Hydrodynamic characteristics of twin rudders

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Abstract

Computational fluid dynamic (CFD) simulations by solving Reynolds-averaged Naviers-Stokes (RANS) equations with a SST two-equation model using OpenFOAM codes are performed. The difference of hydrodynamic forces between the single-rudder and the parallel twin rudders of NACA0012 blades are examined from 5^{o} to 25^{o} angle of attack. It is found that the interaction between the twin rudders becomes strong as the angle of attack increases. Lately, the impact of the distance between the two rudders on the hydrodynamic forces at 15^{o} angle of attack is studied for the parallel twin rudders. It is noticed that the interaction between the twin rudders becomes weak with the lateral spacing increasing, and the lift to drag ratio of the twin rudders monotonously decreases with the lateral spacing. Finally, the effectiveness of the stopping performance of the twin rudders at the different lateral spacing is analyzed. As a result, the drag reaches the largest value as the lateral spacing equals to 1.3c.

Keywords: twin rudders, computational fluid dynamics, hydrodynamic characteristics, RANS

Introduction

The performance of ship rudders depends on the rudder hydrodynamic characteristics, and the rudder forces and moments are determined by the rudder area, angle of attach and incident flow velocity. In practical, the rudder area is sometimes limited due to shallow water. As a solution to solve such a problem, a twin-rudder configuration is commonly regarded.

By far, quite a few studies have been done for twin rudders, and hydrodynamic forces of twin rudders are mostly calculated by adding the corrected lift and drag profiles of the single rudder. Practically, the hydrodynamic characteristics of each rudder in twin rudders are interacted by each other such that the pressure profiles and the ambient flow of each rudder all vary and differ from those of the single rudder. Therefore, the hydrodynamic forces cannot be approximated as a duplication of the single rudder. The interaction between rudders is necessary to be taken into account when calculating hydrodynamic forces of the twin rudders.

For single-propeller twin-rudder ships, the asymmetrical behaviors would occur as the inflow is not parallel to ship's centerline. Hamamoto and Enomoto[1] analytically and experimentally investigated the forces on a couple of rudders and the interaction between both rudders steered with rudder angle. Nagarajan *et al.*[2] measured the rudder's axial force of a single-propeller twin-rudder ship, they proposed a prediction method to estimate the engine power of a ship installed with a special high lift twin-rudder system. The inflow characteristics to each one of the rudders of single-propeller twin-rudder system were investigated by Kang *et al.*[3].

They proposed a method called "virtual zero rudder angle" arrangement to prevent asymmetric maneuvering characteristic of the ship, which were proved to be effective to improve ship's propulsion performance.

Maneuverability and hydrodynamics of a twin-propeller twin-rudder ship were investigated by Yoshimura and Sakurai[4]. They found that hydrodynamic characteristics of a twin-propeller twin-rudder are not so much different from those of a single-propeller single-rudder ship. Yoo *et al*.[5] studied the maneuvering characteristics of a twin propeller/twin rudder ship during berthing and unberthing, and noticed that the tangential force acting on the rudder should be considered separately and that the bank suction effect between the hull and the quay developed an additional force. Khanfir *et al*.[6] proposed a mathematical model for maneuverability and estimation of hydrodynamic coefficients of twin-propeller twin-rudder ship. Lately, captive model tests as well as free-running tests with a single-propeller twin-rudder ship and a twin-propeller twin-rudder ship were carried out by them[7] to evaluate the effect of drift angle on the rudder forces and some peculiar phenomena concerning rudder normal force for twin-rudder ships.

As theoretical researches, Shcherbakov[8] carried out a twin-rudder performance test for NACA 0018 in a water channel at $\mathrm{Re} = 1.5 \times 10^4$ using PIV technique. The effect of the distance between two rudders on the hydrodynamics was examined, and the optimum distance was eventually determined. Liu and Hekkenberg[9] implemented RANS simulations to present an initial study of the hydrodynamic characteristics of twin rudders at small attach angles.

A twin-rudder ship may help reduce the stopping distance by setting the two rudders outwards at 75° (called clam shell angles). Compared to a conventional reverse engine stopping, a twin-rudder at 75° may reduce the stopping distance by 50%[10]. Hamamoto and Enomoto proposed analytical formulas of the ship speed drop and calculated the stopping time, the stopping distance as a ship stops at the clam shell angles. Hasegawa *et al*.[11] carried out stopping test for a large vessel installed with a mariner type super VecTwin rudder. They simplified the complicated flow around the rudders to model the flow speed around the rudders and analyzed the outward rudder angles.

Although a few researches were carried out to investigate the maneuverability of some twin-rudder ships, the complicated flow around the rudders and the hydrodynamic characteristics are still paid little attention. In order to obtain accurate hydrodynamic coefficients of twin-rudder, computational fluid dynamic (CFD) simulations by solving Reynolds-averaged Naviers-Stokes (RANS) equations using a finite volume method with a shear-stress transport (SST) $k-\omega$ two-equation turbulence model in OpenFOAM are implemented to capture the complicated flow field in this study. The study puts a focus on the effect of the lateral spacing (the distance between the twin-rudder blades) on the hydrodynamic coefficients and on the drag coefficients at the clam shell angle.

