Performance Analysis of Single-propeller/Twin-rudder System by Computational Fluid Dynamics

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ABSTRACT

The single-propeller/twin-rudder system composed of single propeller and two high-lift rudders of fish-tail type has been installed on 60 vessels in Japan. With this system, a ship can be maneuvered at any mode including going astern, hovering, dead slow forwarding and turning by means of various rudder angle combination, with propeller revolution being kept in the forward direction. Using a single joystick lever, it is possible to give the required position of each rudder and to develop thrust in all directions. The system has been installed on relatively small size vessels which require easy and short time approaching to and from berth. Studying work has been continued to apply the system to medium size vessels and some of the results are presented in this paper. Geometrical forms of rudder such as blade thickness ratio and shape of rudder section play important roles for the drag characteristics of the rudder. Effect of the thickness ratio and variation of shape of ruder section to the drag is studied by computational fluid dynamics. To improve propulsive efficiency of the twin rudder system, a pair of reaction fins is attached between two rudders where the propeller slip stream passes. Form of the fin affects propulsive performance a great deal and some results are discussed together with experimental results.

1 Preface

The system consisting of single-propeller and twin-high-lift rudders with fish tail is called VecTwin rudder [1 and 2] and the system has been applied for 60 vessels in Japan. VecTwin rudders are applied for small sized vessels which utilize mainly narrow harbors and their superior performances are fully evaluated [3 and 4]. An example of VecTwin system for small vessel is shown in Fig.1. Combining various rudder angles of two rudders with propeller revolution being kept in the forward direction, a ship can be maneuvered at any mode including going-astern with turning, hovering, and dead slow forwarding. Fig.2 shows examples of various maneuvering modes which are controlled by a single joystick lever. The authors have investigated applying the single-propeller/twin-rudder system to medium sized ships as the joint research with Nippon Kaiji Kyokai [5]. The main point of the research is to find the most effective shape of rudder section for the rudder system. The work has been done with CFD simulation and the results of CFD simulation are compared to the model test results.

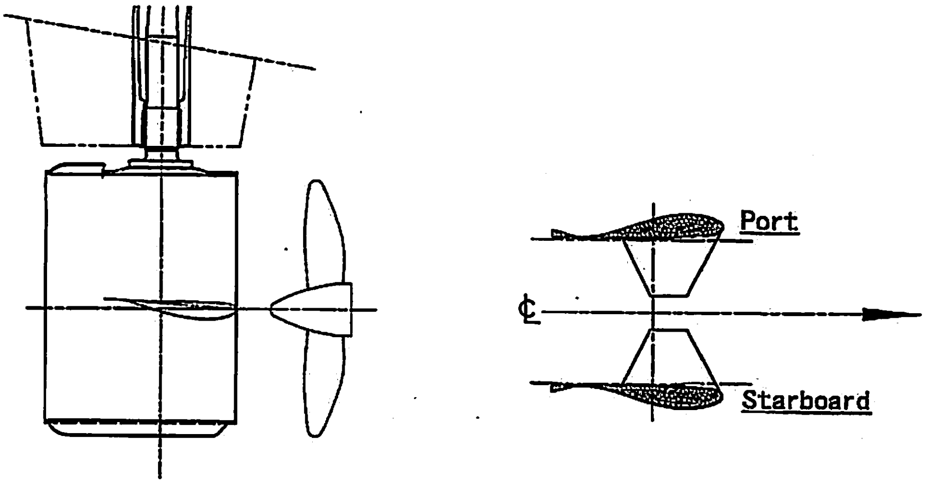


Fig.1 Arrangement of VecTwin rudder

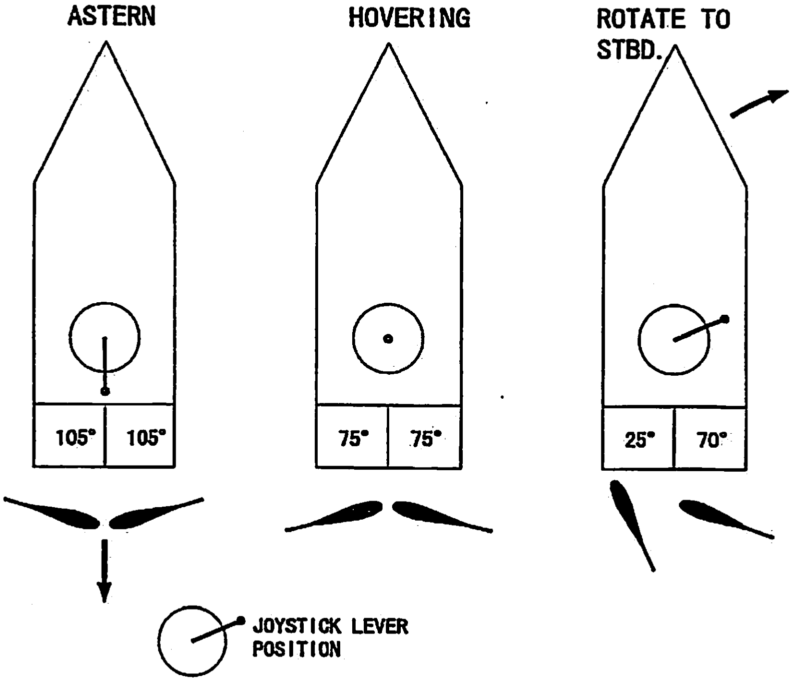


Fig.2 Example of maneuvering mode

2 CFD software

As computer simulation software, commercial software "SolidWorks Flow Simulation" [6] is used.

