

# Hydrodynamic Optimal Design of Ducted Azimuth Thrusters

Isao Funeno<sup>1</sup>

<sup>1</sup> Kawasaki Heavy Industries, Kobe, Japan

## ABSTRACT

In recent years ducted azimuth thrusters are almost essential to propulsion system of such vessels - tugboats, AHTS (Anchor Handling/Tug/Supply) vessels and others. However, it is very difficult to assess accurately their hydrodynamic performance both experimentally and numerically. Mainly the complicated configuration and the specific operations, that is, bollard pull conditions, cause the difficulties to analyze the hydrodynamic performance. The author undertakes serious action to solve the issues by applying the incompressible viscous CFD technique to flow around the ducted azimuth thrusters and conducting the tank tests using sophisticated small waterproof dynamometers. In this paper among the many results obtained during the hydrodynamic optimal design of the ducted azimuth thrusters, the following topics are described,

- Hydrodynamic interaction between the nozzle and the gear case housing,
- Total performance assessment using the complete whole unit models.

Especially the author emphasizes that the unit thrusts can be increased by improving hydrodynamic interaction between the nozzles and the gear case housings even for applying popular nozzles such as MARIN No. 19A.

## Keywords

Ducted Azimuth Thrusters, CFD, Propeller, Nozzle

## 1 INTRODUCTION

In recent years, ducted azimuth thrusters shown in Figure 1 for examples are almost essential to propulsion system of such vessels – tugboats, AHTS (Anchor Handling/Tug/Supply) vessels, cable laying vessels, oceanographic research vessels, drilling vessels and others. Nonetheless there are increasing requirements of better performances; higher free sailing efficiency and higher bollard pull of the ducted azimuth thruster units. However, from a viewpoint of the hydrodynamic design, it is more difficult to analyze accurately the performance of the ducted azimuth thruster units than that of conventional open propellers due to the following issues,

- Shape complexity of the units composed of propellers, nozzles, gear case housings, struts, stays and so on,

- Strong hydrodynamic interaction between propellers and nozzles,
- Specific operating condition: performance assessment in bollard pull condition ( $J=0$ , in zero ship speed, where  $J$ : advance coefficient).



Figure 1 Ducted azimuth thrusters (Kawasaki Rexpeller KST-180).

Regarding numerical approaches, potential flow methods are very useful for performance assessment in the free sailing conditions. However, these can hardly analyze it in the bollard pull condition. On the other hand, at experimental approaches, ducted azimuth thrusters increase the potential of generation of hub vortex in heavily load condition, which results in a loss of energy and affects considerably propeller torque (Funeno 2002), as the ducted azimuth thrusters normally have no rudder behind them. Despite all of that, propeller open-water characteristics were measured by installing a propeller inside a nozzle through a propeller shaft of a propeller open boat behind the ducted propeller and then the measured propeller torques would be underestimated.

Therefore, it is necessary to develop the computational methods taking exactly interaction between propellers and nozzles in bollard condition in account and the measurements including correctly the effect of hub vortex. In connection with these issues, Kawasaki Heavy Industries (KHI) has been actively involved by applying the advanced incompressible viscous CFD

(Computational Fluid Dynamics) technique to flow around the ducted azimuth thrusters and conducting the tank tests using sophisticated small waterproof dynamometers as well as the development of the podded propulsors.

In the following chapters, the author describes the advanced CFD technique and the measurements using the small dynamometer for hydrodynamic optimal design of the ducted azimuth thrusters in KHI. Among a number of the obtained results, the following topics are described in this paper,

- Hydrodynamic interaction between nozzles and gear case housings,
- Total performance assessment using complete whole unit models.

## 2 COMPUTATIONAL METHOD

For the above-mentioned issues, it is appropriate to apply a versatile CFD technique based on the unstructured grid method to complicate geometry such as the ducted azimuth thruster units. In the following sections, the computational method is described in brief.

### 2.1 General

The governing equations to solve were the Reynolds averaged Navier-Stokes equations (RANSE) and the mass continuity equation for incompressible viscous fluid (Ferziger and Peric 2002). The whole computational flow domains around the units were divided into numerous minute cells. The equations were discretized based on the finite volume method to fulfill conservation of momentum and mass for all the cells. Then the equations were solved numerically by using the SIMPLE method. The effect of turbulence was considered with a mathematical turbulent model of the k- $\omega$  SST two equations with the wall function.

