Overview of marine integrated axial flow pump and its control technology

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Abstract. Axial flow pump is an important part of the ship. It is often used as the propeller of the ship or to transport large flow of liquid, so the research on it is very meaningful. This paper describes the development history of marine axial flow pump, introduces the separated axial flow pump and the integrated axial flow pump, and discusses the development of the motor of the integrated axial pump. Because the motor of integrated axial flow pump cannot be installed with high-precision position sensor, the motor is generally controlled without position sensor. It is difficult to control the permanent magnet synchronous motor in the full speed range by a single positionless sensorless control algorithm. Therefore, this paper introduces the motor rotor position estimation and control methods when the motor is running at low speed and medium and high speed. In this paper, the technology of marine axial flow pump and the control technology of its driving motor are prospected, which has reference significance for the selection and control of marine axial flow pump.

1. Introduction
Since the invention of slide pump by Ramelli in Italy, the pump has developed to more than 5000 varieties, spanning more than 400 years of history. The mechanical manufacturing of pumps, namely the pump industry, has a history of more than 200 years since 1790[1]. The development history of the pump is shown in Table 1 in chronological order[2].

| Particular Year | Event |
|----------------|-------|
| 1580           | Ramelli invented the slide pump, Serviere invented the gear pump |
| 1650           | Otto vabGuericke invented the piston vacuum pump |
| 1674           | Sir Samuel Morand has applied for a patent for the seal plunger pump |
| 1689           | Papin invented the prototype machine for centrifugal pump |
| 1830           | Revolution invented the screw pump |
| 1840           | Henry R Worthington invented the first direct acting steam pump |
| 1851           | John Gwynne filed a patent for improving centrifugal pumps |
| 1857           | Jacob Edison invented diaphragm pump |
| 1860           | A. S.Cameron invented the first reciprocating steam pump |
Due to the different functions and configurations of ships, the types, specifications and quantities of marine pumps on ships with different functions and configurations are different. For example, the liquid pump used in a certain type of military ship should not only consider the utilization rate of the internal space of the ship, make it easier for soldiers to integrate into the ship, but also fully ensure the full supply of seawater, fresh water, fuel and lubricating oil. Therefore, the requirements of liquid pump for military ships are higher than those for civil ships. According to incomplete statistics, in addition to special function ships such as cruise ships, dredgers and other ships, in general, the total number of various types of marine pumps accounts for about 20% ~ 30% of the total amount of marine machinery and equipment. The power consumed by marine pumps accounts for about 5% ~ 15% of the total energy consumption of the whole ship according to the performance, function and configuration of the ship[3].

As one of the liquid pumps, axial flow pump is an important part of the ship. It is often used as the propeller of the ship or to transmit large flow of liquid, and has a very wide range of applications on the ship. The traditional marine axial flow pump adopts the separation structure of engine and pump. The driving motor or fuel engine is installed outside the axial flow pump. When working, the driving motor or fuel engine drives the pump blade to rotate to deliver liquid or generate ship thrust[4]. The new integrated axial flow pump directly drives the impeller through the impeller flange by the prime mover, thus eliminating the transmission shaft link. The prime mover of axial flow pump is motor, and the non-contact transmission is realized between the motor and the impeller flange by electromagnetic force. The new type of axial flow pump can reduce the volume of liquid pump, greatly improve the utilization rate of ship cabin space, and make the structure of ship piping more clear, the use and maintenance of equipment is more convenient, and it is easier for crew to integrate into the ship, which will further enhance the vitality and combat effectiveness of the ship.

Permanent magnet synchronous motor (PMSM) has the outstanding advantages of high power factor, small size and high efficiency. Therefore, permanent magnet synchronous motor (PMSM) is usually used as the driving device of axial flow pump. However, due to the high-precision position sensor can not be installed in the motor of axial flow pump integrated with machine, so the motor is generally controlled without position sensor, which puts forward higher requirements for motor control. This paper describes the control strategy of PMSM at low speed, medium and high speed, and prospects the development of axial flow pump technology and its control strategy.
2. Development of marine axial flow pump structure and motor

2.1. Separate structure of engine and pump
The existing marine axial flow pump generally adopts the traditional structure, that is, the pump body is outside the rotating motor, and the two are coaxial. When working, the pump blade is driven to rotate by the motor rotation, and the liquid is transported out, as shown in figure 1.

