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Interaction effects on hydrodynamic characteristics of twin rudders

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Abstract: In order to reach the required manoeuvrability, inland vessels often use twin rudders, but the interaction effects are poorly understood. To achieve a proper configuration, this paper applies 2D RANS simulations to analyse the interaction effects on the twin-rudder hydrodynamics. Various twin-rudder configurations with different profiles and spacing of the rudders are studied. RANS simulations are carried out with a $k-\omega$ SST turbulence model and a pressure-based coupled algorithm. Commercial CFD package ANSYS Meshing and ANSYS Fluent are applied as the mesh generator and the numerical solver. Series of NACA, IFS, and Wedge-tail profiles are tested and compared in various configurations. Finally, the interaction effects on twin-rudder hydrodynamic characteristics are summarised.

Keywords: rudder hydrodynamic characteristics; rudder interactions; twin-rudder ships; Computational Fluids Dynamics

1 Introduction

Ship rudders play a significant role in initial turning, course-keeping, and yaw-checking abilities of ships. The effectiveness of rudders in manoeuvring performance is normally evaluated by the amount of rudder induced side force (Y_R). Since the tangential component is relatively small and negligible, the side force mainly depends on the rudder normal force, which is commonly calculated based on the area of the rudder (A_R), the inflow speed (V_R), and the rudder normal force coefficient (C_N) (Yasukawa and Yoshimura, 2014).

The normal force coefficient is routinely estimated by the well-known Fujii's formula:

$$C_N = f_\alpha \sin \alpha_R = \frac{6.13\Lambda_G}{2.25 + \Lambda_G} \sin \alpha_R$$

where Λ_G is the geometrical rudder aspect ratio and α_R is the effective rudder angle, which is the angle of attack in open water. This formula is sufficient for the common Mariner rudder, which has a NACA 0018 profile. However, this equation is not sensitive to the effect of rudder profiles and the interactions among multiple rudders. In addition, the lack of knowledge in the rudders is one of the challenges for evaluation and prediction of inland vessel manoeuvrability (Liu *et al.* 2015a). Liu, Quadvlieg, and Hekkenberg (2015b) analysed the impacts of rudder profiles on the manoeuvring performance of a KVLCC2 tanker and proposed new regression formulas for the normal

force coefficients of the tested profiles.

To improve the rudder effectiveness for manoeuvring, i.e. increase the rudder induced side force, one feasible approach is to enlarge the total rudder area by using multiple rudders. Liu and Hekkenberg (2015c) reported the hydrodynamic characteristics of three different rudder profiles in single-rudder and twin-rudder configurations through Computational Fluid Dynamics (CFD) simulations. It is clear that various rudder profiles have different hydrodynamic performance. Furthermore, due to the interaction between the twin rudders, the hydrodynamic characteristics of each rudder in the twin-rudder configuration are also different.

To gain further insight into the interaction effects on twin-rudder hydrodynamics, this paper focuses on two questions. One is how these interactions are influenced by the distance between the twin rudders (y_{TR}). The other one is how much of the effect is caused by the rudder profile. To answer these questions, series of CFD simulations are performed. The results are useful for further optimization of twin-rudder configurations and investigation on twin-rudder ship manoeuvrability.

In this article, the CFD method is applied to resolve the interaction effects on twin-rudder hydrodynamic characteristics. Section 2 describes the test configurations of the relative positions and the rudder profiles. Section 3 presents the applied CFD method. Section 4 shows the results and discusses the twin-rudder hydrodynamic characteristics. Finally, Section 5 draws conclusions.

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2 Test configurations

The test configuration presented in this paper contains two aspects. One is the relative position (y_{TR}), i.e. the distance between the twin rudders. The other one is the applied rudder profile. Fig. 1 illustrates an example of the test configuration. Customarily, the twin rudders are placed at equal distances from the propeller shaft axis and y_{TR} is slightly smaller than the diameter of propeller. The value of y_{TR} influences the rudder hydrodynamic characteristics and determines the portion of the rudder area in the propeller slipstream.

