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Impacts of the rudder profile on manoeuvring performance of ships

Jialun Liu [a,*], Frans Quadvlieg [b], Robert Hekkenberg [a]

[a] Delft University of Technology, Mekelweg 2, Delft, 2628 CD The Netherlands
[b] Maritime Research Institute Netherlands (MARIN), Haagsteeg 2, Wageningen, 6700 AA The Netherlands

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ABSTRACT

The profile of a ship rudder influences the forces it generates, which in turn influence the manoeuvring performance of a ship. Thus, rudder forces and moments should be calculated considering the profile. Instead of an empirical estimation of the rudder normal force coefficient, this paper applies a RANS method to determine the hydrodynamic characteristics of various profiles, i.e. lift and drag coefficients. The RANS method is validated with a classic NACA 0012 profile and applied to 9 profiles from the NACA series, the wedge-tail series, and the IFS series. Furthermore, the 2D open-water RANS results are corrected for the effects of the propeller slipstream and the rudder aspect ratio. New regression formulas of the normal force coefficients are proposed for the tested profiles. These formulas are then integrated into a standard MMG model. Taking the KVLCC2 tanker as a reference ship, the manoeuvring model is validated with free-running tests executed by MARIN. Finally, the manoeuvring performance of the reference ship with various rudder profiles are quantified with turning and zigzag manoeuvres. The simulation results confirm that the wedge-tail series is most effective (largest manoeuvring forces) while the NACA series is most efficient (highest lift to drag ratio) among the tested profiles. The IFS series achieves a balance of effectiveness and efficiency.

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1. Introduction

Rudders are the most common steering devices of ships. They determine the response of a ship to navigation orders and affect the manoeuvrability. To satisfy the mandatory manoeuvrability criteria of the International Maritime Organization (IMO) (International Maritime Organization, 2002a,b), a ship must achieve sufficient turning forces and moments from its rudders. Furthermore, the rudder induced resistance also impacts the overall fuel consumption. Thus, rudders do not only affect navigation safety but transport efficiency as well. In the initial design stage of a rudder, a decision has to be made regarding the profile, which has significant impacts on its hydrodynamic performance for manoeuvring (Kim et al., 2012). Additionally, Liu and Hekkenberg (2016) reviewed the design choices of rudders and their impacts on rudder performance in ship manoeuvrability, fuel consumption, and rudder cavitation.

Yasukawa and Yoshimura (2014) introduced the standard MMG model for ship manoeuvring simulations. The MMG model calculates rudder forces (X_R and Y_R) and moments (N_R) based on the rudder's normal force (F_N) as the following:

$$F_N = 0.5\rho A_R V_R^2 C_N, \tag{1}$$

where ρ is the water density, A_R is the rudder lateral area, V_R is the rudder inflow velocity, and C_N is the rudder normal force coefficient, which depends on the rudder profile. Routinely, C_N is obtained by empirical formulas (Fujii, 1960; Fujii and Tsuda, 1961, 1962) as the following:

$$C_N = 6.13 \sin\alpha_R \frac{\Lambda_G}{\Lambda_G + 2.25}, \tag{2}$$

where Λ_G is the rudder geometric aspect ratio, which is the ratio of the rudder span (B_R) to the rudder chord length (C_R), α_R is the effective rudder angle. Normally, the rudder effectiveness is judged by the rudder side force (Y_R), which primarily depends on A_R, V_R, and C_N as shown by Eqs. (1) and (2).

The rudder area (A_R) is determined by the rudder span and the chord, which are constrained by design draught and capacity of the steering gear. Achieving the required rudder area may not be a problem for seagoing ships, but it is critical for inland vessels (Liu et al., 2015). When the rudder size is limited, a twin-rudder or multiple-rudder configuration is the solution. This solution, for example, is frequently applied to inland vessels with multiple rudders and very large seagoing ships with twin rudders.

The rudder inflow velocity (V_R) relates to the ship speed, the propeller working load, the propeller rate of revolution, and the

* Corresponding author.
E-mail address: J.Liu@tudelft.nl (J. Liu).

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Nomenclature

Abbreviations

CFD	computational fluid dynamics
RANS	Reynolds-Averaged Navier–Stokes
IFS	Institute für Schiffbau
NACA	National Advisory Committee for Aeronautics
Re	Reynolds number
SST	shear stress transport

Greek symbols

α_R	effective rudder angle (rad)
β	ship drift angle (rad)
β_P	drift angle at propeller position (rad)
δ	rudder angle (rad)
$\dot{\delta}$	rudder rate ($^\circ s^{-1}$)
η	ratio of propeller diameter to rudder span (–)
γ_R	flow straightening coefficient of the rudder (–)
ℓ	flow-straitening factor due to the yaw rate (–)
κ	experimental constant for expressing u_R (–)
Λ_G	rudder geometric aspect ratio, $\Lambda_G = B_R/C_R$ (–)
∇	ship displacement volume (m^3)
ψ	ship heading angle (rad)
ρ	water density ($kg\ m^{-3}$)