The reasons to use commercial software are:

- Designers can handle the software easily.
- Combination with CAD system is well suited.
- The results are got in a short time.
- The price of the software is cheap.
- Designers other than specialist of fluid dynamics analysis can use it under PC environment.

This software has been introduced to many commercial industries, universities and research institutes etc [6]. It solves the Navier-Stokes equations. It is capable to predict both laminar and turbulent flows. When the Reynolds number exceeds a certain critical value, the flow becomes turbulent, i.e. flow parameters start to fluctuate randomly. It was mainly developed to simulate and study turbulent flows. To predict turbulent flows, the Favre-averaged Navier-Stokes equations are used. It employs transport equations for the turbulent kinetic energy and its dissipation rate, the so-called $\kappa - \varepsilon$ model.

3 Computational model

The present computational study has been done for the flow around the twin-rudders receiving the uniform flow and accelerating flow by a propeller. The model test was also conducted at the circulating water channel of Osaka University. The arrangement of rudder and propeller is shown in Fig.3. The dimension of the observation part of the channel is 900mm wide and 500mm water depth. The model rudder is 1/40 scale model of 54,000DWT bulk carrier and 162.5mm height and 104mm chord length.

The particulars of model propeller are;

- Number of blades : 4
  Diameter : 160mm
  Pitch ratio : 0.800
  Expanded area ratio : 0.400

The model test was carried out on the condition;

Speed of water : 0.80 m/sec
Revolution of propeller : 11 rps
Advance coefficient : 0.45
Reynolds No.: approx. 1.0×10^6

The condition for CFD analysis is corresponding to the model test.

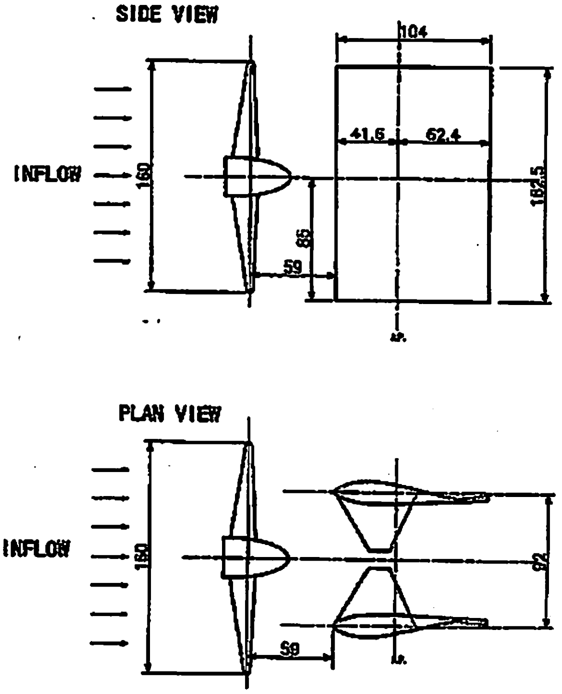


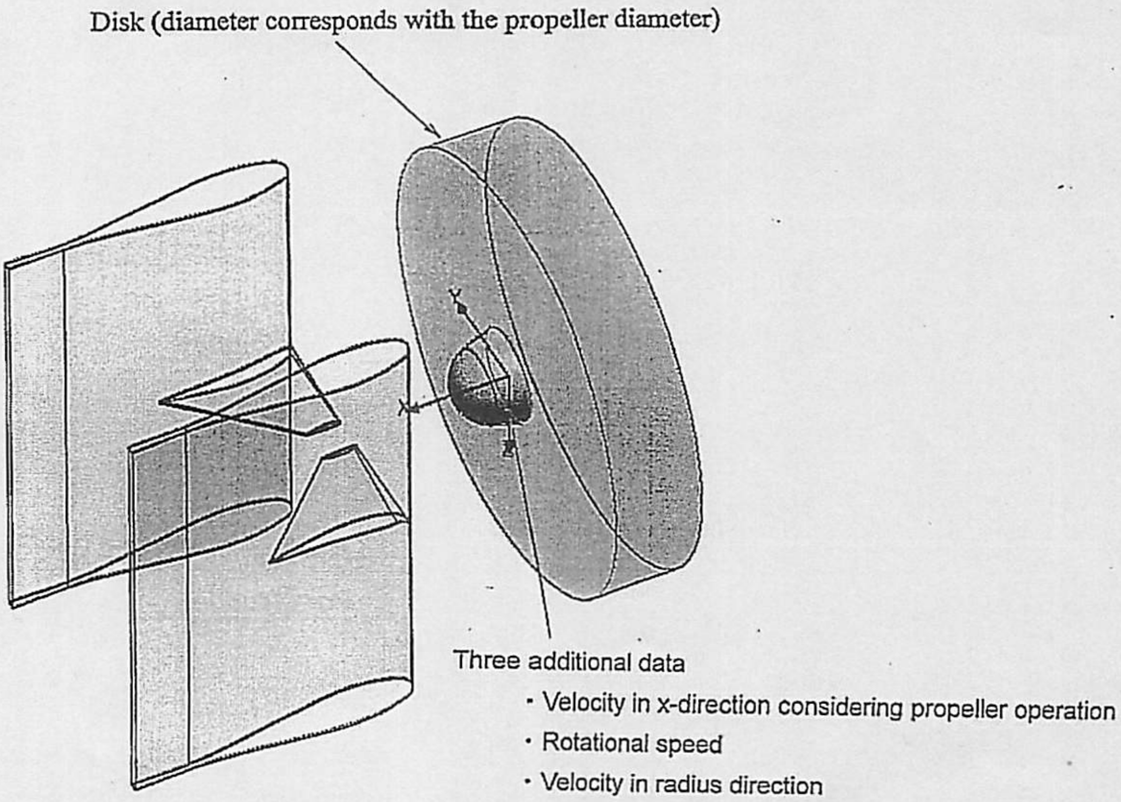
Fig.3 Arrangement of rudder and propeller

To realize rotational flow by propeller revolution, special consideration was made to the input data. As shown in Fig.4, three data are input in addition to the uniform flow.

