A Review of Progress and Hydrodynamic Design of Integrated Motor Pump-Jet Propulsion

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Abstract: The integrated motor pump-jet (IMP) propulsion system is a form of modern underwater vehicle propulsion that uses a modular design paradigm. The integrated motor propulsor is a compact construction consisting of a permanent magnet (PM) and a pump-jet propulsor, as well as the propulsion and electrical systems. Compactness, great reliability, and low noise are the most significant features of this technology. The primary technology research status and main application configurations of propulsion devices with an integrated motor were examined based on the working principles and attributes of the devices. The theoretical and experimental research on the design, performance analysis, and control of IMPs is discussed, covering electric motors; bearing structures; hydrodynamic design; and hydrodynamic, electromagnetic, and bearing coupling design technology. This research investigates the most recent research goals, progress, and applications of IMPs, which includes their hydrodynamic performance, cavitation, and gap flow. Finally, the future essential technologies of high power, low vibration, water-lubricated bearings, electromagnetic and bearing coupling design, and IMP antipollution and antidamage capacity are summarized.

Keywords: rim-driven thruster; propulsion system; hydrodynamic performance; permanent-magnet motor; water-lubricated bearing; integrated motor pump-jet

1. Introduction

An integrated motor pump-jet (IMP) is a propeller in which the motor stator is embedded in the pump-jet duct and the motor rotor is integrated with the tips of the pump-jet impeller blades rotating together at the same speed and in the same direction, with an air gap between the motor stator and rotor. It is a modern kind of underwater vehicle propulsion machine, corresponding to the modular design model, and consists of a propulsion system and an electrical system. The working principle of the IMP is that after energization, the motor air gap is opened into an air-gap magnetic field, and the current-carrying armature winding and the air-gap magnetic field interact to produce raw electromagnetic torque. The electromagnetic torque drives the motor rotor and, at the same time, drives the pump spray rotor circumferential rotation of the water work backward spray and the water flow to the pump spray axial reaction force to drive the propulsion carrier forward, which is used to ensure the rapidity of the propulsion carrier indicators.

The most important characteristics of this system are the compactness, high reliability, and low noise. This system could be directly driven by a high-power-density engine, specifically adapted to low noise, low vibration, and a finite volume as the main design goals of the underwater vehicle.

The core technical advantage of the pump-jet is the complete integration of the shaftless propulsion technology motor with the outstanding advantages of the pump-jet’s low noise and high critical speed, which allows the advantages of the pump-jet’s acoustic performance to be exploited while eliminating the shaft system’s acoustic excitation. At the same time,
the transplantation of the propulsion motor from inside the boat to the interior of the thruster allows for a significant improvement in the effective use of space within the cabin. As with conventional pump-jets, the pump-jets can also be divided into two types: front-mounted stator shaftless pump-jets and rear-mounted stator shaftless pump-jets, depending on the axial position of the pump-jet stator blades in relation to the rotor blades.

In recent years, pump-jet thrusters (also known as pump-jets) have been widely used in underwater vehicles for their advantages such as their high propulsion efficiency, low radiation noise, strong anticavitation ability, and high critical speed [1], especially in submarines and torpedo propulsion. For example, the American “MK48” torpedo, the Seawolf-class submarine, the Virginia-class submarine, and the British Smart-class submarine all make use of this technology.

The propeller is attached to the shaft to drive the propulsion, while the opposite side of the shaft is put on the engine in conventional propulsion (Figure 1a). The main engine is located in the hull, so that the entire structure extends through the nacelle space. The bearings are installed on the stern with the middle circumferential and radial fixed shafts. In addition to this, it is necessary to decelerate the speed using a gearbox for the main propulsion device of a high-speed ship. When the underwater vehicle is operating, considerable frictional power loss, high levels of noise, and high levels of vibration may occur in the shafts, bearings, and gearboxes, etc.

Since the 1990s, researchers have been interested in podded propulsion (Figure 1b), which is now a common design in the marine industry [1]. The pod propeller has a uniformly operated wake, low vibration, and low noise, and it can also provide thrust at multiple angles. Therefore, it plays the role of a rudder compared to the traditional propulsion method. Furthermore, it is beneficial to the interior of the engine room’s space layout, due to its flexible arrangements. A propeller, a bracket, and a pod make up the pod propeller, whereas the general propeller is a four-blade fixed-pitch propeller. Its downside is that an electric-driven motor is mounted in the pod, causing the diameter of the pod to be extremely large, reducing the propulsion efficiency even further [2]. The pump-jet propeller (Figure 1c) is usually composed of a pipe, a writing element (guide vane), and a rotor (impeller). Its working flow field is more complex, as it is an intricate multiconnected area compared to the internal flow field of the pump-jet blade and the open flow of the propeller, due to the existence of the pipe. The interaction between various components, the thruster, and the propulsion carrier affects the overall performance of the thruster.

Figure 1. Different marine propulsion systems: (a) conventional propulsion system; (b) podded propulsor; (c) pump-jet propulsion; and (d) shaftless IMP [3].

The rapid development of today’s power electronics technology has subsequently promoted the birth of a new type of underwater propulsion device, the integrated motor
propulsor (IMP), also known as the shaftless rim-driven propulsor/thruster (RDP/RDT) (Figure 1d). Yan et al. (2017) explained that this type of propeller is driven by the rim instead of by the shaft [3]. In the IMP propeller equipment, the drive motor is integrated into the structure, while the motor stator is embedded in the shield (pipe). The rotor is distributed on the rim or in the rim, and the propeller blades are directly connected to the rim. When the motor is operating, the blades follow the rotor, and they rotate together. The motor rotor and stator need to be equipped with sealing devices to prevent the entrance of water and various marine debris, because the propeller works underwater. Figure 2 shows three integrated motor thrusters with different structures. In Figure 2a,b, the structure is the same, the only difference being whether there is a hub between the two blades, which is evident in Figure 2b. As shown in Figure 2c, Cheng and He (2014) explained that, in addition to the hub, there are more guide vanes (rear spiral) behind the rotor [4]. The rotor blades generate thrust, while the guide vanes are used to eliminate the rotational movement of the liquid flow and play a role of diversion. A deceleration-type duct is used. Most of the ducts in the IMP thruster are of the decelerating type, which can achieve the effect of deceleration and pressurization to delay the generation of cavitation and achieve the purpose of noise reduction [5]. According to Wang et al. (2020), the IMP has several advantages compared to the conventional shaft-driven thruster, pod propulsor, and pump-jet propulsor [6]:

(1) The IMP thruster has a high degree of integration, and the cabin reduces the complicated propulsion drive shaft system, auxiliary components, propulsion motors, and other equipment into a compact structure with a light weight.

(2) According to previous research, it has a low vibration and noise, since the motor and the propeller are integrated; the motor eliminates the noise in the split propulsion device when driving the propeller, and there is no longer any deceleration between the prime mover and the propeller transmission gear reduction gearbox, which is the main source of underwater radiation noise [7]. The back spiral stator eliminates the rotational movement of the fluid, reduces the flow velocity into the rotor blade, and increases the static pressure around the blade. The back spiral stator also delays the onset of cavitation at the tip of the blade and reduces the vortex cavitation noise, thus improving the invisibility.