Methodology

Flow model

The flow around the rudders are governed by the Reynolds-averaged equations for conservation of continuity and Navier-Stokes equations

$$\frac{\partial u_i}{\partial x_i} = 0$$

$$\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}=-\frac{1}{\rho}\frac{\partial p}{\partial x_i}+\nu\frac{\partial^2 u_i}{\partial x_j^2}-\frac{\partial \overline{u_i^{'}u_j^{'}}}{\partial x_j}$$

Where i, j = 1, 2. $\overline{u_i^{'}u_j^{'}}$ represents the Reynolds stress component, which is to be expressed in terms of a turbulent viscosity, ν_T and the mean flow gradients using Boussinesq approximation,

$$-\overline{u_i^{'}u_j^{'}}=\nu_T\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right)-\frac{2}{3}k\delta_{ij}$$

where k is the turbulent kinetic energy and δ_{ij} is the Kronecker delta.

To solve the turbulent viscosity ν_T, a SST $k-\omega$ two-equation model proposed by Menter[12] are used in this study. The two-equation model is given by the following

$$\frac{\partial}{\partial t}(\rho k)+u_j\frac{\partial}{\partial x_j}(\rho k u_i)=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_T}{\sigma_k})\frac{\partial k}{\partial x_j}\right]-\rho\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}-\rho\beta^* k\omega$$

$$\frac{\partial}{\partial t}(\rho\omega)+\frac{\partial}{\partial x_i}(\rho\omega u_i)=\frac{\partial}{\partial x_j}\left[(\mu+\frac{\mu_T}{\sigma_k})\frac{\partial \omega}{\partial x_j}\right]-\frac{\alpha}{\mu_T}\overline{u_i^{'}u_j^{'}}\frac{\partial u_i}{\partial x_j}-\rho\beta\omega^2+2(1-F_1)\rho\sigma_{\omega,2}\frac{\partial k}{\partial x_j}\frac{\partial \omega}{\partial x_j}$$

where k is the turbulence kinetic energy, ω represents the specific dissipation rate and $\mu_T=\dfrac{\rho k}{\omega}$. For more details and the model coefficients, see Menter's paper[12].

Simulation procedure and problem setup

The Reynolds-averaged equations for conservation of mass and momentum are discretized with a finite volume method, and solved by a PISO solver of OpenFOAM, in conjunction with a SST $k-\omega$ two-equation model.

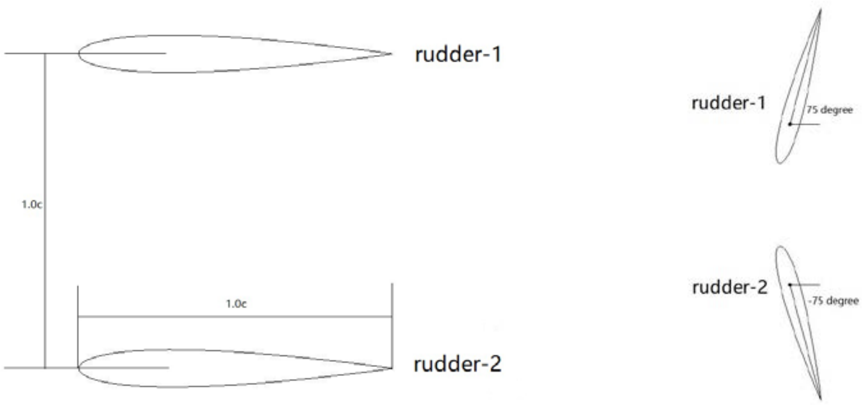


Figure 1. Parallel twin-rudder system of NACA0012 and twin rudders at a clam shell angle.

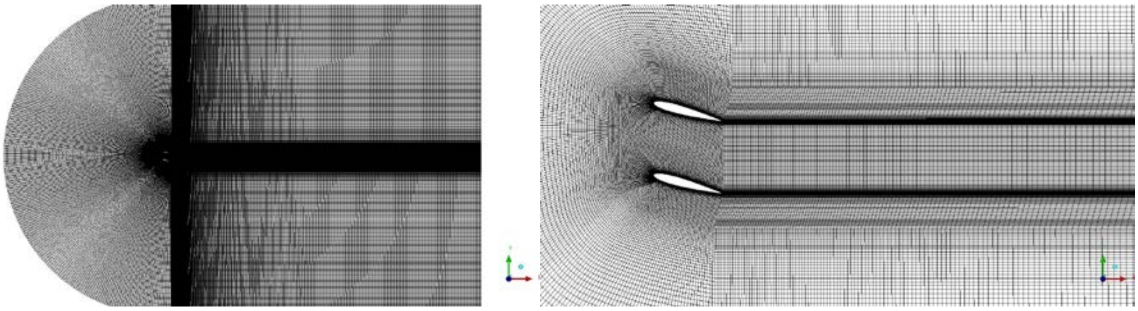


Figure 2. Structured mesh sketch at 15o angle of attack with 195472 elements and 194094 nodes for *d=1.0c*.

In this study, two NACA0012 blades are selected as the targeted parallel twin-rudder system (Figure 1). The computational domain includes a half circular of a radius of 20c (20 times rudder chord) and a $40c \times 40c$ rectangular (Figure 2). The size of the computational domain is sufficient to neglect the far-field effects.

Body-fitted, structured O-meshes for the computational domain are computed by ICEM CFD. A sketch of the mesh for a case with the lateral spacing $d = 1.0c$ is illustrated in Fig. 2. For all simulations, the size of the elements near the blades is set such that the dimensionless off-wall distance y^+ is smaller than 1, where y^+ is defined as $y^+ = u_\tau y / \nu$, u_τ denotes the friction velocity near the blade, and y denotes the normal distance from the blade.