The effect on flow field by propeller rotation was considered by introducing centrifugal forces and Coriolis forces in relative coordinate system fixed at a rotating propeller as body forces in RANSE. For all the computations of the complete whole units, the blades were static at some positions in circumferential direction like a frozen propeller. By the so-called quasi-steady analysis method or the frozen rotor method, hydrodynamic interaction between the rotating propeller, the gear case housing, the strut and the nozzle were taken into account accurately (Funeno 2004).

The computed three velocity components and pressure in each cell enable the calculations of the pressure and shear forces acting on the surface of the thruster units.

The commercial CFD software, STAR-CD (2004), was adopted, since the software provided all the functions above mentioned and the accuracy of computation was extensively examined for this kind of problems.

### 2.2 Grid Generations and Boundary Conditions

All the grid generation were accomplished through the 3D-CAD data of the ducted azimuth thruster units. The unstructured grid method was applied to the grid generation due to complicated geometry of the units. As describing the following section, the computational domains for the heavily load conditions like bollard pull conditions should be tremendous compared to size of the thruster units as Abdel-Maksoud et al recommended (2002). Finally the boundary conditions for all the computations were inlet, outlet and slip wall for the outer surfaces. Figure 2 shows one example of the surface mesh of the complete ducted azimuth thruster unit.

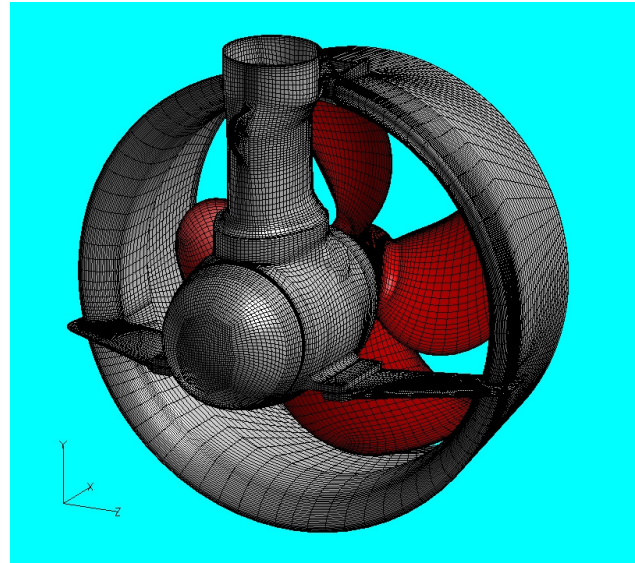


Figure 2 Example of surface mesh of complete ducted azimuth thruster unit.

### 2.3 Conditions for Bollard Pull Computations

At first, the computations in bollard pull conditions (zero ship speed) were executed according to the reference (Funeno 2006) with the tremendous computational domains. Then all the outer boundary conditions set constant static pressure. However, the unreasonable results were obtained, which for example, the ratio of the propeller thrust to the nozzle thrust was about 80:20. Normally the ratio should be expected about 50:50 around zero speed condition ( $J=0.0$ ). Eventually the outer boundary conditions were changed to inlet, outlet and slip wall conditions and the  $J$  set 0.05, consequently the results showed the reasonable ratio as about 50:50 as expected from the experiments. Therefore, in this paper the propeller operating condition with  $J=0.05$  should be treated approximately as the bollard condition. Then just for the reference, the locations of the outer boundaries were about  $80D_p$  at the inlet plane, about  $130D_p$  at the outlet plane and about  $9D_p$  at the outer plane in radial direction from the center of the propellers, where  $D_p$  is diameter of a propeller. Also the total cell numbers were about 1.2 million for the computations of the interaction between the nozzles and the gear case housings, in which

the sector form models for one blade and the cyclic boundary conditions were adopted, and about 2.7 million for the computations of the complete whole unit models.

### 3 EXPERIMENTS

Conventionally the open-water propeller characteristics of ducted propellers at tank tests were measured using dynamometers that were installed in propeller open-boats behind the ducted propellers as shown Figure 3. However, under such circumstances it is difficult to assess accurately the performance including effect of hub vortex shedding from boss cap end in heavily load conditions especially. Besides the hub vortex effect becomes much more pronounced due to no rudder behind the ducted azimuth thrusters usually.