Three data are

- Velocity in x-direction considering propeller operation
- Rotational speed
- Velocity in radius direction

The velocity in radius direction is tuned to get realistic propeller race.



Disk (diameter corresponds with the propeller diameter)

Three additional data

- Velocity in x-direction considering propeller operation
- Rotational speed
- Velocity in radius direction

Fig.4 Arrangement of rudder and propeller

4 Results and discussion

(a) Effect of blade thickness ratio

Smaller blade thickness ratio *t*/c (*t* is blade thickness and c is blade chord) is better from the view point of rudder resistance. The minimum *t*/c is determined from the strength of rudder. It is very important to grasp the effect of *t/c* ratio and three rudders with *t/c* ratio 0.15, 0.20 and 0.25 respectively are investigated. They are symmetric with respect to the longitudinal line through the center of rudder stock except the tail part. Tail part of inner side is parallel to the centerline to reduce drag. The port sides of twin rudder are shown in Fig.5. The resistance coefficients at the rudder angle zero are shown in Fig.6. The larger *t/c* gives the larger resistance as shown in Fig.6 and the results by CFD agree well with that of experiment. The tendency of *t/c* effect of NACA2400 series [7] is also shown in Fig.6, assuming that the resistance coefficient at *t/c*=0.20 is the same as the experiment. The tendency of resistant coefficient to *t/c* of NACA2400 is similar for the experiment and CFD.

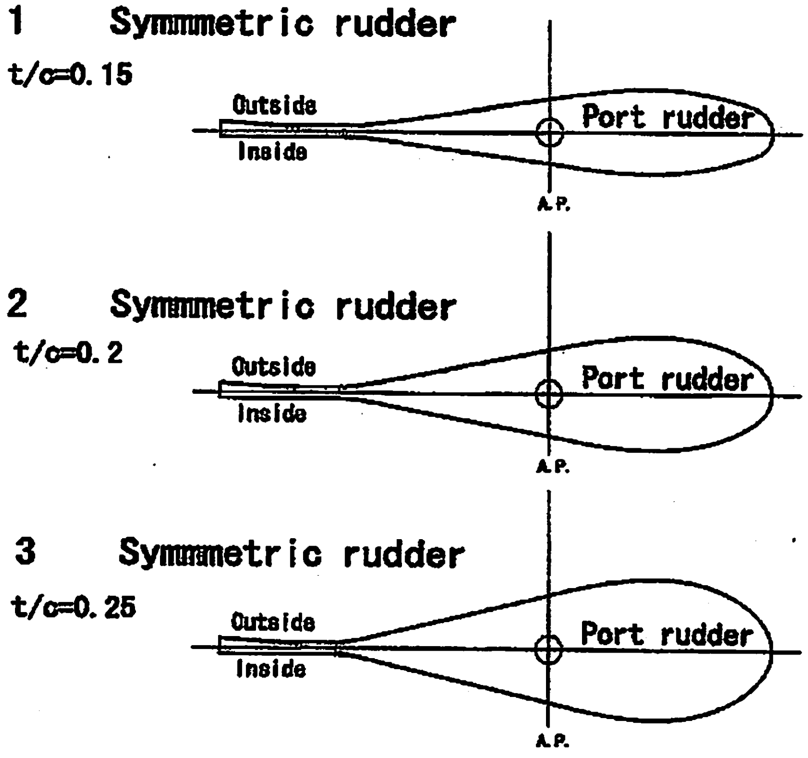
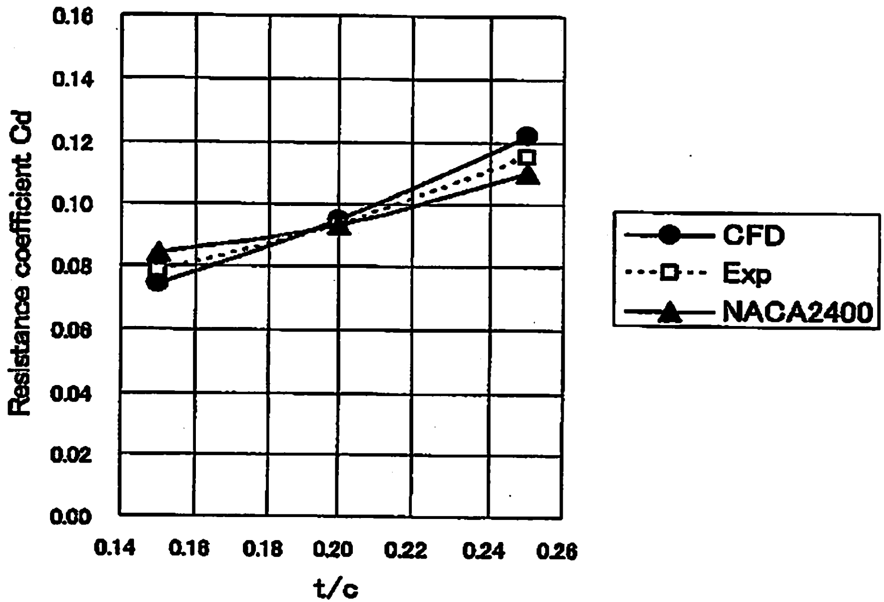