(3) It has a high propulsion efficiency, eliminating friction loss at the output shaft and improving the system propulsion efficiency. The back spiral stator can recover the rotational energy of the liquid flow by effectively increasing the propulsion energy. The IMP thruster is energized by the motor stator coil to generate a magnetic field, and the permanent-magnet motor rotor drives the impeller to rotate. Hence, there is no need to provide electricity to the magnetic field, which can eliminate the power loss of the magnetic field.

(4) It has good operability and strong adaptability—due to the lack of intermediate transmission links, the reliability of the propeller transmission is improved. The pump flow does not change much at different speeds when it has already maintained a certain speed.

(5) The entire system works in fluid, which can solve the heat-dissipation problem of the motor by cooling the motor and the bearing. This can also reduce the energy consumed by these cooling systems. Seawater can lubricate the bearings without oil lubrication, which is not only environmentally friendly but also eliminates the energy consumed by the lubrication system.

As a result, the emphasis of this study is on the advancement of IMP research in terms of theoretical and practical investigations into driven motor performance, motor control systems, hydrodynamic performance, and optimization. Within this study, future research directions are also offered.
According to Qian and An (1997), this battery has a high energy density [9].

The stator is supported by the outermost component, which is a duct similar to that of a pump-jet propeller. The stator of the motor is fixed in the outer pipe, and the outer ring of the rotor impeller is attached with permanent magnet pieces to the main shaft and can rotate around the shaft. The guide vane can be integrated with the shaft as a static blade cascade. Its function is to eliminate the rotational movement of the water sprayed from the back of the impeller so that it can effectively recover the energy of the sprayed water and balance the torque. When operating the motor, the stator coil of the motor is energized to generate a magnetic field. The impeller with permanent magnets rotates as the rotor of the motor. The blades pump water and discharge backward. The rotating energy is recovered by the stator blades, and the guide vanes are sprayed out through the nozzle to provide the device with forward momentum.

Figure 2. Structural diagrams of (a) hubless RDT, (b) hub-type RDT, and (c) hub-type IMP [3,4].

2. Electric Motor and Control Technology

The IMP was first developed by the U.S. Naval Underwater Warfare Center in collaboration with the Applied Research Laboratory of Pennsylvania State University. Originally, it was used for unmanned submersibles. However, the motor was placed in the outer cover of the submersible; hence, the motor and the propulsion impeller were still two separate parts [8]. Then, the IMP was used for a light torpedo (Figure 3). The electric power which the light torpedo uses is an advanced lithium-ion battery and an integrated motor thruster. According to Qian and An (1997), this battery has a high energy density [9].

Figure 3. Prototype of integrated motor propulsion developed by the U.S. Navy [8].

Figure 4 shows a schematic diagram of an IMP thruster. A hub, a duct, a motor stator, a rotor impeller with permanent magnets, and guiding vanes are the major components. The stator is supported by the outermost component, which is a duct similar to that of a pump-jet propeller. The stator of the motor is fixed in the outer pipe, and the outer ring of the rotor impeller is attached with permanent magnet pieces to the main shaft and can rotate around the shaft. The guide vane can be integrated with the shaft as a static blade cascade. Its function is to eliminate the rotational movement of the water sprayed from the back of the impeller so that it can effectively recover the energy of the sprayed water and balance the torque. When operating the motor, the stator coil of the motor is energized to generate a magnetic field. The impeller with permanent magnets rotates as the rotor of the motor. The blades pump water and discharge backward. The rotating energy is recovered by the stator blades, and the guide vanes are sprayed out through the nozzle to provide the device with forward momentum.
As mentioned above, when installing the IMP integrated motor, which is required to be as thin as possible in the radial direction and as short as possible in the axial direction to reduce the duct resistance, the electromagnetic air gap should be large enough to fill in the air gap of the internal stator/rotor anticorrosion sheath [10]. The first publicly disclosed integrated motor propulsion solution was a patent authorized by Luwig Kort, Hannover, Germany [10], as shown in Figure 5. The types of electric motors that are applicable to IMPs are reviewed in the following section to provide a clear overview and detailed summary of the controller of the IMP system (see Table 1).

![Figure 4. Schematic diagram of integrated motor pump-jet thruster.](image)

Traditional permanent-magnet synchronous motors generally use vector control. The control system needs to obtain accurate position information to control the speed and current of the motor. However, because the integrated motor propulsion device stops the rotating shaft, and traditional mechanical position sensors are difficult to install, position sensor control technology [11,12] is used quite often. The control scheme mainly has two technical routes: one is to obtain the rotor position based on the basic equations of the motor, which requires a high degree of accuracy regarding the motor parameters and does not perform well at low speeds; the other is to use the salient pole characteristics of the motor to extract the rotor
position signal after injecting high-frequency signals [13]. This method can also achieve better estimation results in the low-speed and zero-speed range. However, it is not suitable for surface-mount motors with a low salient pole rate, and the algorithm is more complicated. It should be pointed out that the unsteady pulse power and jitter generated by the rotation of the integrated motor propeller blades in the water flow can be directly transmitted to the motor rotor through the integrated rotating structure, which causes the fluctuation of the motor torque. In addition, the integrated motor’s low speed, frequent starting, high acceleration and deceleration dynamic performance, and high system operation noise requirements make its position sensorless control more difficult, and it is also one of the key technologies that restrict the development of high-performance shaftless propellers. Hence, for the high-performance control requirements of integrated motors, new integrated position-sensing technologies can also be explored in the overall plan.

Table 1. Types of electric motors applicable to IMPs.

| Electric Motor Type               | Year | Reference | Geometry of the Electric Motor | Performance                                                                 | Problem                                                                 |
|-----------------------------------|------|-----------|--------------------------------|-----------------------------------------------------------------------------|-------------------------------------------------------------------------|
| Induction motor (IM)              | 1989 | [14]      |                                 | A 16-pole 3-phase motor with 48 stator slots and 72 rotor slots, 394 mm in diameter, and with a 1 mm air gap was used in the system. | The prototype test detected the problem of bearing friction loss and the eddy-current loss of the excessive stator sheath. |
|                                   | 1989 | [15]      |                                 |                                                                             |                                                                         |
|                                   | 2010, 2011, 2013 | [16–18] |                                 | The motor provided the same full-load torque as a regular industrial IM, while only weighing around 60% as much. | Due to a substantial amount of power lost to friction and eddy currents in the stator, the power factor, power density, and efficiency were all low (less than 50%). |
|                                   | 1995 | [19]      |                                 | The motor used a 3-phase 6-pole electromagnetic scheme to complete a 5 kW prototype design. There was anticorrosive paint on the surface, the stator winding was made of insulated cables, and the air gap was 0.6 mm. | The radial thickness of the motor was too large. Hence, this led to the large size of the duct and the low hydrodynamic efficiency of the propeller. The motor structure was to accommodate the stator and rotor sheath in the air gap to prevent corrosion. The protective layer caused the large air-gap size to reduce the electromagnetic performance, which turned out to be a disadvantage in the motor. |
| Electric Motor Type | Year       | Reference | Geometry of the Electric Motor | Performance                                                                 | Problem                                                                 |
|---------------------|------------|-----------|--------------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Permanent-magnet direct-current motor (PM DCM) | 2001, 2004, 2003, 2006 | [20–23] | ![Image](https://via.placeholder.com/150) | In this design, the stator and rotor structure were all installed inside the duct, which eliminated the existence of liquid flow air gaps and did not affect the flow area. This reduced the influence of the stator and rotor structure on the propulsion performance of the propeller blades. | The manufacturing cost was high, and the production of slotted brushless PM machines was complex. |
| Permanent magnet direct-current motor (PM DCM) | 2003 | [24] | ![Image](https://via.placeholder.com/150) | Low eddy-current losses and cost were achieved with a PM motor that used composite materials for the propeller, housings, structural blading, motor canning, and fairings. | To remove eddy-current losses in the motor, the cost and weight must be lowered. |
|                       | 2004 | [25] | ![Image](https://via.placeholder.com/150) | The PMs were rectangular and were installed on the rotor yoke’s surface, which was made of solid soft iron. The stator lamination had a thickness of 0.5 mm. The magnets used were neodymium magnets (NdFeB) with 1.2 T remains. Harmonics and winding overhang were decreased with a two-layer fractional winding. | The RDT was put to the test as an onshore generator, and its average efficiency was far lower than the 0.97 predicted. Losses in parallel circuits and the proximity of the coil ends to the iron case created the difference. |
|                       | 2006 | [10] | ![Image](https://via.placeholder.com/150) | Because a large magnetic gap was required and slot leakages were absent, the slotless motor design avoided the tooth-ripple component of the cogging, decreased harmonic effects, and had low winding inductance. | The slotless motor, which had a longer active length, longer end windings, and thicker magnets, was found to be less efficient in a set of comparative studies with a slotted motor of the same active radial dimensions. |
|                       | 2010 | [26] | ![Image](https://via.placeholder.com/150) | | |
### Electric Motor Type