Figure 1. Structure of traditional axial flow pump
A lot of problems will arise when the pump is applied to the submarine and the shaft. Due to the design defects of the traditional axial flow pump, the traditional pump has large volume, low power density and low space utilization. Due to the special situation of warship, most of the traditional pumps need to be installed vertically. Even the most common ship also needs at least dozens of pumps, and the ship's internal space is narrow and limited, which will inevitably cause installation difficulties and occupy too much space, and bring inconvenience to the crew's daily life. For example, multiple pumps of a certain type of destroyer are vertically installed in the passageway in the cabin, and the crew should pay attention to avoid when going up and down the cabin and walking back and forth. When encountering big waves and emergencies, the accidental collision of the crew will cause non combat casualties, which is a great hidden danger. On the other hand, due to the large number of liquid pumps occupying large space and difficult to install, it is inconvenient for the space optimization design of large ships such as aircraft carriers and nuclear submarines.

2.2. Integrated structure of engine and pump
With the development of ship modernization and the continuous increase of tonnage and capacity, the supply areas of seawater, fresh water, fuel oil and lubricating oil are increasing and the supply situation is becoming more and more complex. In order to enhance the ship's advantages in stealth and cabin space utilization, the design and application of various oil and water pumps should be optimized. By adopting the new integrated structure, the volume of liquid pump can be reduced, and the utilization rate of ship cabin space can be greatly improved. At the same time, the structure of ship piping system will be clearer, the use and maintenance of equipment will be more convenient, and the crew will be easier to integrate into the ship, which will further improve the life and combat effectiveness of the ship. Figure 2 is the schematic diagram of the mechanical pump integrated axial flow pump without mechanical transmission shaft, and figure 3 is the physical diagram of a machine pump integrated axial flow pump designed by our research group.
It can be seen from figure 2 and figure 3 that the impeller of the integrated axial flow pump is driven directly by the prime mover through the impeller flange, thus eliminating the transmission shaft link. The prime mover of axial flow pump is motor, and the non-contact transmission is realized between the motor and the impeller flange by electromagnetic force.

2.3. Development of motor for integrated axial flow pump
The motor of traditional axial flow pump is generally driven by asynchronous motor. However, the asynchronous motor has low rate density, poor economy of wide range smooth speed regulation, heavy burden on the power grid, low efficiency and weak shock resistance, which is not conducive to the miniaturization, lightweight and high efficiency of axial flow pump. The disadvantages of asynchronous motor can be well solved by using permanent magnet synchronous motor with better electromagnetic performance. Figure 4 shows a traditional radial magnetizing permanent magnet synchronous motor developed by our research group.

With the development of permanent magnet motor to high efficiency, high speed, high power density and miniaturization, the traditional rare earth permanent magnet motor also shows some limitations. For example, when the rotor is running at high speed, the eddy current loss of the rotor is large, the efficiency cannot be maintained at a high level, the air gap flux density is difficult to meet...
the requirements, and the torque ripple is relatively large\cite{5}. A new type of magnet structure Halbach magnet structure is produced, which has great advantages in the application of permanent magnet motor. Figure 5 shows a Halbach permanent magnet synchronous motor developed by our research group.

![Halbach permanent magnet synchronous motor](image)

Figure 5. Permanent magnet synchronous motor with Halbach structure

Compared with the traditional radial magnetization permanent magnet synchronous motor, Halbach structure permanent magnet synchronous motor has more obvious advantages. The air gap magnetic field of Halbach permanent magnet motor is sine wave, so it is no longer necessary to take measures such as distributing stator winding or slot of stator and rotor to obtain sine wave. In addition, the motor has a good magnetic shielding effect, which can reduce the thickness of the rotor yoke and even omit the rotor core\cite{6}.

3. Detection of low speed rotor position of pump motor and control

Because the integrated axial flow pump motor can not install high precision position sensor, the motor is generally controlled by no position sensor. The back EMF of permanent magnet synchronous motor in low speed region is very small, and the rotor position can not be determined by fundamental wave in low speed region due to the change of motor parameters and measurement noise. Estimating motor speed and position by using PMSM salient characteristics is one of the most effective methods for PMSM speed sensorless.

