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3D RANS simulations of shallow water effects on rudder hydrodynamic characteristics

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Abstract: An accurate estimation of the rudder forces and moments is essential for manoeuvrability prediction. Previous research has shown that ships have different manoeuvring performance in deep and shallow water. Before considering the rudder's contribution to shallow water manoeuvring, it is meaningful to analyse the shallow water effects on the rudder itself. In shallow water, the rudder gets close to the channel bottom. Therefore, mirror effects are expected, which may greatly affect the rudder effective aspect ratio and the generated rudder forces. Instead of high-cost model tests and time consuming full ship CFD simulations, this paper applies 3D RANS methods to analyse the shallow water effects on rudder hydrodynamic characteristics. 3D RANS simulations are carried out with a pressure-based coupled algorithm through ANSYS Fluent 16.2. The turbulence is simulated by a realisable k-ε turbulence model. Based on a NACA 0020 profile, the method is validated through a comparison of the CFD results with the wind tunnel tests. Then, NACA 0020 spade rudders with geometric aspect ratios of 1.2 and 1.5 are tested with different tip clearance. Rudder lift and drag coefficients are generated to calculate the normal force coefficient for manoeuvring simulations. Finally, shallow water effects on rudder hydrodynamics are summarised.

Keywords: rudder hydrodynamics; shallow water effects; 3D RANS simulations

1 Introduction

Ship manoeuvrability is critical to navigation safety, especially for ships that frequently sail in constrained waterways. Due to the limited water depth and the fluctuation of water levels, shallow water effects on inland vessel manoeuvrability deserve further consideration than the current situation where shallow water studies primarily focus on large seagoing ships in shallow entrance waterways or port areas (Liu *et al.*, 2015b).

Rudders significantly affect ship course-keeping, turning, and yaw-checking abilities. To predict the ship manoeuvrability in both deep and shallow water, an accurate estimation of the rudder forces and moments is essential. Inland vessels have a large range of options in the rudder profiles, the rudder properties, the rudder types, and the configurations in the number and the relative position of rudders while seagoing ships customarily equip one spade NACA 0018 rudder, the so-called Mariner rudder. Furthermore, the shallow water effect should be considered.

The shallow water effect starts noticeable in medium deep water ($1.5 < H/T < 3.0$), becomes significant in shallow ($1.2 < H/T < 1.5$), and dominates in very shallow water ($1.5 < H/T < 1.2$) (Vantorre, 2003). The typical shallow water effect is an increase in the tactical diameter (ITTC Manoeuvring Committee, 2008). On the contrary, the tactical diameter may decrease for twin-propeller wide-beam ships (Kijima & Nakiri, 2004). These differences are caused by the changes in the propeller working load and the rudder forces. To analyse the shallow water effect on the rudder forces and moments for ship manoeuvring, this paper applies Computational Fluid Dynamics (CFD) methods, more specifically the 3D RANS method.

With the fast development of CFD methods and evolution of computer power, CFD simulations provide new possibilities in studies on the hydrodynamic characteristics of ships, propellers, and rudders. In the previous studies of the authors (Liu *et al.*, 2015a, 2015c), the impacts of the profile and the number of rudders on the rudder hydrodynamics and the rudder contribution to ship manoeuvrability have been discussed. To calculate the rudder forces and moments, the rudder open water coefficients and the effective aspect ratio are required. Furthermore, the shallow water effect on rudders can be quantified as a corrector of the effective aspect ratio.

This paper utilises 3D RANS simulations to present the shallow water effects on the rudder hydrodynamics. Following this introduction, Section 2 shows the test configurations of the rudder profile and

