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Ship Adaptive Course Keeping Control With Nonlinear Disturbance Observer

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ABSTRACT This paper investigates a scheme to reject the unknown bounded time varying external disturbance for a ship course keeping control system. A mathematical model of a steering system is derived considering nonlinear features that could affect the control design process. The feedback linearization approach is adopted to simplify the nonlinear system. The adaptive sliding mode control algorithm and nonlinear disturbance observer method are developed for course keeping maneuvers in vessel steering and for providing robust performance for the environment disturbance and rudder dynamics. Furthermore, the overall stability conditions of the presented controllers are analyzed by Lyapunov's direct method. Finally, the effectiveness of the controllers is illustrated by the simulation results on a navy vessel with twin rudders.

INDEX TERMS Course keeping, adaptive, sliding mode control, nonlinear disturbance observer.

I. INTRODUCTION

A ship sailing in a seaway is extensively influenced by external forces and moments caused by winds, waves and ocean currents, waves playing an especially important role. The capacity of vessels to achieve their missions can be affected by these disturbances, and these forces may induce cargo damage and cause variations in motions. Therefore, some devices need to be investigated to maintain ship stability and orientation. The ship autopilot system is used to guarantee safe sailing and force the ship to follow the desired course with a constant speed by controlling the rudder angle, while at the same time, the propulsion losses caused by steering should be minimized by the autopilot controller [1], [2]. The main contributions to the development of practical steering systems were made by the Sperry Gyroscope company. The first automatic ship steering mechanism was constructed in 1911, and Nicholas Minorsky proposed the proportional integral derivative (PID) controller for the surface vessel steering in 1922 [3], [4].

Ocean going vessel steering autopilots are designed to achieve course keeping and course changing maneuvers in the open sea [5]–[7]. For linear controllers, the PID controller with fixed gain is a conventional steering system and it can also show good performance for particular operating conditions. Fang and Luo [8] introduced a PD controller in a track keeping control system and a PD controller was applied to rudder/fin roll stabilization and to maintain a track at sea [9]. Banazadeh and Ghorbani [10] developed a PID autopilot controller for a patrol vessel with the identified steering model. For other linear controllers, the internal model controller and the model predictive controller were applied to steering control system for path following and roll reduction [11], [12]. Li and Sun [13] also addressed a disturbance compensating model predictive heading controller to increase the safety of the state constraints. The ship dynamics can be influenced significantly by sailing conditions and unpredictable environmental disturbances, which may lead a weak performance. Therefore, some optimization algorithms have been applied to steering control, such as the ant colony optimization algorithm [14], the genetic algorithm (GA) [15] and the fuzzy method [16].

One of the major issues in modern marine autopilot systems is to guarantee robust stability and performances under these uncertainty conditions caused by complex ocean disturbances. Linear controllers based on the assumptions of linear state and parameter conditions cannot always be realistic. Several kinds of nonlinear controllers have been proposed to overcome the nonlinear steering problem in recent literature, such as feedback linearization, sliding mode control (SMC) and the adaptive method. The typical state feedback linearization method was adopted for a path following control system [17], [18]. Perera and Soares [19] proposed an input output linearization controller for a steering system. A nonlinear feedback controller was developed with a sine function for marine course keeping [20]. The nonlinear state or parameters in ship steering dynamics are often linearized around specific points in these controllers and always address known bounded disturbances. The sliding mode control is based on the Lyapunov stability theorem and a large number of papers are available on the ship control. For surface vessels, Zhang *et al.* [21] discussed the path following control problem in restricted waters. Alfaro-Cid *et al.* [22] designed two decoupled sliding mode controllers for the navigation and propulsion systems of a supply ship. Fang and Luo [23] compared two sliding mode controllers for roll reduction and a track keeping control system. Harl and Balakrishnan [24] considered a second order sliding mode control strategy for path following. Perera and Soares [25] proposed a pre-filtered sliding mode control law to solve the nonlinear steering dynamic problem (i.e., parameter uncertainties and un-modeled dynamics). Li *et al.* [26] illustrated an active disturbance rejection controller with a sliding mode to overcome the external disturbances. Still considering the following and course keeping problem, to overcome the uncertain environmental disturbances under sensor-less conditions, Qin *et al.* [27] developed a sliding mode controller with a high gain observer for an underactuated ship. Liu *et al.* [28] presented a nonsingular terminal sliding mode controller with an extended disturbance observer (EDO) for a fully submerged hydrofoil craft.

