Sensorless Speed and Position Identification of Rim Electromagnetic Direct-Driven Propeller Based on Sliding-Mode Observer

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\textbf{ABSTRACT} Rim electromagnetic direct-driven propeller (REDP) is a propeller used in the underwater vehicle. It has many merits compared with the traditional propeller. It is difficult to utilize the sensor to get the rotor position and speed that are important to control REDP. An observer based on sliding mode method was proposed to estimate the rotor position and speed in the paper. Its stability was proved and some parameters were obtained. The influence of the switching function on the observation performance was analyzed and the sigmoid function was chosen as the switching function of the sliding mode observer. Then the observation position and speed were analyzed under different parameters to get the better observation performance. Finally, the experiment verified the feasibility of sliding mode observer.

\textbf{INDEX TERMS} Sliding mode observer, speed and position observation, rim direct-driven propeller, switching function, performance analysis.

I. INTRODUCTION

Rim electromagnetic direct-driven propeller (REDP) is a propeller used on the underwater vehicle. It can meet the requirements of the underwater vehicle’s propulsion system for lightweight, low vibration and noise, high reliability and the rest. Due to those reasons, REDP has drawn increasing attention in the underwater vehicle. However, it works underwater, which limits the use of position sensors that control the propeller to work. So the sensorless control method that could improve the robustness of the device, including mechanical oscillations, electromagnetic compatibility, maximum velocity and the like [1], was proposed. Sensorless control means that there is no any mechanical sensors, like position or speed sensor. There are some commonly used sensorless control methods, such as model-based sensorless control, back EMF (electromotive force) method, high-frequency signal injection method and the others [2]–[4]. Through a phase-locked loop, the rotor position could be derived by the cosine and sine functions based on the harmonic currents of stator windings [5]. However, once the extracted envelope was distorted, it might increase the estimated position error [6]. In order to avoid using the injecting signals method that needed to inject additional signals, the excitation machine was utilized as a sensor to obtain the rotor position [7].

For some uncertain systems, sliding-mode controllers are the better control way. With discontinuous control, they are able to reach the chosen sliding manifold in finite time [8], [9]. Sliding-mode observer is based on sliding-mode control method which can keep perfect tracking performance and tolerate some model uncertainties [10]. So many fields have applied it successfully [11], [12]. For permanent-magnet synchronous motors, a terminal sliding-mode observer was utilized to estimate its mechanical parameters. It could reach high steadystate precision in finite time that could meet real application requirements [13]. In order to improve the estimation performance, the traditional sliding-mode observer was improved. To solve the phase delay, an improved current observer was proposed to enhance the sensorless control of the electrical motor [14]. At the same time, there was a large
time delay in the high-speed operations for the conventional observer. By changing the switching function to improve the conventional sliding-mode observer, it could improve the time of reaching the steady state, reducing overshoot and speed error [15]. Based on the BL theory, a hyperbolic function chosen as switching function could solve the LPF and calculation delay problems. This method improved the position estimation accuracy and had better dynamic performance [3].

Back EMF and current are the fundamental components to calculate the rotor position for most sensorless control method. The sliding mode observer can be utilized to observe the current and the back EMF, such as the discrete-time adaptive sliding mode of EMF and current observer [16]. Then the rotor speed and position are derived from the observation of the back EMF and current. For permanent magnet motors which generate non-sinusoidal back EMF, a low-pass filter was utilized to improve the performance of the sliding mode observer. It could get a better performance compared with the traditional sliding mode observer when the speed changes from 60rpm to 750rpm [17]. As we know that the low-pass filter may cause the chattering. So some hybrid terminal sliding mode observers were proposed to obtain the smooth back EMF. Reference [18] proposed a hybrid method that combined the nonsingular terminal sliding mode and the high-order sliding mode. To eliminate the chattering, the boundary layer should be as thin as possible near the sliding surface. So the switching function inside the boundary layer should have a good slope. Some methods have been utilized to improve the switching function, such as adaptive fuzzy system, fault-tolerant control scheme, adaptive gain algorithm and the like [19]–[21].