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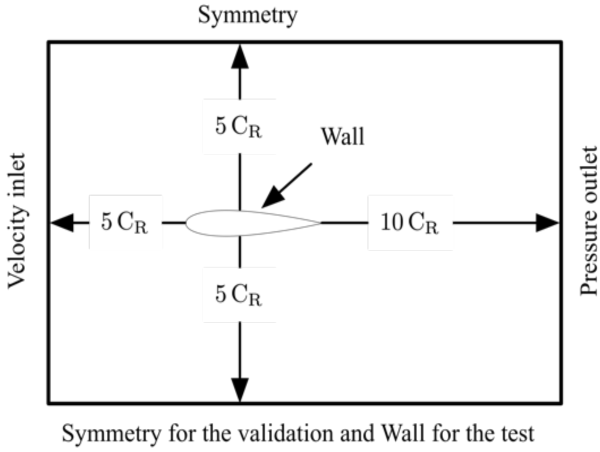
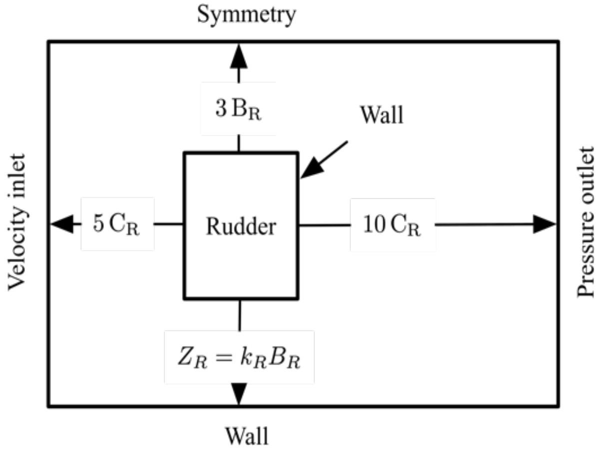
test environment. Section 3 explains the applied RANS method, including the mesh, the solver, and the turbulence model. Section 4 validates the applied RANS method. Section 5 presents the results and discusses the shallow water effect. Finally, Section 6 draws conclusions and proposes research for the future.

2 Test configurations

The presented CFD simulations are set up in a rectangular domain. The dimensions of the domain and applied boundary conditions are illustrated in Fig. 1, where C_R is the rudder chord length, B_R is the rudder span, and Z_R is the clearance between the rudder tip and the bottom of the waterway. In addition, Z_R is given as k_R times B_R. The rudder geometric aspect ratio is defined as $\Lambda_G = B_R/C_R$.



(a) A bird's eye view of the test domain



(b) A side view of the test domain

Fig. 1 Illustrations of the test domain and the applied boundary conditions

The NACA 0020 profile is first taken as a validation case of the RANS method and then tested to analyse the shallow water effect. The test matrix is given in Table 1. In total, 3 spade type NACA 0020 rudders with different geometric aspect ratios (Λ_G) are tested at two water depth. Detail settings of the applied RANS method including the mesh generation, the numerical solver, and the turbulence model are introduced in the following section.

Table 1 Test matrix of spade NACA 0020 rudders

	Λ_G	Λ_E	k_R
Validation case	1.5	3	0.0
Shallow water cases	2.0, 1.5, 1.2	-	0.5, 0.2

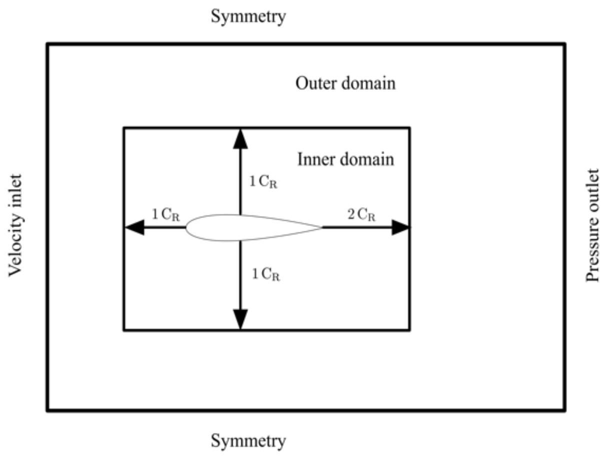
3. Applied RANS method

To achieve solid CFD results, the research problem needs to be properly defined. This paper focuses on the shallow water effect on rudder hydrodynamics. Therefore, incompressible viscous isothermal water is taken as the working fluid. The test Reynolds number is 6 million, above which the hydrodynamic coefficients are not significantly affected by the change of the Reynolds number (Ladson, 1988). The tested angles of attack are in the range of 0° to 35° at an interval of 5°.

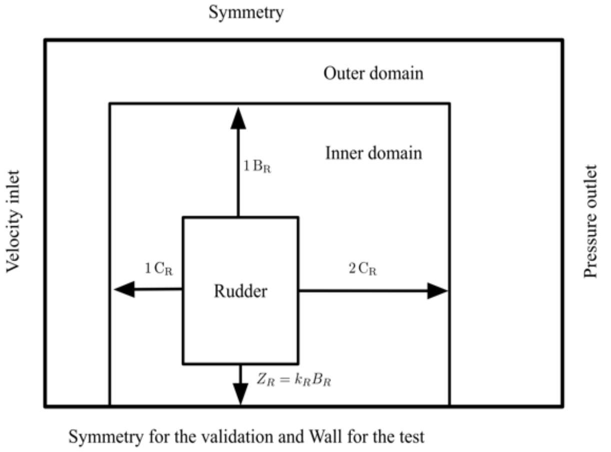
A commercial ANSYS FLUENT 16.1 is chosen as it is a carefully validated and widely used CFD package. The pressure-based coupled solver is applied to reduce the overall convergence time (Kelecy, 2008). The Realisable k-ε model (Shih *et al.*, 1995) is taken due to its robustness, economy, and accuracy for a large range of applications (Eleni *et al.*, 2012). Furthermore, Quérard (2008) noted that the k-ε model requires less CPU time than the k-ω model in CPU time.