The ship dynamics can be changed significantly due to sailing conditions and unpredictable environmental disturbances. Therefore, a nonlinear controller that overcomes unknown bounded external disturbance and guarantees robustness is needed. The adaptive method probably remains a better method to address parameter uncertainties and unknown bounded disturbances. The adaptive technique has been applied to ship motion control areas (e.g., surface vessel and submarine). For the path following and course keeping problem of surface underactuated ships, the adaptive and global robust method based on Lyapunov's direct method are presented to estimate the values of ship unknown parameters and cope with the bounded time varying terms of environmental disturbances [29]. The adaptive neural network (NN) method was developed to consider ship uncertainties and the boundaries of external disturbances without the known information of hydrodynamic structures [30], [31]. The adaptive technique has also been combined with dynamic surface control (DSC) and fuzzy and backstepping methods [32]–[35] for nonlinear ship steering problems, Zhang *et al.* [36] proposed an adaptive neural networks robust course keeping controller by combining the backstepping technique. In the area of underwater vehicles, Cristi *et al.* [37] considered both adaptive and non-adaptive techniques to design robust autonomous underwater vehicles (AUV) robust controllers for changing dynamics and operating conditions. Do [38] introduced a robust adaptive controller for omni-directional intelligent navigator (ODIN) tracking under stochastic environmental loads. An adaptive fully tuned fuzzy NN tracking controller was considered for an unmanned underwater vehicle (UUV) that is subjected to unknown disturbances and dynamic uncertainties [39]. This study is limited to a nonlinear surface vessel course keeping control under the assumption that the forward speed is constant. An adaptive sliding mode controller with disturbance observer is proposed to address unknown bounded external disturbances.

The organization of this paper is as follows. Section II contains the mathematical modeling of the ship steering. Section III formulates the proposed control algorithms of the sliding mode with nonlinear disturbance observer (NDO). The simulation results of the sliding mode controllers are presented in Section IV. Conclusions are given in Section V.

II. MATHEMATICAL MODEL

It is well known that when a ship is moving in an open sea, changes in the environment can have a large influence on its performance. The study of ship motion is very complex because a set of parameters must be determined in the motion dynamics. In this section, the mathematical models for the ship dynamics and waves are introduced, we present the model based on modified experimental results developed by Perez [40].

A. SWAY-YAW DYNAMICS

Assuming a constant forward speed U, the oscillating wave force effect is neglected. The mathematical model for the ship dynamics will now be introduced for a naval vessel. The dynamic equations of motion and corresponding forces in the body fixed frame can be represented as follows:

$$m(\dot{v} + Ur) + mx_G\dot{r} = Y_{hyd} + Y_c \tag{1}$$

$$mx_G(\dot{v} + Ur) + I_{zz}\dot{r} = N_{hyd} + N_c \tag{2}$$

$$\dot{\psi} = r \tag{3}$$

where m is the ship mass, and I_{zz} is the inertias. x_G is the coordinates of the center of gravity with respect to the body fixed frame. Sway velocity is represented by v. Yaw and its angular velocity are denoted by ψ and r, respectively. Y and N are external forces with respect to sway and yaw. Subscripts hyd and c denote hydrodynamic terms and the force or moment produced by the control surface.

The hydrodynamic model equations of the vessel are given as follows:

$$Y_{hyd} = Y_{\dot{v}}\dot{v} + Y_{\dot{r}}\dot{r} + Y_{|U|v}|U|v + Y_{Ur}Ur + Y_{v|v|}v|v| + Y_{v|r|}v|r| + Y_{r|v|}r|v| \tag{4}$$

$$N_{hyd} = N_{\dot{v}}\dot{v} + N_{\dot{r}}\dot{r} + N_{|U|v}|U|v + N_{|U|r}|U|r + N_{r|r|}r|r| + N_{r|v|}r|v| \tag{5}$$

The rudder is the device used for heading control in this investigation. The rudder induced forces and moments can be expressed by the following:

$$Y_c = \frac{1}{2}\rho A_R C_L U^2 \tag{6}$$

$$N_c = -\frac{1}{2}\rho A_R C_L U^2 LCG \tag{7}$$

where ρ is the water density, A_R is the area of the rudder, C_L is the lift coefficient which varies with the effective angle of attack, and LCG is the distance from the center of gravity to the rudder stock.

B. STEERING MODEL

The ship steering system in this study is an underactuated system where the sway motion cannot be directly controlled. The study intends to investigate ship course keeping, so only yaw motion is considered. Combining the rudder action $N_c = N_\delta \delta$ and the wave disturbance, the steering dynamics can be treated as follows:

$$(I_{zz} - N_{\dot r})\dot r = N_{|U|r}|U|r + N_{r|r|}r|r| - mx_G Ur + N_\delta \delta + d \tag{8}$$

where δ is the rudder angle, and d is the yaw moment caused by waves.

This nonlinear model can be modified as

$$\dot r = a_1 r + a_2 r|r| + a_3\delta + a_4 d \tag{9}$$

where $a_1 = \frac{N_{|U|r}|U| - mx_G Ur}{I_{zz}-N_{\dot r}}$, $a_2 = \frac{N_{r|r|}}{I_{zz}-N_{\dot r}}$, $a_3 = \frac{N_\delta}{I_{zz}-N_{\dot r}}$, $a_4 = \frac{1}{I_{zz}-N_{\dot r}}$.

Assumption 1: The position and rate measurements of the yaw motion of the vehicle are available for feedback. The gyroscopic compass measures ψ and the yaw rate gyro measures r.

