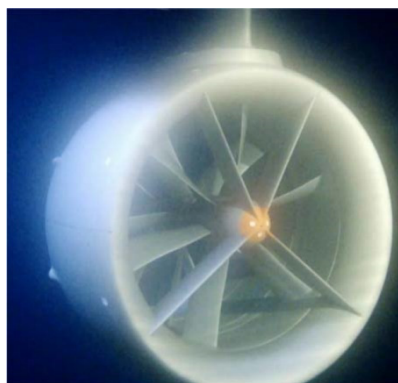


Development of Contra-Rotating Rim-Driven Propulsion System to Meet Needs of Electrification and Diversification of Ocean Mobility



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In order to realize a decarbonized society, we are proposing the concept of an electric propulsion system with flexibility to meet various needs as one of the solutions to reduce CO₂ emissions from ocean mobility for society as a whole. We designed and conducted performance verification a contra-rotating rim-driven propulsion system that reduces the design constraints of ship configuration and has robust propulsion performance under operating conditions.

The rim-driven propulsion system does not have a drive shaft and mounts the propeller blades inside the motor. The system is characterized by its compactness. By applying contra-rotating technology and other elements to this propulsion system, we aimed to achieve high propulsion performance under a wide range of operating conditions. Following the verification, we confirmed that the contra-rotating rim-driven propulsion system has improved propulsion performance compared to a propulsion system that adapt to a wide range of conventional operating conditions, as typified by a nozzle propeller.

1. Introduction

In response to the trend toward decarbonization, the reduction of CO₂ emissions during ocean mobility transportation is an urgent issue for ocean mobility, which is represented by ships. The reduction in CO₂ emissions needs to be achieved not only by the product producer through improved product performance, but also by cooperation of all the stakeholders involved in ocean mobility through more efficient operation and loading/unloading.

On the other hand, stakeholders need to secure their individual interests and their needs vary widely. Products had to be designed on a case-by-case basis to meet individual needs. As a possible solution to these complex problems, we propose the concept of an electric propulsion system that contributes to the electrification of ocean mobility for decarbonization and is flexible enough to meet the design and operational needs of ships.

This report presents the design and performance verification of a contra-rotating rim-driven propulsion system, which has features to reduce the design constraints of the ship configuration and to maintain high propulsion performance under a wide range of operating conditions.

2. Design concept of contra-rotating rim-driven propulsion system

The rim-driven propulsion system is one type of motor-driven electric propulsion system, nevertheless, it has no drive shaft and mounts the propeller blades inside the motor, unlike common propulsion systems which have propeller blades at the end of the drive shaft. As presented in **Figure 1**, which shows the configuration of the rim-driven propulsion system, this system integrates the motor and mechanical parts, thus the ship has no need to have mechanical parts onboard. We considered that the greatest advantage of this feature is that the design constraints of the ship configuration is reduced by enabling the propulsion system to be more compact and the arrangement

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more flexible, and aimed to improve the efficiency by applying contra-rotating technology that takes advantage of the absence of a drive shaft.

This system has an outer peripheral surface called rim on the outside of the propeller blades, and the propeller blades are rotationally driven by permanent magnets installed on the rim and electromagnets placed on the outer side of the permanent magnets. The combination of the permanent magnets and the electromagnets is referred to as a motor. By arranging two of the motors in forward and aft, two-stage propellers can be driven. Furthermore, by setting the rotation directions of the front and back propellers to be opposite from each other, a contra-rotating configuration can be made, in which the swirling flow generated by the front propeller is absorbed by the back propeller. We believe that this will dramatically improve the propulsion performance compared to a single-stage configuration.

The shroud covering the motor is designed to be streamlined so as to generate thrust using the suction force generated along with the propeller operation, thereby suppressing the reduction of propulsion performance under high load conditions. We considered that this design could be realized by utilizing the conventional nozzle-propeller technology with a shroud on the outside of the propeller.

We considered reducing the design constraints of the ship configuration and providing flexibility to meet operational needs as issues. Our design concept for a contra-rotating rim-driven propulsion system is to maintain high propulsion performance under a wide range of operating conditions by combining the compactness and high degree of freedom of the ship layout of the rim-driven propulsion system with the contra-rotating technology and nozzle propeller technology.