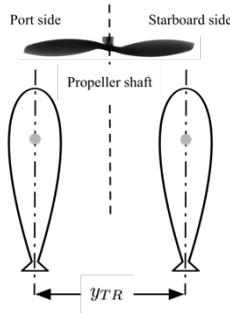


Fig. 1 An example of the test configuration

The most widely used and mostly studied rudder profile is the NACA series. It is efficient to generate lift with minimal drag. To have a steeper lift slope and a larger stall, the IFS series is developed. Frequently, for inland vessels which may have a limited total rudder area, high-lift profiles are applied, such as wedge-tail and fishtail. These high-lift profiles are also used for vessels that need extraordinary manoeuvrability like tugs or push boats. Commonly, the concave point of the wedge-tail profile is sharp while that of the fishtail profile is soothed. However, how to smooth the fishtail profile is not clearly defined in literature or available to public. This paper chooses similar wedge-tail profiles, which are designed based on the NACA series by the authors, as representatives of the high-lift profiles. Fig. 2 shows the tested 10 rudder profiles.

To resolve the two research questions of this paper, series of tests are carried out as presented in Table 1. The NACA 0018 is selected to study the effect of y_{TR} for the first question. In addition, nine profiles from the NACA, IFS, and wedge-tail families are tested at y_{TR} of $0.5 C_R$ and $1.0 C_R$ respectively to show the impacts of profiles on twin-rudder hydrodynamic characteristics for the second question.

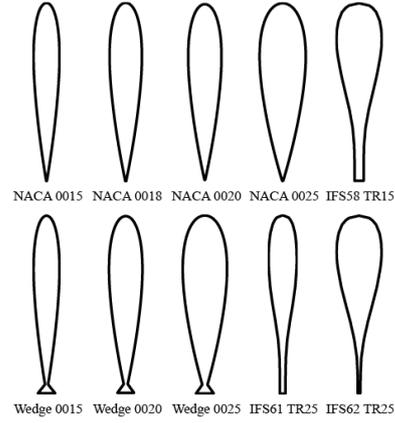


Fig. 2 Test rudder profiles

Table 1 Test configurations

Profiles	$y_{TR} (C_R^*)$
NACA 0018	0.4, 0.5,
	0.6, 0.7,
	0.8, 0.9,
	1.0
NACA 0015, NCA 0020, NACA 0025; wedge-tail 0015, wedge-tail 0020, wedge-tail 0025; IFS 58 TR 15, IFS61 TR25, and IFS 62 TR25	0.5, 1.0

* Unit chord length of the test rudder

3 Computational Fluid Dynamics methods

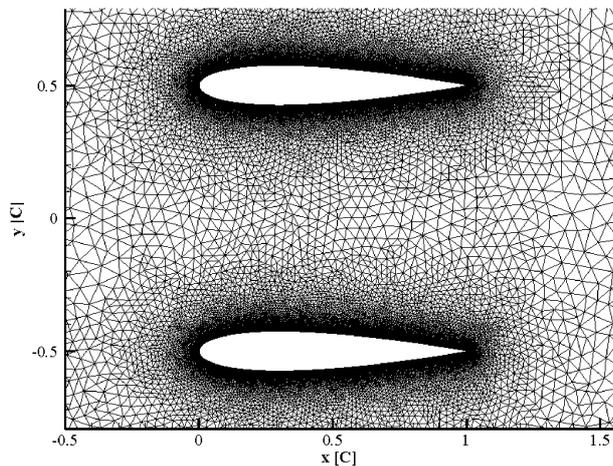
In recent years, Computational Fluid Dynamics (CFD) methods are applied more and more often in marine applications (Stern *et al.* 2015). The increase in the computer power and the decrease in the equipment price make it possible to carry out complex CFD tests at a large scale. Even though CFD methods encounter accuracy and convergence challenges, they are especially useful to test various options at relatively low cost in the initial design stage. This section presents the applied CFD methods in this paper.

To achieve reliable CFD results, the numerical solver, the turbulence model, and mesh generation should be carefully considered. This paper uses a commercial CFD solver, ANSYS Fluent 16.1, as it is a widely applied and validated RANS code. The analyses use a $k-\omega$ SST turbulence model and a pressure-based coupled algorithm. More advanced Large Eddy Simulation (LES) or Direct Numerical Simulation (DNS) methods can achieve better results than the RANS method. However, the LES and the DNS methods are much more expensive in time and computational power and normally not feasible to be applied for initial stage studies.

