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Global Terminal Sliding Mode Control With the Quick Reaching Law and Its Application

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ABSTRACT In order to overcome the disadvantages of the conventional sliding mode reaching law, such as the large chattering and the slow convergence rate, an improved quick reaching law is proposed. The reaching law is composed of two terms which can, respectively, play the leading role when the system is far away from or near to the sliding mode surface. Thus, the system can arrive at the sliding mode surface with the faster convergence rate from beginning to end. Some other advantages of the reaching law, such as converging to the sliding mode surface in a finite time, and the second-order sliding mode characteristic are proved. Furthermore, in order to speed up the convergence rate to the equilibrium point along the sliding mode surface, the global terminal sliding mode control based on the quick reaching law is designed. It is used to control the unmanned surface vehicle. Simulation results show that the control method has better control performance than the conventional methods.

INDEX TERMS Global terminal sliding mode, reaching law, sliding mode control, unmanned surface vehicle.

I. INTRODUCTION

Sliding mode variable structure control has been a valid control method for the uncertain system because of its good robustness to both the external disturbances and the internal parametric variations [1]–[5]. Sliding mode variable structure control has many advantages, such as strong robustness, and fast response. However, its chattering phenomenon is a serious problem which limits its applications in the practical engineering fields. The chattering phenomenon means the system would go back and forth through the sliding surface with a small amplitude and the high frequency, which increases energy consumption and even causes the instability. It is important to eliminate the chattering of the sliding mode control for the practical engineering applications. The high order sliding mode control [6]–[9] or the nonsingular terminal sliding mode control [10]–[12] could resolve the problem. However, the respective defects of the two methods are obvious. Such as, the high order sliding mode control could not be applied in the first-order system, and the reaching law of the nonsingular terminal sliding mode control is slow when the state of the system is close to the sliding mode surface.

For all this, a series of practical reaching laws of sliding mode control were proposed to resolve the chattering problem [13], [14]. These reaching laws, such as the constant reaching law, the exponential reaching law and the power reaching law, are the most commonly used [15], [16].

Generally speaking, the reaching speed of the constant reaching law is slow [17]. The exponential reaching law which could be designed by adding an exponential into the constant reaching law has the higher reaching speed [18]. However, both of them could not eliminate the chattering phenomenon theoretically [19], [20]. The power reaching law could reduce the chattering, but its reaching speed is slower. Combing the power reaching law and the exponential reaching law, a fast power reaching law could be designed, and it could overcome the disadvantages of the power reaching law [21], [22]. In the same way, the double power reaching law which could also be designed by the linear combination of two power reaching laws could improve the performance of the power reaching law further and reduce the chattering amplitude [23], [24]. Some deep investigations on the convergence time and the control quality of the double power reaching law have been done in [25], and both the theoretical analysis and the simulation results show that the double power reaching law has better control performance than the reaching laws above [26]. Another novel power rate reaching law was proposed to ensure fast reaching to the sliding surface along with properties of complete elimination of chattering and bounded control inputs [27]. In general, the power reaching law shows the good reaching performance in the sliding mode control. Furthermore, over the past few decades, the global sliding mode control has also been widely studied and many researchers have investigated in this field. Such as, an adaptive global sliding mode control technique was designed for the tracking control of uncertain and non-linear time-varying systems [28]. Combining the particle swarm optimization method, an adaptive global second-order sliding surface was designed for perturbed dynamical systems with matched and unmatched external disturbances [29]. An adaptive super-twisting global nonlinear sliding mode control technique was designed for n-link rigid robotic manipulators [30]. Therefore, the performance of sliding mode control would be further improved by combining the global terminal sliding mode surface with the reaching law.

Many practical systems belong to the nonlinear complex control systems [31]–[33]. For instance, in the unmanned surface vehicle system [34], [35], the fast response of the system is very important to route a reasonable the course or trajectory. In order to improve the control quality of the nonlinear complex system, based on the researches above, a novel improve quick reaching law is proposed to speed up the convergence of the system. The characteristics of the reaching law are analyzed, and the reaching law can make the system always have fast reaching speed whenever the system is far from or near to the sliding surface. Furthermore, the global terminal sliding mode control based on the quick reaching law is designed to control the unmanned surface vehicle.

