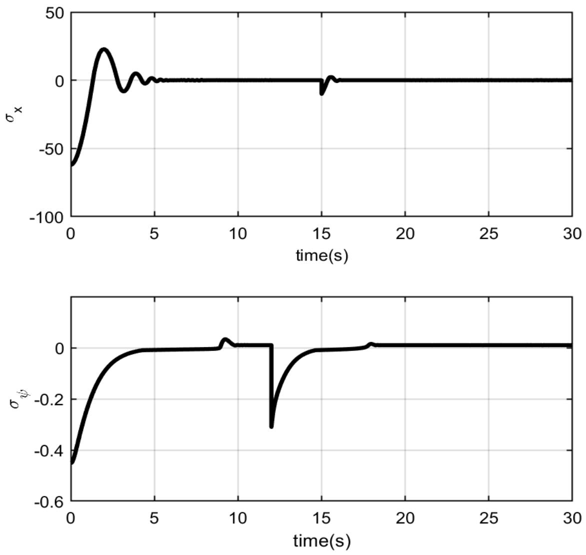

Fig. 6. Time histories of sliding surfaces due to disturbance.

Finally, it was found that adaptive mechanism based on STA successfully contributed to chattering reduction, non-estimating control gain and high performance against the severe disturbances. ASTA is an effective method for ship control in the ocean since it can reduce the chattering of actuators. The parameters of the two cases affect each performance as well as chattering attenuation. So, when designing the controller, suitable parameters should be set.

4. Conclusions

This paper investigated the effectiveness of SMC with ASTA for MASS in external disturbances. Controlled surge and yaw motion are exhibited with some simulation results for a real ship model. Since two controllers affects the sliding surface of surge motion, an input-output feedback linearization method for MIMO system was introduced to solve equivalent control part. The chattering problem of SMC is greatly improved by means of adaptive algorithm based on STA. Also, the over-estimated value of control gains is reduced by the adaptive mechanism. Surge and yaw variables converge to the desired point and compensate its steady-states responses despite step inputs. No overshoot can be seen in transient responses. Two controllers resulted in smoother curves without excessive activities of actuators, such as propeller and rudder.

This paper merely focuses on the control of surge position and yaw angle against harsh conditions. Next work will be extended to consider interaction forces as one of external disturbances in close proximity of MASS. Robust control mechanism is necessary for MASS exposed to ocean environments. Although SMC has advantages of robustness and simplicity, it is impossible to reduce the chattering of a real ship subjected to disturbances. The proposed ASTA is considered as one of the effective methods to overcome the disadvantages of conventional SMC.

References

[1] Davila, A., J. Moreno and L. Fridman(2010), Variable Gains Super-Twisting Algorithm: A Lyapunov Based Design, Proceedings of American Control Conference, Baltimore, MD, USA, pp. 968-973.

[2] Do, K. D., Z. P. Jiang and J. Pan(2004), Robust Adaptive Path Following of Underactuated Ships, Automatica, Vol. 40, pp. 929-944.

[3] Do, K. D. and J. Pan(2009), Control of Ships and Underwater Vehicles, Design for Underactuated and Nonlinear Marine Systems, Springer-Verlag London Limited, pp. 52-56.

[4] Edwards, C. and Y. B. Shtessel(2016), Adaptive Continuous Higher Order Sliding Mode Control, Automatica, Vol. 65, pp. 183-190.

[5] Fossen, T. I.(2011), Handbook of Marine Craft Hydro dynamics and Motion Control, First Edition, John Wiley & Sons Ltd. pp. 133-136.

[6] Han, Y. and W. Pan(2016), Gain-scheduled Continuous High order Sliding Mode Control for Uncertain Nonlinear System, Optik, Vol. 127, pp. 4345-4354.

[7] Lee, H. and V. I. Utkin(2007), Chattering Suppression Methods in Sliding Mode Control Systems, Annual Reviews in Control, Vol. 31, pp. 179-185.

[8] Lee, S. D., B. K. Lee and S. S. You(2018), Sliding Mode Control with Super-Twisting Algorithm for Surge Oscillation of Mooring Vessel System, Journal of the Korean Society of Marine Environment & Safety, Vol. 24, No. 7. pp. 953-959.

[9] Li, J. H., P. M. Lee, B. H. Jun and Y. K. Lim(2008), Point-to-point Navigation of Underactuated Ships, Automatica, Vol. 44. pp. 3201-3205.

[10] Plestan, F., Y. Shtessel, V. Bregeault and A. Poznyak(2010), New Methodologies for Adaptive Sliding Mode Control, International Journal of Control, Vol. 83, pp. 1907-1919.

[11] Shtessel, Y., M. Taleb and F. Plestan(2012), A Novel Adaptive-gain Super-twisting Sliding Mode Controller: Methodology and Application, Automatica, Vol. 48, pp. 759-769.

[12] Shtessel, Y., J. A. Moreno and L. M. Fridman(2017), Twisting Sliding Mode Control with Adaptation: Lyapunov Design, Methodology and Application, Automatica, Vol. 75, pp. 229-235.

[13] Yi-geng, H.(2010), Research of Nonlinear System High Order Sliding Mode Control and its Applications for PMSM, Ph.D. Dissertation, pp. 65-70.

Received : 2019. 05. 10.
Revised : 2019. 05. 24.
Accepted : 2019. 05. 28.