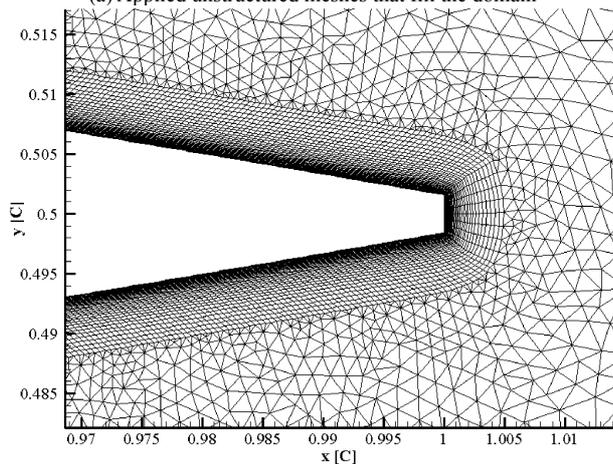
After the selection of the numerical solver and the turbulence model, extra thinking and experience are required to generate good mesh. The quality of the

mesh significantly affects the convergence and accuracy of the CFD solutions. In addition, configurations of the mesh need to be associated with the choice of the solver and the turbulence model. For instance, the applied $k-\omega$ SST model needs y^+ of the boundary layers to be smaller than 1. Furthermore, the size of the domain, which is filled by the mesh, should be as large as possible.

Commonly, an unstructured mesh is easier and faster to converge than a structured mesh. Additionally, the unstructured mesh is much more convenient to generate than the structured mesh, especially for complex geometries like the wedge-tail profiles, while structured mesh may achieve more accurate results. Considering the accuracy of the results and the cost of the calculation, this paper uses unstructured triangular meshes with structured quadrilateral boundary layers as shown in Fig. 3. The whole computational domain is $90 C_R$ long and $60 C_R$ wide.



(a) Applied unstructured meshes that fill the domain



(b) Connection of the structured boundary to the unstructured mesh

Fig. 3 Applied mesh in CFD simulations

4 Results and discussion

After configuring the test cases and setting up the

CFD model, this section presents the results from the simulations.

4.1 Relative positions

The distance between the twin rudders (y_{TR}) affects the pressure distribution around the twin rudders changing their hydrodynamic characteristics. For twin rudders with y_{TR} of unit chord length, Liu and Hekkenberg (2015c) showed that the hydrodynamic characteristics of each rudder in the twin-rudder configuration is different from those of the single-rudder case. To analyse the impacts of y_{TR} on twin-rudder hydrodynamic characteristics, single NACA 0018 rudder and twin NACA 0018 rudders with y_{TR} in range of $0.4 C_R$ to $1.0 C_R$ are tested. The tested angles of attack are in the range of 0° to 35° at an interval of 1° . Fig. 4 illustrates the conventions of forces and angles of the presented results. Fig. 5 presents the lift and drag coefficients of the single rudder and each rudder in the twin-rudder configurations with various y_{TR} .

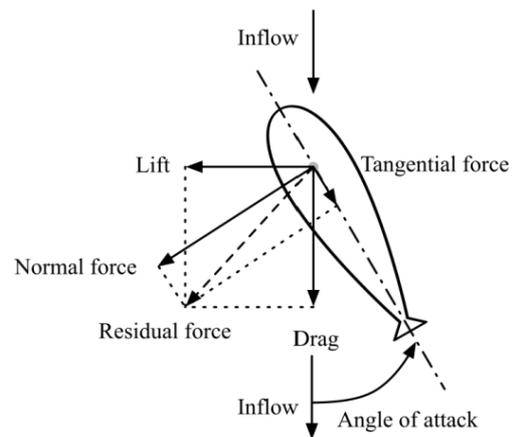
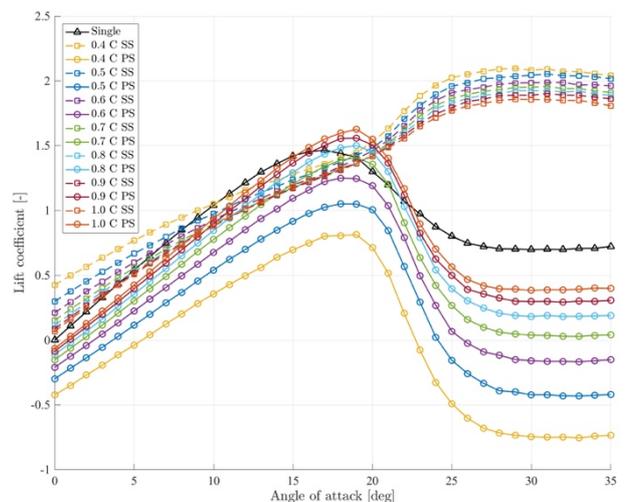