Result and discussion

Liu and Hekkenberg[9] performed an initial study of the hydrodynamic characteristics of twin rudders, and analyzed the variation of the hydrodynamic coefficients with the attack angles. The present study extends Liu's work and examines the effect of the lateral spacing between the two rudders on the hydrodynamic coefficients. The discussion as follows contains the effect of angle of attack, the lateral spacing on the hydrodynamic coefficients of the parallel rudders, and the effect of the lateral spacing on the drag coefficients of the rudders at the clam shell angles.

Difference between single-rudder and twin-rudder

The first set of cases start with the twin rudders with 1.0c lateral spacing. Figure 3 shows the drag coefficients of the single-rudder and the twin rudders versus angle of attack. It can be seen that the drag coefficients of both system increases with the attack angle increasing. The drag coefficients of the twin rudders over all the attack angles are larger than those of the single rudder. It is noticed that rudder 1 causes the similar drag to the single rudder, while that the drag of rudder 2 decrease much due to the hydrodynamic interaction between the two rudders.

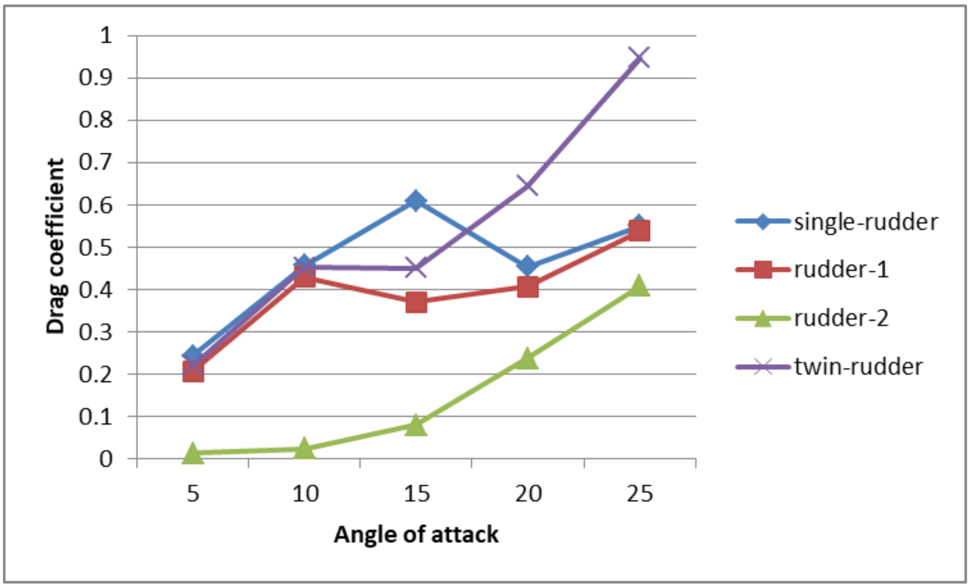


Figure 3 Drag coefficients versus angle of attack.

Figure 4 shows the lift coefficients of the single-rudder and the twin rudders versus angle of attack. For both systems, the lift coefficients reach the highest value at 15^{o}. And the twin-rudde give rise to much larger lift coefficients than the sinlge rudder. For the lift of the two rudders, it is noticed that rudder 2 causes the larger value than rudder 1 as the attack angle increases, and that the total lift is not just twice the lift of the single rudder, which is because that the hydrodynamic interaction of the two rudders becomes strong when the attack angle increase.

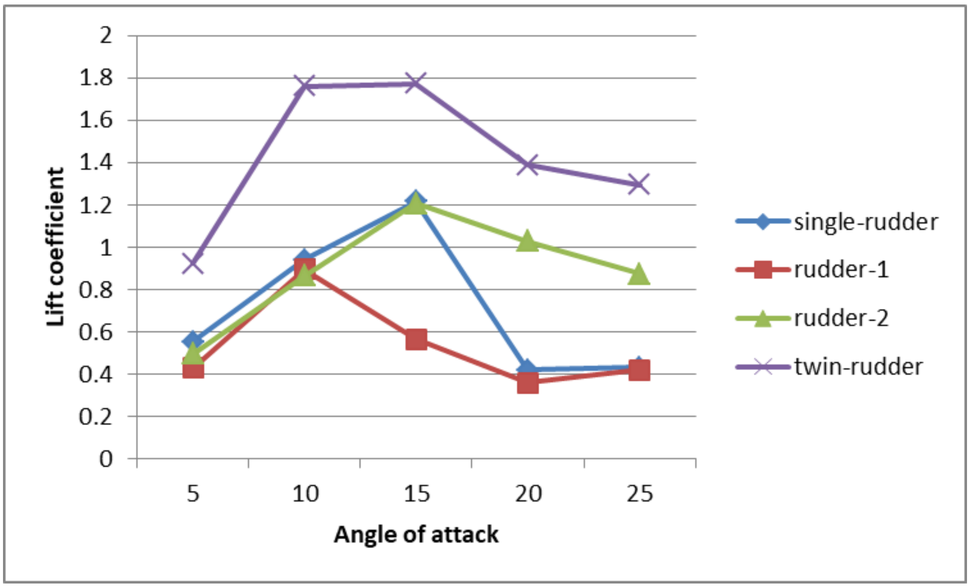


Figure 4 Lift coefficients versus angle of attack.