The quality of the mesh is crucial to the convergence of the simulation and the accuracy of the result. This paper uses a hybrid mesh. Structured cells surround the rudder body in the boundary layers while unstructured cells fill the domain. To properly capture the viscous effect with the Realisable k-ε model, the nondimensional grid distance y^+ is set as 35. Furthermore, an inner domain is built to refine the necessary cells around the rudder. The dimensions and the mesh structure is shown in Fig. 2. In average, the applied number of cells is around 5 million.

The boundary conditions are needed to define the initial and boundary states of the variables to solve the governing equations. The applied boundary conditions are shown in Fig. 1. The velocity-inlet condition defines the inflow velocity according to the tested Reynolds number (6000000 in water) or the value specified in the validation experiment (20 m/s in air). The pressure-outlet condition sets the pressure as constant and atmospheric. The wall boundary specifies the geometry of the rudder and counts for the viscous effects of the rudder and the bottom of the domain. Symmetry boundaries are in fact no-shear wall boundaries.



(a) A bird's eye view of the mesh structure



(b) A side view of the mesh structure

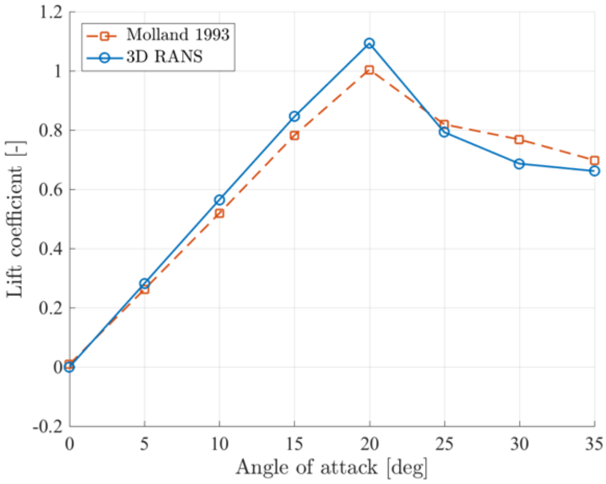
Fig. 2 Illustrations of the mesh structure and applied boundary conditions

4. Validation of the RANS method

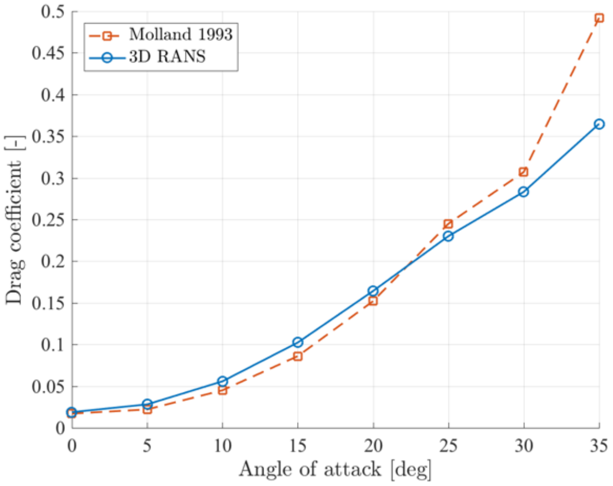
To validate the RANS method, a model is set up according to the wind-tunnel tests of a spade NACA 0020 rudder carried out by Molland and Turnock (1993). The chord length and the span of the test rudder are 0.667 m and 1 m. The geometric aspect ratio is 1.5. As the gap between the rudder and the bottom of the wind tunnel is very small (2.5 mm), the effective aspect ratio of the rudder is 3. The wind tunnel is 3.5 m long, 2.5 m wide, and 2.5 m high. The inflow velocity is 20 m/s. The working fluid is air.