Fig. 4 Conventions of forces and angles



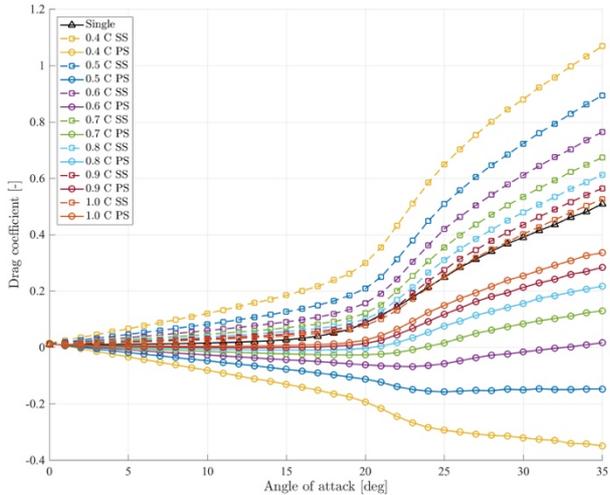


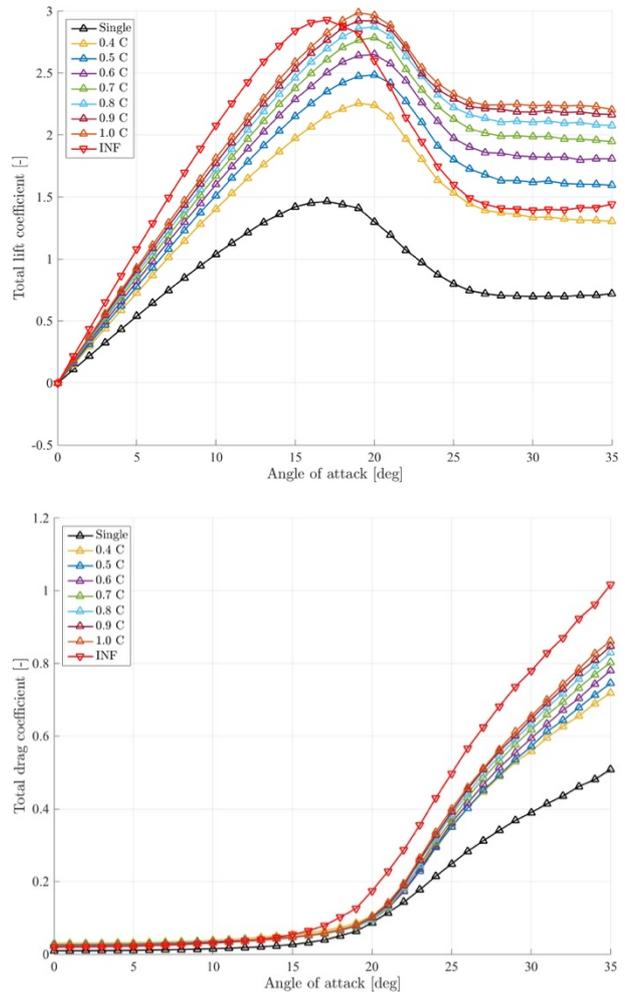
Fig. 5 Lift and drag coefficients of single (Single), portside (PS), and starboard side (SS) NACA 0018 rudders

Compared to the hydrodynamic coefficients of the single rudder, the starboard side rudders in twin-rudder configurations with different y_{TR} have about 10° larger stall angles while the port side rudders have 2° to 4° larger stall angles. With different y_{TR} , the lift slopes of the starboard side rudder are similar, while those of the port side rudders increase with an increase of y_{TR} . In addition, the lift slopes of the twin rudders are smaller than that of the single rudder. For starboard rudder angles, the variation of y_{TR} has larger impacts on the rudder lift coefficients of the port side rudder than the starboard side rudder, and vice versa. In general, the starboard side rudder has higher lift and drag coefficients than the port side rudder. However, with y_{TR} larger than 0.6 C_R , the starboard side rudder under angles of attack in range of 10° to 20° has smaller lift coefficient than the port side rudder.

The drag coefficients of starboard side and port side rudders in twin-rudder configurations are approximately symmetric with the drag coefficient of the single rudder. The drag coefficients at large angles of attack (larger than 15°) are more sensitive to the change of y_{TR} . It should be noted the port side rudder may have a negative drag coefficient, generating thrust instead of resistance, while the starboard side rudder has much higher drag coefficient than the single rudder. In this case, some turning moment on the ship is generated by the difference in the rudder forces. This moment is commonly small, but it can be large at large angles of attack. A future study investigating the impacts of such turning moment on ship manoeuvrability is needed. For the lift coefficients, an increase of y_{TR} leads to an increase in the port side C_L and C_D , while a decrease in the

starboard side C_L and C_D .