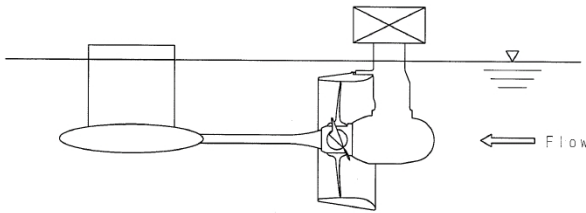


Figure 3 Conventional test equipment for open-water tests with ducted azimuth thruster units.

In recent years the propeller performances of podded propulsion system have been measured by using effectively waterproof dynamometers built inside the pods. Although the performance measurements with the dynamometers were attempted for the models of the ducted azimuth thrusters, the dynamometers were too oversized so as to build into the shorter gear case housings with normal model propellers of about 200 to 250 mm in propeller diameter.

As a result, the very smaller waterproof dynamometers were newly developed and applied to the model thruster units. Figure 4 shows an appearance of the dynamometer to measure propeller thrusts and torques. Figure 5 shows a picture of the measuring equipment.

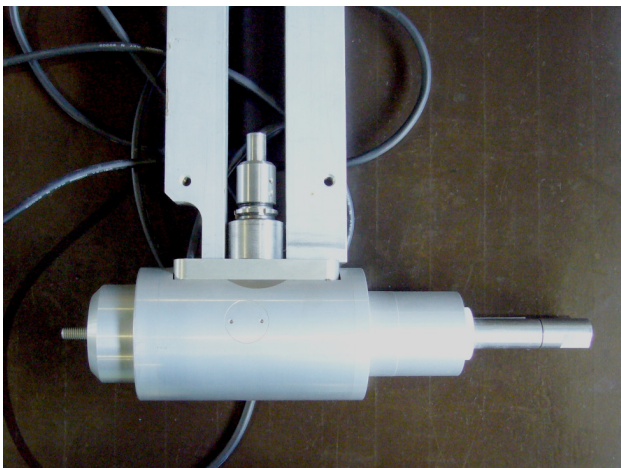


Figure 4 Appearance of small waterproof dynamometer for thruster units.



Figure 5 Test equipment using small waterproof dynamometer inside gear case housing.

Furthermore the load cell was installed in the upper part of the measuring unit. It enabled to measure the total thrusts, lateral forces and moments around vertical axis of the whole thruster units. This setup allowed the accurate propeller performance measurements under near-circumstances of the productions, since the effect of hub vortex as well as the disturbance potentials due to the struts and gear case housings were exactly taken into account in the measured data.

### 4 EFFECT OF GEAR CASE HOUSING

#### 4.1 Thrust Trade-off Between Propeller and Nozzle

Normally the improvements of hydrodynamic performance of the ducted azimuth thrusters have been ever tackled focusing on the propellers and the nozzles. However, it seems that there is little remarkable progress. In fact, it is very difficult to achieve drastic increase in performance due to strong hydrodynamic interaction between the propellers and the nozzles. For example, Figure 6 shows thrust distribution ratios of  $K_{TP}$ : propeller thrust coefficient and  $K_{Tn}$ : nozzle thrust coefficient to  $K_{TT}$ : total thrust coefficient of the ducted propellers with MARIN nozzle No. 18, 19 and 20 with  $f/l$ : camber ratios at  $J=0$ , bollard condition and then the propeller pitch ratio at  $0.7R$ :  $P_{0.7}/D = 1.018$  representatively (van Manen et al 1959). Figure 7 shows  $\eta_d$ : merit coefficient defined as Equation (1) with  $f/l$  of the same ducted propellers.

$$\eta_d = \frac{(K_{TT}/\pi)^{3/2}}{K_Q} \quad (1)$$

Where  $K_Q$ : propeller torque coefficient. From Figure 6 and 7, although the nozzle thrusts increase with increasing  $f/l$ , the propeller thrusts decrease to the contrary. Eventually it is found that  $\eta_d$  is almost the same for all the nozzles in bollard condition.