Figure 5 shows the ratio of the lift to the drag of the single-rudder and the twin rudders versus angle of attack . It can be seen that, for NACA0012, the value of the lift to drag ratio decreases with the angle of attack increasing for both systems. And it is found that the lift to drag ratio of the twin rudders is much better than the single rudder, which implies that the twin rudders can be used to improve the hydrodynamic performance when the single rudder is limited.

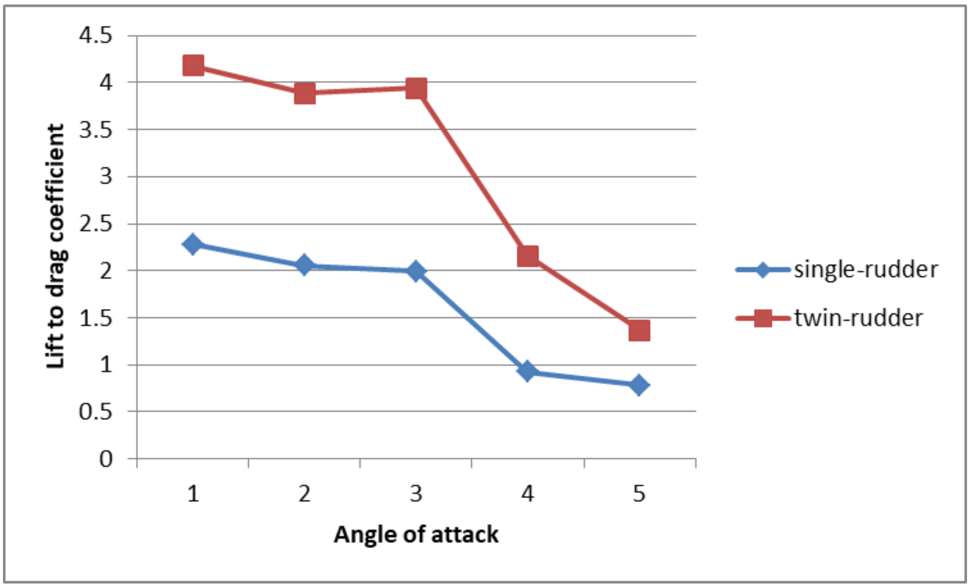


Figure 5 Lift to drag ratios versus angle of attack.

When performing the simulation of the flow around the rudders, it is found that the drag and lift coefficients of the two rudders start vibrating periodically (Figure 6) as the angle of attack is larger than 15^o. While, at all angles of attack, the drag and lift coefficients of the single rudder normally converge to a stable value. This is possiblly because that the flow interaction between the two rudders leads to more unstable vortices downstream so that the pressrue downstream of the rudders becomes periodically unstable.

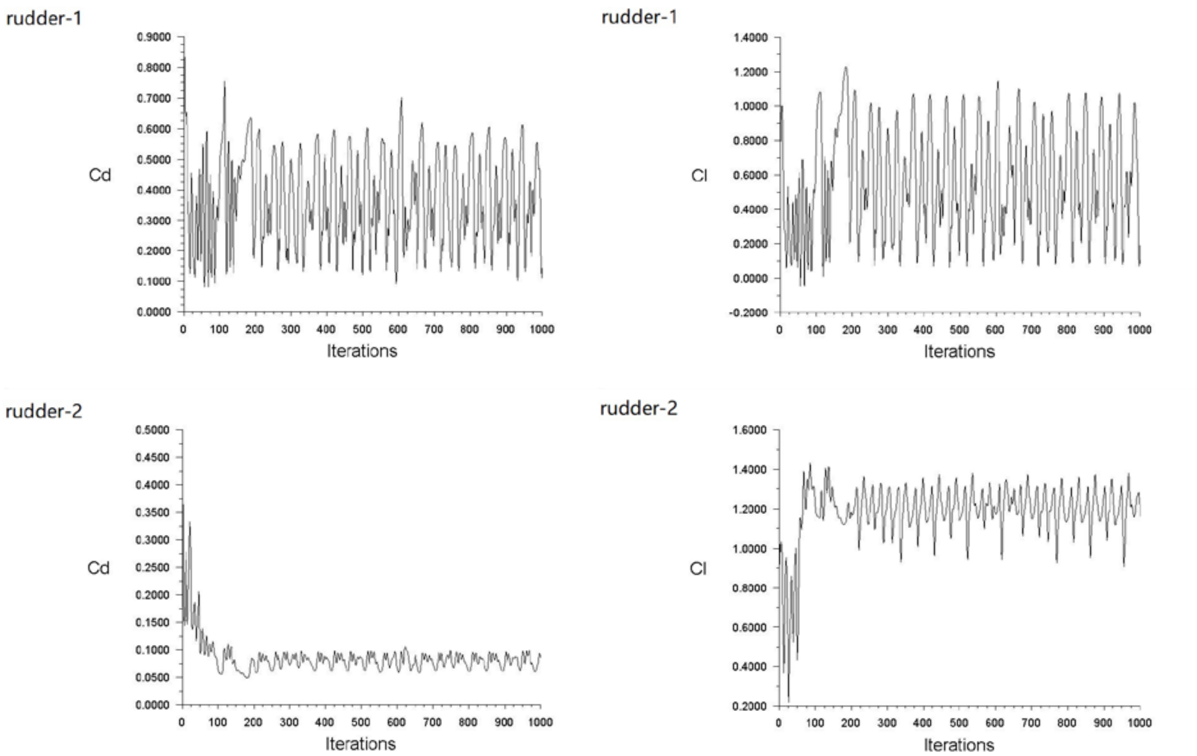
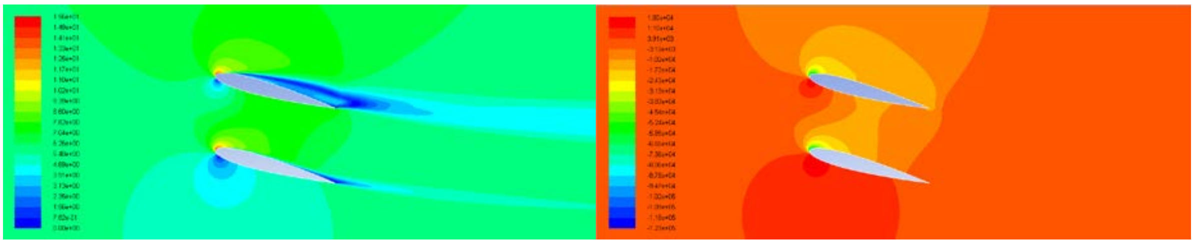