| Electric Motor Type | Year | Reference | Geometry of the Electric Motor | Performance | Problem |
|--------------------|------|-----------|--------------------------------|-------------|---------|
| IMP motor          | 2019 | [27]      |                                | The IMP motor was shown to have two-segment Halbach-array permanent magnets with unequal segment arcs. The uneven-segment-arc Halbach array was optimized to maximize the electromagnetic torque, according to the optimization and fabrication results, as well as the experimental motor performance results. | Because of the friction loss, the rotational speed and output thrust were lower than expected. |
| Permanent magnet alternating-current motor (PM ACM) | 2013 | [28]      |                                | A narrow rotor and a large air gap characterize the Halbach-array motor. When the PM thickness reached a particular value, the air-gap flux density rose, and thus the Halbach array would have a clear advantage. | The PM brushless motor’s most significant dimensional limitation was the high current density induced by the stator’s thermal condition. |
| High-temperature superconducting motor (HTSM) | 2013 | [30]      |                                | A two-segment Halbach array was used to produce good cooling and strength performance in a seawater-cooled high-power-density magnetically slotless PM brushless AC motor. The closed-slot stator tooth body of the magnetically slotless structure was made of stainless steel, which had good thermal conductivity, anticorrosion, compressive strength, and magnetic nonconductivity. | The power loss was high, and the RDT was not so compact. |
|                     | 2016 | [29]      |                                | This type of motor could obtain higher electromagnetic efficiency, and the thinner structure could reduce resistance to a certain extent. This was a big improvement compared to the previous motor type. | The cost was very high. |
3. IMP Bearing and Hydrodynamic Design

3.1. Bearings Used in IMPs

The open structure of the integrated motor propeller requires its bearings to be able to operate in a seawater environment. If a nonaqueous lubricant is used for the bearing, a sealing device is required, which increases the difficulty, complexity, and cost of the entire system and is likely to cause water pollution. The use of water-lubricated bearings can reduce the weight and complexity of the integrated motor thruster system and better reflect the advantages of the integrated motor thruster. The suitable bearing arrangement is determined according to the application characteristics and use requirements of the device. The bearings can be arranged either on the hub or rim or in a mixed arrangement (Figure 6). To obtain a good hydrodynamic performance from the IMP propeller, the thickness of the duct and the diameter of the hub must be as small as possible, which leads to the complexity of the bearing design.

![Figure 6. The location of the bearings in an IMP [10].](image)

The research work on water-lubricated bearings started earlier in countries with developed shipbuilding industries, such as the United States, Canada, Japan, Australia, and the United Kingdom. As early as the 1940s, there are records of American ships using water-lubricated bearings. After years of development, some companies have formed a series of water-lubricated bearing products suitable for various working conditions, such as the Thordon bearing series [31], the Perform bearing series [32] of the British TENMAT company, the water-lubricated bearing material of the British Countrose company [33], the American Duramax Marine Johnson Cutless water-lubricated bearing series [34], and the water-lubricated bearing series of BFGoodrich and Johnson Rubber (Figure 7). The types of bearing suitable for IMPs are covered in this section to provide a clear picture and complete explanation of the IMP system’s controller (see Table 2).

![Figure 7. (a) Thordon bearing of Thomson–Gordon, (b) water-lubricated bearing material of Countrose, (c) Feroform bearing of TENMAT, (d) Johnson Cutless bearing of Duramax Marine [35].](image)
Table 2. Types of bearings applicable to IMP.

| Bearing Type                        | Year | Reference | Geometry of the Bearing | Performance                                                                 | Problem                                                                 |
|-------------------------------------|------|-----------|--------------------------|-----------------------------------------------------------------------------|--------------------------------------------------------------------------|
| Rolling bearing structure           | 1995 | [36]      | Hubless RDT with grooved bearing races on both edges of the rotor ring | The test results of these prototypes were not ideal, mainly due to the low reliability of the ball bearings in the mud and sand environment and the excessive bearing wear; furthermore, due to bearing friction, the rotor could not reach the predetermined speed under rated voltage conditions. In addition, ball bearings also have inherent shortcomings in terms of vibration, noise, and load-carrying capacity. In high-power propellers, large axial thrust is required, and rolling bearings experience excessive strain under high loads. |
| Oil-lubricated bearings             | 2017 | [39]      | Low noise and high carrying capacity | The difficulty, complexity, and cost of the entire system is increased, and it is likely to cause water pollution. |
|                                     | 2017 | [40]      | The bearing capacity and service life of oil-lubricated bearings are higher than those of water-lubricated bearings. | The construction, on the other hand, is complex, with significant machining and installation requirements. Oil-leakage prevention and sealing systems must also be reliable. |
|                                     | 2017 | [41]      | The thrust bearing supported by rubber pads uses rubber deformation to adjust the inclination of the pad, which has great potential for damping vibration. | To obtain a good hydrodynamic performance from the IMP propeller, the thickness of the duct and the diameter of the hub must be as small as possible, which leads to the complexity of the bearing design. |
| Water-lubricated thrust bearings    | 2016 | [42]      | Many units are also exploring the use of a support/thrust integrated structure which can bear both gravity and thrust loads. | The practicality has yet to be tested by engineering. |
|                                     | 2016 | [43]      |                                                                           |                                                                           |
|                                     | 2017 | [44]      |                                                                           |                                                                           |
|                                     | 2017 | [45]      |                                                                           |                                                                           |

3.2. Hydrodynamic Design
3.2.1. Hydrodynamic Performance

The hydrodynamic performance of an IMP thruster is the key to ensuring its thrust and power index, which directly affect the propulsion efficiency, vibration, and noise. With the continuous development of computer technology, numerical testing has gradually become an important means of keeping pace with and complementing physical testing in the research and development of the hydrodynamic performance of propulsion devices, as well as effectively promoting the research and development of propulsion devices in general. It is critical to match propeller hydrodynamic characteristics to specific factors to achieve efficient IMP.
The most significant metric is the propeller pitch ratio. The hydrodynamic efficiency is further affected by the propeller’s structural design, the form and size of the duct, the air-gap thickness, and other parameters. Computational analyses and experimental research on some IMP parameters are presented in this section to provide a clear picture and detailed explanation of IMP thrusters’ hydrodynamic performance (see Table 3).