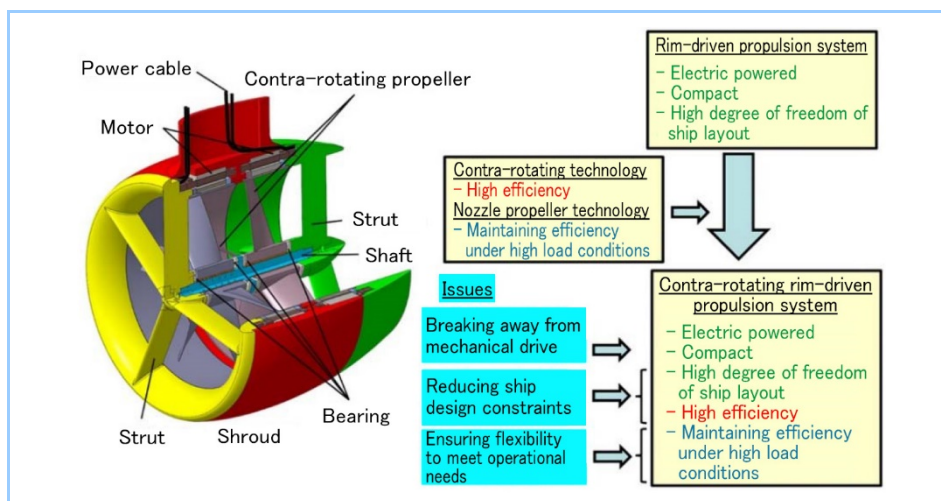


Figure 1 Configuration and design concept of contra-rotating rim-driven propulsion system

3. Design

We classified the design into the following major categories: fluid design, electromagnetics design, strength/sliding bearing design, thermal design, and manufacturing design.

Since the geometry and structure obtained in each design interact with each other, the design was carried out while adjusting the specifications of each one. This report describes the fluid-electromagnetic design, which has a direct influence on the propulsion performance, which is directly related to CO₂ emissions.

Among the principal items, the propeller/motor diameters, shroud thickness, length, and rotational speed have optimal solutions for fluid efficiency and motor efficiency. Therefore, the system efficiency, which is the product of fluid efficiency and motor efficiency, cannot be optimized by sequential design.

For this reason, we developed and operated a fluid-electromagnetics design tool incorporating the numerical analysis shown in Figure 2 to optimize the system efficiency in terms of the principal items. By adjusting detailed geometry parameters based on the principal items obtained with this tool, we found design solutions for the propeller/shroud shapes and motor dimensions/structure.