The RANS model for validation is configured according to the wind-tunnel tests, except that the domain is larger than the wind tunnel as shown in Fig. 1. The larger domain is chosen to minimise the influence of the location of the boundaries on the RANS results. The rudder tip is connected with the bottom of the domain for simplification. The viscous effect of the bottom is not accounted in the validation case, but it is accounted in the simulations for the shallow water effect. Furthermore, the inflow is air at 20 m/s in the validation case while it is water at a Reynolds number of 6 million for the tests.

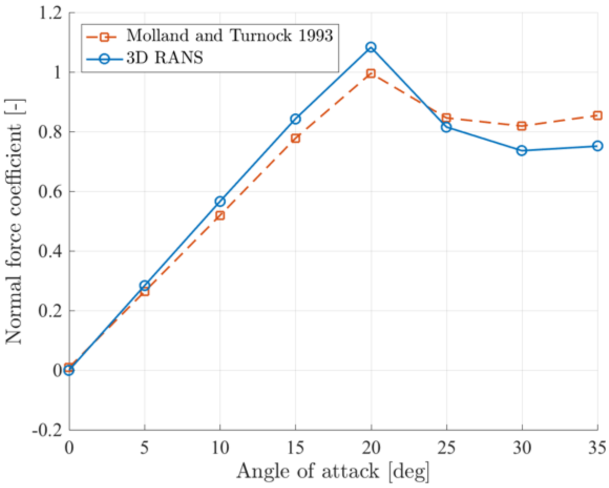
Fig. 3 compares the results of the 3D RANS model and the wind-tunnel tests. In general, the absolute relative differences of the lift, drag, and normal force coefficients are 8% to 11%, 6% to 28%, and 4% to 12% respectively. The accuracy of the model can be improved by changing the turbulence model, increasing the number of cells, and enlarging the domain, the computational time increases significantly with these modifications. We, therefore, accept the current accuracy.



(a) Lift coefficients



(b) Drag coefficients

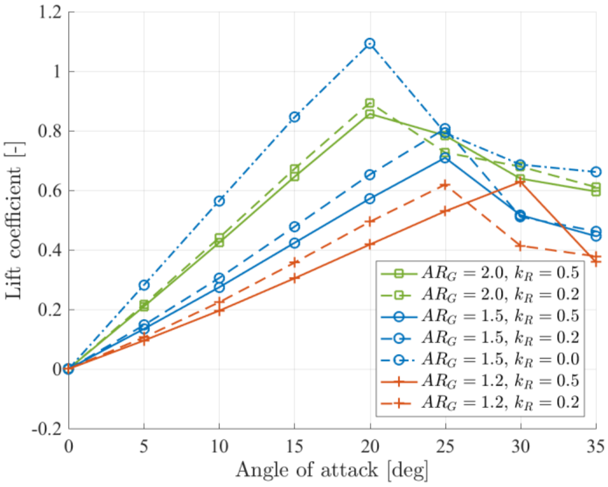


(c) Normal force coefficients

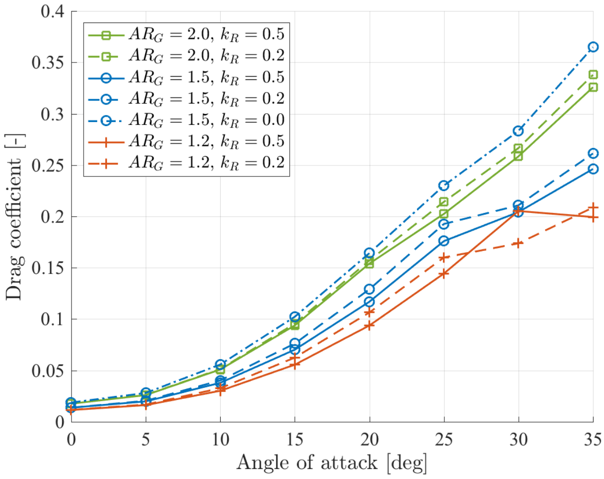
Fig. 3 Comparison of the 3D RANS results and the wind-tunnel tests in lift, drag, and normal force coefficients