Figure 5 Evolution of the drag and lift coefficients of the two rudders.

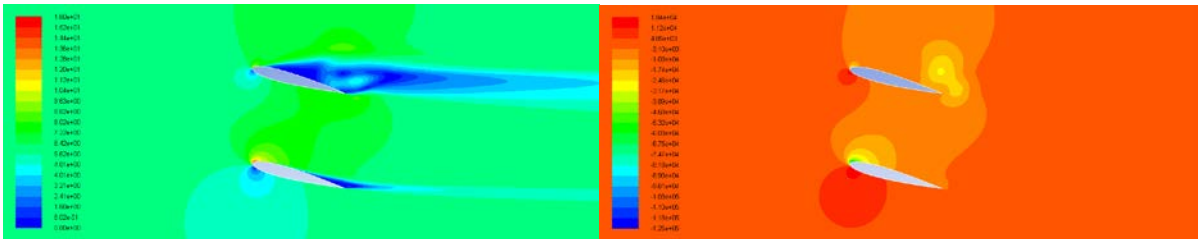
Impact of the lateral spacing on the hydrodynamics

The distance between the two rudder blades (*d*, lateral distance) is one of the most imoportant factors which directly affects the flow interaction between the twin rudders. As rudders are mostly performed at small angles of attack within 15 degrees of course keeping and initial turning, here the twin rudders with the different lateral spacing at 15^o angle of attack are considered. Figure 6 shows the velocity and static pressure contours around the twin rudders of the cases with the different lateral spacing. It can be seen from the velocity contours that the small distance causes an velocity increase between the two rudders as *d=0.6c*, such that the velocity at the leading edge of rudder 2 decreases and the vortex downstream of rudder 2 declines. As the lateral spacing increases, the interaction between the two rudders becomes relatively weak. Therefore the flow around the two rudders approaches to be similar. Similarly, the same phenomena occrues to the static pressure aroun the two rudders.

d=06.c



d=1.0c



d=1.4c

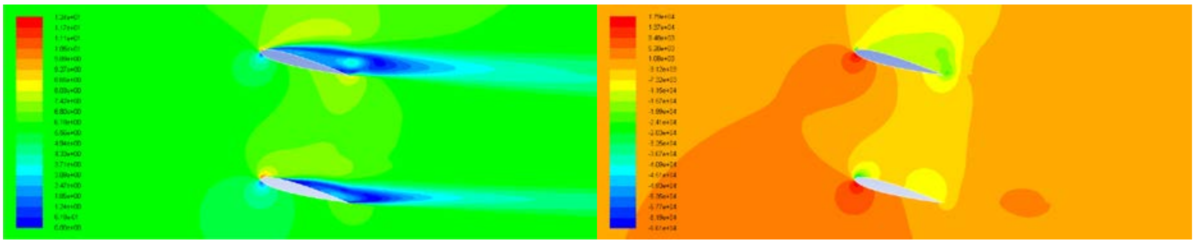


Figure 6. Velocity and static pressure contours of the cases with the different lateral spacing.

Figure 7 shows the evolution of the drag coefficient of the twin rudders at 15^o versus the lateral spacing. It is noticed that the drag of rudder 1 dominates between the two rudders, and its value increases as the lateral spacing increases. The drag of rudder 2 is relatively smaller than that of rudder 1 and reaches the smallest value at *d=1.2c*. The total drag of the twin rudders increase with the lateral spacing increasing.