Fig. 6 shows the total hydrodynamic coefficients of the twin rudders with different y_{TR} , i.e. total lift, total drag, total lift to drag ratios, and total normal force coefficients. When two rudders are infinitely far away from each other, there is no interaction effect. Therefore, the total hydrodynamic coefficients of twin rudders with infinite y_{TR} is assumed to be two times of those of the single rudder. To show the interaction effects, coefficients of the single-rudder (Single) and the twin rudders with infinite y_{TR} (INF) are also plotted in Fig. 6.



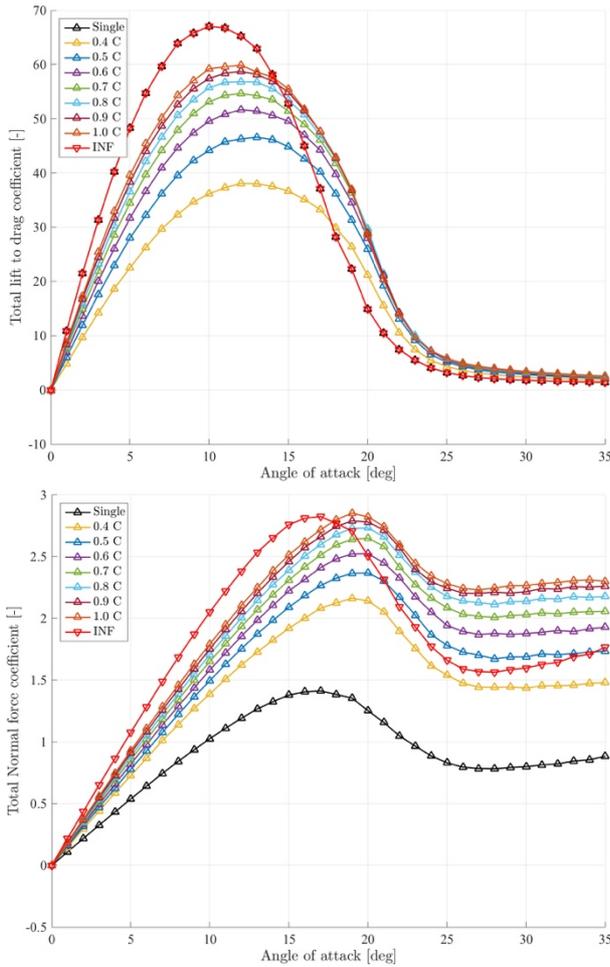


Fig. 6 Total hydrodynamic characteristics of the single and twin NACA 0018 rudders with various y_{TR}

The total lift coefficients and the total lift slopes increase with an increase in y_{TR} as the interaction effects decrease. An increase in y_{TR} slightly decreases the total drag at small angles of attack (smaller than 20°) while increases the total drag at large angles of attack. To compare the efficiency of each configuration, lift to drag ratios (C_L/C_D) are plotted. C_L/C_D decreases with a decrease of y_{TR} due to the larger decrease in lift and smaller decrease in drag. Furthermore, twin rudders with large y_{TR} have higher normal force coefficients than those with small y_{TR} . More specifically, an increase in y_{TR} improves the effectiveness of the twin rudders for manoeuvring.

The variation in y_{TR} changes the pressure distribution between the twin rudders and around each rudder. Fig. 7 illustrates the pressure distributions of twin rudders with y_{TR} of $0.5 C_R$, $1.0 C_R$, and infinity (as the same as single rudder) at angle of attack of 15° . From $0.5 C_R$ to $1.0 C_R$, the pressure difference between the two sides of the port side rudder increases while that of the starboard side rudder decreases, which leads to an

increase in the port side lift coefficient and a decrease in the starboard side lift coefficient.

