

Fuel Consumption and Performance Prediction in Outboard Motors for High-speed Planing Boats using CFD Simulation

Shunsuke KURIOKA*

ABSTRACT

The research discussed in this paper set out to develop a simulator able to quantitatively predict the cruising fuel consumption and cruising performance of an outboard motor used for a small, high-speed planing boat; the target accuracy for prediction was within a range of $\pm 5\%$. The research focused on the fact that the thrust performance of a propeller has a significant impact on cruising fuel consumption and cruising performance. In order to evaluate the accuracy of the fuel consumption and performance simulator, simulation results were compared with the results of a full-scale cruising test. This comparison suggested that the simulator was able to satisfactorily predict the cruising fuel consumption and cruising performance of outboard motors. In particular, prediction results agreed with full-scale measurement results to within a range of $\pm 2.79\%$ (± 1.7 km/h) for maximum speeds and $\pm 4.55\%$ for cruising fuel consumption. These results indicate that the simulator is able to quantitatively predict the cruising fuel consumption and the cruising performance of an outboard motor. More importantly, the results demonstrate that the simulator can be used to identify optimal propeller specifications and gear reduction ratios, which have traditionally been based on experience. It was therefore concluded that the simulator possesses considerable potential as an effective tool able to be used in the development of environmentally friendlier outboard motors with outstanding cruising fuel economy and cruising performance.

1. Introduction

The world's first practical outboard motor was developed in the 1900s in the U.S. More than 100 years later, outboard motor engines offer pleasure and utility to users throughout the world as compact, lightweight, and high-power sources of drive power for small boats. Historically, the majority of outboard motors have used lightweight 2-stroke motors with simple configurations. However, there is a global demand for increased levels of environmental performance in internal combustion engines, and the engines used in outboard motors are no exception. Today, the use of 4-stroke engines in outboard motors in order to satisfy stringent exhaust gas regulations and environmental standards is increasing, and the manufacturers of engines for outboard motors have continued to rise to the technological challenge of balancing environmental performance and cruising performance⁽¹⁾⁻⁽³⁾. With an expansion in the scale of developments due to the recent trend towards larger displacement and increased horsepower in outboard motor engines, the reduction of development costs and the

realization of increased development efficiency are two of the most important issues facing manufacturers. One of the keys to the realization of these goals is the prediction of a variety of aspects of performance using simulations⁽⁴⁾⁻⁽¹⁰⁾.

Experience of outboard motor development to date has shown that even for identical motor engines, differences in propeller specifications and gear reduction ratios have a significant effect not only on cruising performance, but also on fuel consumption when the unit is in operation. The research discussed in this paper focused on the fact that propeller thrust performance significantly affects cruising fuel consumption, and conjectured that if it were possible to accurately determine propeller thrust performance, including the gear reduction ratio, by means of CFD simulation, and create a database combining engine performance data and fuel consumption maps obtained from tests, it would be possible to make numerical predictions of cruising fuel consumption, which have conventionally been obtained from tests or based on experience, at the initial stage of development.

The goal of the research was to develop a simulator

* Power Products R&D Center

capable of numerical predictions of cruising fuel consumption and cruising performance for an outboard motor used to power a small, high-speed planing boat to within an accuracy of $\pm 5\%$.

2. Overview of Simulator for Prediction of Fuel Consumption and Cruising Performance

2.1. Configuration of Simulator Database

The simulator for the prediction of fuel consumption and cruising performance in an outboard motor for a small, high-speed planing boat proposed in this research is made up of four databases, comprising engine power data, fuel consumption maps, hull resistance data, and propeller performance data (Fig. 1). Experimentally determined engine power curves are stored in the engine power database. The corresponding fuel consumption maps are similarly determined by experiment. The hull resistance database stores several types of data generated by a one-dimensional simulator created on the basis of experience from data derived from tests. The propeller performance database stores predictions and data based on CFD simulation.

The accuracy of the results of CFD simulation of propeller performance was verified by comparison with the results of model tests conducted in a towing tank. This process will be discussed later in the text.