5. Results and discussions

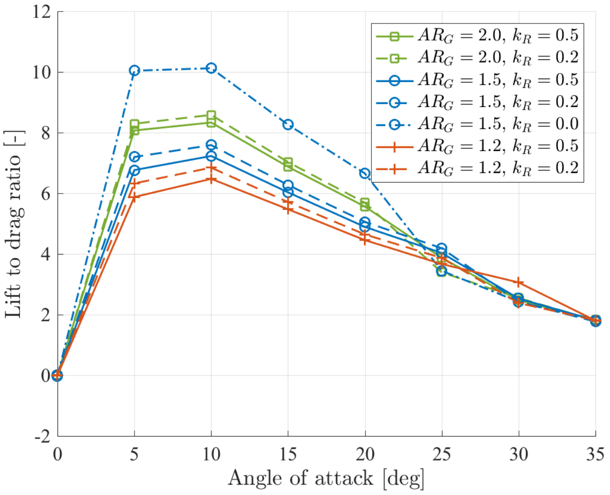
With the validated 3D RANS model, NACA 0020 spade rudders with different geometric aspect ratios (Λ_G) are tested with different tip clearance (k_R). The test matrix is shown in Table 1. The lift coefficients, the drag coefficients, the lift to drag ratio, and the normal force coefficients of the tested rudders are presented in Fig. 4. Based on these results, we can discuss the shallow water effect on rudder efficiency (the lift to drag ratio) and effectiveness (the normal force coefficient).



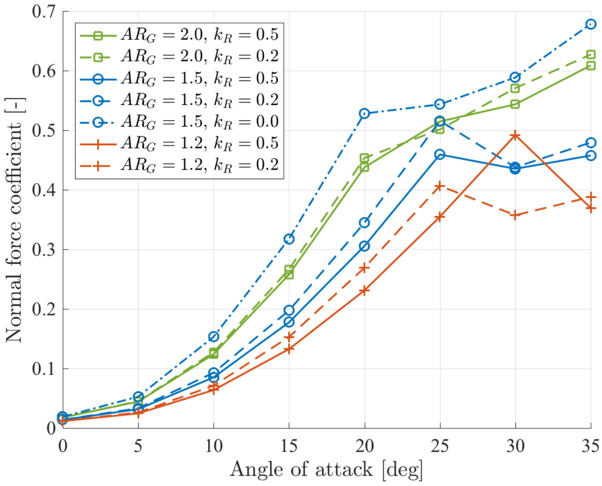
(a) Lift coefficients



(b) Drag coefficients



(c) Lift to drag ratios



(d) Normal force coefficients

Fig. 4 3D RANS results of NACA 0020 spade rudders with various aspect ratios (Λ_G) and tip clearances (k_R)

With the same tip clearance (k_R), a decrease in the geometric aspect ratio (Λ_G) decreases the slopes of all the four coefficient curves, i.e. the lift coefficient, the drag coefficient, the lift to drag ratio, and the normal force coefficient, while extends the stall angle. Therefore, a large Λ_G improves the rudder efficiency and effectiveness. Owing to the larger stall angels, rudders with smaller Λ_G may be more effective at larger rudder angles than those with larger Λ_G. With the same Λ_G, rudders with smaller k_R have higher slopes of the four coefficient curves. As k_R gets smaller, the shallow water effect shows, which enlarges the effective aspect ratio of the rudder (Λ_E).

It is known that the ratio of the effective and geometric aspect ratios (k_Λ) is 2 when the rudder tip connects with the bottom. As k_R gets larger, k_Λ becomes smaller. As k_R increases from 0.2 to 0.5, the reduction of k_Λ is more noticeable for rudders with smaller Λ_G than those with larger Λ_G. This effect shows that the small water depth or the smaller tip clearance, in fact, improves the efficiency and effectiveness of the rudder itself. Furthermore, it shows the benefit of using endplates to enhance the rudder performance, especially for rudders with small geometric aspect ratios.

6 Conclusions

This paper uses 3D RANS simulations to study the shallow water effect on rudder hydrodynamic characteristics. The 3D RANS model is first validated with the wind-tunnel test results of a NACA 0020 spade rudder. Then, the model is used to test NACA 0020 spade rudders with various geometric aspect ratios in different water depth, i.e. different rudder tip clearance. The test results draw the following conclusions:

1. In the same water depth, the lift coefficient, the drag coefficient, the lift to drag ratio, and the normal force coefficient increase with the increase of the geometric aspect ratio. A large aspect ratio is recommended whenever it is applicable.

2. The shallow water effect (the rudder tip clearance) affects the effective aspect ratio of the rudder. A decrease in the rudder tip clearance increases the ratio of the effective geometric aspect ratio to the geometric aspect ratio. This increase is more significant for rudders with smaller geometric aspect ratios. It is recommended to use endplates to improve the rudder performance, especially for rudders with small aspect ratios.

We aware this research is only for rudders in open water. The range of the test cases should be enlarged, including more profiles, more geometric aspect ratios, and more water depth. The relationship of the rudder hydrodynamics in shallow water and deep water should be established, which is the future topic for the authors.

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