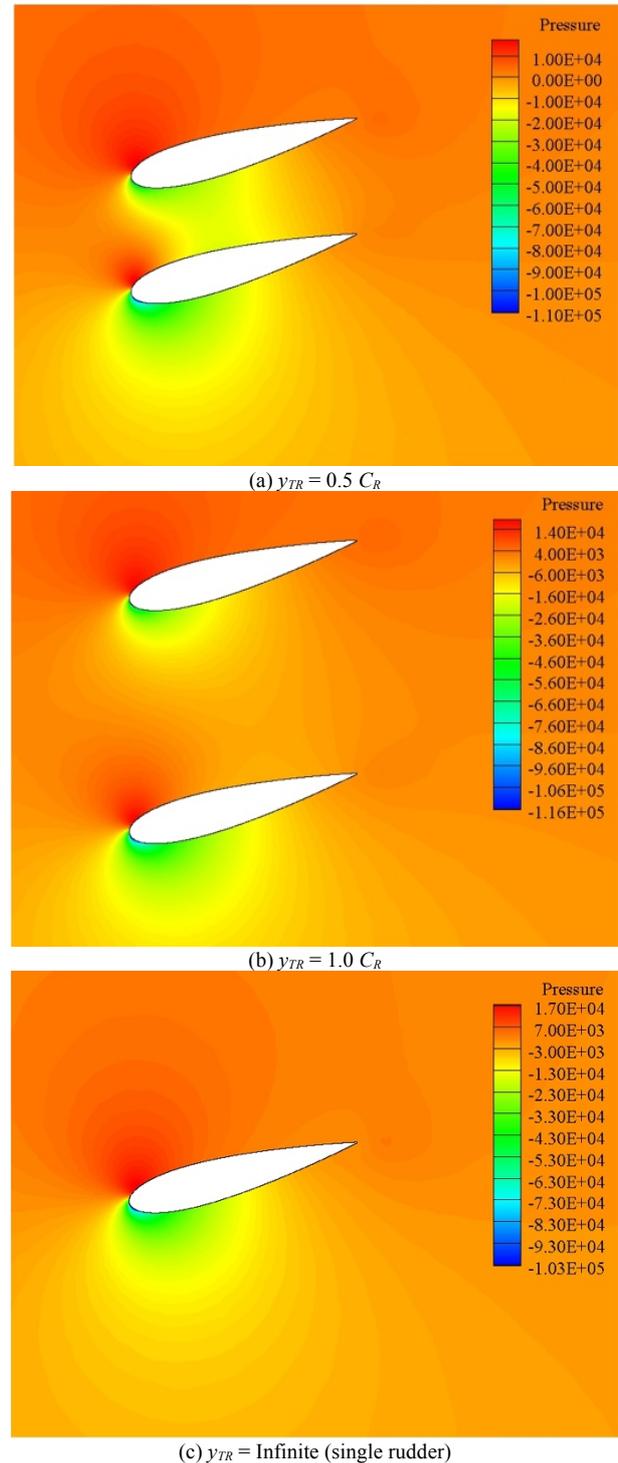


Fig. 7 Pressure distributions of twin rudders at an angle of attack 15° with y_{TR} of $0.5 C_R$ and $1.0 C_R$

On the whole, the two cases of the twin rudders with infinite y_{TR} (INF) and zero y_{TR} (Single) set the maximum and minimum bounds of the twin-rudder hydrodynamic coefficients respectively. With an

increase of y_{TR} , both the efficiency (the lift to drag ratio) and effectiveness (the normal force) of twin rudders in open water increase. But the efficiency of the twin-rudder system cannot be as high as that of the single-rudder case.

4.2 Applied profiles

In the last section, we discussed the impacts of the distance between the twin rudders y_{TR} on the twin-rudder hydrodynamics. To analyse the impacts of the rudder profile on twin-rudder performance, this section presents the test results of nine profiles from 3 families as listed in Table 1. Fig. 8 and Fig. 9 present the total lift, total drag, total lift to drag ratios, and total normal force of these profiles at y_{TR} of $0.5 C_R$ and $1.0 C_R$ respectively. The tested angles of attack are in the range of 0° to 35° at an interval of 5° .