II. IMPROVED QUICK REACHING LAW

In order to quickly arrive at the sliding mode surface in the whole approaching process, a novel improved quick reaching law is designed as:

$$\dot{s} = -k_1\left(b^{|s|}-1\right)\operatorname{sgn}(s) - k_2|s|^a\operatorname{sgn}(s) \tag{1}$$

where, $0 < a < 1$, $k_1 > 0$, $k_2 > 0$, and $b = 1 + k_2/k_1$. When the state of the system is far away from the sliding surface, i.e., $|s| > 1$, the first term in Eq.(1) plays the leading role. Its change rate is larger than that of the power function, which can speed up the reaching rate in this case. Likewise, when the state of the system is near to the sliding surface, i.e., $|s| < 1$, the second term in Eq.(1) plays the leading role, which can make the system arrive at the sliding surface with a slightly higher speed than the power function. Combing the roles of the two terms, the reaching law in Eq.(1) can make the system have the better dynamic characteristic in the whole reaching process.

A. CHARACTERISTIC ANALYSIS

Theorem 1: For the system described in Eq.(1), the state variables, s and $\dot{s}$ can converge to the equilibrium point (0, 0) in a finite-time. That is, the state variables would be $\dot{s} = s = 0$ after a finite convergence time.

Proof: According to the system in Eq.(1) and the conditions, $0 < a < 1$, $k_1 > 0$, $k_2 > 0$, $b = 1 + k_2/k_1$, the expression can be obtained as:

$$\begin{aligned} s\cdot\dot{s} &= s\left[-k_1\left(b^{|s|}-1\right)\operatorname{sgn}(s) - k_2|s|^a\operatorname{sgn}(s)\right] \\ &= -k_1|s|\left(b^{|s|}-1\right) - k_2|s|^{a+1} \le 0 \end{aligned} \tag{2}$$

In Eq.(2), the equality holds up only when s =0. Therefore, the sliding mode meets the reachability condition. The proposition that the system can reach the sliding mode in a finite-time can be proved as follows:

When the initial state $s(0) > 1$, the motion process from the initial state to the sliding mode can be divided into two stages: $s(0) \to s = 1$ and $s = 1 \to s = 0$. The motion time of the two stages could be calculated separately.

In the first stage, $s(0) \to s = 1$, i.e., $s > 1$. According to the conditions: $b = 1+k_2/k_1$, i.e., $k_1(b^{|s|}-1) > k_2|s|^a$, it can be seen that the first term in Eq.(1) plays a greater role than the second term, so the second term can be ignored. Then:

$$\dot{s} = -k_1\left(b^{|s|}-1\right)\operatorname{sgn}(s) = -k_1\left(b^{s}-1\right) \tag{3}$$

Integrate Eq.(3):

$$\int_0^{t_1} dt = \int_{s(0)}^{1} \frac{1}{k_1\left(1-b^{s}\right)}ds = \int_{s(0)}^{1} \frac{1}{k_1\ln b}d\left(\ln\left(1-b^{-s}\right)\right) \tag{4}$$

Thus, the convergence time of the first stage could be calculated as:

$$t_1 = \frac{\ln\left(1-b^{-1}\right) - \ln\left(1-b^{-s(0)}\right)}{k_1\ln b} \tag{5}$$

In the second stage, $s = 1 \to s = 0$. According to the conditions: $b = 1+k_2/k_1$, i.e., $k_1(b^{|s|}-1) < k_2|s|^a$, it can be seen that the second term in Eq.(1) plays a greater role than the first term, so the first term can be ignored. Then:

$$\dot{s} = -k_2|s|^a\operatorname{sgn}(s) = -k_2 s^a \tag{6}$$

Integrate Eq.(6):

$$\int_0^{t_2} dt = \int_1^0 \frac{1}{-k_2 s^a}ds \tag{7}$$

Thus, the convergence time of the second stage could be calculated as:

$$t_2 = \frac{1}{k_2(1-a)} \tag{8}$$

The convergence time of the two stages above is calculated in the condition of ignoring the minor term, so the total convergence time $t_{s(0)>1}$ of the reaching law could be calculated as:

$$t_{s(0)>1} < t_1 + t_2 = \frac{\ln\left(1-b^{-1}\right) - \ln\left(1-b^{-s(0)}\right)}{k_1\ln b} + \frac{1}{k_2(1-a)} \tag{9}$$

Similarly, when the initial state $s(0) < -1$, the motion process from the initial state to the sliding mode can also be divided into two stages: $s(0) \rightarrow s = -1$ and $s = -1 \rightarrow s = 0$. The motion time of the two stages could also be calculated separately.