Fig.5 Symmetric type rudders

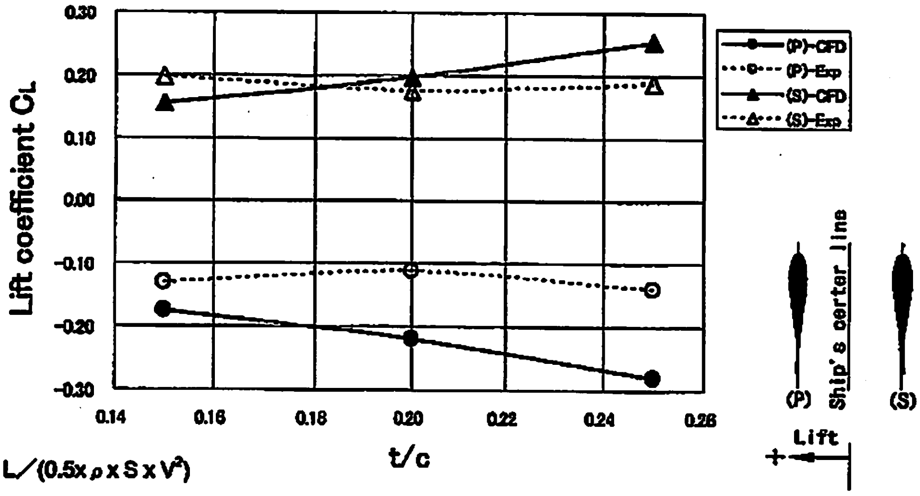


$Cd = R/(0.5 \times \rho \times S \times V^2)$

Where S = rudder surface area (both side)

Fig.6 Resistance of symmetric type rudders

The lift coefficients of symmetric type rudders at the rudder angle zero are shown in Fig.7. In case of symmetric rudders, inflow stream between two rudders is asymmetric due to propeller revolution, therefore lift is not zero. However they are immaterial, and data by CFD and those of experiment differ very little.



$C_L = L/(0.5 \times \rho \times S \times V^2)$

Where S = rudder surface area (both side)

Fig.7 Lift of symmetric type rudders

From the view point of resistance the smaller thickness to chord ratio is better, but the limitation exists from strength aspect. Lifts of symmetric type rudder are different for port rudder and starboard rudder but they are small and less important for the performance of the rudder.

(b) Effect of shape of rudder section

To investigate the effect for different shape of rudder section on resistance, three kinds of asymmetric rudders are selected as shown in Fig.8 as well as symmetric type rudder. Rudder 9 (asymmetric rudder 1) is applied for the smaller ships and it has small curvature inside. Rudder 12 (asymmetric rudder 2) has more curvature inside aiming to get larger lift at larger rudder angle. And rudder 13 (asymmetric rudder 3) is modified rudder 9 of which the location of max thickness is shifted fore to reduce resistance. As shown in Fig.9, it was found reasonable agreement between CFD and experiment values and rudder 13 have a little bit higher resistance.

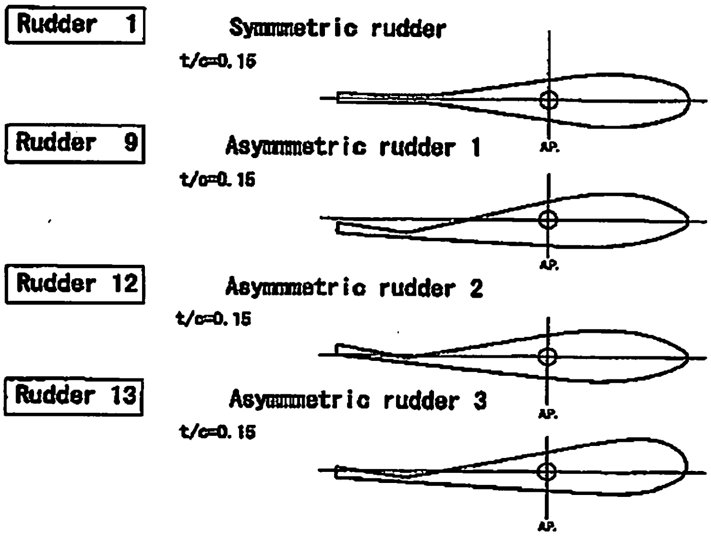


Fig. 8 Symmetric and asymmetric type rudders

As the shape of rudder section, symmetric type rudder and asymmetric rudder 1 with small curvature inside are better from the view point of resistance.