In addition to the self-factors influence, some external factors, which would affect the observation accuracy, should be considered. For example, the nonlinearity of voltage source inverter would make large rotor position and speed estimation error [22]. So some methods were combined with sliding mode observer to achieve performance, such as the adaptive super-twisting algorithm, a higher order method, indirect vector method and others [23], [24].

This paper consists of three main objectives. First, the mathematical model of REDP was built based on the phase voltage equation. Then, a sliding mode observer of back EMF was designed. Its stability was analyzed and some parameters were obtained. Eventually, according to the mathematical model and sliding mode observer, some numerical simulations and experiments were carried out to validate the effectiveness of the proposed observer. In general, this paper provides a novel method to achieve the sensorless position and speed identification of REDP based on sliding mode observer which could improve the performance of REDP.

II. MATHEMATICAL MODEL

Rim electromagnetic direct-driven propeller works in electromagnetic driven mode like brushless motor. Assuming that the magnetic circuit is not saturated, excluding the effects of eddy current and hysteresis loss, the phase voltage equation can be written as

\[ \begin{align*}
  u_a &= Ri_a + (L - M) \frac{di_a}{dt} + e_a \\
  u_b &= Ri_b + (L - M) \frac{di_b}{dt} + e_b \\
  u_c &= Ri_c + (L - M) \frac{di_c}{dt} + e_c
\end{align*} \]  

(1)

where \( R, L, M, ea, eb, ec, ia, ib \) and \( ic \) are the stator resistance, the stator inductance, the stator self-inductance, A-phase back EMF, B-phase back EMF, C-phase back EMF, A-phase current, B-phase current and C-phase current, respectively.

Back current and back EMF are selected as status variable. Stator voltages are selected as input variables. Stator currents and the back EMF are selected as status variable. Stator variables are

\[ e = [e_a e_b e_c]^T \]

and \( u = [u_a u_b u_c]^T \) are the status variable, and \( u = [u_a u_b u_c]^T \) is the input vector. The other variables are

\[ A_{11} = -\frac{R}{L - M}I \\
A_{12} = -\frac{1}{L - M}I \\
C = \begin{bmatrix} I & 0 \\
0 & 0 \end{bmatrix} \\
I = \begin{bmatrix} 1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1 \end{bmatrix} \]

III. SLIDING MODE OBSERVER OF BACK EMF

A. SLIDING MODE OBSERVER DESIGN

Assuming that armature reaction has no effect on the circuit and the winding inductance values are the constant, then the sliding mode observer can be built based on (2), as following

\[ \frac{d}{dt} \begin{bmatrix} \hat{i} \\ \hat{\dot{i}} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\
0 & 0 \end{bmatrix} \begin{bmatrix} \hat{i} \\ \hat{\dot{i}} \end{bmatrix} + \begin{bmatrix} B \\ 0 \end{bmatrix} u + K \text{sgn}(\hat{i} - i) \]

(4)

where \( \hat{i} \) is observed value, and \( K = [K_1 -HK_1]^T \) is the gain matrix of sliding mode.

\[ K_1 = \begin{bmatrix} k_1 & 0 & 0 \\
0 & k_2 & 0 \\
0 & 0 & k_3 \end{bmatrix} \]
\[ H = \begin{bmatrix} h_1 & 0 & 0 \\ 0 & h_2 & 0 \\ 0 & 0 & h_3 \end{bmatrix} \]

with

\[
\text{sgn}(\theta) = \begin{cases} 1, & \text{if } \theta > 0 \\ 0, & \text{if } \theta = 0 \\ -1, & \text{if } \theta < 0 \end{cases}
\]

Here the sliding mode surface is

\[ s = \hat{i} - i = 0 \]