Assumption 2: The disturbance signal satisfies $|d(t)| \le d_{max}$, and d_{max} is an unknown positive constant.

C. DISTURBANCE MODEL

Complex sea states are the superposition of an infinite number of monochromatic waves, distributed in all directions. To simulate the random waves, an ITTC long-crest wave spectrum is adopted to recreate a fully developed sea environment. The spectral density formula (PDF) is given as follows:

$$S(\omega_i) = \frac{173H_{1/3}}{T^4\omega_i^5} exp(-\frac{691}{T^4\omega_i^4}) \tag{10}$$

where $H_{1/3}$ is the significant wave height, T is the wave period and ω_i is the wave frequency of the *ith* regular wave component.

In this paper, 60 regular wave components are used to form the irregular wave. The amplitude of each regular wave component ζ_i and the resultant wave ζ can be obtained by the following equations:

$$\zeta_i = \sqrt{2S(\omega_i)\Delta\omega} \tag{11}$$

$$\zeta = \sum_{i=1}^{60} \zeta_i \cos(\omega_i t + \varepsilon_i) \tag{12}$$

where ε_i is the random phase angle of the *ith* regular wave, which ranges from 0 to 2π. In this calculation, the resultant wave ζ is used to calculate the external forces. This calculation is performed using code prepared in MATLAB, along with the calculation of the wave excitation forces and moments.

For a ship moving with forward speed, the wave frequency will be modified as the encounter frequency,

$$\omega_{ei} = \omega_i - \frac{\omega_i^2}{g}\cos\beta \tag{13}$$

where β is the encounter angle.

Base on the strip theory, then the wave induced yaw moment is derived as follows:

$$d = \sum_{i=1}^{n}[d_{i1}\zeta_i\cos(\omega_{ei}t + \varepsilon_i) + d_{i2}\zeta_i\sin(\omega_{ei}t + \varepsilon_i)] \tag{14}$$

where $d_{i1} = 2\rho g \sum_{j=1}^{N}\{\exp(-k_i T_j/2)T_j x_j \sin[k_i B_j \sin(\beta/2)]$ $\cos(k_i x_j \cos\beta)\Delta x\}$ and $d_{i2} = 2\rho g \sum_{j=1}^{N}\{\exp(-k_i T_j/2)T_j x_j$ $\sin[k_i B_j \sin(\beta/2)]\sin(k_i x_j\cos\beta)\Delta x\}$. ζ_i and k_i are the wave amplitude and the wave number of the wave component i. N and Δx are the section number of ship and the length of each section. T_j, B_j and x_j are the draft, the breadth and the coordinate point of the section j.

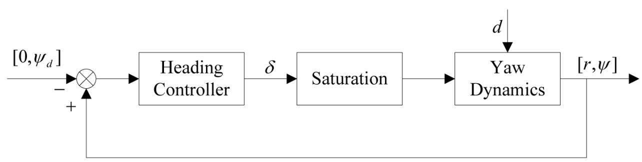

FIGURE 1. Autopilot control system.

III. CONTROL SYSTEM

The closed loop autopilot control system is shown in Figure 1. Here, ψ_d is the predetermined heading angle and the other desired values are set to zero. To reduce wear and tear on the steering machine, the saturation block is selected to limit the amplitude of the rudder angle.

The sliding mode control (SMC) used here can accommodate system parameter uncertainties and reject external bounded disturbances as well as quantify the modeling and performance trade-off. In this section, we present an adaptive sliding mode controller with nonlinear disturbance observer to address the unknown bounded disturbance that can maintain the system robustness.

A. ADAPTIVE SLIDING MODE CONTROLLER

Considering (9), the nonlinear steering system contains a nonlinear term (i.e., the absolute value of yaw rate). The feedback linearization method is adopted to convert the nonlinear part. By defining a new control signal u and the rudder angle order can be treated as follows:

$$\delta = \frac{1}{a_3}(u - a_2 r|r|) \tag{15}$$

Then, the nonlinear steering system is expressed in a linear equation

$$\dot{r} = a_1 r + u + a_4 d \tag{16}$$

And the state space format is

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}u + \bar{d} \tag{17}$$

where $\mathbf{x} = \begin{bmatrix} r \\ \psi \end{bmatrix}$, $\mathbf{A} = \begin{bmatrix} a_1 & 0 \\ 1 & 0 \end{bmatrix}$, $\mathbf{B} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}$, $\bar{d} = a_4 d$.

Let the reference state be $\mathbf{x}_d = [0, \psi_d]$ and $\dot{\mathbf{x}}_d = 0$, a sliding manifold is used to obtain the control law and is defined as follows:

$$s = \mathbf{h}^{\mathrm{T}}\mathbf{x}_e = \mathbf{h}^{\mathrm{T}}(\mathbf{x} - \mathbf{x}_d) \tag{18}$$

where $\mathbf{h} = [h_1, h_2]^{\mathrm{T}}$ is a right eigenvector of $\mathbf{A}_c$ (i.e. $\mathbf{A}_c^{\mathrm{T}}\mathbf{h} = \lambda\mathbf{h}$), and the weighting vector $\mathbf{h}$ is selected by computing the equation $\mathbf{A}_c^{\mathrm{T}}\mathbf{h} = 0$ for $\lambda = 0$ [3], [41].