**Table 3. Summary of numerical studies on the hydrodynamic performance of IMP thrusters.**

| Parameter          | Year | Reference | Model                  | Method/Experimental Method | Findings                                                                 |
|--------------------|------|-----------|------------------------|----------------------------|--------------------------------------------------------------------------|
| Propeller pitch ratio | 2003 | [22]      | RDT                    | The interaction velocity-field approach was used in this lifting-surface panel code. | 1. The torque provided by the motor reduced as the rpm rose, whereas the torque required by the propeller rose.  
2. The propeller’s torque requirements rose as the pitch ratio increased, although this was limited. |
|                    | 2003 | [23]      |                        |                            |                                                                          |
| Shape and size of the rim | 2015 | [46]      | Ka-series thruster     | Reynolds-averaged using varied-length rims to solve the Navier–Stokes equation. | 1. A lengthy rim raised the friction torque slightly and caused the local flow to have a circumferential velocity.  
2. If immediately converted from the Ka-series, the rim-driven propeller easily generated a cavitation problem.  
3. A thin blade outperformed a thick one in terms of efficiency. |
| Shape and size of the hub | 2015 | [47]      | Open-water performance of hub-type and hubless RDTs (rim-driven thrusters), the propeller Ka4-70 and duct JD7704 | Contrastive analysis, with Reynolds-averaged Navier–Stokes (RANS) equations and a multiple-frames-of-reference (MFR) method | 1. The efficiency of a hubless RDT was higher than that of a hub-type RDT.  
2. The efficiency gap widened as the hub diameter and advance coefficient grew. The hubless RDT efficiency was 2.2 percent greater than the hub-type RDT for a hub ratio of 0.25 and an advance coefficient of 0.7 (the design point).  
3. The disappearance of the hub resulted in increased thrust, torque, and a smaller thrust ratio. |
| The MARIN Ka4-70 in 37A duct | 2000 | [48]      | Comparison between a symmetrical propeller and a standard asymmetric ducted propeller | A symmetrical propeller provided less thrust per unit power, because it had a lower KT value and a greater KQ value. | 1. The S2037 produced somewhat higher thrust than the other two profiles in a symmetrical duct layout, with the F2637 being the worst.  
2. At bollard pull in the forward direction, the asymmetrical propeller produced slightly more thrust than the symmetrical propeller, but still far less than the thrust produced by the MARIN Ka4-70 in a 37A duct. |
| S2037, S2637, F2637 | 2001 | [20]      |                        |                            |                                                                          |
### Table 3. Cont.

| Parameter                                      | Year | Reference | Model                  | Method/Experimental Method                                    | Findings                                                                                                                                                                                                 |
|------------------------------------------------|------|-----------|------------------------|----------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Shape and size of the propeller blade          | 2019 | [49]      | Low-order surface panel approach based on velocity potentials | 1. Changing the size of the duct gap had the opposite effect on overall and rotor efficiency.  
2. Increasing the duct camber could improve the pump-jet propulsor’s efficiency, improve the rotor blades’ cavitation resistance, improve the rotor’s load distribution, and lessen the trend of duct resistance increasing with advance speed.  
3. In comparison to camber, the angle of attack had a stronger impact on hydrodynamic performance, and lowering the angle of attack improved the overall efficiency of the pump-jet propulsor. |
|                                                |      |           |                        |                                                                |                                                                                                                                                                                                                                                                   |
| Shape and size of the propeller stator         | 2012 | [50]      | Contrastive analysis, with Reynolds-averaged Navier-Stokes (RANS) solver | 1. Increasing the stator prewhirl angle could increase the circumferential velocity of the rotor inflow as well as the overall thrust and propulsion efficiency of the pump-jet propulsor.  
2. The fluctuation amplitudes of the unsteady forces would decrease significantly if the spacing was increased properly.  
3. The stator chord length was found to have little effect on the propulsion performance and the maximum fluctuation amplitudes of the unsteady forces. |
|                                                |      |           |                        |                                                                |                                                                                                                                                                                                                                                                   |
| Experimental study                             | 2011 | [52]      | Deep-water towing tank of the Krylov Shipbuilding Research Institute | 1. The test rig for measuring forces and moments on rim-driven propellers met the defined requirements and demonstrated that it was suitable for the experimental examination of hub and hubless propellers.  
2. Analytical and experimental research was carried out to identify approaches to improve design methods for rim-driven thrusters. |
|                                                |      |           |                        |                                                                |                                                                                                                                                                                                                                                                   |
|                                                | 2012 | [50]      | Integral hydrodynamic measuring method | 1. The measurement was compared to the calculated findings using empirical rim surface corrections. It was demonstrated that the devised numerical method could accurately forecast the rim-driven thruster’s hydrodynamic performance. |                                                                                                                                                                                                                                                                   |
Table 3. Cont.

| Parameter                  | Year | Reference | Model                                                                 | Method/Experimental Method                  | Findings                                                                                                                                                                                                 |
|----------------------------|------|-----------|----------------------------------------------------------------------|----------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Bollard pull,              | 2019 | [53]      | Bollard pull, self-propulsion point (SPP), and bare-hull resistance tests | Computational fluid dynamics (CFD) used to analyze and compare the hydrodynamic performances of a shaftless pump-jet thruster (SPT), a traditional mechanical pump-jet thruster (MPT), and an E779A propeller | 1. In comparison to conventional propellers, the changes of the hydrodynamic coefficients, particularly the torque coefficient, versus the advance coefficients were substantially reduced.  
2. In all settings, the net imbalance roll moment was very minimal, indicating that the stator was designed correctly. In the behind-hull state, the stator also generated additional thrust, boosting the overall performance by up to 82 percent. |
| Performance predictions    | 2021 | [54]      | Performance predictions                                           | The capture of the unsteady rotor–stator interaction | 1. The SPT’s open-water efficiency was 0.662, which was lower than the traditional propeller’s.  
2. The SPT’s high-efficiency operating range was somewhat broader than that of the propeller, implying that the SPT could perform well in a wider range of working situations. |
| Frozen-rotor method        | 2015 | [55]      |                                                                 | Performance predictions                      | 1. The frozen-rotor approach was insufficient to capture the entire unpredictability of the rotor–stator interaction.  
2. If time accuracy is required, the authors advocate using a sliding mesh technique, which was used in this study’s unstable simulations. |
| Mechanical pumping and IMP | 2016 | [56]      | Mechanical pumping and IMP                                         | Contrastive analysis                         | 1. The spray water efficiency of the IMP pump was about 5% lower than that of the conventional mechanical pump at the same speed.  
2. When the torque increased, the friction loss increased and the power consumption increased at the same advance speed, compared with the conventional mechanical pumps.  
3. Under the same speed and different feed speeds, with the increase in the feed speed, the difference between the flow, thrust, and power of the IMP pump and the conventional pump gradually decreased. |
### Table 3. Cont.

| Parameter | Year | Reference | Model | Method/Experimental Method | Findings |
|-----------|------|-----------|-------|----------------------------|----------|
|           |      |           |       |                            |          |
|           |      |           |       |                            |          |
|           |      |           |       |                            |          |
|           |      |           |       |                            |          |
|           |      |           |       |                            |          |

#### 2018 [57]
Ducted propellers (DPs) Panel method

1. An adequate forecast of the propeller and duct loads required an alignment model of the wake shape with the local flow.
2. Because the technique was insufficient to accurately anticipate propeller forces near bollard pull, an extra gap strip adjustment was recommended.