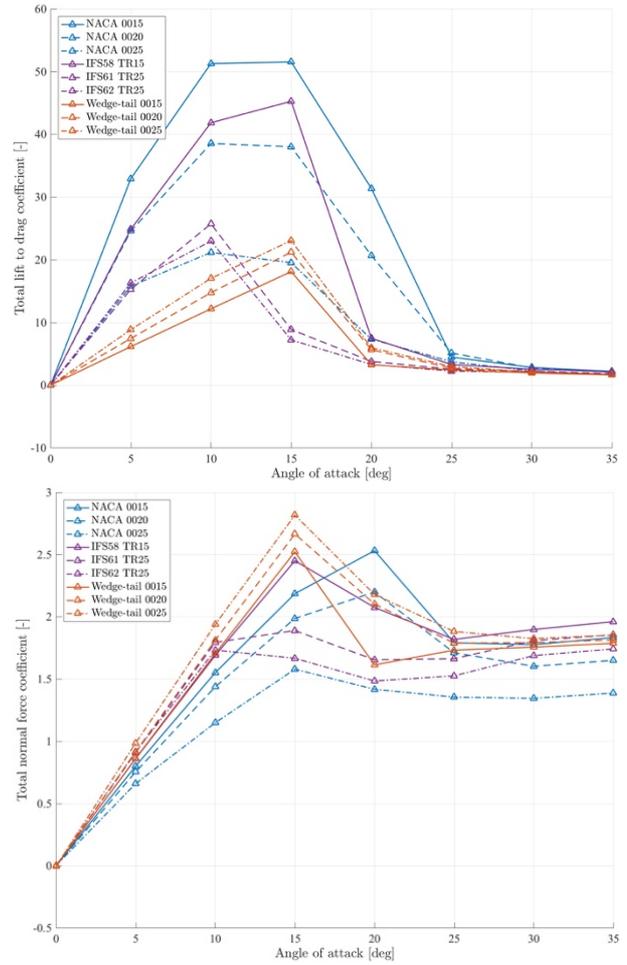
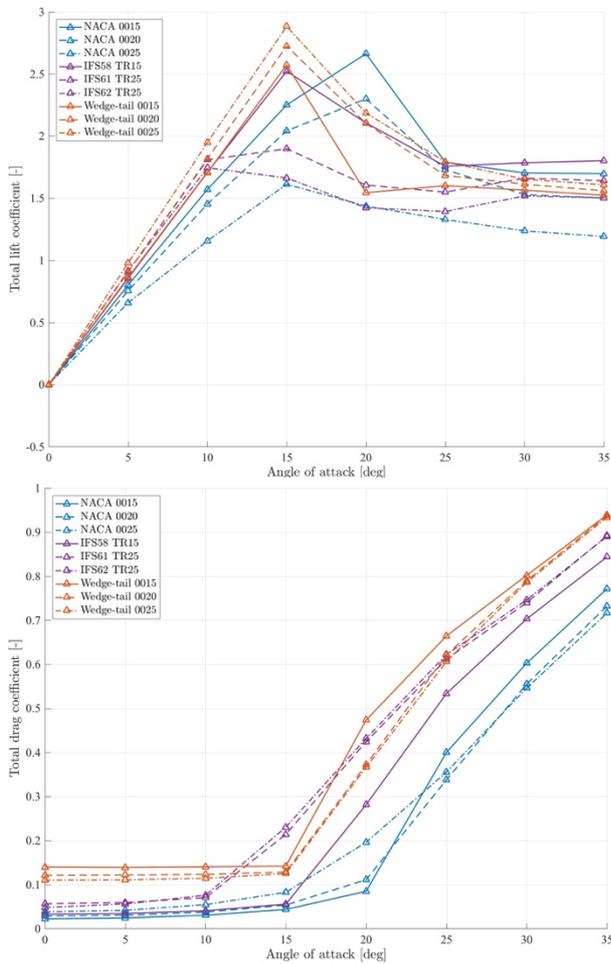
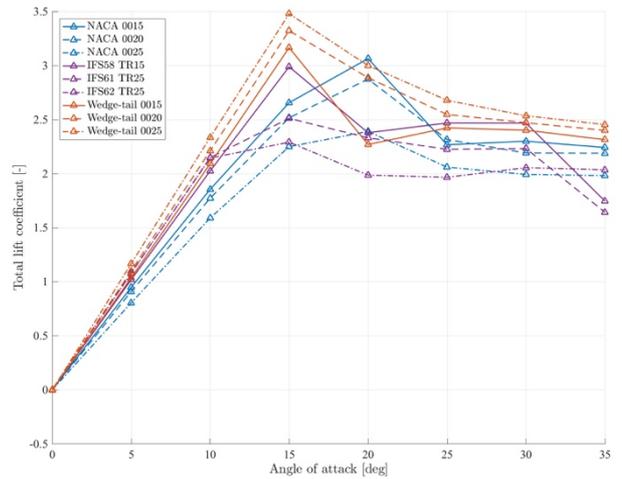


Fig. 8 Hydrodynamic characteristics of twin rudders of various profiles with $y_{TR} = 0.5 C_R$



