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Optimization Design Method of Pre-Swirl Fairing in Front of the Propeller

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Abstract. To meet the requirements of the Energy Efficiency Existing Ship Index (EEXI) and achieve the goal of energy saving and emission reduction, energy-saving devices are commonly installed on ships, such as the pre-swirl fairings in front of propellers. This device changes the direction of the water flow into the propeller, thereby reducing the rotational loss of the propeller and enhancing propulsion efficiency. This paper proposes an automatic optimization design method for the pre-swirl fairing in front of the propeller. The parametric deformation of the shroud is realized by the secondary development of 3D CAD software. The computational fluid dynamics (CFD) method is used to evaluate its performance, and the adaptive particle swarm optimization (APSO) algorithm is used to realize automatic optimization. The design and optimization of the pre-swirl fairing in front of the propeller of a bulk carrier are carried out. The results show that the energy-saving effect of the optimized energy-saving device can reach 4.18 %, which verifies the feasibility and effectiveness of the method proposed in this paper.

Keywords. Optimization, pre-swirl fairing in front of propeller, secondary development, CFD, APSO

1. Introduction

With the global energy shortage and environmental issues becoming increasingly severe, the high energy consumption and pollution in the shipping and maritime sectors have garnered significant attention. Energy conservation in ships has become a critical topic in the research of the shipbuilding and shipping industries worldwide. There are various methods to save energy on ships, including hull optimization for drag reduction, development of energy-saving devices, energy-saving measures for ship equipment (such as main engine energy savings and waste heat recovery), and operational energy savings (such as reducing speed and optimizing dynamic trim) [1], etc. Among them, the installation of ship energy-saving devices is a relatively cost-effective way of ship energy saving. On the one hand, it has a simple structure, convenient installation, low cost of production and use, and good energy-saving effect. On the other hand, many of the existing ships have not yet met the EEXI requirements, so it is necessary to make these ships meet the EEXI requirements. The pre-swirl fairing in front of the propeller [2] is a common energy-saving device for ships. It improves the propulsion efficiency by improving the hydrodynamic characteristics of the ship, so as to achieve the purpose of energy saving and emission reduction.

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This device is usually composed of an accelerating duct and several guide vane stators. The accelerating duct can make the water flow closer to the hull, improve the flow separation, and make the water flow into the propeller more uniform, while the guide vane stator provides pre-swirl for the propeller and reduces energy loss. According to different stern flow characteristics, the pre-swirl shroud in front of the propeller needs to be adjusted accordingly. In the past, the design of pre-swirl shrouds for different ship types was usually based on experience design and model test, which has the problems of high cost and low efficiency. To address this, this paper proposes an optimization design method for the pre-swirl fairing in front of the propeller. Design variables are based on parameters that need adjustment according to the ship type. The APSO algorithm generates deformation parameters, and parametric deformation is achieved through the secondary development of 3D CAD software. The fairing is modified according to these deformation parameters, and the modified model is then imported into CFD software for performance evaluation. The evaluation results are fed back to the optimization algorithm for iterative refinement, thus enabling the automatic optimization design of the pre-swirl fairing in front of the propeller.

2. Automatic Optimization Design Method of Pre-swirl Fairing in front of the Propeller

2.1. Secondary Development of 3D CAD Software

The 3D CAD software used in this paper is Solidworks. The secondary development of the software refers to the use of the application programming interface (API) provided by it to enable users to expand or customize the functions of the software. This development method allows users to automate complex design tasks according to their specific needs, and improve design efficiency and quality.

The API of SolidWorks is based on OLE or COM interfaces, which usually requires developers to use programming languages that support these interfaces [3]. Although Python is not a programming language that supports these interfaces, Python can effectively interact with COM-compatible API interfaces through the pywin32 library, thus simplifying the development process and improving development efficiency. Using Python for secondary development provides a unique advantage. Python's syntax is simple and easy to learn, coupled with its rich library support and strong cross-platform capabilities, making it a preferred language for automated design tasks and scripting. The steps of automatically modifying the model by calling the software in Python include: establishing a connection, quickly obtaining the required API function through macro recording, and then processing and converting it into Python code. Through the above steps, the secondary development of SolidWorks can be effectively carried out to realize the automatic deformation of the pre-swirl fairing.

2.2. The Computational Fluid Dynamics (CFD) Method

In this paper, the STAR-CCM + software of RANSE (Reynolds Averaged Navier-Stokes Equations) solver is used to calculate the hydrostatic resistance and self-propulsion simulation of ships. The K-Epsilon model is selected as the turbulence model, which can effectively describe the dynamic behavior and energy dissipation of turbulence. The free surface uses the VOF model to track the formation and movement of water surface waves. The multiphase flow model is simulated by solving the momentum equation and the fluid volume fraction, and the finite volume method is used to discretize the control equation to ensure the accuracy of the numerical solution. In the discrete process, the central difference scheme is used to deal with the diffusion term, and the second-order upwind difference scheme is used to deal with the convection term, so as to reduce the numerical dissipation and improve the accuracy of the simulation. In the self-propulsion simulation, the multi-reference frame (MRF) model is used to specially process the propeller rotation motion area.