2.2. Method of Prediction of Cruising Fuel Consumption and Cruising Performance

This section will discuss the prediction method employed by the simulator for the prediction of fuel consumption and cruising performance in an outboard motor for a small, high-speed planing boat proposed in this research. The method comprises the following three steps.

2.2.1. Prediction of propeller performance

Prediction of propeller performance is made up of

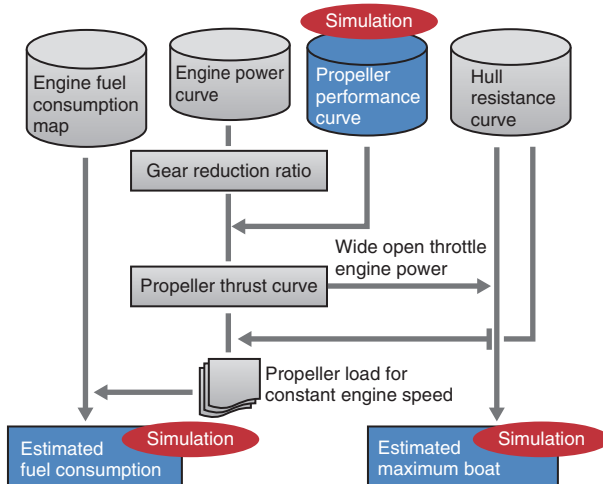
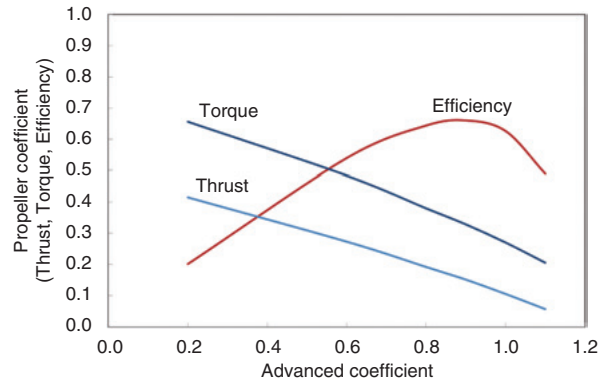


Fig. 1 Database components of simulator

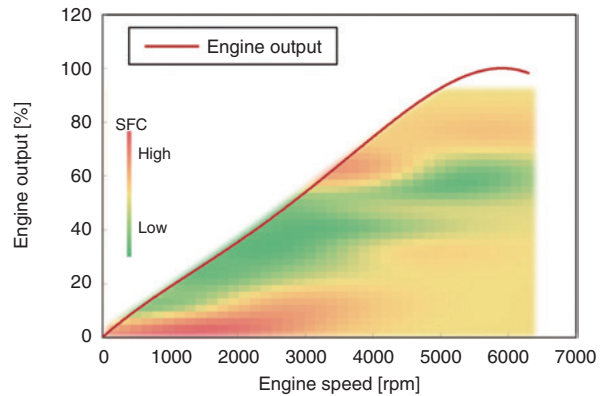
propeller performance curve [Fig. 2(a)] and engine power curves that take into consideration the horsepower loss from the engine to the propeller shaft and the gear reduction ratio of the propeller shaft [Fig. 2(b)]. Propellers used for planing boats generally convert input torque into thrust with a 60–80% range of propeller efficiency. Propeller thrust curves are estimated in relation to engine power on this basis.

2.2.2. Prediction of maximum cruising speed

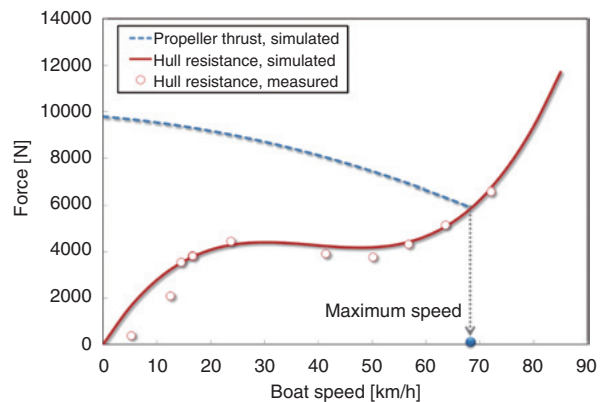
This prediction method combines the estimated propeller



(a) Propeller performance curves (Nondimensionalized)



(b) Engine power curve and fuel consumption map



(c) Hull resistance and propeller thrust curves

Fig. 2 Sample diagrams of database used in simulator

thrust curve and hull resistance curve. The propeller thrust curve combined with the engine power curve provides the thrust curve in relation to engine speed. In order to combine this curve with the hull resistance curve, it is necessary to convert it into a thrust curve in relation to cruising speed. The speed at which hull resistance and propeller thrust are in equilibrium is the final maximum speed of the planing boat [Fig. 2(c)].