In the SMC system, a feedback control law is written as

$$u = -\mathbf{k}\mathbf{x} + u_0 \tag{19}$$

where the first item of the controller is a state feedback control law (i.e., an equivalent controller), the second term is a nonlinear switching control law.

Substituting (19) into (17), we obtain

$$\dot{\mathbf{x}} = \mathbf{A}_c\mathbf{x} + \mathbf{B}u_0 + \bar{d} \tag{20}$$

where the combined state matrix is $\mathbf{A}_c = \mathbf{A} - \mathbf{B}\mathbf{k}^{\mathrm{T}}$, $\mathbf{k} = [k, 0]^{\mathrm{T}}$ is the feedback gain vector and the zero gain in $\mathbf{k}$ represents the integration in the yaw angle channel.

The nonlinear switching control law to reject the disturbance is chosen as follows:

$$u_0 = -(\mathbf{h}^{\mathrm{T}}\mathbf{B})^{-1}[\mathbf{h}^{\mathrm{T}}\hat{\bar{d}} + \eta\,\mathrm{sgn}(s)] \tag{21}$$

where $\hat{\bar{d}}$ is the estimate of $\bar{d}$.

Differentiating the sliding surface function gives

$$\begin{aligned} \dot{s} &= \mathbf{h}^{\mathrm{T}}\mathbf{A}_c\mathbf{x} + \mathbf{h}^{\mathrm{T}}\mathbf{B}u_0 + \mathbf{h}^{\mathrm{T}}\bar{d} - \mathbf{h}^{\mathrm{T}}\dot{\mathbf{x}}_d \\ &= \lambda\mathbf{x}^{\mathrm{T}}\mathbf{h} - \eta\,\mathrm{sgn}(s) + \mathbf{h}^{\mathrm{T}}\Delta\bar{d} \\ &= -\eta\,\mathrm{sgn}(s) + \mathbf{h}^{\mathrm{T}}\Delta\bar{d} \end{aligned} \tag{22}$$

where the first item in the right of the above equation $\lambda\mathbf{x}^{\mathrm{T}}\mathbf{h} = 0$ if $\mathbf{h}$ is a right eigenvector, and $\mathbf{h}^{\mathrm{T}}\dot{\mathbf{x}}_d = 0$ because the reference signal $\mathbf{x}_d$ is a constant vector. The parameter $\Delta\bar{d} = \bar{d} - \hat{\bar{d}}$ is the estimation error.

Since the disturbance is unknown, a better guess for it is $\hat{\bar{d}} = 0$. Hence, the nonlinear switching control law becomes

$$u_0 = -(\mathbf{h}^{\mathrm{T}}\mathbf{B})^{-1}\eta\,\mathrm{sgn}(s) \tag{23}$$

where $\eta > a_4 d_{max}\|\mathbf{h}\| = \bar{d}_{max}\|\mathbf{h}\|$.

The equation (23) leads to the sliding mode controller (SMC)

$$\delta = \frac{1}{a_3}[-kr - \frac{1}{h_1}\eta\,\mathrm{sgn}(s/\phi) - a_2 r|r|] \tag{24}$$

In this controller, a larger switching gain η corresponds to a shorter time to reach $s = 0$ and the system robustness against the environmental disturbance is proven. However, the upper bound of disturbance is often difficult to find in practice. Therefore, the adaptive method is adopted to tune the controller gain without the knowledge about the disturbance. Still, considering that the estimation of disturbance is zero, the robust switching control law of the total controller is modified as

$$u_0 = -(\mathbf{h}^{\mathrm{T}}\mathbf{B})^{-1}\hat{\eta}\,\mathrm{sgn}(s) \tag{25}$$

where $\hat{\eta}$ is the estimate of the adjustable gain and is a positive value.

The adaptation law is written as

$$\dot{\hat{\eta}} = \frac{1}{\alpha}|s| \tag{26}$$

where $\alpha > 0$ is the adaptation gain.

To avoid the over increased control value caused by the adaptation law, the projection algorithm [42] is selected to limit the value of $\hat{\eta}$ in a suitable range, written as

$$\dot{\hat{\eta}} = \mathrm{Proj}_{\hat{\eta}}(\dot{\hat{\eta}}) \tag{27}$$

where $\mathrm{Proj}_{\hat{\eta}}(\bullet) = \begin{cases} 0 \text{ if } \hat{\eta} \geq \eta_{max} \text{ and } \bullet > 0 \\ 0 \text{ if } \hat{\eta} \leq \eta_{min} \text{ and } \bullet < 0 \\ \bullet \quad \text{otherwise} \end{cases}$