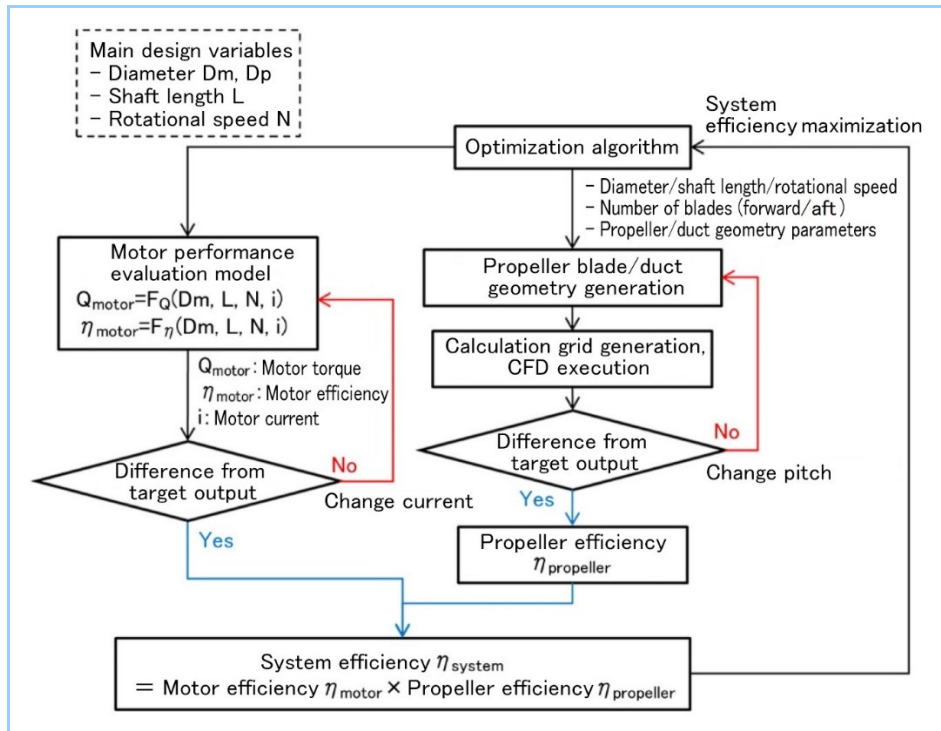


Figure 2 Design system flow of principal items

4. Verification

4.1 Verification with numerical simulation

We conducted numerical analysis using CFD to evaluate the propulsion system efficiency as a fluid performance, which is the efficiency gained through converting motor torque into thrust under a given external flow velocity condition.

In general, the propulsion system efficiency is determined by the propeller load coefficient, and the propulsion system efficiency, as typified by an open propeller, often shows a downward trend with respect to the propeller load coefficient. The load coefficient is the ratio of the amount of pressure increase per unit area to the dynamic pressure, and the higher the load coefficient, the more the power applied to a small area. A high load coefficient means that the acceleration of fluid passing through the propeller disk of the propulsion system is large in relation to the external flow velocity. In this case, the momentum loss is large due to the large difference in momentum between the inside and outside of the slipstream, resulting in low efficiency.

The propulsion system efficiency of the contra-rotating rim-driven propulsion system obtained by CFD is low in the extremely low load coefficient range, while it tends to remain high in the medium to high load coefficient range. This is due to the thrust generating effect that is produced by the fluid force applied to the shroud accompanied by the suction of the propeller, and is the result of utilizing the design technology of nozzle propellers. The maximum efficiency of nozzle propellers is low as around 50-60% (1), whereas the maximum efficiency of the contra-rotating rim-driven propulsion system exceeds 60% as shown in Figure 3. As shown in Figure 4, the contra-rotating system greatly suppressed the release of the swirl velocity component downstream of the propulsion system, which is believed to have improved the efficiency.

This characteristic indicates that the propulsion system maintains high efficiency over a wide range of operating conditions, which means that it has the potential to meet diverse operational needs.