3.1. Inductance parameter method

For the permanent magnet synchronous motor with different direct axis inductance and quadrature axis inductance, the linear independent voltage vector can be applied to the armature winding twice through the inductance parameter method, and the inductance parameter matrix can be calculated by measuring the instantaneous response current, thus the rotor position information can be solved. The specific calculation steps are as follows:

$$L_1 = \frac{L_d + L_q}{2}, L_2 = \frac{L_d - L_q}{2}$$

(1)

The inductance parameter matrix is as follows:

$$\begin{bmatrix} L_{11} & L_{12} \\ L_{21} & L_{22} \end{bmatrix} = \begin{bmatrix} L_1 - L_2 \cos(2\theta_c) & L_2 \sin(2\theta_c) \\ L_2 \sin(2\theta_c) & L_1 + L_2 \cos(2\theta_c) \end{bmatrix}$$

(2)

When enough short test voltage $u_{a_1}, u_{a_2}, u_{\beta_1}, u_{\beta_2}$ is applied to armature winding twice, the measured instantaneous response current is $i_{a_1}, i_{a_2}, i_{\beta_1}, i_{\beta_2}$ respectively, so the parameter matrix is:
The electric angle of rotor position is obtained as follows:
\[
\theta_e = \frac{1}{2} \arctan \frac{L_{12} + L_{21}}{L_{11} - L_{22}}
\]

Reference [7] shows that the inductance parameter method can be used to determine the rotor position angle at low speed.

3.2. Signal injection method

The signal injection method is to inject the test voltage signal through the motor stator, and the rotor position information can be separated from the response current detected by the system. According to the different applied signals, it can be divided into high-frequency pulse voltage injection method, rotating high-frequency voltage injection method, low-frequency voltage signal injection method, pulse signal injection method and so on.

The static high-frequency pulse voltage injection method is implemented in the rotating coordinate system. The high-frequency pulse voltage signal is injected into the d-axis or q-axis of the static high-frequency pulse voltage injection method, and then the phase-locked loop algorithm is used to obtain the rotor position information from the response current. Rotating high frequency voltage injection method is mainly used for rotor speed and position detection of IPMSM with large salient pole ratio, and its performance is good at low speed.

The rotating high-frequency current injection method is to add a three-phase balanced high-frequency current excitation on the fundamental excitation current, and the rotor position information is in the induced negative phase sequence high-frequency voltage component phase. Rotating high frequency current injection method uses PMSM fundamental wave model to observe the current peak value of PMSM after input of rotating high frequency current to estimate rotor position and speed.

The low frequency signal injection method estimates the motor speed by injecting the low frequency stator current signal and using the generated voltage response. In reference [8], the low-frequency signal injection method was applied to speed sensorless control of permanent magnet synchronous motor (PMSM), and the experimental results show that the speed sensorless control of surface permanent magnet synchronous motor can achieve better control effect in extremely low speed region or even zero speed. In order to realize speed sensorless control in full speed range, the method based on fundamental model of motor and the method based on salient pole characteristic of motor are generally combined.
High frequency pulse voltage injection method injects high frequency sinusoidal voltage signal into d-axis of PMSM to estimate rotor position and speed. The high frequency pulse voltage signal injection method can also be used to detect the rotor speed and position of the surface mounted permanent magnet synchronous motor with small salient pole ratio.

The pulse injection method is to inject a specific pulse voltage vector signal into the motor winding to obtain the rotor position angle information from the response current. The PWM harmonic pulse injection method is provided in reference [9]. The PWM harmonic pulse injection method adopts the conventional PWM modulation mode, and the control mode is easy to realize, but the hardware needs to have higher sampling accuracy and sampling speed, and it is more suitable for the permanent magnet synchronous motor system with small inductance.

4. Detection of medium high speed rotor position of pump motor and control

In the medium speed or high speed stage, the back EMF of permanent magnet synchronous motor is stable. At this time, the use of signal injection method will increase the loss of the motor and destroy the stability of the system. Therefore, the method based on the properties of fundamental wave model is generally used at medium or high speed. These methods include model reference adaptive method, sliding mode observer method and extended Kalman filter method.

4.1. Model reference adaptive method

The basic structure of MRA is shown in figure 7. The basic idea is to design a reference model without unknown parameters and an adjustable model with parameters to be observed. The two models are excited by the same external input U and have the same physical meaning output. The generalized error e between the two outputs is fed into the adaptive algorithm. By adjusting the parameters to be observed in the adjustable model, the generalized error e tends to zero, thus realizing the parameter observation.

![Figure 7. Model reference adaptive control structure](image)

Reference [10] proposed a speed observation method based on model reference adaptive for sensorless vector control of high-speed permanent magnet synchronous motor. The sensorless vector control system of high speed permanent magnet synchronous motor (PMSM) based on model reference adaptive (MRA) is simulated and verified by experiments. The results show that the proposed method has good dynamic response and steady-state response, high speed observation accuracy, strong robustness and good system operation.