Then, the differentiation of the sliding surface is

$$\begin{aligned} \dot{s} &= \mathbf{h}^{\mathrm{T}}(\dot{\mathbf{x}} - \dot{\mathbf{x}}_d) = \mathbf{h}^{\mathrm{T}}(\mathbf{A}_c\mathbf{x} + \mathbf{B}u_0 + \bar{d}) \\ &= \mathbf{h}^{\mathrm{T}}\mathbf{B}u_0 + \mathbf{h}^{\mathrm{T}}\bar{d} = -\hat{\eta}\,\mathrm{sgn}(s) + \mathbf{h}^{\mathrm{T}}\bar{d} \end{aligned} \tag{28}$$

Selecting the Lyapunov function,

$$V = \frac{1}{2}s^2 + \frac{1}{2}\alpha\tilde{\eta}^2 \tag{29}$$

where $\tilde{\eta} = \hat{\eta} - \eta$ is the estimate error.

$$\begin{aligned} \dot{V} &= \frac{1}{2}s\dot{s} + \frac{1}{2}\alpha\tilde{\eta}^2 = s[\mathbf{h}^{\mathrm{T}}\bar{d} - \hat{\eta}\,\mathrm{sgn}(s)] + \alpha(\hat{\eta} - \eta)\dot{\hat{\eta}} \\ &= s\mathbf{h}^{\mathrm{T}}\bar{d} - \hat{\eta}|s| + (\hat{\eta} - \eta)|s| = s\mathbf{h}^{\mathrm{T}}\bar{d} - \eta|s| \leq 0 \end{aligned} \tag{30}$$

Equation (30) holds for all time the external disturbance. The parameter is chosen in (25), which implies that the system trajectory will move and reach the sliding surface in a finite period of time and the sliding surface declines to zero, so the control law given by the equation of (19) guarantees the sliding mode sustained [43]. The *tanh* function is takes the place of the *signum* function to attenuate the chattering effect. Hence, the adaptive sliding mode controller (ASMC) is

$$\delta = \frac{1}{a_3}[-kr - \frac{1}{h_1}\hat{\eta}\tanh(s/\phi) - a_2 r|r|] \tag{31}$$

where ϕ is the boundary layer thickness.

B. NONLINEAR DISTURBANCE OBSERVER

In the last section, the estimate of the disturbance is treated as zero because no knowledge of the disturbance is available. An alternative method to process this problem is known as disturbance observer (DO). The yaw acceleration is not easily obtained, and it is also difficult to construct the acceleration signal from the yaw rate by differentiation. Therefore, a modified observer known as a nonlinear disturbance observer (NDO) [44], [45] is adopted here.

Define a variable

$$z = \hat{d} - p(r, \psi) \tag{32}$$

Let the function $p(r, \psi)$ be given by the following equation

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{L(r, \psi)}{a_4}\dot{r} \tag{33}$$

Define the observer error signal

$$\tilde{d} = d - \hat{d} \tag{34}$$

According to the linear disturbance observer, a DO is proposed as

$$\begin{aligned}
\dot{\hat{d}} &= L(r, \psi)(d - \hat{d}) \\
&= L(r, \psi)(\frac{1}{a_4}\dot{r} - \frac{a_1}{a_4}r - \frac{a_2}{a_4}r|r| - \frac{a_3}{a_4}\delta) - L(r, \psi)\hat{d} \\
&= L(r, \psi)(\frac{1}{a_4}\dot{r} - \frac{a_1}{a_4}r - \frac{a_2}{a_4}r|r| - \frac{a_3}{a_4}\delta) \\
&\quad - L(r, \psi)[z + p(r, \psi)] \\
&= L(r, \psi)[\frac{1}{a_4}\dot{r} - \frac{a_1}{a_4}r - \frac{a_2}{a_4}r|r| - \frac{a_3}{a_4}\delta - p(r, \psi)] \\
&\quad - L(r, \psi)z
\end{aligned} \tag{35}$$

In general, the prior information about the derivative of the environment disturbance is unavailable, and the disturbance varies slowly relative to the observer dynamics. Then, it reasonable to suppose that

$$\dot{d} = 0 \tag{36}$$

Hence, the derivative of the observer error is

$$\dot{\tilde{d}} = \dot{d} - \dot{\hat{d}} = -\dot{\hat{d}} = -L(r, \psi)\tilde{d} \tag{37}$$

Let the functions in (33) be chosen as

$$L(r, \psi) = a \tag{38}$$

where is a positive constant.

Then, we obtain equations

$$p(r, \psi) = \frac{a}{a_4}r \tag{39}$$

$$\frac{\mathrm{d}p}{\mathrm{d}t} = \frac{a}{a_4}\dot{r} \tag{40}$$

Combining the above equations, the update law can be written as

$$\begin{aligned}
\dot{z} &= \dot{\hat{d}} - \frac{\mathrm{d}p}{\mathrm{d}t} = \dot{\hat{d}} - \frac{a}{a_4}\dot{r} \\
&= -az + a[-\frac{a_1 + a}{a_4}r - \frac{a_2}{a_4}r|r| - \frac{a_3}{a_4}\delta]
\end{aligned} \tag{41}$$