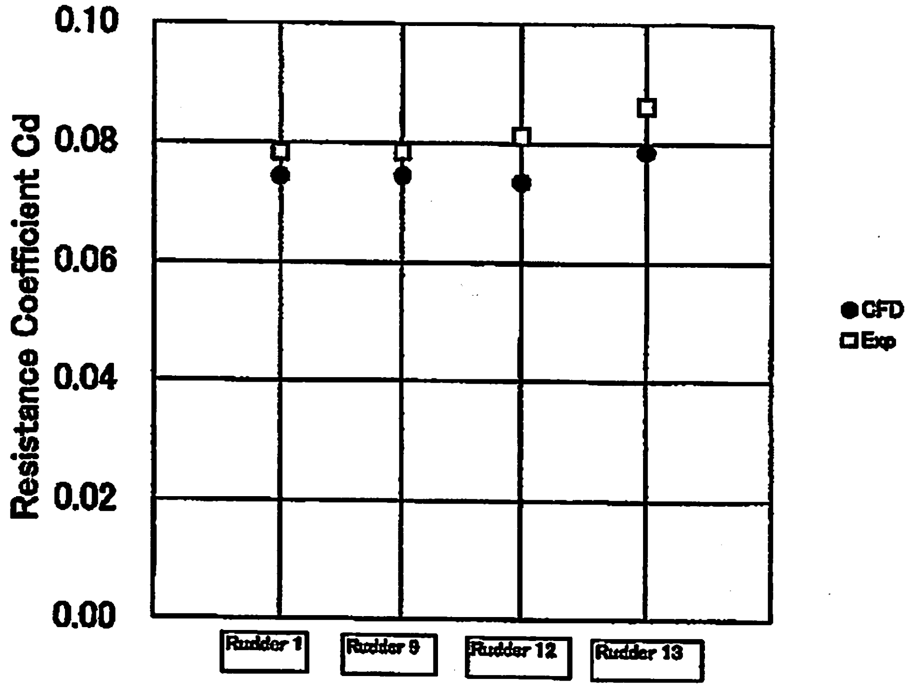


Fig.9 Resistance of symmetric/asymmetric type rudders

(c) Effect of fin

There are many ideas to provide horizontal fins for single rudder [8, 9, 10 etc]. The idea to provide horizontal fins inside VecTwin rudder has been proposed for the sake of improving propulsive efficiency utilizing lift of fin as thrust force [11]. Screw race flows into the fins, and it has upward flow to one fin and downward flow to the other fin. The rotating stream produces thrust force and the propulsive efficiency improves. In this study, the size of fin is taken as the same as one for the smaller VecTwin rudders with NACA4415 section [7] and three inclination angle of leading edge are studied to investigate optimum inclination angle. The three forms are illustrated in fig.10 and the results are shown in fig.11.

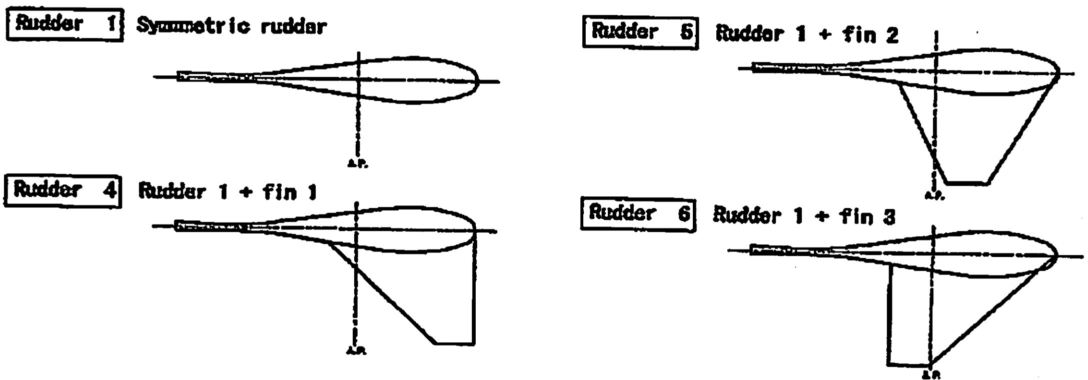


Fig.10 Rudder with fin

The rudder 4, 5 and 6 with fin shows smaller resistance than rudder 1, which means effect of fin is favorable. Rudder 4 shows the most effective. Pressure distribution and velocity distribution by CFD simulation for rudder 4, 5 and 6 are shown in Fig.12, 13 and 14. The pressure difference between upper side and lower side of fin is the most extinctive for rudder 4. It results in the smallest resistance of rudder 4 in Fig.11. As would be expected, it is possible to find an effective fin shape attached to the rudder horizontally by CFD. Smaller inclination angle of leading edge is better from the performance point of view. However, to avoid interference when moving the rudders inside, some practical consideration is necessary.