According to the recommendations of ITTC (ITTC, 2011) [4] [5] and STAR-CCM + help document [6], the computational domain and boundary conditions set by numerical simulation in this study are shown in figure 1. The hull mesh and free surface are shown in figures 2 and 3. Furthermore, in addition to the top and bottom boundaries of the computational domain, the wave damping is added to the boundary of the remaining computational domain to avoid the influence of wave reflection on the flow field around the hull.

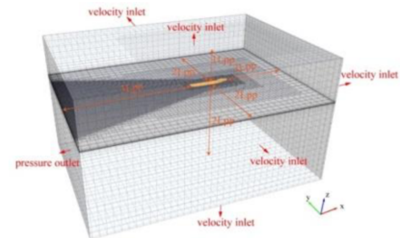

Figure 1. Computational domain.

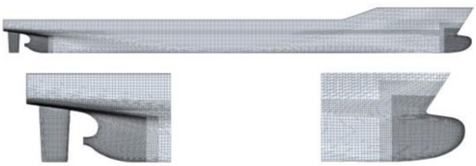

Figure 2. Hull grid.

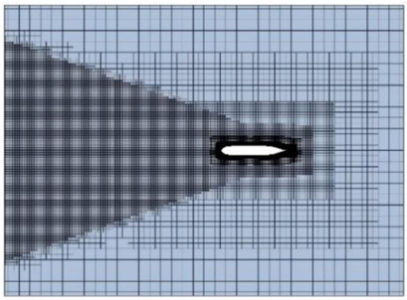

Figure 3. Free surface grid.

2.3. The Adaptive Particle Swarm Optimization Algorithm

The adaptive particle swarm optimization (APSO) [7] algorithm used in this paper is a heuristic optimization algorithm, which imitates the behavior of bird swarming and fish swarming. It is a variant of the PSO algorithm. Different from the PSO algorithm, the APSO algorithm introduces an adaptive mechanism, which can dynamically adjust the parameters and strategies of the algorithm to adapt to different optimization problems and stages. In the APSO algorithm, the particle swarm is represented as a potential solution, and each particle i is related to two vectors, namely the velocity vector $V_i = [v_i^1, v_i^2, \cdots, v_i^D]$ and the position vector $X_i = [x_i^1, x_i^2, \cdots, x_i^D]$, where D represents the dimension of the solution space. The speed and position of each example are initialized by random vectors in the corresponding range. In the process of evolution, the velocity and position of particle i on dimension d are updated as:

$$v_i^d = \omega v_i^d + c_1 rand_1^d (pBest\,_i^d - x_i^d) \\ + c_2 rand_2^d \left(nBest^d - x_i^d\right) \tag{1}$$

$$x_i^d = x_i^d + v_i^d \tag{2}$$

where, ω is the inertia weight, c_1 and c_2 are the acceleration factors, and $rand_1^d$ and $rand_2^d$are two uniformly distributed random numbers generated independently in the range of [0, 1] in the d-dimension. $pBest_i$ is the position with the best fitness found by the i th particle so far, and $nBest$ is the best position in the field. The APSO algorithm used in this study introduces evolutionary state assessment and elite learning strategies. Evolutionary state evaluation establishes a rule base, which includes four evolutionary states: exploration, exploitation, convergence and jumping out. It can dynamically adjust the inertia weight ω , acceleration factors c_1 and c_2 according to different evolutionary states during operation, thereby improving the search efficiency and convergence speed of the algorithm. When the evolutionary state is classified as a convergent state, an elite learning strategy will be executed, which will act on the global best particle to jump out of the possible local optimum.

2.4. Comprehensive Integration

This paper implements the secondary development of SolidWorks and the APSO algorithm through Python programming. STAR-CCM + software is selected as the numerical evaluation tool, and it is automatically called through the subprocess library in Python. Therefore, the integration of the final modules is also achieved through Python. The CAD deformation module will adjust the deformation of the pre-swirl fairing according to the deformation parameters generated by the APSO algorithm, and the newly generated model file is then imported into the CFD module for detailed numerical simulation analysis. In order to ensure the consistency and repeatability of the simulation process, the mesh generation, physical model selection, and simulation conditions after the model is imported are recorded in the macro file. After the model is imported, the relevant settings of the macro file for numerical simulation are automatically executed, which ensures that the parameters and conditions of each simulation are consistent. In addition, the comprehensive integration not only refers to the simple integration of each module, but also ensures that the data between each module can be effectively exchanged and circulated. This problem has also been effectively solved in the fully automatic optimization framework based on Python. The overall integration diagram is shown in figure 4:

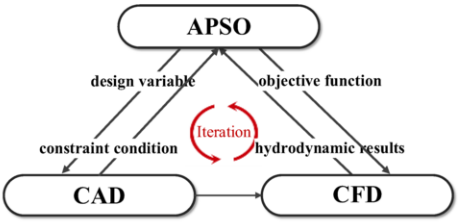

Figure 4. The overall integration diagram

3. Optimization Cases

In order to verify the effectiveness of the optimization method, this paper takes a bulk carrier as an example to design and optimize the pre-swirl fairing in front of the propeller. The bulk carrier has a tonnage of 59,000 tons, a square coefficient of 0.84, and a ship speed of 12 knots, which belongs to the low-speed fat ship type. The main dimensions and propeller parameters of the ship model are shown in table 1, and the scaling ratio of the real ship model is 32:1.