2.2.3. Prediction of cruising fuel consumption

The propeller thrust curve calculated in Section 2.2.1 uses engine power at wide-open throttle. In order to evaluate cruising fuel consumption at a constant engine speed, that is, a state of partial throttle, propeller thrust curves for various engine speeds are formulated. Using the efficiency expressed in the propeller performance curve, this propeller thrust is converted to the engine horsepower absorbed by the propeller. Cruising fuel consumption is estimated by reading the absorbed horsepower for each engine speed off a fuel consumption map [Fig. 2(b)].

It was assumed that given the configuration of this simulator, realizing a level of accuracy of prediction of propeller performance exceeding that of prediction by CFD would represent a challenge. Based on the fact that the predictive accuracy of the propeller CFD used in the initial stages of the development process to date was around $\pm 5\%$, the target predictive accuracy for the simulator was set at $\pm 5\%$.

3. Method of Numerical Computation of Propeller Performance

3.1. CFD Solver

The research discussed here used commercially available CFD simulation software in order to predict propeller performance. The simulation solver was a CFD solver based on a finite volume method that handles unstructured grids, the efficacy of which in CFD analyses for propeller performance prediction has been indicated in a number of reports⁽⁶⁾⁻⁽⁹⁾.

The fluid equation was a standard incompressible Reynolds averaged Navier-Stokes (RANS) equation. The research adopted a method of steady-state analysis in which the coordinate system was rotated using the multi-rotating frame (MRF) method⁽¹¹⁾. The semi-implicit method for pressure-linked equations (SIMPLE) was used as the discretization method for pressure equations, while the high-accuracy quadratic upstream interpolation for convective kinematics (QUICK) scheme was used for momentum. A second-order central difference scheme was applied for space discretization accuracy apart from this.

3.2. Turbulence Model

This section will discuss the turbulence model used in the CFD simulation. The commercial software used in the research offered several types of turbulence model.

Turbulence models should be selected carefully with consideration of the flow fields of the subject of simulation. Because propeller performance was being databased in the present research, a $k-\omega$ SST model offering robust performance was selected based on the assumption that several hundred cases of CFD simulation would be conducted. The advantages presented by this turbulence model in research on CFD simulation for propeller performance prediction have already been reported by a number of researchers⁽⁶⁾.

3.3. Computational Domain

This section will discuss the analytic domain set for the CFD simulation. For this research the computational domain and the computational mesh size were rendered dimensionless by means of the propeller diameter, D ⁽⁶⁾. This offered the advantages of making it easier to realize accuracy and making it possible to compare results with the results of past research even in the case of predictions for propellers of differing diameters. The analytic domain was the domain shown by the cylinder in Fig. 3. With the propeller as the point of origin, the upstream side was set as distance $1.5D$, the downstream side as $3D$, and the radial direction as $2D$. The shape of the shaft at the front and rear of the propeller was the same as the shape used for the model in the towing tank test. The details of this test will be discussed later in the text.