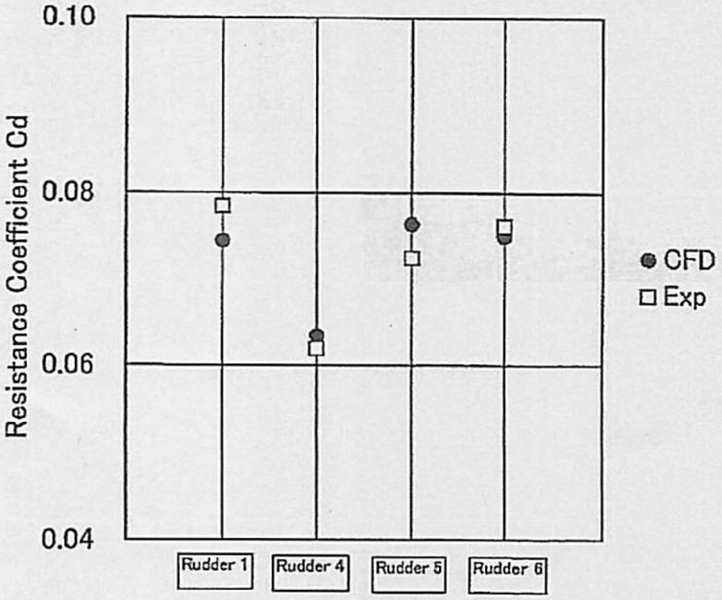
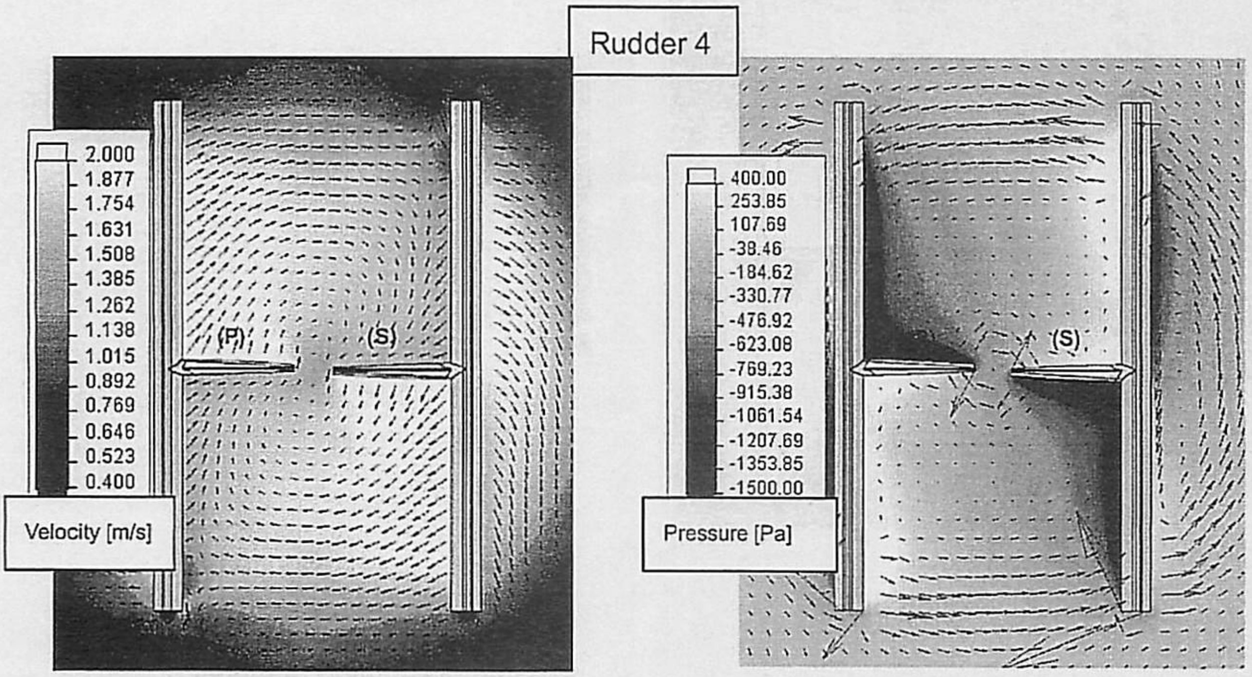


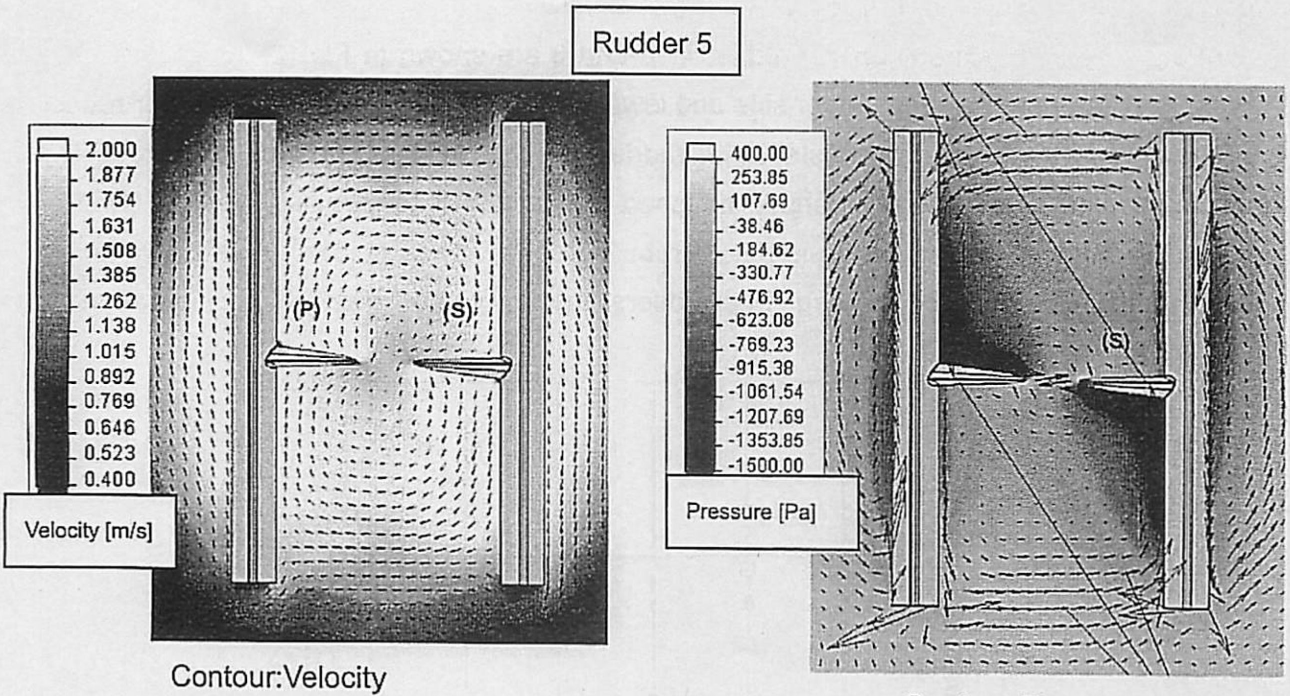
Fig.11 resistance coefficient of rudders with fin