#### 2019 [58]
Potsdam Propeller Test Case (PPTC) Hexahedral block-structured grids

In certain ranges of advance ratios, hexa and hybrid grids produced similar results; however, for low and high ratios, structured grids in combination with the realizable model could produce more accurate results.

#### 2019 [59]
The open-water characteristics of the propeller Contrastive analysis between different mesh types and turbulence models

1. The SST k-omega turbulence model outperformed the realizable k-epsilon two-layer turbulence model by a small margin.
2. The capacity of hexahedral meshes to deliver good-quality results in the SST k-omega turbulence model was greater compared to other case studies in this research.

#### 2021 [2]
A detailed comparative study of hydrodynamic performance between a rim-driven thruster (RDT) and a ducted propeller (DP)

Contrastive analysis, CFD analysis

1. The gap flow in the RDT had a significant impact on the performance.
2. The RDT’s total efficiency was much lower than the ducted propellers.

### Structural design

| Parameter | Year | Reference | Model | Method | Findings |
|-----------|------|-----------|-------|--------|----------|
| Hub-type and hubless propellers | 2011 | [52] | Hub-type and hubless propellers of RDIs | Contrastive analysis | The efficiency curves were similar, but the hubless propeller had a higher thrust and torque as compared to the hub propeller. |

#### 2014 [60]
A rim-driven water-jet pump of hub-type and hubless guide vanes

A simple steady-state CFD model, contrastive analysis

The results showed that the impeller efficiency of the pump with hubless guide vanes was reduced by about 10%, due to energy losses in the center line.
| Parameter | Year | Reference | Model | Method | Findings |
|-----------|------|-----------|-------|--------|----------|
|           |      |           |       |        |          |
| Design of pump-jet propulsion | 2007 | [63] | Pump-jet propulsion aimed at a submarine model | Lifting-line method, surface element method, axial-flow pump lifting method | Calculations for a pump-jet thruster designed for a virtual submarine showed that the pump-jet thruster designed using this method met the design requirements and had high efficiency. |
| 2021      | [62] | Rim-driven thrusters | 1. The direct design methods, the lifting and lifting-line design methods, followed by further geometric optimization (Isight) of the better model; the stator was designed by the modified coefficient method. 2. The inverse design methods, the mutual iteration method | 1. The lifting method was more suitable for low and medium speeds, while the lifting-line method was more suitable for medium and high speeds. 2. After optimization, the $K_T$ and $\eta$ curve shifted towards the direction of high speed as a whole, and the optimal operating point was also slightly shifted. 3. The $K_T$ of the model designed by the inverse design method was greater than the direct design method under different working conditions. |
| 2020      | [61] | Rim-driven thrusters | A simulation-based design optimization (SBDO) tool The open-source CFD tools OpenFOAM and cfMesh libraries, and a genetic-type optimization algorithm | 1. A simulation-based design optimization (SBDO) tool 2. The open-source CFD tools OpenFOAM and cfMesh libraries, and a genetic-type optimization algorithm | The result of the optimizations proved the flexibility and the reliability of the SBDO framework in dealing with unconventional configurations. |
| 2011      | [52] | Rim-driven thruster blading system | Direct blade pitch optimization method | The design method presented here for the rim-driven thruster, including the propeller blading system design, made it possible to achieve the required thruster performance. |
| 2015      | [47] | Hub-type and hubless propellers of RDTs in open-water performance | Contrastive analysis, CFD analysis | 1. The hub-type RDT had less hydrodynamic efficiency than the hub with less RDT. 2. The efficiency difference increased with hub diameter as well as an advance coefficient. 3. Eliminating the hub also led to a larger thrust, larger torque, and smaller thrust ratio. |

Table 3. Cont.
3.2.2. Cavitation

Cavitation is a very important hydrodynamic phenomenon that occurs in IMPs and causes severe vibration, noise, material damage, and other problems. Consequently, cavitation in IMPs has piqued our interest throughout the years. Few scholars have summarized the related papers to boost research on cavitation in IMPs. Turbulence is involved in the majority of cavitation occurrences. Both the cavitation model and the turbulence-modeling approach influence the numerical accuracy of cavitating turbulent flow simulations. The latest advances in the study of cavitation in IMPs are reviewed in this section to provide a clear picture and detailed explanation of the methods for cavitation modeling as well as the accomplishments based on IMP thruster numerical simulations (see Table 4).

Table 4. Summary of methods for cavitation simulation and the achievements based on numerical calculations for IMP thrusters.

| Year | Reference | Geometry of the Model | Type of Cavitation/Vortex | Cavitation Model | Findings |
|------|-----------|-----------------------|---------------------------|------------------|----------|
| 2009 | [66]      | The extent of cavitation and thrust | Vortex lattice (MPUF-3A) and boundary element (PROPCAV) methods | 1. A vortex lattice approach (MPUF-3A) and a boundary element method were used to forecast the tunnel thruster’s performance (PROPCAV). When compared to experimental measurements, the numerical results from PROPCAV and MPUF-3A appeared to fairly accurately anticipate the level of cavitation and thrust. |
| 2014 | [67]      | The influence of rotation speed, cavitation number, and inlet velocity on the cavitation characteristics of the pump-jet thruster | The homogeneous multiphase model of the Rayleigh–Plesset equation and the slip grid technology, and the three-dimensional full-channel steady turbulence calculation | 1. When cavitation occurs in the blades of the pump-jet propeller, the thrust and torque of the propeller are significantly reduced, which in turn causes a decrease in the open-water efficiency, and the reduction rate is more than 15%.
2. Under the same cavitation number with an increase in speed, the cavitation phenomenon of pump-jet propeller blades tends to be obvious. At the same speed, the smaller the cavitation number, the more obvious the cavitation phenomenon. When the cavitation number is greater than a certain value, the cavitation phenomenon of the blade disappears. |
Table 4. Cont.