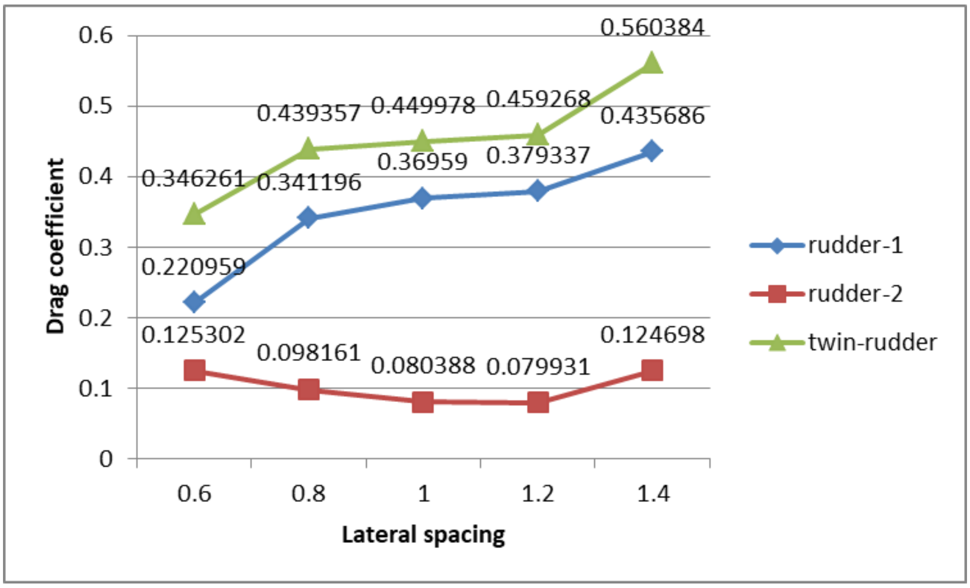


Figure 7. Drag coefficients of the twin rudders versus the lateral spacing.

Figure 8 shows the variation of the lift coefficients of the twin rudders at 15^o versus the lateral spacing. Instead, for the lift, rudder 2 give rise to the larger values than rudder 1. As the lateral spacing increases, the lift of rudder 1 increases and the lift of rudder 2 decreases. The total lift coefficients of the twin rudders reaches the highest value at *d=1.0c*. Additionally, it is noticed that the value of the lift coefficients of the two rudders approaches to each other as the lateral spacing is 1.4, and the total lift is approximate to twice the lift of the single rudder, which indicates that the effect of the interaction between the two rudders on the lift coefficients becomes weak when the lateral spacing is large.

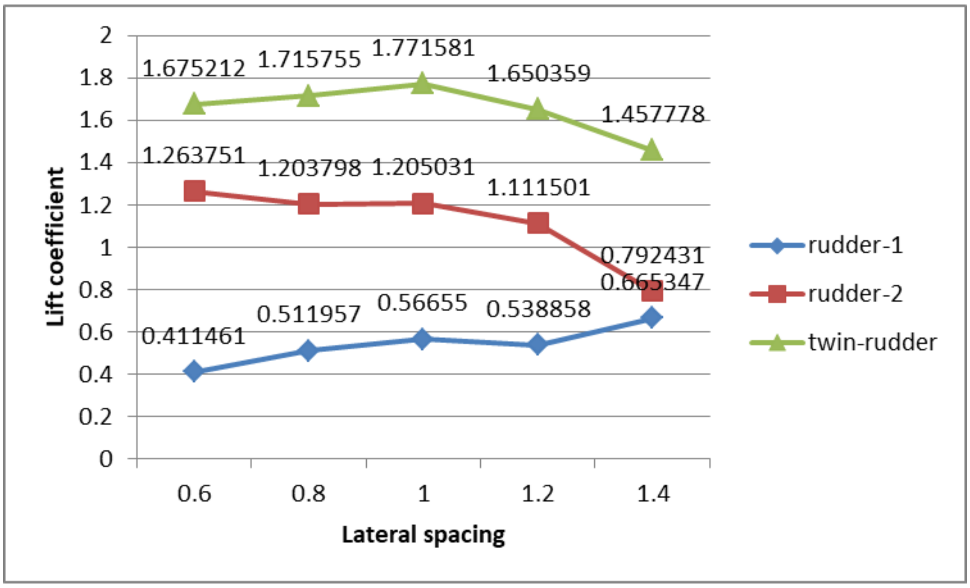


Figure 8. Lift coefficients of the twin rudders versus the lateral spacing.

The profile of the lift to drag ratio versus the lateral spacing is shown in Figure 9. It is clear that the lift to drag ratio of the twin rudders at 15^o monotonously decreases with the lateral spacing increasing. According to the variation of the lift to drag ratio, it is suggested to have a reasonably small lateral spacing for a high lift to drag ratio in practical.

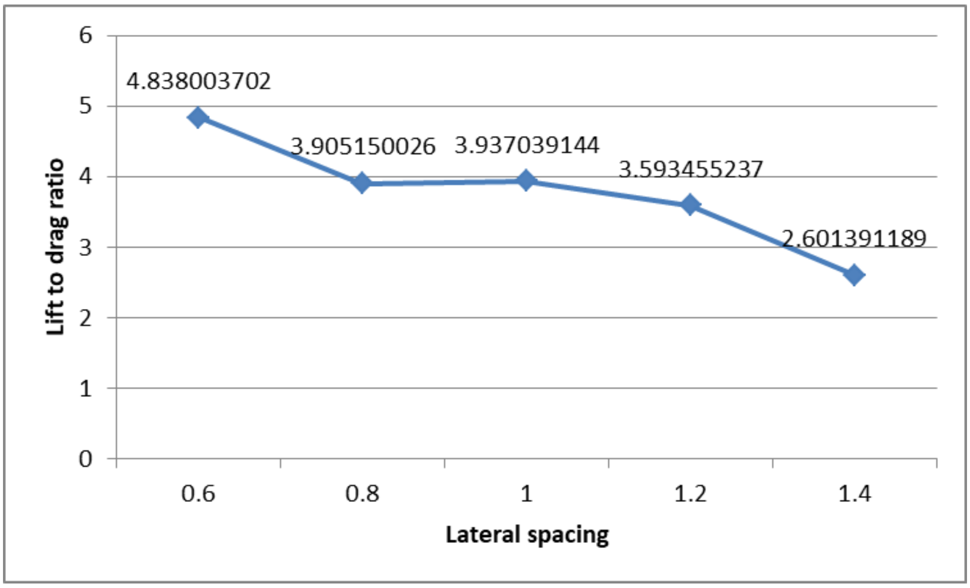


Figure 9. Lift to drag ratios of the twin rudders versus the lateral spacing.