Provided that the size of the nozzles are the relative same to the standard nozzle, for example MARIN 19A and the ducted propellers are operating with the isometric propellers in the same input power condition, in bollard condition even the nozzles that exert larger nozzle

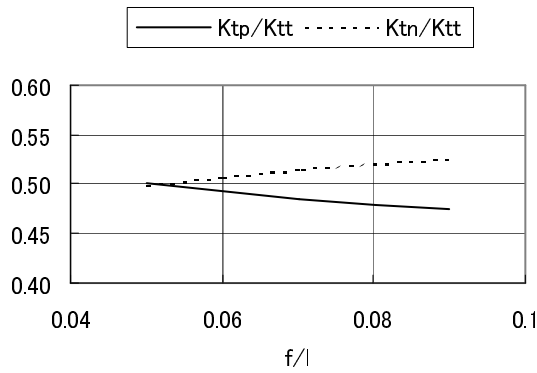


Figure 6 Thrust distribution ratios of propellers and nozzles to total units.

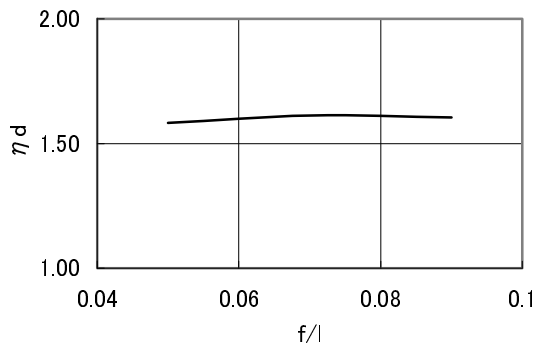


Figure 7 Merit coefficients with camber ratio of nozzles.

thrusts are likely to generate larger nozzle-induced velocity inside the nozzles concurrently. Then the propeller thrust is likely to decrease relatively due to increasing inflow speed to the propellers, that is, discrepancy of pitch distribution from the original one, which causes decrease of the relative attack angle into the propeller blades around the propeller tips. On the whole, the trade-off between the propellers and the nozzles causes a little improvement of the total thrust of the ducted propellers.

In addition, provided that high-performance nozzles have been developed barely, they are rarely accepted due to high manufacturing cost caused by those complex curved surfaces. The hydrodynamic improvement is normally not worth the expense for manufacturing such as the nozzles with the complex curved surfaces.

#### 4.2 Interaction Between Nozzle and Gear Case Housing

Differently, it should be noticed to consider hydrodynamic interaction between the nozzles and the gear case housings. Therefore the investigations were carried out by using the CFD technique with the models truncated the struts (see Figure 8). In this study, as shown in Figure 9 changing  $Dg/Dp$ : the ratio of  $Dg$ : the maximum diameter of the gear case housings to  $Dp$ : the propeller diameter parametrically, provided that the

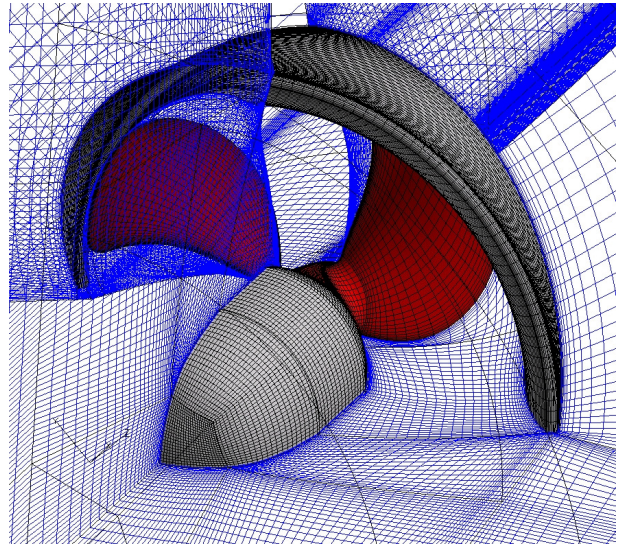


Figure 8 Sector form model truncated struts and surface mesh.

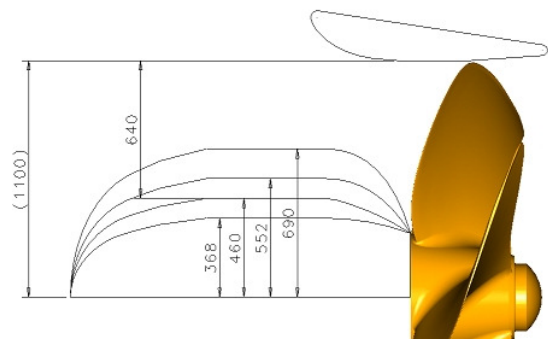


Figure 9 Parametrically changing maximum diameters of gear case housings.