When the observed status deviates from the actual status of the REDP, the observed output value \( \hat{i} \) is not equal to the actual output value \( i \). \( K \cdot \text{sgn}(\hat{i} - i) \), in (4), will play a negative feedback role to adjust the observed output value. Then \( (\hat{i} - i) \) will approach zero as soon as possible. Finally, the sliding-mode observer enters sliding mode, it must meet the following condition

\[
\begin{cases} h_1 > 0 \\ h_2 > 0 \\ h_3 > 0 \end{cases}
\]

According to Lyapunov stability theorem that is an important theory in control field [25], \( V_e \) can be written as

\[
V_e = \frac{1}{2} E_e^T E_e
\]

When (9) and (12) are met, Equation (13) can converge to zero that means sliding-mode observer of REDP is stable.

\section*{IV. NUMERICAL SIMULATION AND EXPERIMENT}

To verify the effect of our proposed sliding-mode observer, some simulations are performed based on REDP. The simulation schematic diagram is shown in Fig.2.

A 3-phase 18-pole 20-slot REDP prototype, as shown in Fig.3, was utilized to validate the sliding-mode observer. Angle sensor was used to measure the rotating angle of the rotor. Then the rotating speed and position of REDP could be obtained. Driving motor was used to drive the rotor to rotate. Then back EMF could be measured at different rotating speeds. The simulations were carried out by a numerical simulation platform. According to the measurement of REDP prototype, each phase resistance \( R \) and inductance \( L-M \) are 4.3\( \Omega \), 8.25mH respectively. The rotor inertia is 0.005Kg-m\(^2\).
of observation results can be obtained. Here an improved sigmoid function, which is shown in (14), was selected as switching function.

\[
f(t) = \frac{2}{1 + e^{-ax}} - 1
\]  

(14)

where \(a\) is a coefficient that determines the sigmoid function slope. Fig.4 shows the curves trend of sign function and sigmoid function with different \(a\). The bigger the value of \(a\) is, the closer the sigmoid function is to the sign function. So a larger \(a\) will cause a serious chatter like the sign function.

In order to compare the performance of sign function and sigmoid function, the rotating speed of REDP was set to 200rpm and the load was set to 3Nm at 0.5s. \(a\) was set to 1 in the sigmoid function. Then the back EMF of A-phase was obtained, as shown in Fig.5.

From Fig.5, the value of sign function and sigmoid function could follow the theoretical value well. They could still follow the theoretical value well when the load was applied at 0.5s. From a partially enlarged view, sign function made a larger chatter that was a problem needed to be overcome in sliding-mode observer, while sigmoid function was smooth. So comparing with sign function, sigmoid function could generate a better following characteristic.

Fig.6 shows the error of A-phase back EMF between sign function, sigmoid function and the theoretical result. The maximum error values of sign function and sigmoid function were less than 0.015V. The maximum error accounts for 1.2% of the A-phase maximum back EMF. The error of sigmoid function changed smoothly, comparing with the sign function error that produced chatter. So sigmoid function had better dynamic performance. In the paper, the sigmoid function was chosen as switching function.

B. SLIDING-MODE OBSERVER PERFORMANCE ANALYSIS

Sensorless position identification utilized back EMF and current to obtain the rotor position. Therefore, the accuracy of the back EMF can directly affect the accuracy of obtained position and speed. Fig.7 shows the back EMF of sigmoid function used as the switching function in sliding-mode observer and theory. Figures show that the back EMF of A-phase, B-phase and C-phase could follow the theoretical value well.

To analyze the following performance of sliding-mode observer, the error of every phase between observed value and theory was obtained, as shown in Fig.8. The maximum error was 0.015V that was about 1.2% of back EMF. The error mainly occurred at the moment of commutation, and then stayed around a stable value. At non-commutation moment, there was no error between the observed value and theoretical value. That meant an accurate back EMF could be obtained through the sliding-mode observer.