In the first stage, $s(0) \rightarrow s = -1$, the first term in Eq.(1) plays a greater role than the second term, so the second term can be ignored. Then:

$$\dot{s} = -k_1 \left(b^{|s|} - 1\right) \mathrm{sgn}\,(s) = k_1 \left(b^{|s|} - 1\right) = k_1 b^{-s} - k_1 \tag{10}$$

Integrate Eq.(10)

$$\int_0^{t_1} dt = \int_{s(0)}^{-1} \frac{1}{k_1 \left(1 - b^{-s}\right)} ds = \int_{s(0)}^{-1} \frac{1}{k_1 \ln b} d(\ln(1 - b^s)) \tag{11}$$

Thus, the convergence time of the first stage can be calculated as:

$$t_1' = \frac{\ln\left(1 - b^{-1}\right) - \ln\left(1 - b^{s(0)}\right)}{k_1 \ln b} \tag{12}$$

In the second stage, $s = -1 \rightarrow s = 0$, the second term in Eq.(1) plays a greater role than the first term, so the first term can be ignored. Then:

$$\dot{s} = -k_2 |s|^a \mathrm{sgn}(s) = k_2 (-s)^a \tag{13}$$

Integrate Eq.(13):

$$\int_0^{t_2} dt = \int_{-1}^{0} \frac{1}{k_2 (-s)^a} ds \tag{14}$$

Thus, the convergence time of the second stage can be calculated as:

$$t_2' = \frac{1}{k_2(1 - a)} \tag{15}$$

Similarly, the convergence time of the two stages above is calculated in the condition of ignoring the minor terms, so the total convergence time $t_{s(0)<-1}$ of the reaching law could be described as:

$$t_{s(0)<-1} < t_1' + t_2' = \frac{\ln\left(1 - b^{-1}\right) - \ln\left(1 - b^{s(0)}\right)}{k_1 \ln b} + \frac{1}{k_2(1 - a)} \tag{16}$$

In conclusion, the system can reach the sliding mode in a finite-time. Furthermore, according to Eq.(1), when $s = 0$, it can be got that $\dot{s} = 0$. Therefore, the velocity at which the system reach the sliding mode is zero, which could effectively reduce the chattering.

B. THE STABLE BOUND FOR THE DISTURBANCE

When the uncertain bounded disturbance exists in the system, the state variables, s and $\dot{s}$, of the system in Eq.(1) could converge to a neighborhood of the equilibrium point (0, 0) in a finite-time.

Lemma 1 [36]: Let $x \in D \subset R^n$, $\dot{x} = f(x)$, $f : R^n \rightarrow R^n$ is continuous on an open neighborhood D of the origin and locally Lipshitz on $D\backslash\{0\}$ and $f(0) = 0$. Suppose there is a continuous function V: $D \rightarrow R$ such that the following conditions hold

(i) V is positive definite;

(ii) $\dot{V}$is negative on $D\backslash\{0\}$;

(iii) there exist real numbers $k > 0$ and $\alpha \in (0, 1)$, and a neighborhood $N \subset D$ of the origin such that $\dot{V} + kV^a \leq 0$ on $N\backslash\{0\}$.

Then, the origin is a finite-time-stable equilibrium of $\dot{x} = f(x)$.

Theorem 2: Suppose an uncertain system as:

$$\dot{s} = -k_1 \left(b^{|s|} - 1\right) \mathrm{sgn}(s) - k_2 |s|^a \mathrm{sgn}(s) + d(t)d \tag{17}$$

where, $d(t)$ is a bounded disturbance, that is, $|d(t)| \leq \delta$, and $\delta > 0$ is a positive constant. The state variables s and $\dot{s}$ of the uncertain system could separately converge to the regions as follows:

$$|s| \leq \log_b \left(\frac{\delta + k_1}{k_1}\right) \tag{18}$$

$$|\dot{s}| \leq k_2 \left(\log_b \left(\frac{\delta + k_1}{k_1}\right)\right)^a + 2\delta \tag{19}$$