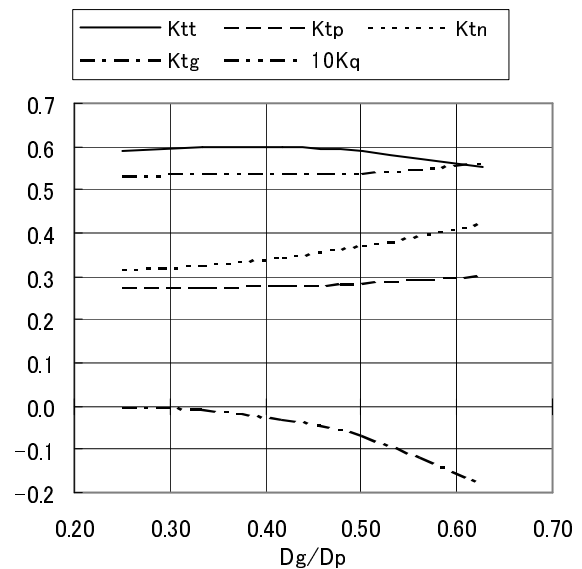


Figure 10 Each component of thruster and torque with ratio of maximum diameter of gear case housing to propeller diameter.

propeller operating conditions were the same in all the computations, the results were investigated. Figure 10

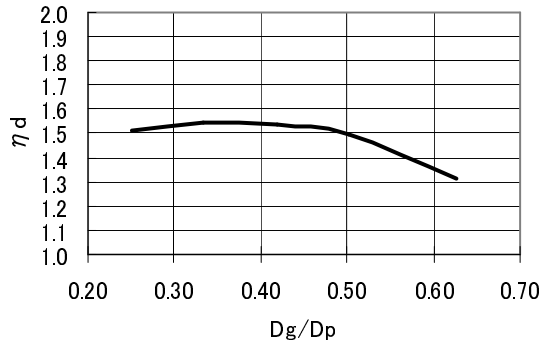


Figure 11 Merit coefficient with ratio of maximum diameter of gear case housing to propeller diameter.

shows each component of the thrusts and the torque with  $Dg/Dp$ . Note that with increasing  $Dg/Dp$ , surprisingly the nozzle thrust increases steeply, meanwhile the thrusts and the torques of the propellers remain almost unchanged. The increasing nozzle thrusts are mainly attributed to the fact that the pressure on the inner surface around the leading edge of the nozzles decreases due to the increasing flow velocity between the nozzles and the gear case housings with those increasing diameters, which result in the reduced inflow area into the nozzles. On the other hand, after passing the inlet of the nozzles, as the flow velocity into the propellers decreases due to the rapidly expanded flow passages, the propeller thrusts remain almost in the original condition. As a result, the convex distribution in diameter of the gear case housing around the nozzle inlet influences the nozzle thrust to a greater degree than the propeller thrust. Consequently, not the linearly-tapered but the proper raised rearward shape of the gear case housing increases potentially the nozzle thrust without decreasing the propeller thrust.

However, it is likely that  $K_{Tg}$ : the gear case drag increase quite with the increasing diameter of the gear case housings. As a practical measure, the better streamlining of the gear case cap, for example, provides the depression of the drag at least.

In addition, the optimal diameter ratio:  $Dg/Dp$  is around 0.3 – 0.5 according to the efficiency for bollard condition known as the merit coefficient:  $\eta_d$  in Figure 11. In the free sailing condition, the similar results were obtained as well.

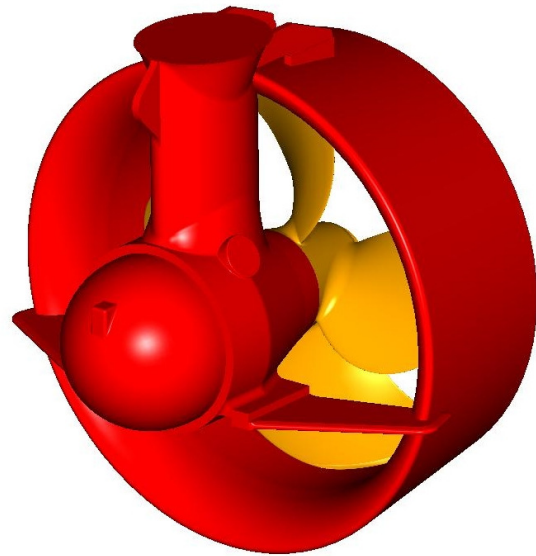
## 5 ASSESSMENTS BY WHOLE UNIT MODELS

It is very useful for the design to investigate the flow around the ducted azimuth thrusters and estimate the performance by using the advanced CFD technique to apply to the complete whole thruster units, before conducting the tank tests to confirm the performance.