3.4. Computational Mesh

This section will discuss the computational mesh used in the CFD simulation. Commercial grid generation software was used for the generation of the computational mesh. In terms of mesh type, tetra elements were employed for standard sections, while triangular elements called prism elements were used for boundary layers close to wall surfaces in order to increase analytic accuracy close to the wall surfaces. Propeller performance was calculated from thrust and torque calculated from the force obtained by integration of the pressure on the surfaces of the propeller blades. Given this, the computational resolution of the surfaces of the propeller blades was the most important factor. The mesh for the propeller surfaces was set at $D/200$, and the mesh for the first boundary layer was set at

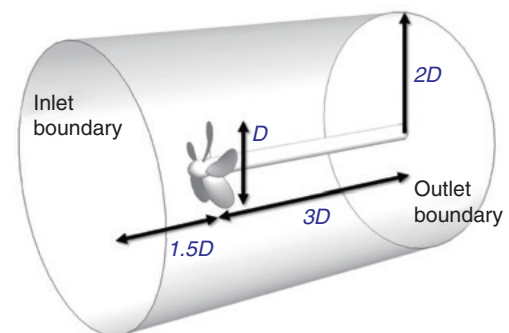


Fig. 3 Computational domain for propeller simulation

Table 1 Principal particulars of computational mesh for propeller simulations

Propeller diameter	D
Outside boundary surfaces	$D/4$
Propeller surfaces	$D/200$
1 st height of boundary layer	$D/1000$
Number of boundary layers	15
Growth rate of boundary layers	1.05
Growth rate of volume cells	1.20

$D/1000$. Fifteen boundary layers were employed, and the mesh growth rate for the boundary layer was set at 1.05. The computational mesh for the standard sections of the computational domain grew steadily larger at a growth rate of 1.2 from the surfaces of the propeller blades, and the outermost mesh of the computational domain was restricted to be $D/4$ at its maximum. Figure 4 shows an example of the computational mesh. Table 1 shows the mesh setting parameters.

3.5. Boundary Conditions

This section will discuss the boundary conditions set for the CFD simulation. A steady-state analysis was conducted, with a constant angular velocity imparted to the coordinate system. A velocity inlet boundary was employed in front of the propeller, and a pressure-fixed outlet boundary was employed behind the propeller. A free slip wall boundary was used for the walls of the cylindrical computational domain, and a non-slip wall boundary was used for the propeller blade surfaces. Propeller performance was derived from calculations of the thrust and torque coefficients, conducted while altering the speed of the inflow to the propeller.



Fig. 4 Propeller CAD model (left) and computational mesh (right)

4. Results and Considerations

4.1. Unit Performance of Propeller

For the simulator proposed by this research, propeller performance represented an important element that affects the cruising fuel consumption and thrust performance of an outboard motor and the selection of specifications for its

gear reduction ratio. Given this, high-accuracy prediction of propeller performance via CFD simulation was closely related to the realization of a high level of accuracy in the prediction results produced by the simulator. This chapter will discuss the accuracy of CFD simulation in relation to the prediction of propeller performance.

4.1.1. Benchmark computations (Propeller for displacement-type boats)

Prior to its use in predicting the performance of propellers used for planing boats, benchmark computations were conducted for the CFD solver employed in this research using publicly available test results for a five-bladed propeller used for displacement-type boats. The propeller used in the computations was the Seiumaru-I five-bladed propeller for displacement-type boats, generally termed a conventional-type propeller. This propeller has previously been used by numerous researchers in benchmark computations for model tests and numerical tests⁽⁶⁾. Figure 4 shows a CAD model and computational mesh for this propeller.

In this research, propeller performance was evaluated using performance curves that are in general use in the field of boat engineering. The performance curves were rendered dimensionless using the advance coefficient J , the thrust coefficient K_T , the torque coefficient K_Q , and propeller efficiency η , and were expressed using the following equations.

$$J = \frac{V_A}{nD}$$

$$K_T = \frac{T}{\rho n^2 D^5}$$

$$K_Q = \frac{Q}{\rho n^2 D^4}$$

$$\eta = \frac{J \cdot K_T}{2\pi \cdot K_Q}$$

Here, n is the propeller speed, D is the propeller diameter, V_A is the inflow velocity to the propeller, and ρ is fluid density. Figure 5 compares CFD simulation results with the results of model tests drawn from a published reference⁽¹²⁾.

The comparison between CFD simulation results and model test results for propeller thrust and torque coefficients indicated levels of predictive accuracy from the design point (approximately 80% of the point of maximum efficiency) to the point of maximum efficiency for CFD simulation of $\pm 2.8\%$ for thrust coefficient and $\pm 2.0\%$ for torque coefficient.