Proof: Set a Lyapunov function as:

$$V = \frac{1}{2} s^2 \tag{20}$$

Then:

$$\begin{aligned}
\dot{V} &= s \cdot \dot{s} \\
&= s\left(-k_1 \left(b^{|s|} - 1\right) \mathrm{sgn}(s) - k_2 |s|^a \mathrm{sgn}\,(s) + d\,(t)\right) \\
&= -k_1 |s| \left(b^{|s|} - 1\right) - k_2 |s|^{a+1} + sd\,(t) \\
&\leq -k_1 |s| \left(b^{|s|} - 1\right) - k_2 |s|^{a+1} + |s|\,|d\,(t)|
\end{aligned} \tag{21}$$

Thus:

$$\begin{aligned}
\dot{V} &\leq -k_1 |s| \left(b^{|s|} - 1\right) - k_2 |s|^{1+a} + |s|\,|d\,(t)| \\
&\leq -k_2 |s|^{a+1} - \left(k_1 \left(b^{|s|} - 1\right) - \delta\right) |s|
\end{aligned} \tag{22}$$

When $k_1(b^{|s|}$-1)-$\delta \geq 0$, that is,

$$|s| \geq \log_b \left(\frac{\delta + k_1}{k_1}\right) \tag{23}$$

Then,

$$\dot{V} \leq -k_2 |s|^{a+1} \tag{24}$$

According to Eq.(20),

$$|s| = 2^{1/2} V^{1/2} \tag{25}$$

So,

$$\dot{V} \le -k_2 2^{(1+a)/2} V^{(1+a)/2} \tag{26}$$

Thus, according to Lemma 1, the origin is a finite-time-stable equilibrium of the system in Eq.(17). That is, according to Eq.(23), the region $|s| \le \log_b\left(\frac{\delta+k_1}{k_1}\right)$ is a finite-time convergence region. So, the state variable s of the system in Eq.(17) can converge to the region $|s| \le \log_b\left(\frac{\delta+k_1}{k_1}\right)$in a finite-time.

Furthermore, the state variable $\dot{s}$ of the system could converge to the following region in a finite-time.

$$\begin{aligned}|\dot{s}| &\le \left|-k_1\left(b^{|s|}-1\right)\operatorname{sgn}(s)\right| + \left|-k_2|s|^a \operatorname{sgn}(s)\right| + |d(t)| \\ &\le k_1\left(b^{|s|}-1\right) + k_2|s|^a + \delta \\ &\le k_2\left(\log_b\left(\frac{\delta+k_1}{k_1}\right)\right)^a + 2\delta \end{aligned} \tag{27}$$

Therefore, the theorem 2 is proved.

III. IMPROVED GLOBAL TERMINAL SLIDING MODE BASED ON THE QUICK REACHING LAW

From the discussion above, the quick reaching law can drive the system to converge to the sliding mode surface with a faster speed. After the system arriving at the sliding mode surface, in order to make the system still converge to the equilibrium point with a high speed along the sliding mode surface, the global terminal sliding mode surface, instead of the linear sliding mode surface, is used to construct the control law. That is, an improved global terminal sliding mode control based on the quick reaching law above is designed to enhance the control performance. For instance, a second-order single-input single-output system is described as:

$$\begin{cases}\dot{x}_1 = x_2 \\ \dot{x}_2 = u + d\end{cases} \tag{28}$$

where, d is the uncertain disturbance, $|d| \le D$, and D is the disturbance boundary.

The global terminal sliding mode surface is designed as:

$$s = \dot{x}_1 + cx_1 + \beta x_1^{q/p} \tag{29}$$

Thus,

$$\dot{s} = \dot{x}_2 + c x_2 + \beta\frac{q}{p}x_1^{(q-p)/p}x_2 \tag{30}$$

Combining the quick reaching law, a new global terminal sliding mode controller based on the quick reaching law could be designed as:

$$\begin{aligned} u = &-cx_2 - \beta\frac{q}{p}x_1^{q/p-1}x_2 \\ &- \left[k_1\left(b^{|s|}-1\right) + k_2|s|^a + (D+\eta)\right]\operatorname{sgn}(s) \end{aligned} \tag{31}$$