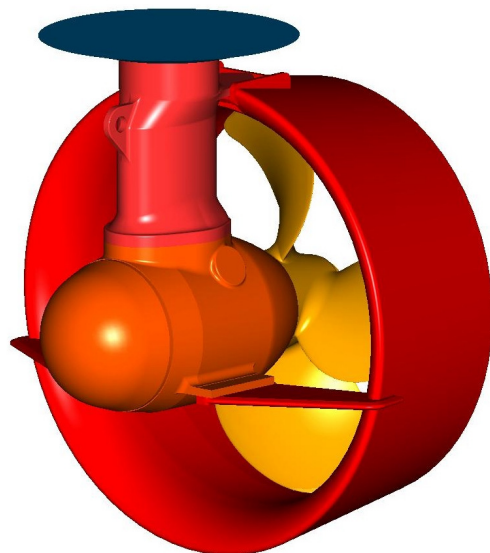
The computations were carried out for both the bollard conditions (heavily load conditions) and the free sailing conditions. Figure 12 shows the both CAD models of “Type 1” and “Type 2”. The same propellers and the

nozzle MARIN No.19A were installed in both the models. As an example of the computation results, Figure 13 shows the pressure distribution on the surface of the unit “Type 2” in bollard condition. The performances were assessed by the merit coefficient:  $\eta_d$  for bollard condition and the open water efficiency:  $\eta_o$  for free sailing condition. Figure 14 and 15 show the calculated and measured comparative results of both the models about  $\eta_d$  and  $\eta_o$ , respectively. The performance tendencies of the calculated results agree rather well with those of the measured ones. As a result, the Type 2 has superior both performances in some degree than the Type 1.

A lot of the factors are observed as the cause of the efficiency differences. Mainly the interaction between the nozzles and the gear case housings causes the



(a) Type 1



(b) Type 2

Figure 12 Complete thruster unit CAD models of Type 1 and Type 2.

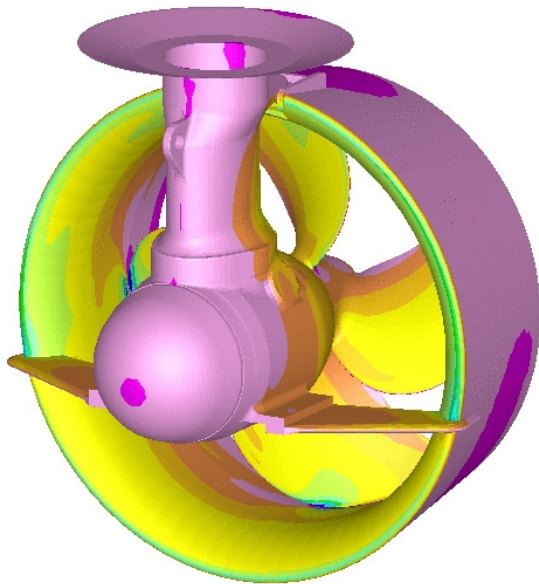


Figure 13 Pressure distribution on surface of ducted azimuth thruster unit Type 2 in bollard condition.

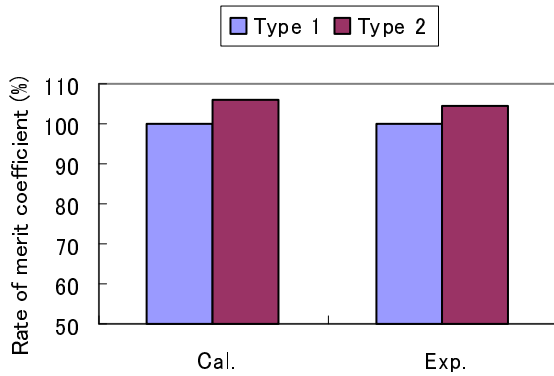


Figure 14 Comparative results of merit coefficients.