4.1.2. Benchmark calculations (Propeller for planing boats)

Performance predictions for a three-bladed planing boat

propeller were conducted using CFD simulation. In order to verify the predictive accuracy of the CFD simulation results, they were compared with the results of towing tank model tests. The towing tank model tests for this research were conducted at the Shipbuilding Research Centre of Japan in Mitaka City, Tokyo. Figure 6 shows the model propeller and the computational mesh used in the tests. The propeller was a 60% scale model manufactured by aluminum machining. As in the previous section, the performance of the three-bladed planing boat propeller was evaluated by means of performance curves. Figure 7 shows a comparison between the results of the towing tank model tests and the results of CFD simulation. The comparison between CFD simulation results and model test results for propeller thrust and torque coefficients indicated levels of predictive accuracy from the design point (approximately 80% of the point of maximum efficiency) to the point

of maximum efficiency for CFD simulation of $\pm 4.55\%$ for thrust coefficient and $\pm 4.58\%$ for torque coefficient. Generally, the effects of cavitation, which can be predicted to have an effect of several percent on efficiency, should be considered in the case of planing boat propellers. However, CFD simulation that takes cavitation into consideration presents issues of stability. Given that the present research prioritized computational stability, and conducted several hundred cases of CFD simulation in order to achieve stability, it was decided to ignore the effects of cavitation.

4.2. Prediction of Cruising Performance

In order to verify the predictive accuracy of the simulator proposed in this research, results for the cruising performance of a large-horsepower class outboard motor fitted to a high-speed planing boat were compared with the results of full-scale cruising tests. The planing boat used in this verification of the predictive accuracy of the simulator for cruising performance was a standard three-to-four passenger pleasure boat known as an offshore boat (Fig. 8). Any specific type of planing boat propeller will generally be sold with several propeller pitches set, making it possible for the user to select cruising performance characteristics depending on whether maximum cruising speed or acceleration performance is prioritized. Propeller selection will differ depending on the type of planing boat being used, and outboard motor manufacturers and sales outlets will normally offer assistance such as propeller matching charts that show recommended propellers.

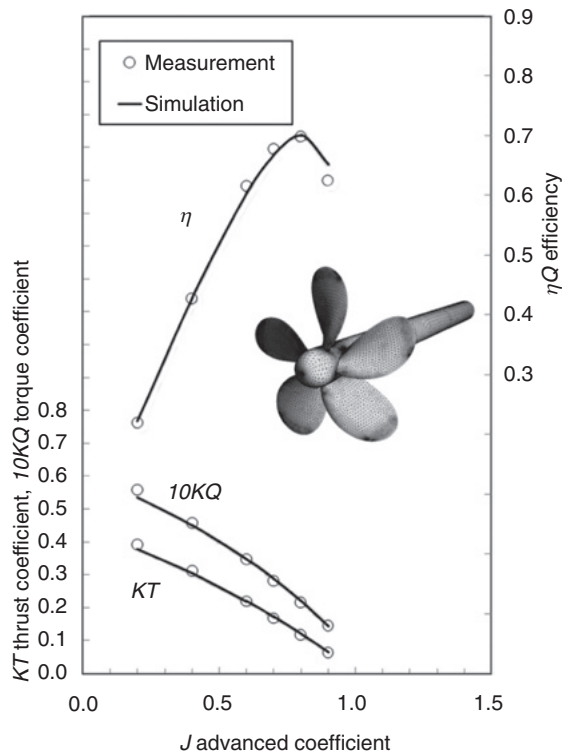


Fig. 5 Propeller performance curves compared with model test results

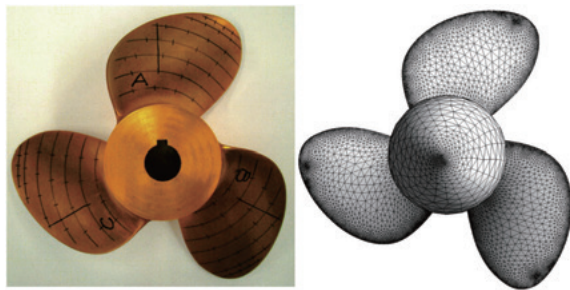


Fig. 6 Model propeller (left) and computational mesh (right)