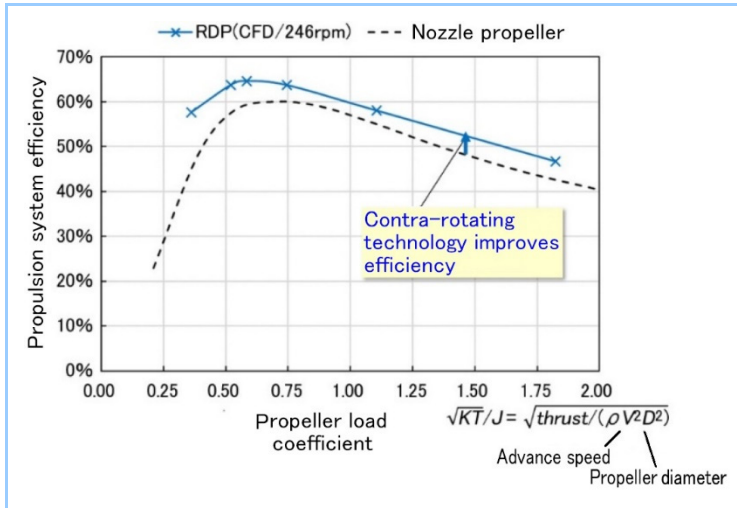


Figure 3 Simulation result of propulsion system efficiency

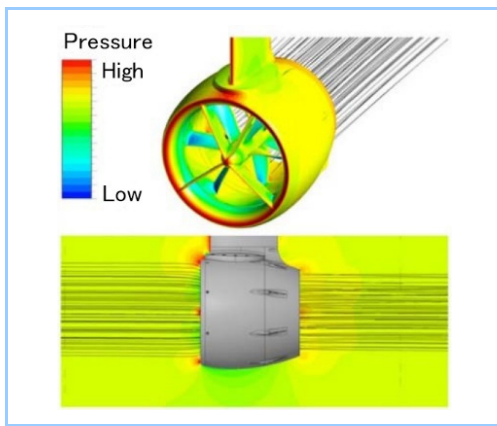


Figure 4 Simulation result of propulsion system wake flow field

4.2 Prototype design

For the purpose of performance verification through tank tests, we developed a prototype through strength/sliding bearing design, thermal design, and manufacturing design, assuming use in actual operation.

This prototype is a one-package contra-rotating propulsion system with a simple shaft configuration that does not require a drive shaft. It employs a structure in which the thrust from the propeller is transmitted to the fixed shaft via a water-lubricated plain sliding bearing on the fixed shaft. In addition, an underwater direct motor cooling system was adopted, in which water is circulated between the rotor and stator of the motor using the pressure increase before and after the propeller.

In this way, we could realize a compact-design propulsion system connected by six power cables, which is expected to be almost free from the design constraints of the ship configuration. This suggests that the system has the potential to meet a wide variety of design needs. **Figure 5** shows the configuration of the prototype, and **Table 1** shows principal items of the propulsion system.

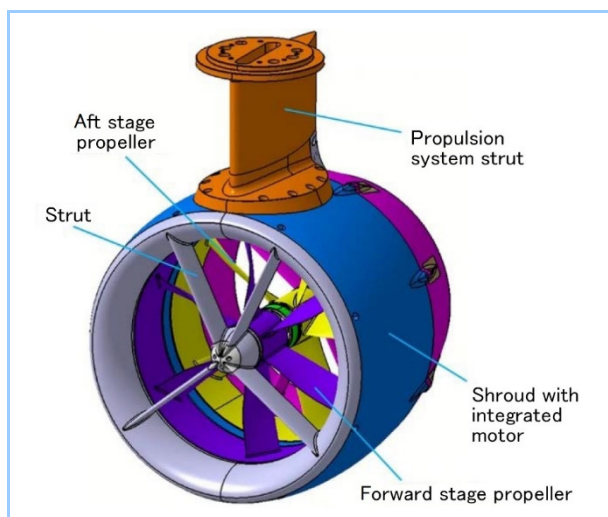


Figure 5 Configuration of prototype propulsion system

Table 1 Principal items of prototype propulsion system

Output power	4 kW x 2 stage = 8 kW
Rotation speed	246 rpm
Design ship speed	4.21 m/s
Motor rotor - Inner diameter	450 mm
Motor rotor - Outer diameter	475.9 mm
Motor axial length	85 mm for each
Motor type	3 phases, 30 poles IPMSM
Propeller diameter	440 mm
Propeller boss diameter	90 mm
Number of blades of forward stage propeller	6
Number of blades of aft stage propeller	5

4.3 Verification by testing

This report describes the results of a towing tank tests aimed at verifying the fluid performance among various elemental tests. In the towing tank tests, the propeller was rotationally driven by supplying electric power to the motor while the propulsion system was towed at a predetermined speed in the water using towing equipment. **Figure 6** shows an overview of the test equipment. Since a contra-rotating rim-driven propulsion system does not have a drive shaft, it is difficult to directly measure the thrust and torque of the propeller. Therefore, the thrust of the entire system was evaluated by measuring the fluid forces acting on all the propulsion system components, such as the propeller, shroud and struts, and the input power to the propulsion system was measured. Then, by using the previously obtained input power and speed-load torque characteristics of the motor, the propeller torque was evaluated.