Hence, the NDO is given by

$$\hat{d} = z + \frac{a}{a_4}r \tag{42}$$

The nonlinear switching control law in this SMC is defined as

$$u_0 = -(\mathbf{h}^{\mathrm{T}}\mathbf{B})^{-1}[\mathbf{h}^{\mathrm{T}}a_4\hat{d} + \hat{\eta}_0\mathrm{sgn}(s)] \tag{43}$$

where $\hat{\eta}_0$ is the estimate of the adjustable gain. Assuming there is a positive η_0 that $u_0 = -(\mathbf{h}^{\mathrm{T}}\mathbf{B})^{-1}[\mathbf{h}^{\mathrm{T}}a_4\hat{d} + \eta_0\mathrm{sgn}(s)]$ is the terminal solution, the gain must satisfy $\eta_0 > \|\mathbf{h}\| \cdot \|\Delta\bar{d}\|$ and $\hat{\bar{d}} = a_4\hat{d}$.

Let the Lyapunov function be chosen as

$$V = \frac{1}{2}s^2 + \frac{1}{2}\alpha\tilde{\eta}_0^2 + \frac{1}{2}\tilde{d}^2 \tag{44}$$

Differentiation of the Lyapunov function with respect to the trajectory of states gives

$$\begin{aligned}
\dot{V} &= s\dot{s} + \alpha\tilde{\eta}_0\dot{\tilde{\eta}}_0 + \tilde{d}\dot{\tilde{d}} \\
&= s[\mathbf{h}^{\mathrm{T}}\mathbf{A}_c\mathbf{x} - \hat{\eta}_0\mathrm{sgn}(s) + \mathbf{h}^{\mathrm{T}}\bar{d} - \mathbf{h}^{\mathrm{T}}a_4\hat{d}] \\
&\quad + (\hat{\eta}_0 - \eta_0)|s| - a\tilde{d}^2 \\
&= s[-\hat{\eta}_0\mathrm{sgn}(s) + \mathbf{h}^{\mathrm{T}}\Delta\bar{d}] + (\hat{\eta}_0 - \eta_0)|s| - a\tilde{d}^2 \\
&= -\hat{\eta}_0|s| + \mathbf{h}^{\mathrm{T}}\Delta\bar{d}s + (\hat{\eta}_0 - \eta_0)|s| - a\tilde{d}^2 \\
&= \mathbf{h}^{\mathrm{T}}\Delta\bar{d}s - \eta_0|s| - a\tilde{d}^2 \leq 0
\end{aligned} \tag{45}$$

Hence, it is observed that (45) always makes a negative semi-definite condition, and the controller can obtain semi global stabilization. Still selecting *tanh* function, the final rudder angle control law is written as

$$\begin{aligned}
\delta &= \frac{1}{a_3}[-kr - a_4\hat{d} - \frac{1}{h_1}\hat{\eta}_0\tanh(s/\phi) - a_2r|r|] \\
&= \frac{1}{a_3}[-kr - \frac{1}{h_1}\hat{\eta}_0\tanh(s/\phi) - a_2r|r|] - \frac{a_4}{a_3}\hat{d}
\end{aligned} \tag{46}$$

where the first part in (46) can be treated as an adaptive sliding mode controller (ASMC) that rejects the disturbance $\Delta\bar{d}$. The structure of this controller is shown in Figure 2.

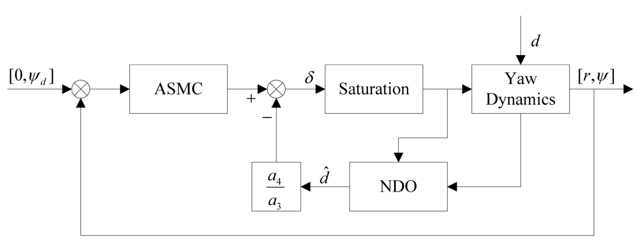

FIGURE 2. Modified autopilot control system.

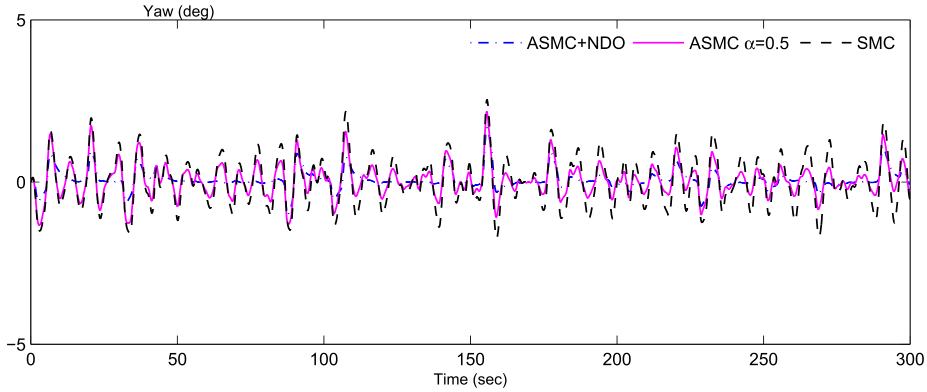

FIGURE 3. The comparison of yaw angles with different controllers.