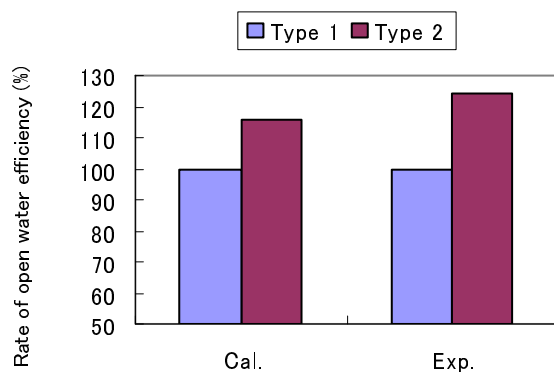
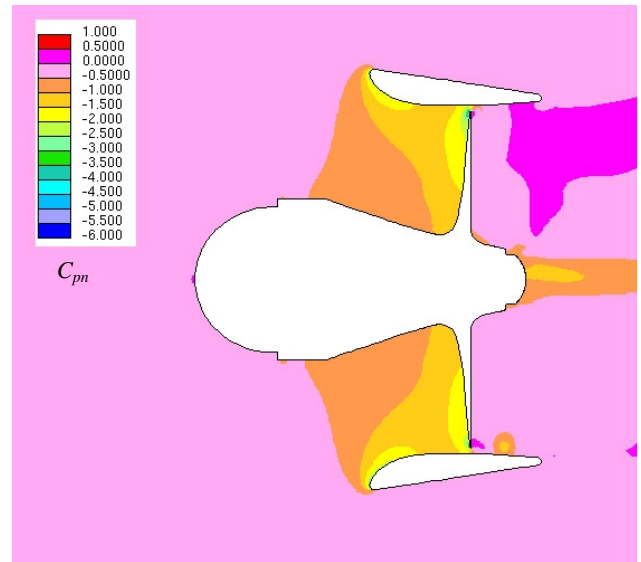
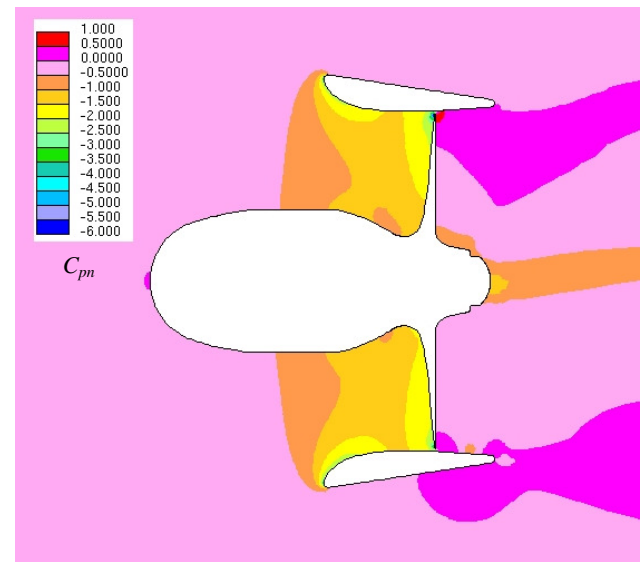


Figure 15 Comparative results of open water efficiency.

differences in performance. Figure 16 shows the pressure distribution,  $C_{pn}$ : pressure coefficient defined as Equation (2), where  $p$ : static pressure,  $p_0$ : standard pressure,  $\rho$ : fluid density,  $n$ : propeller revolution, in the cross-section profile in bollard condition. Compared to the Type 1 with the tapered fairing around rearward of the gear case



(a) Type 1



(b) Type 2

Figure 16 Pressure distributions in cross-section profile in bollard conditions.

housing, the raised fairing of the Type 2 makes the pressure distribution around the leading edge of the nozzle decrease and then improves the nozzle thrust without modifying the nozzle shape.

$$C_{pn} = \frac{P - P_0}{\frac{1}{2} \rho (nD_p)^2} \quad (2)$$

## 6 CONCLUSIONS

The performance improvement of a ducted azimuth thruster is a very difficult issue due to the complicated interaction between the nozzle, the propeller, the strut, the gear case housing and so on. The accurate CFD technique with the complete whole models and the advanced experimental method with the small waterproof dynamometer are very useful tools for the optimal design of ducted azimuth thrusters. Instantiated as follows,

- Possible increased nozzle thrust by the raised fairing around rearward of the gear case housing,
- Good agreements between the calculations and the experiments of the total performance,
- Discussion supported by the computed detailed flow data with the complete whole models.

In the future it is necessary that these methods are furthermore validated and utilized to improve the performance of the ducted azimuth thrusters.

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