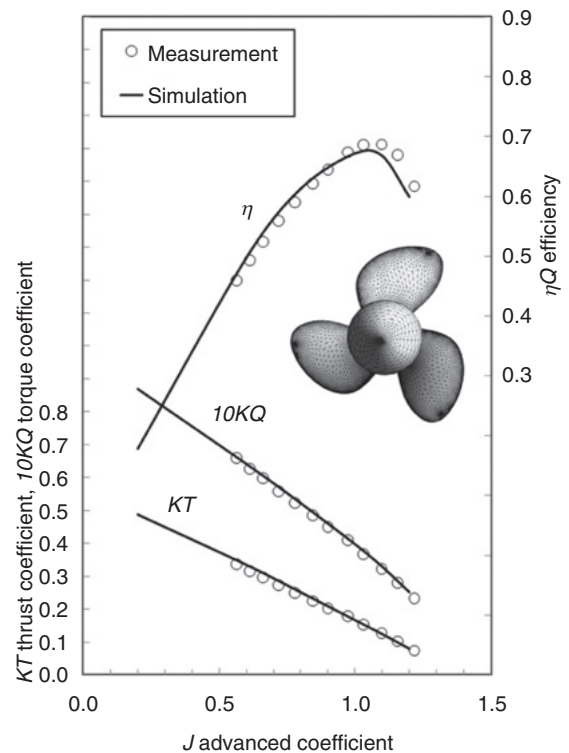


Fig. 7 Propeller performance curves compared with model test results

Table 2 Principal particulars of propellers used in evaluation of simulator

Propeller name	Photo	Diameter [inch]	Pitch [inch]	Gear reduction ratio
A-1		14.7	15.0	2.00
A-2			17.0	
A-3			19.0	
B		16.0	18.5	2.15
				2.33
				2.53
C		14.3	15.0	1.85
				2.15
				2.33

Given this, in the present research predictive accuracy was verified by conducting cruising performance predictions for planing boat propellers with different propeller pitches and two different types of hull. In addition, in order to study the effect on cruising performance of the gear reduction ratio, the framework of an outboard motor drive system, predictions were also conducted for cases in which the gear reduction ratio differed for the same propeller. Table 2 shows the planing boat propeller specifications employed. Propellers A-1, A-2, and A-3 were fitted to the hull shown in Fig. 8(a), and propellers B and C were fitted to the hull shown in Fig. 8(b).

Cruising performance predictions using the simulator proposed in this research demonstrated a predictive accuracy of $\pm 2.79\%$ (± 1.7 km/h) for maximum cruising speed. Figure 9 compares results for prediction of maximum cruising

speed and the results of tests using actual boats. These results indicate that the simulator is capable not only of predicting cruising performance in the case of differences in hull type and propeller pitch, but also in the case of differences in the gear reduction ratio, the framework of the drive system. The computations conducted by the simulator are automated via spreadsheet script software, and computations for a single propeller specification can be conducted in several seconds. In addition, because the different types of data can be managed by spreadsheet software or text data, the simulator also presents the advantage of simple handling of data. This indicates that the simulator will be sufficiently flexible for use at the design stage of the outboard motor development process.

4.3. Prediction of Cruising Fuel Consumption

In order to verify the predictive accuracy of the simulator developed in this research, results for the cruising fuel consumption of a large-horsepower class outboard motor fitted to a high-speed planing boat were compared with the results of full-scale cruising tests. The same hulls and outboard motor as described in the previous section were used in this verification. However, in order to use the same conditions as the test conditions for measurement of cruising fuel consumption, cruising fuel consumption at a fixed engine speed was evaluated at a variety of engine speeds. As in the previous section, predictive accuracy was verified by conducting predictions of cruising fuel consumption for planing boat propellers with different propeller pitches and two different hulls. In addition, predictions were also conducted for different gear reduction ratios for the same propellers in order to verify the effect of this parameter, the framework of outboard motor drive systems, on cruising fuel consumption. The planing boat propeller specifications employed were identical to those shown in Table 2.