Table 1. The main characteristics of the ship.

Parameters	model data
Length Between Perpendiculars $(L_{BP})/m$	6.125
Beam $(B)/m$	1.063
Design Draft $(d)/m$	0.353
Froude Number (Fr)	0.14
Propeller Diameter $(D_P)/m$	0.206
Rotational Speed $(n)/(r/min)$	461.04
Number of Blades $/pieces$	4
Propeller Rotation Direction	right

The preliminary design of the pre-swirl fairing for the ship is shown in figure 5. Due to the thin stern of the ship, the pre-swirl effect of the conventional fairing is not obvious, and the expected energy-saving effect is not achieved. Therefore, the light fairing is finally adopted. The three stators on the left side extend 1200 mm, which can better pre-swirl the inflow to offset the circumferential induced velocity from the propeller and reduce the energy loss. The energy-saving effect of the guide cover can reach 3.1 %, which has achieved a good energy-saving effect, but it has not reached the expectation. Therefore, the optimization method of this paper is used to optimize the design.

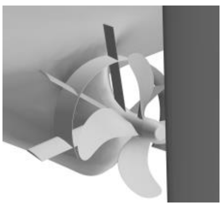

Figure 5. The preliminary design.

Firstly, the design variables of the optimization process are determined as the torsion angle of the stator (that is, the contact surface between the stator and the stern is kept unchanged, and the contact surface between the stator and the duct is rotated, so that the stator is twisted) and the angle of attack of the duct. Then, the optimization goal is determined as the energy-saving effect. The evaluation process of the energy-saving effect of the pre-swirl shroud is as follows: Firstly, the CFD software is used to simulate the self-propulsion of the pre-swirl shroud before and after the self-propulsion point, and the efficiency at the self-propulsion point is calculated. The energy-saving device is evaluated according to the obtained efficiency. The relevant calculation formulas of the evaluation process will be edited using Python and integrated into the optimization process to achieve automatic optimization of the pre-swirl fairing. The pre-swirl Fairing before and after optimization is shown in figure 6:

It can be seen from the diagram that the stator of the optimized pre-swirl Fairing in front of the propeller has been twisted to a certain extent, and the angle of attack of the duct has also increased. This change is more obvious in the front view and side view of the fairing before and after the following optimization in figure 7. After this change, the inlet flow of the diversion cover increases, which makes the incoming flow closer to the hull, and its pre-swirl effect is also improved, so that its energy-saving effect finally reaches 4.18 %.

Figure 6. The pre-swirl fairing before and after optimization.

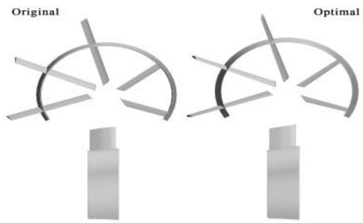

Figure 7. The front view and side view.

As shown in figure 8, after the installation of the pre-swirl fairing in front of the propeller, the ship wake is divided into multiple regions. In the wake distribution, the tangential velocity on the left side changes more slowly to the starboard direction, and even in some regions, the tangential velocity is facing the port side. This indicates that the device increases the pre-swirl in the opposite direction of the propeller rotation. At the same time, due to the wing-shaped profile of the fairing, the fluid within its coverage, especially the fluid near the duct, is accelerated in the axial direction. So as to achieve such a significant energy saving effect, which also verifies the feasibility and effectiveness of the optimization method proposed in this paper.

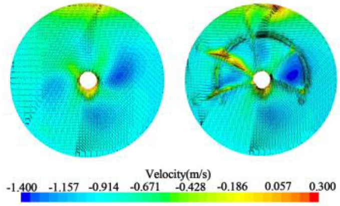

Figure 8. Velocity distribution of flow field in front of propeller.

4. Conclusion

(a) In this paper, an automatic optimization method for the pre-swirl fairing in front of the propeller is proposed. The tools (optimization algorithm, CAD modeling, CFD simulation) in different fields are integrated together to realize the closed-loop cycle of automatic generation of design parameters, model modification, simulation calculation and optimization feedback. This automated closed-loop optimization process can significantly improve efficiency during the design cycle and explore a wider design space.

(b) The APSO algorithm is more adaptive than the traditional PSO algorithm, and can better deal with complex multi-peak optimization problems, which is very suitable for the optimization design of the pre-swirl fairing in front of the propeller.

(c) This method can verify the actual performance of the design in each iteration through the close coupling of SolidWorks and CFD tools, rather than relying solely on theoretical derivation. The optimization algorithm automatically optimizes the design parameters of the fairing, such as angle of attack, length, etc., based on the feedback results of CFD simulation, forming a real performance-based optimization process.

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