According to Fig.4, \(a\) would affect the sigmoid function. That meant the sliding-mode observer would obtain different observed results when \(a\) changed. Fig.9 shows the observed back EMF with different \(a\) in sigmoid function chosen as switching function. A larger \(a\) could make a better observation.
effect of sliding-mode observer when the back EMF changed. While $a$ was large enough, the influence of $a$ on the sliding-mode observer was kept unchanged. The observation error of sliding-mode observer with different $a$ was shown in Fig.10. $a = 16$ and $a = 32$ had the same error variation. And their maximum error value was less than that $a = 1$.

Based on the back EMF observed by sliding-mode observer, the position and angle speed of the rotor could be obtained. Fig.11 shows the observation curves of angular speed and position compared with the theoretical value. A 3Nm load was added on the REDP at 0.5s, so the angular speed dropped. From Fig.11(a), the observed angular speed was lower than the theoretical value. But it was the same as the theoretical value after the load was added on the REDP. From Fig.11(b), the observed position could follow the theoretical value well, except a little time delay.

C. EXPERIMENT

Fig.12 was the experiment platform for the sliding-mode observer. REDP was the prototype needed to be observed. Industrial computer was utilized to collect the rotating angle of the rotor, the line voltage and current data. According to the collected data, REDP observation position, angular speed and theoretical angular speed could be obtained by sliding-mode observer. Oscilloscope was used to inspect the waveform of the input voltage before experiment. Voltage source provided stable voltage for the experiment platform.
Current measurement could convert the current to voltage for detection. Voltage sensor was utilized to measure voltage. Host computer could download the observation model to the industrial computer. Controller could control the REDP to run, but it was an open loop control. Angle sensor could get the angle of the rotor that was used to calculate the angular speed. The resolution of the angle sensor is about 0.18 degree. The observation model was implemented in the industrial computer with a NI board PCI-6229. The sampling time was set to 0.001s with the fixed-step ode4 solver. Finally, the parameters of REDP were measured as $R = 4.3\ \Omega$, $L-M = 8.25\ \text{mH}$.

The speed of REDP was set to 190rpm. Then the voltage and current of A, B, C phases were measured as shown in Fig.13. The observer mode utilized the measured voltage and current to observe the back EMF of REDP. Fig.14 shows the back EMF that was observed in the experiment. From Fig.13(a) and Fig.14, the trend of the back EMF is the same as the input voltage with the steady changes.

When the back EMF and input current were obtained, the angular speed of REDP could be observed. Fig.15 shows the angular speed and rotating speed of REDP that observed by the sliding-model observer. The experiment showed that the angular speed was about 20rad/s. The sliding-mode observer could well observe the angular speed and the observation result was smooth. The rotating speed was about 190rpm and the observation value is very close to the true value.
The performance of sliding-mode observer, two switching theorem and some parameters were obtained. To improve its stability was verified according to Lyapunov stability. Then a observer based on the sliding mode was designed. The REDP was established to analyze REDP’s characteristics. So a sliding-mode observer was proposed to estimate the rotor position. The REDP with good accuracy.

To summarize, the experimental results could verify the sliding-mode observer well. The sliding-mode observer proposed could observe the angular speed and rotating speed of REDP with good accuracy.

V. CONCLUSION

The propeller plays an important role in the underwater vehicle. REDP is a novel propeller that has many advantages than traditional propeller. But the rotor position and speed could not measured by the sensor due to the working environment. So a sliding-mode observer was proposed to estimate the rotor position.

In order to design the observer, the mathematical model of the REDP was established to analyze REDP’s characteristics. Then a observer based on the sliding mode was designed. Its stability was verified according to Lyapunov stability theorem and some parameters were obtained. To improve the performance of sliding-mode observer, two switching functions were compared with each other. The sigmoid function was chosen as switching function to analyze the performance of the sliding-mode observer. The position of the rotor and back EMF could be well identified through the numerical simulation. Finally, the experiment verified the feasibility of the sliding-mode observer. This method could be applied on REDP to achieve the sensorless control of REDP.

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