The results for prediction of cruising fuel consumption by the simulator corresponded well with test results. In particular, comparison of prediction results for cruising fuel consumption at 40 km/h and above when the boat is planing with the results of cruising tests show an average predictive accuracy of $\pm 4.55\%$, within the target range of $\pm 5\%$ set for this research. This is equivalent to the accuracy of the benchmark computations of propeller performance discussed in Section 4.1.2. Figure 10 shows a graph comparing the results of prediction of cruising fuel consumption for propeller A with the results of tests using an actual boat. This is a case in which a difference in propeller pitch produces a difference in fuel consumption, but the simulator is able to reproduce the fact that propeller A-3 offers better fuel consumption figures than propeller A-1. Figures 11 and 12 show graphs comparing the results of predictions of cruising fuel economy for propellers B and C with the results of actual boat tests. These are cases in which a difference in the gear reduction ratio for the same propeller pitch results in differences in fuel consumption,

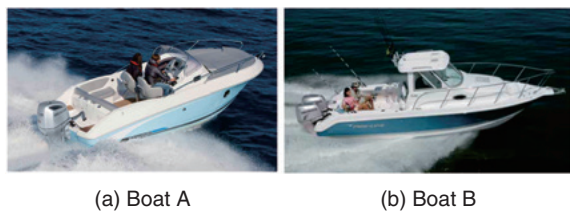


Fig. 8 Small planing boats used in the simulator

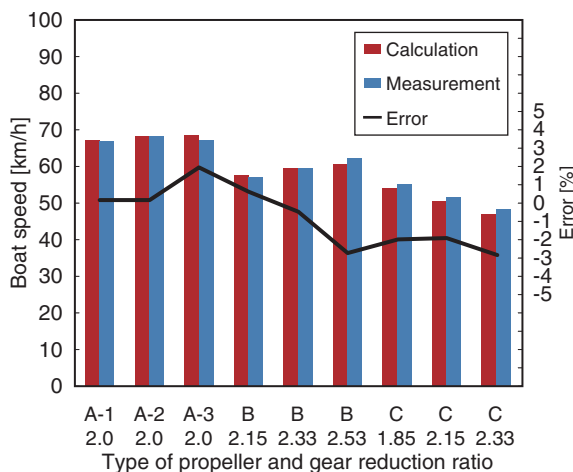


Fig. 9 Predicted maximum boat speeds and full-scale test results

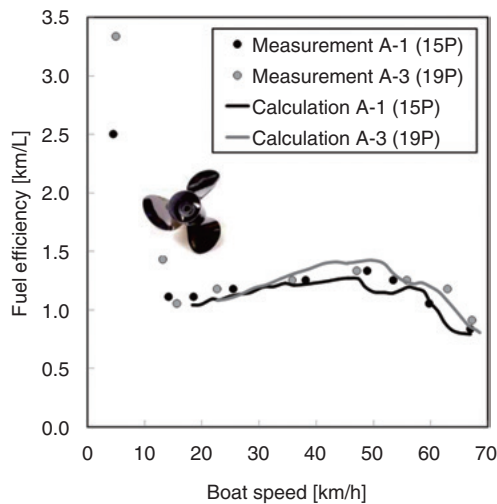


Fig. 10 Fuel consumption simulation compared with full-scale measurement results

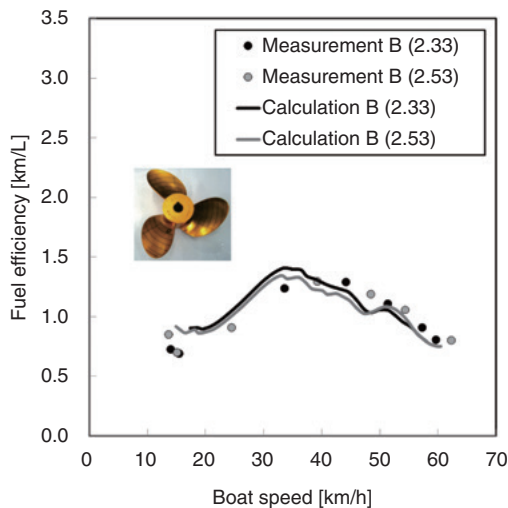


Fig. 11 Fuel consumption simulation compared with full-scale measurement results

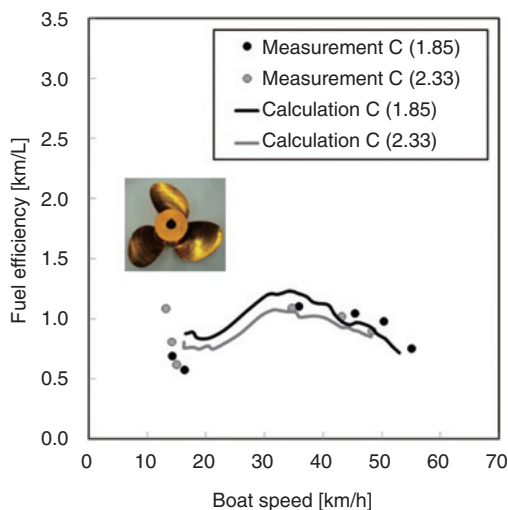


Fig. 12 Fuel consumption simulation compared with full-scale measurement results

and the simulator is able to reproduce the better fuel consumption results for the respective gear reduction ratios.

These results indicate that using the developed simulator, it is possible to numerically predict differences in cruising fuel consumption due not only to differences in propeller specifications, but also due to differences in gear reduction ratios, the framework of the drive system, within a fixed range of accuracy, without conducting boat tests. In addition, the fact that it has been possible to achieve a level of accuracy sufficient for practical use ($\pm 5\%$, the target predictive accuracy) without consideration of the effect of cavitation, as mentioned in Section 4.1.2., indicates that it will be possible to make effective use of the simulator in the initial stage of the outboard motor development process, the framework design stage, in order to develop motors displaying good environmental performance balancing cruising fuel consumption performance and cruising performance. The use of this simulator can be expected to make it possible to offer users not merely propellers possessing good cruising performance (maximum cruising speed and acceleration performance), but also propellers that possess good cruising fuel consumption performance.