| Year | Reference | Geometry of the Model | Type of Cavitation/Vortex | Cavitation Model | Findings |
|------|-----------|-----------------------|---------------------------|------------------|----------|
| 2015 | [68]      | Research on unsteady-flow cavitation performance, blade pressure distribution, tip vortex, and cavitation | The Zwart-Gerber-Belamri (ZGB) cavitation model | 1. The numerical simulation can better forecast the onset and progression of the pump-jet cavitation event, as well as its shape and position. 2. When the cavitation phenomena occur, the pump-jet propeller’s efficiency drops dramatically, reaching more than 20%. 3. The pressure distribution between the surface of the unmanned underwater vehicle (UUV) and the stator’s rotor blades is more reasonable and commensurate with the cavitation phenomenon. 4. The tip vortex and cavitation of the top clearance are caused by the pressure difference between the pressure and the suction surface of the rotor blade’s tip area, resulting in the pump-jet propulsion’s efficiency being depleted. |
| 2016 | [69]      | Turbopumps, hydro turbines, and various other types of machinery | Leading-edge cavitation, inter-blade vortex cavitation, and traveling-bubble cavitation | 1. Homogeneous mixture flow model 2. Three-component two-phase flow model 3. Turbulent flow modeling | Future research will focus on advanced themes such as a density-based solver for highly compressible cavitating turbulent flows and a virtual cavitation tunnel. |
| 2016 | [70]      | Experimental observations of Schiffbau-Versuchsanstalt (SVA) Potsdam, OpenFOAM, StarCCM+, and BEM computations | The OpenFOAM native Schnerr-Sauer interphase mass transfer model |  | The comparison of traditional boundary element methods with available experimental measurements and calculations performed with StarCCM+ and a proprietary boundary element method code in a very demanding test case further validated the reliability of traditional boundary element methods that are still widely used for design and optimization (thanks to their much higher computational efficiency). |
| 2017 | [71]      | A symmetric NACA0015 hydrofoil | Sheet and cloud cavitation | The Zwart-Gerber-Belamri (ZGB) cavitation model in OPENFOAM | 1. The main differences lie in the value of $-C_{p,\min}$, which in our simulation was coherently equal to $\sigma$. 2. The cavitation model used by Zwart et al. (2004) in combination with the turbulence model $k - \omega$ can give the best results in comparison with the experimental data. |

3.2.3. Gap Flow

The main structural difference between an IMP and a traditional pump-jet propulsor is that the motor is located in the duct, and the motor rotor is seamlessly coupled to the impeller blade surface. The stator is also installed in the duct. This structure gives it the
advantages of flexibility, high reliability, a compact structure, low vibration, and low noise. The structure of an IMP includes a gap between the inner surface of the stator of the motor and the outer surface of the rotor. When the propeller is working and water flows through the gap, it can not only cool the heat-generating parts, such as the stator of the motor, but to a certain extent, due to the viscosity and density of the water and air, it will produce a large friction torque at the connection point (motor rim) between the motor rotor and the impeller blade, which will cause the propeller to experience a large power loss when rotating at a high speed. Therefore, to design IMP thrusters with low power loss and good heat dissipation performance, it is necessary to study the gap-flow law. To acquire a clear picture and detailed explanation of the effect of the gap-flow model on the hydrodynamic performance of IMP thrusters, the numerical studies and experimental research on the IMP gap are discussed in this section (see Table 5).

Table 5. Summary of the effect of the gap-flow model on the hydrodynamic performance of IMP thrusters.

| Year | Reference | Geometry of the Model | Parameter | Method/Experimental Method | Findings |
|------|-----------|-----------------------|-----------|-----------------------------|----------|
| 2000 | [72]      | Brushless permanent-magnet motor of a rim-driven thruster | The gap size | CFD analysis | 1. The gap size is an important parameter for the entire thruster. 2. The design of the propeller considered in the study was very limited. |
| 2015 | [73]      | The axial and radial gap flow | The axial and radial gap flow | A new predicted formula to calculate the outer surface’s torque: $C_{rimout} = 0.01668 \eta^{1.818} (1 - \eta)^{-1.757} Re^{1.8}$ | 1. A circular flow exists in the axial gap, consisting of a radial outflow emanating from the rim’s end faces, arriving at the duct’s inner surface, and a radial inflow developing along the duct’s side surfaces for momentum commutation. The axial gap clearance changes the position of the circular flow. 2. When the axial and radial clearances are all minute, Taylor vortices develop solely at the rim’s outer edge. The radial clearance ratio increases [74] the number and location of Taylor vortices in the radial gap. 3. As the axial clearance ratio increases, the dimensionless torque of the end faces increases. 4. When the radius ratio is less than $\eta > 0.97$, the dimensionless torque remains constant, but when the radius ratio is greater than $\eta < 0.97$, the gap between empirical and numerical values expands as the radial gap ratio increases. As the radial gap clearance is increased, the torque coefficient rises. |
Table 5. Cont.

| Year | Reference | Geometry of the Model | Parameter | Method/Experimental Method | Findings |
|------|-----------|-----------------------|-----------|----------------------------|----------|
| 2015 | [74]      | Rim-driven thrusters   | The pressure difference in the axial and radial gap | The boundary layer theory and semiempirical formulas: the RANS solver and the turbulent model SST k-ω | 1. The pressure difference has a significant effect on the flow pattern of the gap, and it also has a significant effect on the torque of the rim. 2. In the gap flow with pressure difference, the hollow part of the duct midsection and the sum of the thrust of the outer surface of the rim at the front and rear ends cancel each other out. 3. The calculated rim torque coefficient of the gap flow with differential pressure is larger than that under the condition of no differential pressure. |
| 2015 | [55]      | Rim-driven propulsor   | The axial and radial gap | The Daily and Nece, and Bilgen and Boulos models | 1. A combination of the Daily and Nece, as well as the Bilgen and Boulos models for torque contributions, was shown to under-predict torque, which could be due to the former’s low aspect ratio and the latter’s axial pressure gradient effects. 2. The interplay between the two gaps’ probable flows caused torque effects. |
| 2017 | [75]      | Motor cooling          | The different structural parameters and different working conditions | Contrastive analysis, CFD analysis | 1. The larger the axial and radial gap size, the higher the rotation speed, and therefore, the greater the water flow speed. As a result, the greater the power consumption and the greater the frictional power consumption of the gap fluid. 2. Increasing the gap size is beneficial to the heat dissipation of the motor. |
| 2018 | [76]      | L-shaped bearing and tapered bearing | The change in the law of clearance friction power consumption | Contrastive analysis, CFD analysis | 1. For L-shaped bearings, as the number of grooves increases, the thrust of the propeller and propulsion increases, and the thrust of the rotor ring decreases with the increase in the number of grooves. 2. The tapered bearing has relatively small clearance friction power consumption due to its structural advantages. 3. As the number of bearing grooves increases, the thrust and torque generated by the propeller gradually decrease; however, the thrust and torque generated by the rotor ring increase as the number of bearing grooves increases. |
Table 5. Cont.

| Year | Reference | Geometry of the Model | Parameter | Method/Experimental Method | Findings |
|------|-----------|-----------------------|-----------|-----------------------------|----------|
| 2019 | [49]      | Pump-jet propulsor    | The rotor and stator thrust as well as the torque performance | Mesh approach for flat-topped blades based on a circular truncated cone and a tip leakage vortex model | 1. There is an intensive leaking vortex at the rotor tip for low advance speed coefficients, and the addition of a tip vortex model improves the calculation results noticeably. 2. However, it ignores the effect of gap flow on the surrounding flow field, resulting in rotor-tip load forecast findings that are inaccurate. |
| 2019 | [77]      | Rim-driven propulsor  | The different speeds of the rotor and the advanced coefficient | Reynolds-averaged equation (RANS), and the rotation of the rotor was simulated by moving reference frame (MRF) | The axial gap flow increases with the increase in the rotation speed. Changes in the fluid pattern within the gap result in changes in the differential pressure within the gap. |
| 2017 | [78,79]   |                       | The different gap ratios in a radial and axial direction, speed, and pressure | $C_M = 0.080(s/a)^{-1/6}Re^{-0.25}$ $C_M = 2 M/\rho \omega^2 a^3$ | 1. As the gap widened, the friction torque rose. 2. Friction torque had mutual effects in both the axial and radial directions, and the heat created in the motor dissipated fast in the gap flow. |
| 2022 | [75]      |                       | The effect of fluid viscosity in the gap zone | Combining the existing tip leakage vortex model and a suitable gap-flow model | 1. The inclusion of the gap-flow model has the greatest impact on the duct of the pump-jet propulsor, bringing the duct’s hydrodynamic performance and pressure distribution more in line with the trend of the viscous flow calculation findings. 2. The gap-flow model has a minor effect on the overall hydrodynamic performance of the pump-jet propulsor’s calculation findings, and its determined value is only slightly raised. |
| 2021 | [80]      |                       | The effect of fluid viscosity in the gap zone, as well as the height of the gap | A low-order panel method based on velocity potential combining the existing tip leakage vortex model and a suitable gap-flow model | 1. The gap height should be 0.98–1.0 times the total gap height. 2. The flux coefficient (CQ) range of 0.8–0.84 was found to be suitable. |