Thus,

$$\begin{aligned}\dot{s} &= cx_2 + \beta\frac{q}{p}x_1^{q/p-1}x_2 - cx_2 - \beta\frac{q}{p}x_1^{q/p-1}x_2 \\ &\quad - \left(k_1\left(b^{|s|}-1\right) + k_2|s|^a + D + \eta\right)\operatorname{sgn}(s) + d \\ &= -\left(k_1\left(b^{|s|}-1\right) + k_2|s|^a + D + \eta\right)\operatorname{sgn}(s) + d \end{aligned} \tag{32}$$

Then,

$$s\dot{s} = -\left(k_1\left(b^{|s|}-1\right) + k_2|s|^a + D + \eta\right)|s| + d\cdot s \tag{33}$$

The parameters $b > 1$, $b^{|s|}-1 \ge 0$, $|s|^a \ge 0$, $\eta > 0$ and $D \ge |d|$, so $\dot{V} \le 0$, and the equality holds up if and only if $s = 0$. Thus, the reachability of the sliding surface could be proved.

The quick reaching law is composed of two terms which is similar to the form of some conventional reaching laws, such as the fast power reaching law, the double power reaching law, and so on. Therefore, comparing with the existing methods, no extra complexity need to be considered in the method.

IV. EXPERIMENT RESULT

A. NUMERICAL EXPERIMENT

In order to prove the validity of this method, several control methods, the linear sliding mode control method (SMC), the global terminal sliding mode control method (TSMC), the linear sliding mode control method based on the quick reaching law (SMCQ) and the method proposed in this paper (TSMCQ), are respectively used to control the system in Eq.(28). The initial state is set as: $[x_1, x_2] = [1, 0]$, and the parameters of the control method are set as: $c = 1$, $k_1 = 1.1$, $k_2 = 0.7$, $b = 1 + k_2/k_1 = 1.636$, $a = 0.2$ and $\eta = 0.5$. The disturbance is set as: $d = \cos 25t$, and $D = 1$. The control results obtained separately by four control methods are shown in Fig.1, Fig.2 and Fig.3.

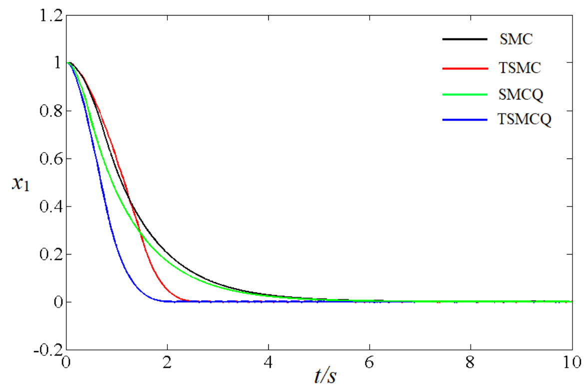

FIGURE 1. The response of the state variable x_1.

From Fig.1 to Fig.3, the global terminal sliding mode control method based on the quick reaching law has the higher convergence rate than others because the quick reaching law

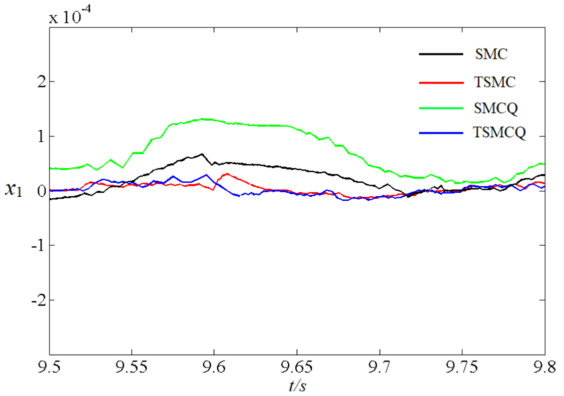

FIGURE 2. The partial enlargement of the Fig.1.