Contour:Velocity
Vector:Direction of flow

Contour:Pressure
Vector:Vorticity

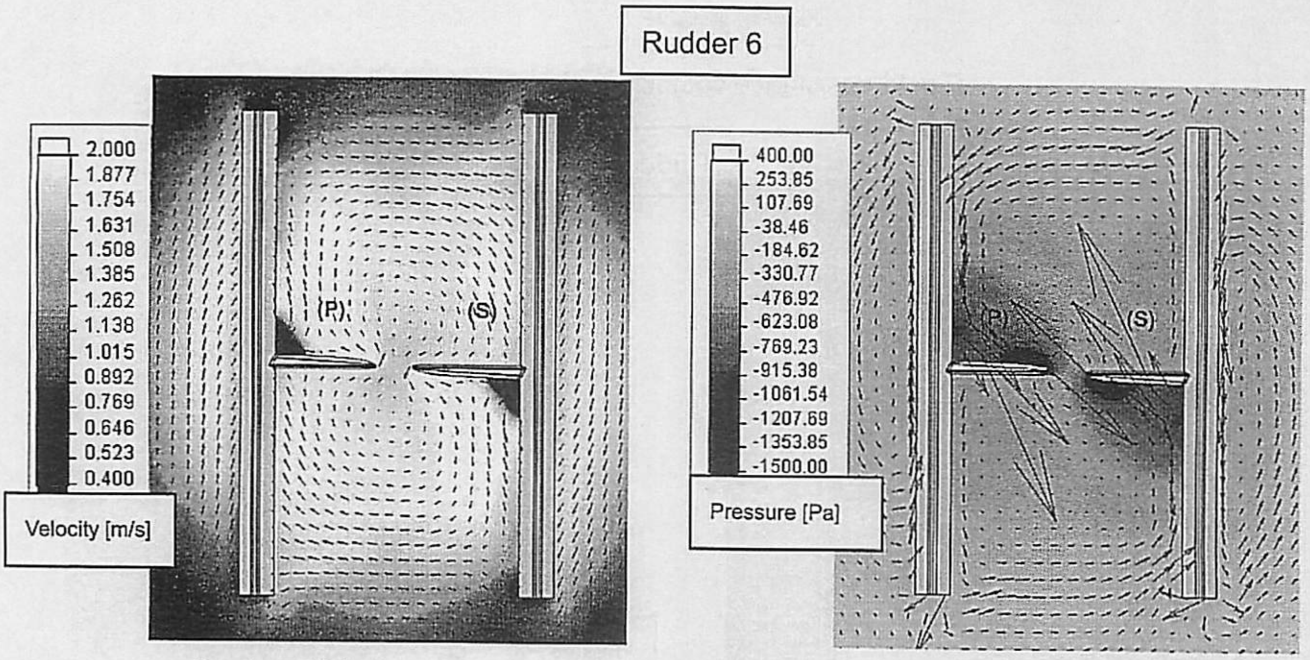
Fig.12 Velocity and pressure distribution of rudder 4



Contour:Velocity
Vector:Direction of flow

Contour:Pressure
Vector:Vorticity

Fig.13 Velocity and pressure distribution of rudder 5



Contour:Velocity
Vector:Direction of flow

Contour:Pressure
Vector:Vorticity

Fig.14 Velocity and pressure distribution of rudder 6

(d) Influence of different rudder angle combination on lift

By differentially angling the two rudders as in Fig. 15, the ship can achieve various maneuvering modes. In Fig.16, lift characteristics of rudder 1 are shown keeping the angle of port side rudder constant (5 degrees, 15 degrees and 25 degrees) changing the angle of starboard side rudder from 0 to 75 degrees. The lift is for total of two rudders. Both CFD and experiment results shows that max lift occur at 50 degrees angle of starboard rudder. When the rudder angle getting larger, there is difference between CFD and model test results. This comes from that κ-ε model is used in the CFD simulation and it cannot show the complex turbulent flow with large separation. The tendency with respect to rudder angles show similar between CFD and model test. CFD will be a tool to investigate the influence of such rudder combination, although the accuracy at large rudder angle is not confirmed well.