For more details, the static pressure coefficients around the rudders are shown in Figure 10. It is shown that, for *d=0.6c*, the pressures in the front of the rudders are quite close, while the ones in the back of rudder 1 is much smaller than those in the back of rudder 2, which is due to the strong interaction between the two rudders. For *d=1.0c*, the pressure around the two rudders are still much different, which means that the interaction still makes much sense. As the lateral spacing approaches to 1.4c, the difference of the pressure around the two rudders becomes small, which agrees to a statement that the interaction weakens as the lateral spacing increases.

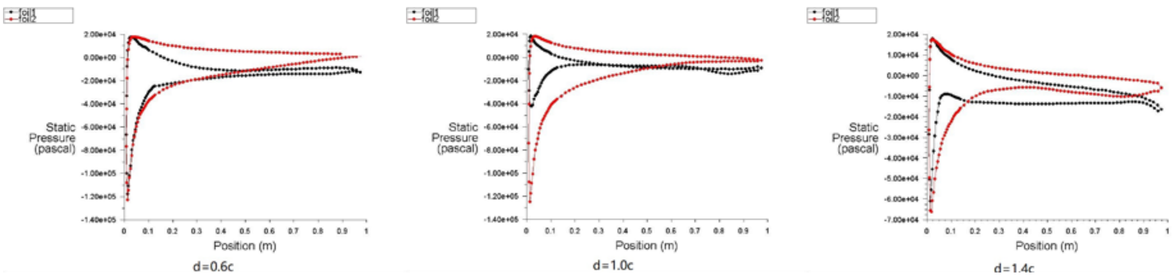


Figure 10. Static pressure coefficients around the rudders with the different lateral spacing.

Impact of the lateral spacing on stopping performance

As the rudders are stimultaneously set at a clam shell angle (75o outward) for a stopping performanc, the gap between the leading edge of the twin rudders, which is determined by the lateral spacing, may affect the drag of the rudders as well as the stopping distance. Here flow around the twin rudders with the different lateral spacing at a clam shell angle are simulated. Figure 11 shows the flow and static pressure contours for *d=0.6c, 1.0c* and *1.4c*. It is noticed that the flow field downstream of the rudders are not symmetrical. For *d=0.6c* and *1.0c*, the flow cross the gap with high velocity travels downwards downstream of the rudders, which causes that the pressure downstream of rudder 1 is larger than that dwonstream of rudder 2. As *d=1.4c*, the flow cross the gap travels upwards downstream of the rudders, namely, the pressure downstream of rudder 1 is smaller than that downstream of rudder 2. The flow cross the gap would instantaneously vibrate. The asymmetry of the flow downstream of the rudders is likely due to the limitation of the numerical method used in the present study.