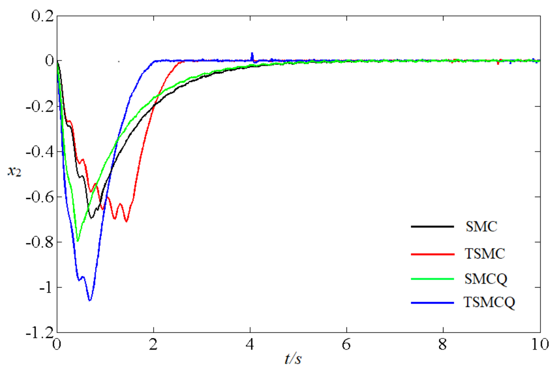

FIGURE 3. The response of the state variable x_2.

can drive the system from any initial position to reach the sliding mode surface with the high speed and the global fast terminal sliding mode can make the system converge to the equilibrium point quickly along the sliding mode surface. From Fig.2, the method proposed in this paper has the smaller chattering amplitude than others because of its second order sliding mode characteristic.

The phase trajectories of the system based on the control methods above are shown in Fig.4.

From Fig.4, because the state x_2 is the derivative of the state x_1, for the global fast terminal sliding mode control method based on the quick reaching law, the state x_1 can arrive at the sliding mode surface with the high speed x_2. And the chattering of the methods with the quick reaching law are significantly lesser than that of others.

B. THE CONTROL OF UNMANNED SURFACE VEHICLE

Unmanned surface vehicle is a self-propelled manned small surface watercraft. The hydrodynamic coefficients of the hull would vary with the speed variation. Therefore, the system is easy to be affected by the disturbances of the marine environment, such as wind, waves and currents during the navigation. That is, the unmanned surface craft has the characteristics of nonlinearity, uncertainty and time-varying [34], [35].

In order to further improve the control performance of the system, the global fast terminal sliding mode control method with the quick reaching law is used to control the unmanned surface vehicle. In the design of automatic steering system, taking into account the disturbance and uncertain factors from the external environment and the interior parameters, the yaw response model of the unmanned surface vehicle could be described as [37]:

$$\begin{cases} \dot{\psi} = r \\ \dot{r} = -\frac{1}{T}r - \frac{\alpha}{T}r^3 + \frac{K}{T}\delta + d \end{cases} \tag{34}$$

where, ψ represents the steering angle, $r$represents the yaw angular velocity, T represents the time constant, K represents the revolving parameter, α represents the nonlinear coefficient, i.e., Norbbin coefficient, δ represents the rudder angle, i.e., the nozzle angle of the water jet nozzle, d is the uncertainty caused by the unknown external disturbances, and $|d| \leq D$.

The course and the velocity of the unmanned surface vehicle could be controlled by changing the nozzle angle and the jet quantity which can be controlled by changing the engine speed.

Set $\psi = x_1$, $r = x_2$, and $\delta = u$, the model above can be simplified as:

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -\frac{1}{T}x_2 - \frac{\alpha}{T}x_2^3 + \frac{K}{T}u + d \end{cases} \tag{35}$$

The global terminal sliding mode surface could be designed as:

$$s = \dot{x}_1 + cx_1 + \beta x_1^{q/p} \tag{36}$$

where, $c > 0$, $\beta > 0$, both p and q are positive odd numbers, and $q < p$.

Thus,

$$\dot{s} = \dot{x}_2 + cx_2 + \beta \frac{q}{p} x_1^{(q-p)/p} x_2 \tag{37}$$

Combining the improved quick reaching law, the sliding mode controller could be designed as:

$$u(t) = \frac{T}{K}\left(\frac{1}{T}x_2 + \frac{\alpha}{T}x_2^3 - cx_2 - \beta\frac{q}{p}x_1^{q/p-1}x_2 - \left(k_1(b^{|s|}-1) + k_2|s|^a + D + \eta\right)\operatorname{sgn}(s)\right) \tag{38}$$

Substitute Eq.(38) and Eq.(35) into Eq. (37),

$$\begin{aligned} \dot{s} &= -\frac{1}{T}x_2 + \frac{1}{T}x_2 - \frac{\alpha}{T}x_2^3 + \frac{\alpha}{T}x_2^3 - \beta\frac{q}{p}x_1^{q/p-1}x_2 \\ &\quad - cx_2 - \left(k_1(b^{|s|}-1) + k_2|s|^a + D + \eta\right)\operatorname{sgn}(s) \\ &\quad + d + cx_2 + \beta\frac{q}{p}x_1^{q/p-1}x_2 \\ &= -\left(k_1(b^{|s|}-1) + k_2|s|^a + D + \eta\right)\operatorname{sgn}(s) + d \end{aligned} \tag{39}$$

where, $b > 1$, $b^{|s|} - 1 \geq 0$, $|s|^a \geq 0$, $\eta > 0$, $|s| \leq 0$, and $|d| \leq D$, so,

$$s\dot{s} = -\left(k_1(b^{|s|}-1) + k_2|s|^a + D + \eta\right)|s| + d \cdot s \leq 0 \tag{40}$$