4.2. Sliding mode observer method

Sliding mode observer control is a method that uses sliding mode variable structure gain to observe motor rotor position. The system control structure is shown in figure 8. It is necessary to construct a sliding surface of the ideal state of the motor, and adjust the input according to the error between the collected signal and the ideal value, so that the operation state can be maintained on the ideal sliding surface, and the observation error of rotor position parameters gradually decreases to zero.
In the two-phase static coordinate system, the sliding mode observer equation of two-phase current state is as follows:

\[
\begin{aligned}
\frac{d\hat{i}_\alpha}{dt} &= -\hat{R}_s \hat{i}_\alpha + \frac{1}{L_s} u_\alpha - \frac{k}{L_s} F(\hat{i}_\alpha - i_\alpha) \\
\frac{d\hat{i}_\beta}{dt} &= -\hat{R}_s \hat{i}_\beta + \frac{1}{L_s} u_\beta - \frac{k}{L_s} F(\hat{i}_\beta - i_\beta)
\end{aligned}
\] (5)

The control system with sliding mode observer has good adaptability and stability, but this algorithm has a large amount of calculation, and is not suitable for low-cost controller, and static disturbance will be introduced. Many scholars have proposed a series of improvements to the sliding mode observer method. In reference [11], in order to improve the dynamic performance and robustness of the traditional speed estimation strategy based on the model reference adaptive system, a new speed estimation strategy based on the new super helix sliding mode adaptive observer is proposed. The results show that: compared with the speed estimation method based on the adaptive method, the speed estimation error of the new super spiral sliding mode adaptive observer can converge to zero faster, and the accuracy of the speed estimation is less affected when the motor parameters change. Therefore, compared with the estimation strategy based on model reference adaptive, the new super helix sliding mode adaptive observer has better dynamic performance and robustness.

4.3. Extended Kalman filter

The position sensorless control of PMSM based on extended Kalman filter adopts the optimal linear estimation method, and its control framework is shown in figure 9. In this method, the noise signal is used to recurse the dynamic system of PMSM in real time, so as to obtain the optimal rotor position and speed estimation. In essence, extended Kalman filter is also an observer method, which is more similar to a random frame observation. The position sensorless control of PMSM Based on extended Kalman filter has higher control accuracy, does not depend on the parameters of the motor body, and has the advantages of Kalman filter to suppress disturbance noise and measurement error interference. However, this method needs to run on a high-performance processor because of its large amount of computation and high real-time requirements.
In reference [12], aiming at the problems of low accuracy and easily divergent parameters of the existing permanent magnet synchronous motor (PMSM) observer, a novel direct torque controller for permanent magnet synchronous motor (PMSM) using attenuated memory Kalman filter was proposed. By establishing the state model of permanent magnet synchronous motor in rotating coordinate system, the current, rotor position and speed in rotating coordinate system are selected as state variables, and the attenuated memory Kalman filter estimation system of motor torque and flux linkage is realized. The attenuation factor is introduced to reduce the influence of the past measurements on the system, which improves the divergence of the attenuation memory Kalman parameters. Simulation and experimental results show that the method can accurately observe the motor torque and flux linkage, and has strong robustness and reliability when the load torque changes suddenly.

5. Conclusion
With the development of science and technology and the improvement of marine pump technical requirements, marine axial flow pump has to face the situation of updating. Now, a series of gratifying scientific research achievements have been made in the design and simulation calculation of fluid field, the design and manufacture of axial flow pump motor, and the standardization, serialization and generalization of products[13]. On the basis of the achievements, the development and research trends of the marine axial flow pump are as follows:

1. Miniaturization, lightweight and integration;
2. Reliable operation performance, good shock resistance;
3. Low vibration and low noise;
4. Reliable sealing structure and sealing performance;
5. It is easy to disassemble, maintain and replace;
6. Standardization, serialization and generalization.

In addition, for the problem that the position sensor of the integrated axial flow pump motor is difficult to install, the motor control mode is mostly sensorless control. However, the current single control mode can not meet the requirements of motor control at low speed and medium high speed. Therefore, for sensorless control in the full speed range, the composite control method combining salient pole model method and fundamental wave model method is adopted in industry application and academic research[14]. The technology of compound control method in full speed range is mainly to study how to ensure smooth switching of transition point. Combined with the current technology application and problems, the research trend of sensorless permanent magnet synchronous motor control technology may be as follows:

1. At low speed, the signal injection method is often used to improve and optimize to ensure the stable starting of the motor;
(2) The identification range of motor speed is enlarged, the identification accuracy is improved and the system stability is improved;

(3) In the transition stage of low speed and medium high speed, the smooth switching of the two control algorithms at the switching point is ensured.

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