4. Dynamic Coupling Technology

4.1. Dynamic Coupling between IMPs and Ship Hulls

The interaction of a yacht’s duct and hull was investigated by Voith (2017) [39]. Figure 8a depicts the RDT installation, while Figure 8b depicts the water flow pattern (b). Between the propeller and the hull, this configuration created a flow vortex and negative pressure.
To optimize the structure and installation site of RDTs, it is critical to comprehend the interaction and nonlinear coupling between the wakefield, the RDT, and the hull. The efficiency of the system can be improved while minimizing sailing resistance by optimizing the RDT design, hull lines, and installation sites. To study the interactions between the hull and RDTs, Lu et al. (2014) [82] investigated the influence of the number of RDTs (either two or four sets) and the location of the RDT installation on the hydrodynamic performances of an underwater vehicle (Figure 9). Due to the influence of the stern wake, reducing the distance between the RDT and the hull improved the RDT’s efficiency and the thrust deduction factor. To increase the vehicle’s hydrodynamic performance, the RDTs could be placed at the parallel middle body towards the aft body. This would result in a negative thrust deduction factor. When RDTs were installed on the stern planes, increasing the number of RDTs resulted in a significant reduction in the total propulsive efficiency; however, when the RDTs were mounted on the parallel middle body, there was only a small reduction in the total propulsive efficiency. The design, integration, and testing of a steerable rim-driven thruster for the short takeoff aviation support ship (STASS) model was the subject of Newacheck et al. (2019) [83]. To analyze the influence of the newly designed and integrated system on the drag force, the testing matrix used four configurations of the bare hull, supplemented with SHIPS, bollard pull, and self-propelled phases. The drag force for SHIPS was found to be enhanced by 20% due to a variety of factors, including the increased wetted surface area and the blocking effect caused by the presence of the motor cage and steering column in the flow direction. After the thruster was integrated, there was a further increase in the drag force.

Figure 8. Interaction between duct and hull of a yacht: (a) yacht equipped with two RDTs; (b) water flow pattern behind the RDT [39].

Figure 9. Different numbers and installation locations of RDTs [82].
4.2. The Coupling Design Technology of Hydrodynamics, Electromagnetics, and Bearings

Numerical simulation methods also play an irreplaceable role in analyzing the coupling effects of the electromagnetic–hydrodynamic–thermal structure of the integrated motor propulsion devices, according to Hu et al. (2016) [84,85] and Shen et al. (2016) [29]. To tackle the heat dissipation problem of permanent-magnet motors, slots are positioned at the front and rear ends of the motor rotor to facilitate communication with the air gap between the stator and rotor. Figure 10 depicts the design and simulation of a natural circulation seawater cooling method.

Figure 10. Multifield simulation of IMP [85].

Liang et al. (2012) used a combination of the finite element method and the finite volume method to carry out the study of electromagnetic–thermal coupling [86,87]. The back electromotive force and temperature were measured in this study through experiments to demonstrate that the integrated permanent magnet can improve the effectiveness of the motor-cooling system, as illustrated in Figures 11 and 12.

Figure 11. Simplified PM model for multifield coupled analysis [86].
back electromotive force and temperature were measured in this study through experiments to demonstrate that the integrated permanent magnet can improve the effectiveness of the motor-cooling system, as illustrated in Figures 11 and 12.

Figure 11. Simplified PM model for multifield coupled analysis [86].

Figure 12. Temperature distribution of stator and windings [86].

5. Discussion

5.1. The Design of the IMP

The lifting-line theory has significantly promoted the development of IMP propeller design technology. Many researchers have proposed a corresponding design theory, mainly focused on the design method and design object. In terms of design methods, the IMP propeller lifting-line theory was improved because of the defects of the heavy-duty propeller and the basic design theory under nondesign conditions. For IMP propellers with a side slope and pitch, the corresponding lifting-line design method is perfected. In recent years, scholars have combined the IMP propeller lifting-line theory with the panel method and the Reynolds-averaged Navier–Stokes (RANS) method to improve the accuracy and efficiency of IMP propeller performance prediction. In addition, it is combined with modern optimization design theory, and the performance optimization of an IMP propeller is considered in the design stage, which improves the design efficiency. In terms of the design objects, as the calculation speed increases, the lifting-line theory can be applied to the performance prediction and design of complex thrusters.

The lifting-surface method is used by many studies to deal with the forward prediction of IMP propellers. The current research focuses include the shrinkage and curling of the wake vortex in the transition zone of the IMP propeller and the tip vortex separation model, which considers the trim and side slope, etc., establishing a model of the IMP propeller trailing vortex and tip vortex, and the separation vortex of the leading edge and corresponding improvement methods are also proposed. In addition, when the IMP propeller interacts with other components, the influence of the hub and the coupling panel method are introduced to consider the influence of other components to improve the accuracy of the performance prediction. Regarding the inverse problem of the lifting-surface design method, since the shape of the blade profile is closely related to its load form, efficiency, cavitation, and other hydrodynamic properties, the main research focus is the precise and rapid design of the vortex grid method to meet the given lift distribution, the design of the arcuate surface of the blade arch under the circulation distribution, and the three-dimensional refinement of the theoretical boundary value problem of the IMP propeller lifting surface. In addition, when considering the interaction between the hull and its appendages, ducts, and propellers, the lifting surface is coupled with other theories such as RANS for design, and the influence of other components is more accurately considered in the design stage to further improve the design accuracy and efficiency.

At present, the lifting-line model is relatively mature and can solve the problems related to the calculation of the propeller thrust, torque, efficiency, and induced speed field behind the propeller; the calculation time required is relatively short, but it has certain
limitations. Compared with the lifting-line method, whether it is a forward prediction problem or a reverse design problem, the lifting-surface method can fully consider the blade chord length, camber, and pitch distribution, which has great advantages. Regarding IMP propeller design issues, most of the past studies have focused on the deformation of the tail vortex, the effect of the hub, and the related lifting-surface design of the profile load distribution. It is particularly important to refine the design of some special propellers, such as ducted propellers and pump-jet propellers, to couple the lifting-line and lifting surface design methods with methods such as the surface element method or RANS, and to consider the interaction of the components. This aspect is worthy of further study.