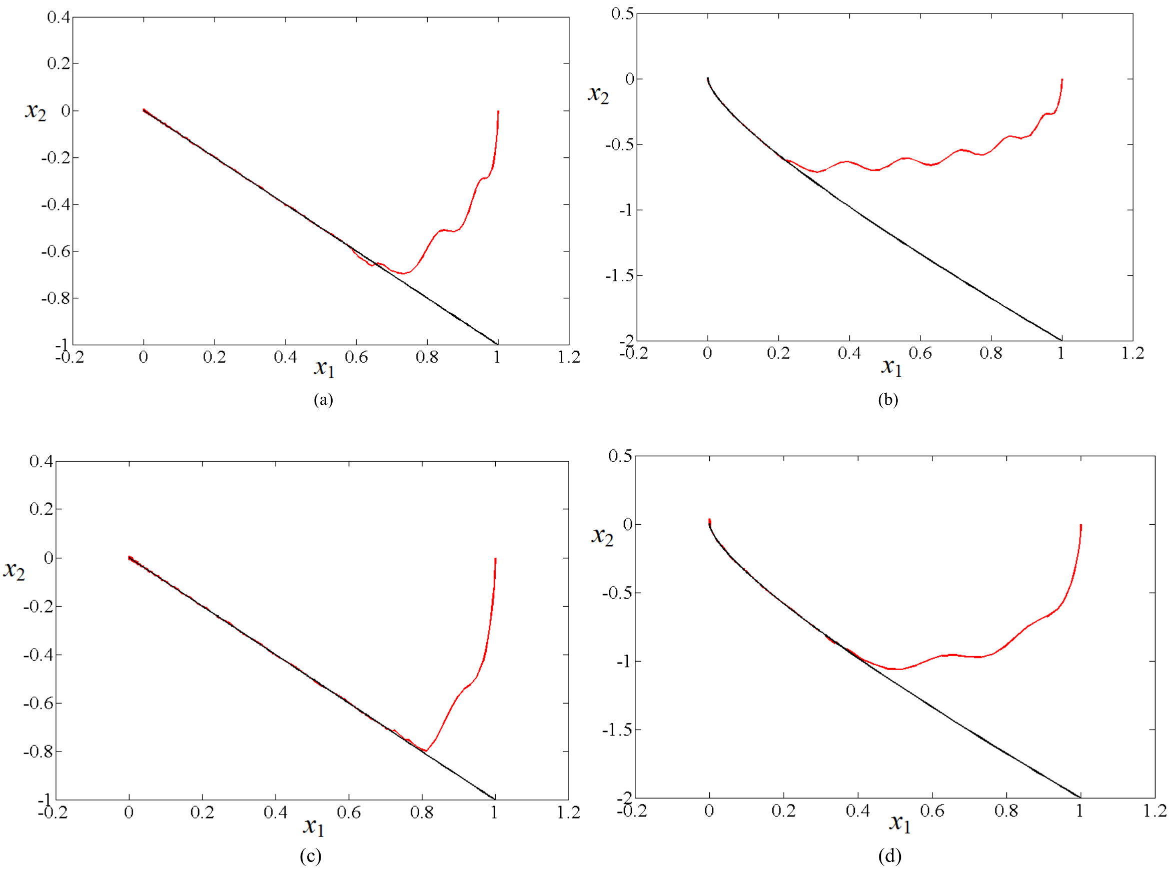

FIGURE 4. **The phase trajectories. (a) The linear sliding mode control method. (b) The global terminal sliding mode control method. (c) The linear sliding mode control method with the quick reaching law (d) The global fast terminal sliding mode control method with the quick reaching law.**

The equality in Eq.(39) holds up if and only if $s = 0$. Therefore, the sliding mode surface is reachable.