5. Conclusion

The research discussed in this paper developed a predictive simulator with the goal of predicting the cruising fuel consumption and cruising performance of outboard motors used for small, high-speed planing boats with a range of error within $\pm 5\%$. Based on previous experience with outboard motor development, the research focused on the fact that propeller thrust performance has a significant effect on cruising fuel consumption, and created databases combining propeller performance predicted using CFD simulation and engine performance data and fuel efficiency maps obtained from tests.

In order to verify the predictive accuracy simulator for the prediction of fuel consumption and cruising performance proposed in this research, prediction results were compared with the results of full-scale cruising tests. These comparisons produced the following findings:

- (1) Comparison of the results of CFD simulation for the thrust coefficient and torque coefficient of propellers used for small, high-speed planing boats with the results of model tests conducted in a towing tank indicated that the simulator displayed a level of predictive accuracy of $\pm 4.55\%$ for the thrust coefficient and $\pm 4.58\%$ for the torque coefficient.
- (2) The simulator was used to predict the cruising performance of a large-horsepower class outboard motor fitted to a small, high-speed planing boat, and the results were compared with the results of cruising tests. The results of this comparison indicated that the simulator achieved a predictive accuracy of $\pm 2.79\%$ (± 1.7 km/h) for maximum cruising speed, and showed an extremely good correlation between simulator and cruising test results.

- (3) The simulator was used to predict the cruising fuel consumption of a large-horsepower class outboard motor fitted to a small, high-speed planing boat. The results showed a good correlation with the results of cruising tests. In particular, comparison of results for cruising fuel consumption when the boat is planing indicated that the simulator achieved an average predictive accuracy of $\pm 4.55\%$.

These results show that the simulator achieves a level of predictive accuracy within a $\pm 5\%$ range of error, the target set for the research. This indicates that the simulator will be able to be used to predict specifications offering good cruising fuel consumption performance and cruising performance, without conducting cruising tests, during the selection of propeller specifications and gear reduction ratios at the initial stage of the development process, which has previously been based on test results and experience. In addition, the results suggest that the simulator will be effective in the development of motors displaying good environmental performance balancing cruising fuel consumption performance and cruising performance.

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■ Author ■



Shunsuke KURIOKA