5.2. Hydrodynamic Performance of IMP Thrusters

When predicting the propulsion performance of an IMP thruster, the CFD method considering the viscous effect can accurately simulate the complex flow of the IMP thruster’s wakefield and the slight vortex structure of the blade. At the same time, it can accurately simulate the flow near the wall through the boundary layer grid, and the effect of turbulent flow is fully considered on the propulsion performance of IMP thrusters. With the development of high-performance computers, the viscous-flow CFD method strongly supports the prediction of the hydrodynamic performance of IMP thrusters. At present, it seems to be the most mainstream method for the numerical simulation of IMP thrusters’ flow fields.

In terms of CFD preprocessing for IMP thrusters, the CFD grid discrete method is relatively mature. The main research work is focused on comparing different grid types and corresponding grid layout methods to automatically generate grids for specific calculation conditions and to investigate the combined use of different grid discretization methods.

In terms of the IMP thruster CFD calculation method, the aim is to evaluate the applicability of different turbulence models in the calculation of an IMP thruster’s hydrodynamic performance. At present, it seems that different turbulence models have certain differences when measuring the hydrodynamic performance of IMP thrusters. These works also provide a reliable reference for the reasonable selection of turbulence models that are suitable for specific research topics. For the flow field of rotating machinery such as IMP thrusters, numerical methods such as multireference system models, sliding grids, overlapping grids, moving grids, and periodic boundaries also have corresponding suitable application scenarios.

In terms of CFD calculations for IMP thrusters, the current research work is mainly focused on the open-water performance of IMP thrusters, the numerical prediction of unsteady forces, the fluid–structure interaction, the performance in a nonuniform flow field, and the cavitation of IMP thrusters. Regarding the open-water performance, the research content includes the impact analysis of IMP thruster parameters, such as side slope and pitch, and the geometric parameters of duct IMP thrusters, such as blade tip clearance. For the application of different turbulence models in the calculation of the unsteady force of IMP thrusters, more extensive research has been carried out at home and abroad, mainly comparing the calculation accuracy of different turbulence models. According to the research results, the DES method and the LES method deal with nonstationary forces and are most widely used for steady problems. There are also related studies on the influence of calculation settings on unsteady calculations and the calculation of the unsteady performance of new types of thrusters.

5.3. Optimization Technology of IMP Thrusters

Previous studies pay more attention to the design goals of IMP propulsion efficiency, cavitation performance, blade strength, and noise performance. The introduction of multiobjective optimization design methods is aimed at the occasions that require multiple performance indicators. Generally, more multiobjective methods are being used, such as the dualobjective optimization design of propulsion efficiency and cavitation performance, and performance optimization under multiple operating conditions.
During the optimization design process of IMP propellers, many scholars have analyzed the sensitivity of IMP propeller design parameters to design goals through design of experiment (DOE), Sobol sensitivity analysis, and regression analysis. Studies have shown that the maximum chord length of the blade is the main factor affecting the cavitation performance, and the dimensionless radius of 0.7–0.9 has a greater impact on the low-frequency broadband noise of the IMP propeller. In addition, the thinner the blade, the more obvious the effect of improving the efficiency of the propeller, but thinner blades have an adverse effect on the strength and other mechanical properties of the blade. The influence of the parameters of IMP propellers on the performance and the restrictive relationships between the parameters are more easily reflected in the optimization design process. It is very important to apply modern optimization design theory to IMP propeller design optimization.

6. Conclusions

This paper analyzes the IMP thruster’s working structure, major structural application technology, current hydrodynamic performance research, and important technologies that require further resolution. The IMP thruster completely embraces the principle of extensive electric modularization and integration, better reflecting the high power density, high efficiency, low radiation noise, and maneuverability of electric propulsion systems. As a result, integrated motor propulsion technology has gradually expanded its application areas to other rotating machinery such as pumps, turbines, and fans. However, there are still some uncertain issues with IMP thrusters, for example, that the output power is still in the megawatt range due to power loss at the intake. Furthermore, using IMPs in shallow water, especially around gravel, is exceedingly risky. To design an IMP, numerous critical technologies must be resolved. Because the stator of the motor in the IMP propeller is embedded in the duct, the rotor and the impeller blade are seamlessly connected. This structure thickens the duct and affects the entire flow field. In addition, it is necessary to ensure that the propeller motor has a large enough flow area by limiting the thickness of the stator yoke, rotor yoke, and the magnet of the motor. If the size is too thin, the electromagnetic field will saturate prematurely, further reducing the magnetic flux density of the motor, causing the motor to fail to work normally. In addition, as the IMP thruster eliminates the use of the drive shaft, bearings, and vibration isolation devices that support the traditional motor and reduce the internal noise of the hull, the thrust and torque generated by the thruster are directly coupled with the electromagnetic excitation force generated by the motor, which then increases the electromagnetic noise, hydrodynamic noise, etc. Therefore, the complexity and necessity of designing a high-power, low-vibration, low-noise, and high-performance motor are increased.

If a nonaqueous lubricant is used for bearing lubrication, then the sealing devices must be considered. This will increase the complexity and design cost of the entire IMP propeller structure and, at the same time, may cause some other marine pollution problems. Therefore, the use of water-lubricated bearings can reduce the weight and complexity of the IMP thruster system to better reflect the advantages of the IMP thruster. However, due to the low viscosity of the water medium, the bearing capacity of the water film is not large enough, which means that the water-lubricated bearings experience a mixed-lubrication state. As a result, this will affect the bearing capacity and working performance of the bearing. In addition, the adaptability of the bearing material to water and the influence of different flow conditions on the dynamic pressure lubrication characteristics of the bearing will affect the load transfer in the bearing. Therefore, the load-bearing reliability characteristics and design optimization of the bearing should consider the above-mentioned series of issues. To obtain an IMP thruster with a high propulsion efficiency and high output power, the design method for these components must be very strict, because the degree of coupling between high-power thruster components must be higher. Therefore, hydrodynamic–electromagnetic–thermal–fluid–solid coupling research can effectively help us to understand the complex working conditions of the coupling between the internal
components and the whole of the IMP thruster. Additionally, it can obtain the key influencing factors that affect the propulsion performance, which will provide technical support for the design of high-power IMP thrusters in the future.

When the IMP propeller is working, as it is completely immersed in seawater, all impurities in the seawater will be sucked into the air gap of the propeller, which will then reduce the amount of flowing fluid in the air gap, affecting the cooling of the motor and ultimately reducing the efficiency of the motor. When the IMP is operating in shallow waters, especially in sandy waters, the motor may be directly damaged. The failure of the motor will cause the ship to lose power. Therefore, improving the antipollution and anti-damage abilities of IMP thrusters is of great significance for improving the hydrodynamic performance and efficiency of the thrusters.

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Nomenclature

| Symbol | Description |
|--------|-------------|
| $K_T$  | Thrust coefficient |
| $K_Q$  | Torque coefficient |
| $\eta$ | Propulsion efficiency, $\eta = (K_T/K_Q) \cdot (J/2\pi)$ |
| $J$    | Advance coefficient, $J = U/nD$ |
| $U$    | Inflow velocity |
| $n$    | Rotational speed |
| $D$    | Diameter of propeller |
| $\Omega$ | Vorticity |
| $\sigma$ | Cavitation number |
| $C_p$  | Pressure coefficient |
| $C_M$  | Gap moment coefficient |

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