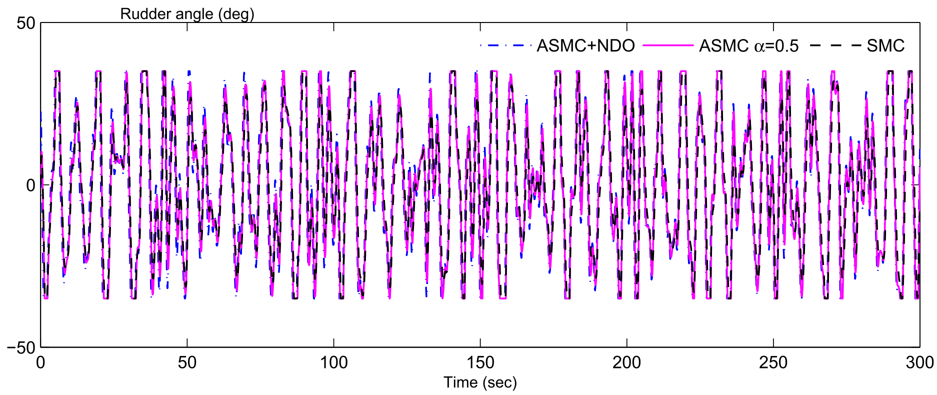

FIGURE 4. The comparison of rudder angles with different controllers.

IV. SIMULATION RESULTS

The heading control system simulation of a navy vessel is demonstrated [40]. The nominal ship speed is 15 knots, and it is modeled as sailing in a sea environment by assuming the water depth is infinitely deep. The wave disturbance is simulated with a significant wave height of 4 m and an average period of 8 s. The magnitude constraint for the rudder angle of 35° and twin rudders are equipped. The desired state trajectory is assumed to be $\mathbf{x}_d = (0, 0)^{\mathrm{T}}$, the initial state vector is $\mathbf{x} = (0, 0)^{\mathrm{T}}$, the initial guess of η is 2 for SMC. The initial values of the adaptation law are set as $\hat{\eta}(0) = 2.5$ and $\hat{\eta}_0(0) = 2$. Both of η and η_0 are set as the same form of the adaptation law with $\alpha = 0.5$. The boundary layer is chosen as $\phi = 1$. The linear state feedback gain is $k = 0.1$ and (η_{min}, η_{max}) is considered as $(1, 10)$. The NDO parameter is selected as $a = 30$. The vessel is sailing in an oblique wave condition with the encounter angle 135°, and the time domain simulation is performed by the variable step numerical integration method.

The simulation results of the course keeping maneuvers of a nonlinear ship autopilot system are presented in Figures. 3 to 5. These simulations consist of the vessel response of adaptive sliding mode controller with nonlinear disturbance observer (ASMC+NDO), adaptive sliding mode controller (ASMC) with adaptation gain $\alpha = 0.5$ and the normal sliding mode controller (SMC). The corresponding values of the heading response and rudder cost are given in Table 1.

TABLE 1. Cost values of simulation.

Controller	Yaw response	Rudder angle
SMC	2094.87	59471.21
ASMC+NDO	645.67	69397.12
ASMC with $\alpha = 0.5$	1294.16	67352.13

The data of Table 1 show that the ASMC+NDO can obtain better course keeping performance with its smaller adaptation gain in comparison with ASMC, because a larger switching gain corresponds to a shorter time to reach $s = 0$, and the system robustness against the environmental disturbance is proven. A good heading control performance can be achieved, but at the cost of larger rudder responses that may increase the wear and tear of the steering machine. The yaw responses of ASMC are reduced 50.1% by the NDO. Meanwhile, the rudder cost is increased by only 3%. As the rudder actuation system is limited by the rudder angle limitation, the ASMC+NDO makes realistic conditions in the course keeping maneuvers and generates the fastest