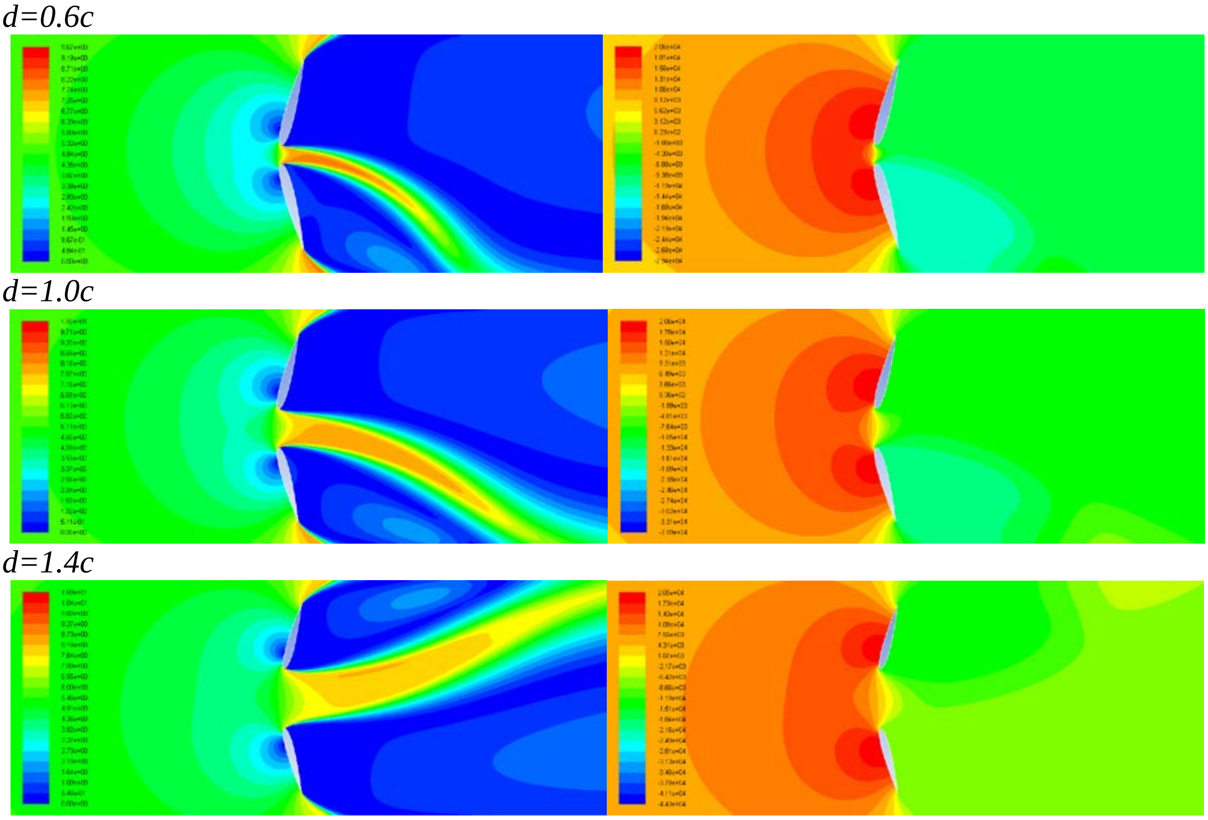


Figure 11. Flow and static pressure contours around the twin rudders with the different lateral spacing at a clam shell angle.

To exmine the stopping performance of the twin rudders with the different lateral spacing, the drag coefficients of the twin rudders at a clam shell angle are tested. Figure 12 shows the variation of the drag coefficients of the twin rudders at outward versus the lateral spacing. It can be seen that the drag coefficients of the two rudders are different due to the flow asymmetry downstream of the rudders. The drag of rudder 1 is smaller than that of rudder 2, which agrees to the statement about pressure distribution addressed above. The drag of rudder 1 slowly increases as d increases, and reaches to the largest value at *d=1.3c*. Instead the drag of rudde 2 deccrease as d increases, and reaches to the lowest point at *d=1.3c*. The drags of the two rudders approaches to each other at d =1.4c. This is because that a larger gap between the leading edge weaken the interaction of the flow downstream. The value of the total drags of the twin rudders are almost twice that of the single rudder, which indicates that the twin rudders makes better sense than the single rudder during the stopping performance. It is shown that the variation of the total drag with the lateral spacing is small. It reaches the largest value at *d=1.3c*, and decreases as d is larger than 1.3.

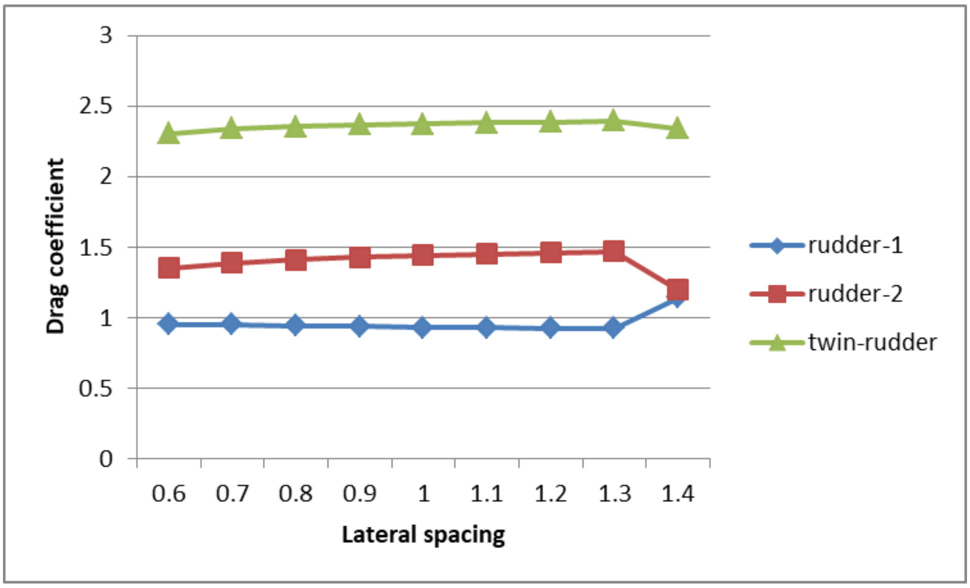


Figure 12. Drag coefficients of the twin rudders at a clam shell angle versus the lateral spacing.

Conclusions

Computational fluid dynamic simulations of the twin rudders are performed by solving Reynolds-averaged Navier-Stokes equations with a SST $k-\omega$ two-equation model using OpenFOAM codes. The difference of hydrodynamic forces between the single-rudder and the parallel twin rudders of NACA0012 blades are examined from 5^{o} to 25^{o} angle of attack. The impact of the distance between the two rudders on the hydrodynamic forces at 15^{o} angle of attack is studied for the parallel twin rudders. Finally the effectiveness of the stopping performance of the twin rudders at the different lateral spacing is analyzed. According to the results and discussions, conclusions of the present study can be summarized as follows

(1) The hydrodynamic forces of the twin rudders at all tested angles of attack are larger than those of the single rudder. The interaction between the twin rudders becomes strong as the angle of attack increases.

(2) The interaction between the twin rudders becomes weak with the lateral spacing increasing. The drag of the twin rudders increases with the lateral spacing increasing. The lift reaches the largest value at *d=1.0c*. And the lift to drag ratio monotonously decreases with the lateral spacing.

(3) The total drag of the twin rudders is almost close to twice that of the single rudder. The drag slowly increases with the lateral spacing, and decreases as the lateral spacing is larger than 1.3c.

This study present some limited results due to the limitation of the numerical method used. To obtain more accurate flow data around the twin rudders, it is requested to use a transient solver or a large eddy simulation, which would be the further research of the authors.

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