When the uncertainty d is larger, the switching gain η must be chosen a bigger value, which would cause a bigger chattering. For this, the sign function sgn(s) in Eq.(37) could be replaced by the saturation function sat (s):

$$sat(s) = \begin{cases} 1 & s > \Delta \\ ks & |s| \le \Delta, \quad k = 1/\Delta \\ -1 & s < -\Delta \end{cases} \tag{41}$$

where, Δ is a smaller positive const named the boundary layer. In this way, the switching control can be used to approach to the sliding mode rapidly outside the boundary layer, and the feedback control can be used to reduce the chattering inside the boundary layer.

In the simulation experiments, the parameters are chosen as: $K = -2.364$, $T = 5.489$, $\alpha = 0.94$. The external disturbance is set as: $d = \cos 25t$, $D = 1$. The initial conditions are set as : $\psi_0 = 60°$ and $r_0 = 0$, and the desired values are set as: $\psi_d = 0°$. The control parameters are set as: $c = 1$, $k_1 = 1.1$, $k_2 = 0.7$, $b = 1 + k_2/k_1 = 1.636$, $a = 0.2$, $\eta = 0.5$.

The above-mentioned experiments have proved the global terminal sliding mode control method with the quick reaching law (TSMCQ) has better control performance, so it would be used to control the unmanned surface vehicle. Furthermore, the performances of the different reaching laws, the exponential reaching law, the double power reaching law, the novel power rate reaching law [27] and the quick reaching law, are compared in Fig. 5 and Fig. 6.

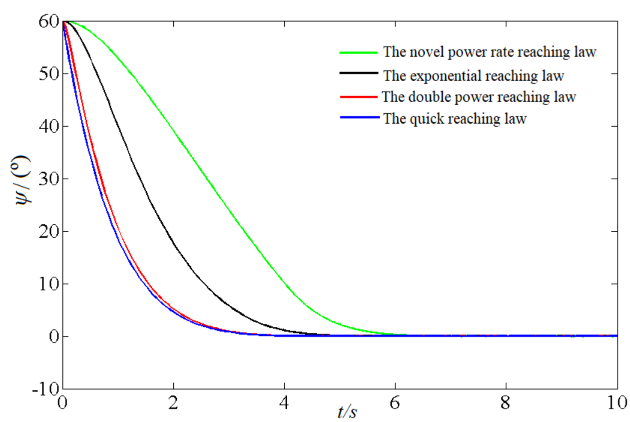

FIGURE 5. **The response of the steering angle ψ.**

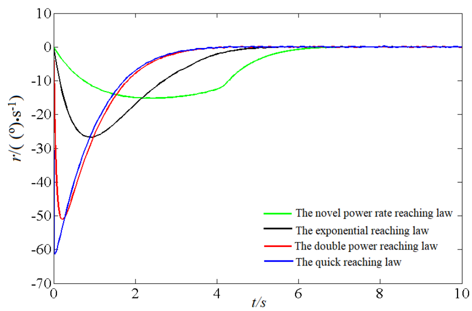

FIGURE 6. The response of the yaw angular velocity *r*.

From Fig.5 and Fig.6, all the control methods with the different reaching laws above can complete the accurate tracking control of unmanned surface vehicle. However, compared with the other reaching laws, the quick reaching law has significantly better control performance. It can enhance the response rate and reduce the chattering.

V. CONCLUSION

Combining the global terminal sliding mode, a new global terminal sliding mode control method with the quick reaching law is proposed. The quick reaching law has the second-order sliding mode characteristic, and it can make the system arrive at the sliding mode surface with faster convergence rate. In this way, the dynamic response of the system could be quicken and the dynamic characteristic could be improved. Furthermore, the smooth transition from the initial states to the sliding mode surface can be completed by the improved quick reaching law, which make the system have smaller chattering and better control performance. The global terminal sliding mode control with the quick reaching law could be used effectively to control the heading of unmanned surface vehicle. Compared with the double power reaching law, the exponential reaching law and the novel power rate reaching law, it has faster dynamic response. And the experiment results prove its validity. The further studies can be performed on the design of the sliding mode control based on the quick reaching law for the multi input multi output (MIMO) non-linear systems.

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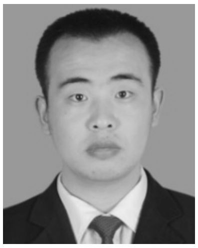

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