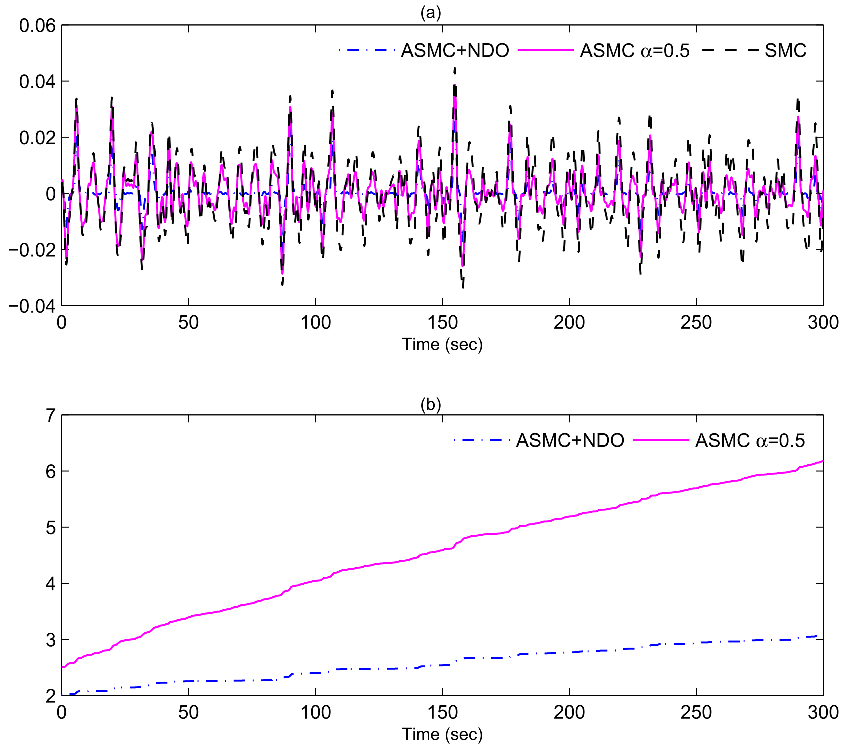

FIGURE 5. The comparison of sliding surfaces angles with different controllers. (a) Sliding surface. (b) η estimate

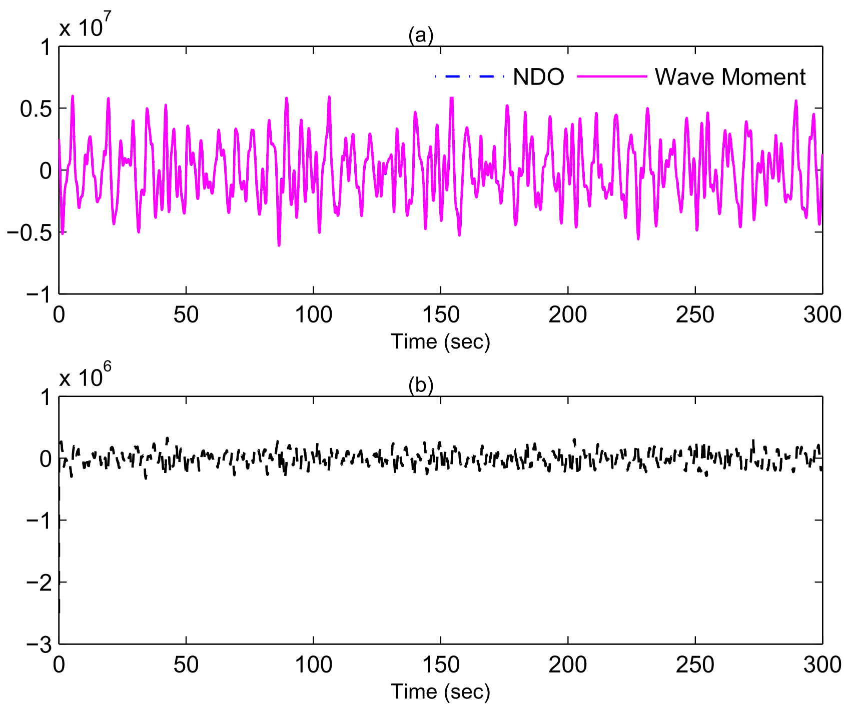

FIGURE 6. The simulation results of NDO. (a) Observer (N.m). (b) Estimation error (N.m)

performance when it converges to the reference heading. This is mainly due to the accurate estimation of the wave disturbance that control actions demanded by the controller in (44) can effectively reject the motion responses caused by the external disturbance, and this controller will not depend on the larger switching gain. The switching gain η_0 may be more easily selected than the gain η, because the former is decided by the upper bound of the disturbance estimation error, however the later is decided by the upper bound of the external disturbance which is unavailable. A guess is that the SMC can obtain a good performance by selecting a higher gain, and this performance will be obtained at the cost of higher rudder actuations that should be avoided in practice.

Figure 6 presents the time series of the NDO, where the mean amplitude of the estimation error is approximately 5% of the disturbance's mean amplitude. Better estimation performance can be obtained when a larger value of $L(r, \psi)$ is chosen, since an overlarge value can cause an algebraic loop problem in the process of numerical calculation, the value ($a = 30$) decided in this study is reasonable.

V. CONCLUSION

This paper discusses several schemes to address the unknown bounded external disturbance for the nonlinear vessel course keeping control system (i.e., sliding mode controller, adaptive controller and nonlinear observer) based on feedback linearization. As presented in the simulation results, all controllers can achieve the course keeping performance by assuming that all required heading states could be measured accurately by sensors. As noted in the simulations, the rudder response could overshoot beyond the limitation of rudder angle due to the control output signals requirement. The vessel autopilot system performance is evaluated under a trade-off between the rudder control gain and the course keeping response. Compared to the control performance, the ship heading response under the ASMC+NDO represents superior performance that requires similar rudder cost and achieves faster heading response. Under the rough weather sailing condition, the further work will focus on the parameter identification method of nonlinear steering system [46], [47] and the heading controller based on nonlinear robust disturbance observer (NRDO) [48], [49], including the course keeping controller and the course changing controller.

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