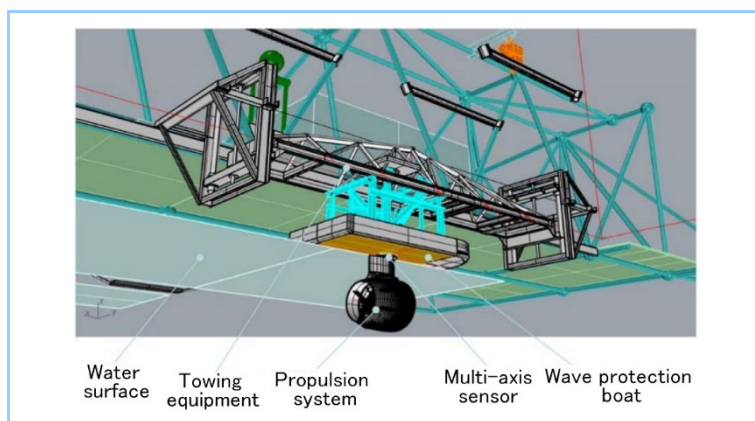


Figure 6 Arrangement of towing tank tests equipment

Based on the measurement results, the fluid performance was calculated and are shown in **Figure 7**. One of the differences between the test and the CFD is that the tank test took into account the friction loss of the bearings, which the CFD did not. Therefore, the test may have resulted in a lower evaluation of the propulsion system efficiency compared to the CFD. However, similar to the CFD results, the test showed that the propulsion system efficiency of the prototype propulsion system was improved compared to that of the nozzle propeller.

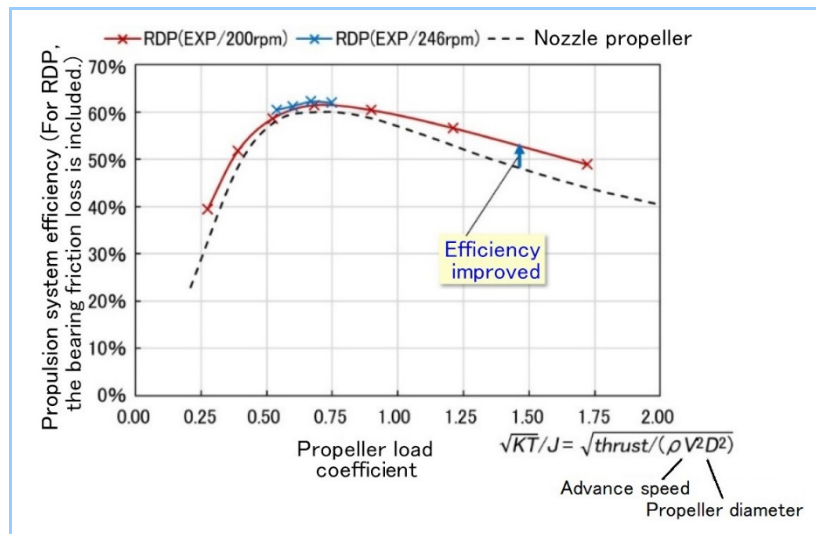


Figure 7 Propulsion system efficiency obtained by test

5. Conclusion

We have developed a contra-rotating rim-driven propulsion system that will lead to the electrification of ocean mobility, aiming to contribute to the realization of a decarbonized society. The issue to be solved by the contra-rotating rim-driven propulsion system is the necessity of meeting the diverse needs of the stakeholders involved in ocean mobility, and the development aimed to reduce the design constraints of the ship configuration and to provide flexibility to meet operational needs.

For the design of the developed system, the contra-rotating and nozzle propeller technologies were applied while maintaining the features of the rim-driven propulsion system, which is a compact motor-propeller integrated design that eliminates the need for mechanical parts onboard. Through simulation and a prototype test, we believe that the developed system can achieve higher propulsion performance than a nozzle propeller, which has a lower reduction in propulsion performance over a wide range of operating conditions.

Finally, we will present the issues to be solved for the commercialization of a contra-rotating rim-driven propulsion system. This report reported the results of prototyping and verification of a small (8 kW) propulsion system, but bringing the system into actual use requires consideration of an entire electric propulsion system, including the inverter, battery, and control. In addition, one of the most important issues for propulsion system users is the cost of installation. To suppress the installation cost, it is necessary to thoroughly reduce the manufacturing costs. We will adjust the manufacturing issues obtained through prototyping and work toward the realization of lower costs.

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