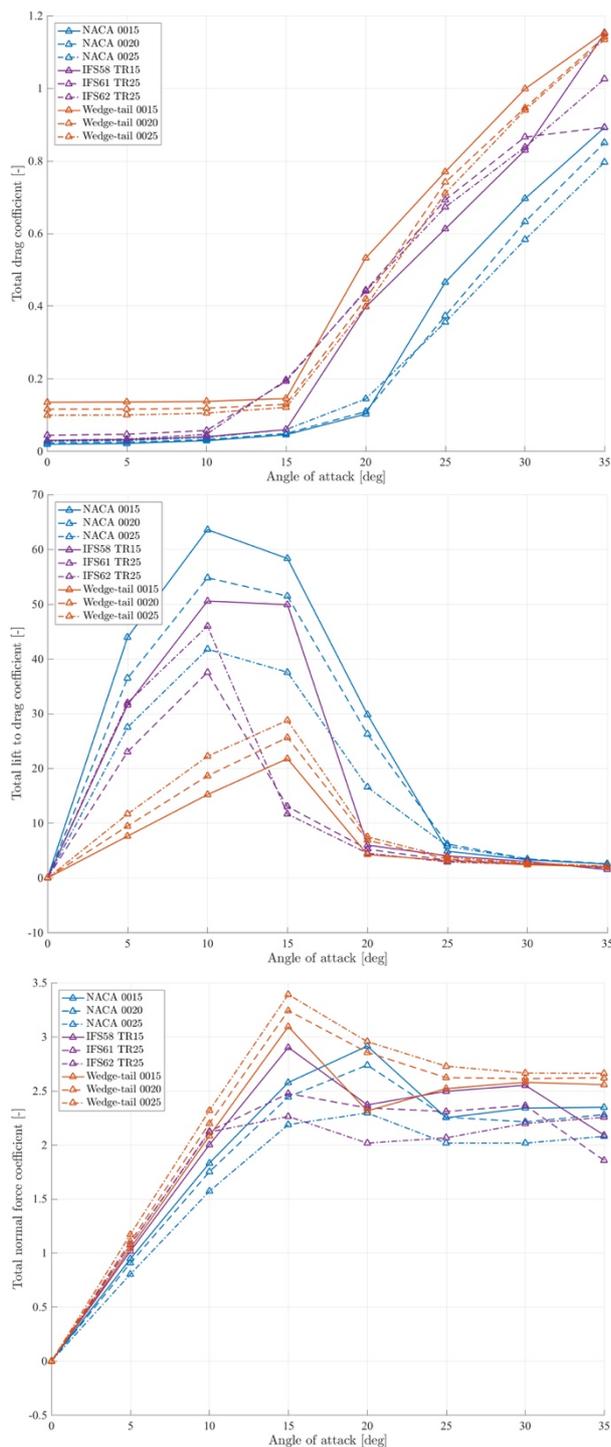


Fig. 9 Hydrodynamic characteristics of twin rudders of various profiles with $y_{TR} = 1.0 C_R$

Comparing Fig. 8 and Fig. 9, we conclude that the impacts of y_{TR} on the hydrodynamic characteristics of different rudder profiles are similar, i.e. an increase of y_{TR} increases the total lift coefficient, the slope of the total lift curves, and the total drag coefficient. Thus, the total normal force become larger, which enhances the effectiveness of the twin rudders. Since the

increase in the total lift coefficient is larger than the increase of the total drag coefficient, the total lift to drag ratio gets larger leading to an improvement of the efficiency of the twin-rudder system. Furthermore, the thin profiles have better performance than thick ones. Among the three tested profile families, in general, wedge-tail is most effective, NACA is most efficient, and IFS is balanced in efficiency and effectiveness.

5 Conclusions

Throughout this paper, RANS simulations of different twin-rudder configurations in the rudder profile and the distance between the twin rudders (y_{TR}) are performed. The test results answer the following two questions:

1. Effects of y_{TR} on twin-rudder hydrodynamics.

In general, an increase of y_{TR} increases the total lift coefficient, the total drag coefficient, the total lift to drag ratio, and the total normal force coefficient. Therefore, both the effectiveness and efficiency of the twin-rudder system improve as the rudders are placed further apart.

2. Effects of y_{TR} on twin-rudder hydrodynamics.

Different rudder profiles have different hydrodynamic characteristics. However, the profile does not significantly affect the tendency of the impact of y_{TR} on the twin-rudder hydrodynamics.

We realise the above conclusions are based on 2D RANS results in open water. The impacts of the propeller slipstream and the 3D shape of the rudder should also be considered to draw more critical conclusions. These topics require further study.

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