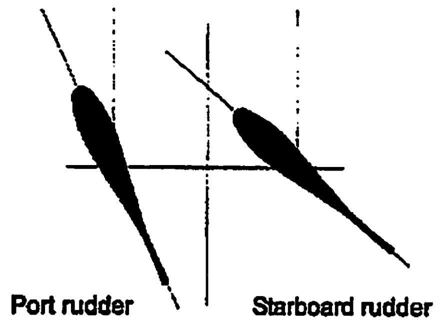


Fig.15 Differentially angling the two rudders

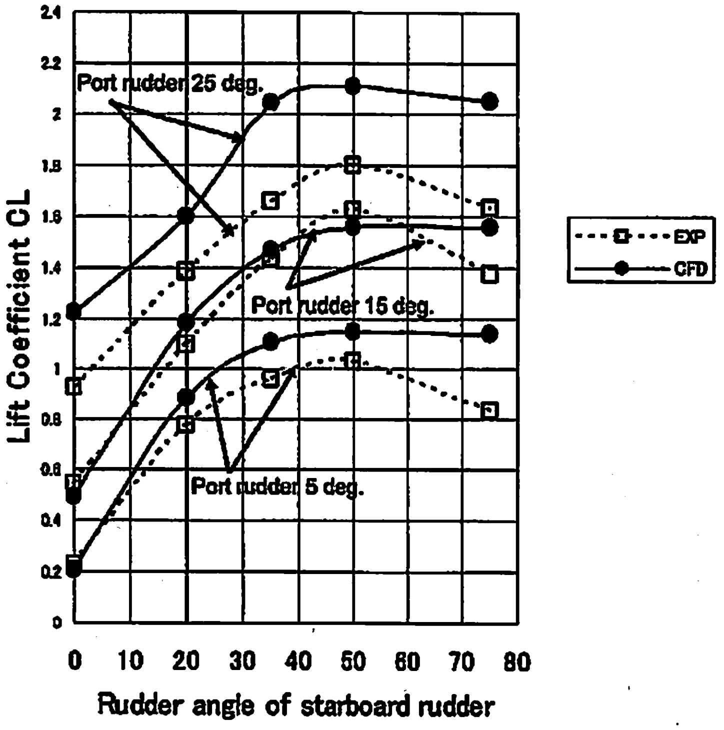


Fig.16 Lift coefficient for differentially angle cases

(e) Zero setting angle

Rudder angle of zero is usually set as the datum lines of rudder section are parallel to the ship's center line. For VecTwin rudder, there is some possibility to set the zero angle such as a manner shown in Fig.17. In this case a port rudder is turned to starboard side and a starboard rudder is turned to port side as much and this angle is defined as zero setting angle. For rudder No.1 and rudder No.5, resistance coefficients agaist zero setting angle are investigated and they are shown in Fig.18.

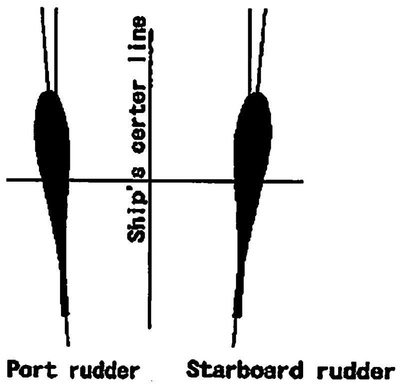


Fig.17 Zero setting angle

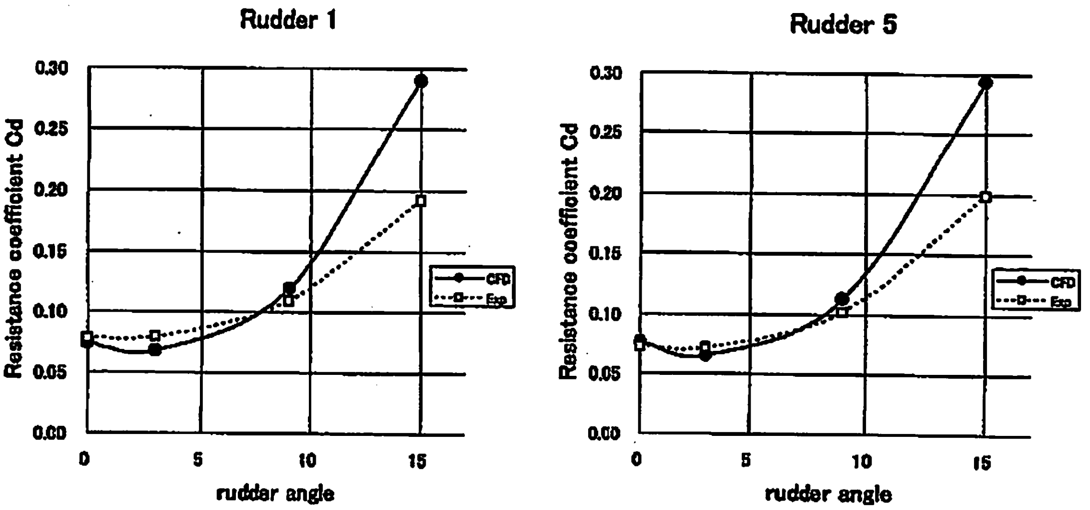


Fig.18 Resistance coefficient versus zero setting angle

Both rudder 1 and rudder 5 have a minimum resistance at about 2~3 degrees and the results by CFD agree well with the results of model test against the zero setting angle zero to 10. It is found that the best zero setting angle is approximately 2~3 degrees from the view point of resistance of rudder.

5. Conclusion

Studying work has been done to apply the single-propeller/twin-rudder system to medium size vessels and main point of the research is to find the most effective shape of rudder section. The work has been done with commercial CFD software and as the conclusion:

1. From the view point of resistance the smaller thickness to chord ratio is better, but the limitation exists from strength aspect. Although lifts of symmetric type rudder are different for port rudder and starboard rudder, they are small and less important for the performance of the rudder.
2. As for the shape of rudder section, symmetric type rudder and asymmetric rudder with small curvature inside are better from the view point of resistance.
3. It is possible to find an effective fin shape attached to the rudder horizontally by CFD. Smaller inclination angle of leading edge is better from the performance point of view. However, to avoid interference when moving the rudders inside, some practical consideration is necessary.
4. CFD will be a tool to investigate the influence of different rudder angle combination of two rudders, although the accuracy at large rudder angle is not confirmed well.
5. The best zero setting angle is approximately 2~3 degrees from the view point of resistance of rudder.

6. Acknowledgement

Some data of the joint research with Nippon Kaiji Kyokai on "Study on medium sized energy saving type VecTwin ship" are used in this study.

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