Roman symbols

A_D	advance of turning circle test (m)
A'_D	non-dimensional advance of turning circle test, $A'_D = A_D/L_{pp}$ (–)
a_H	rudder force increase factor (–)
A_R	rudder lateral area without the horn part (m^2)
T_D	tactical diameter of turning circle test (m)
T'_D	non-dimensional tactical diameter of turning circle test, $T'_D = T_D/L_{pp}$ (–)
B_R	rudder span (m)
B_{wl}	maximum moulded breadth at design water line (m)
C_b	block coefficient (–)
C_N	normal force coefficient of the rudder with specific aspect ratio in propeller slipstream (–)
C_R	rudder chord length (m)
$C_{N\infty}$	normal force coefficient of the rudder with infinite aspect ratio in open water (–)
D_P	propeller diameter (m)
F_N	rudder normal force (N)
I_z	yaw moment of inertia of the ship around centre of gravity ($kg\ m^2$)
J_P	propeller advance ratio (–)
J_z	added moment of inertia of the ship around centre of gravity ($kg\ m^2$)
K_T	propeller thrust coefficient (–)
L_{pp}	length between perpendiculars (m)
m	ship mass (kg)
m_x	added mass due to ship motion in *x*-direction (kg)
m_y	added mass due to ship motion in *y*-direction (kg)
N_H	hydrodynamic moment due to hull acting on the ship around *z*-axis (N m)
n_P	propeller revolution (s^{-1})
N_R	hydrodynamic moment due to rudder acting on the ship around *z*-axis (N m)
$\dot{r}$	yaw acceleration around midship *z*-axis (rad s)
r	yaw rate around midship *z*-axis (rad s)
T	ship draught (m)
t	rudder profile section thickness (m)
T_P	propeller thrust (N)
t_P	propeller thrust deduction factor in manoeuvring motions (–)
t_R	steering resistance deduction factor (–)
$\dot{u}$	ship acceleration in the direction of *x*-axis ($m\ s^{-2}$)
u	surge speed in the direction of *x*-axis, $u = V\cos\beta$ ($m\ s^{-1}$)
u_0	service speed of the ship (the initial speed for manoeuvring simulations) ($m\ s^{-1}$)
u_G	longitudinal speed in the direction of *x*-axis at centre of gravity, $u_G = u$ ($m\ s^{-1}$)
u_R	longitudinal velocity of the inflow to rudder ($m\ s^{-1}$)
$\dot{v}$	ship acceleration in the direction of *y*-axis ($m\ s^{-2}$)
V	ship velocity on midship, $V = \sqrt{u^2 + v^2}$ ($m\ s^{-1}$)
v	sway speed in the direction of *y*-axis on midship, $v = -V\sin\beta$ ($m\ s^{-1}$)
V_A	propeller advance speed ($m\ s^{-1}$)
v_G	sway speed in the direction of *y*-axis at centre of gravity, $v_G = v + x_G r$ ($m\ s^{-1}$)
V_R	rudder inflow velocity ($m\ s^{-1}$)
v_R	lateral velocity of the inflow to rudder ($m\ s^{-1}$)
w_P	wake factor at propeller position in manoeuvring (–)
w_R	wake factor at rudder position in manoeuvring (–)
w_{P0}	wake factor at propeller position in straight moving (–)
x_G	longitudinal position of centre of gravity in $o - xyz$ (m)
X_H	hydrodynamic force due to hull acting on midship in *x*-direction (N)
x_H	longitudinal position of acting point of additional lateral force (m)
X_P	hydrodynamic force due to propeller acting on midship in *y*-direction (N)
x_P	longitudinal position of propeller in $o - xyz$ (m)
X_R	hydrodynamic force due to rudder acting on midship in *x*-direction (N)
x_R	longitudinal position of rudder in $o - xyz$ (m)
y_+	non-dimensional first cell height (–)
Y_H	hydrodynamic force due to hull acting on midship in *x*-direction (N)
Y_R	hydrodynamic force due to rudder acting on midship in *y*-direction (N)

location of the rudder relative to the propeller. However, these parameters are rarely optimised on purpose for the rudder effectiveness. Therefore, the rudder normal force coefficient (C_N) mainly depends on the rudder profile. As the empirical method (Eq. (2)) only considers the aspect ratio, it does not enable an analysis of the profile impact on rudder forces and moments regarding the ship manoeuvring performance.

To obtain the normal force coefficients of various profiles, the rudder hydrodynamic characteristics should be analysed, i.e. the lift and drag coefficients. These coefficients are traditionally obtained in wind tunnels (Thieme, 1965), towing tanks (Vantorre, 2001), or by Computational Fluid Dynamics (CFD) (Söding, 1998; El Moctar, 2001). Even though CFD methods may encounter challenges in convergence and accuracy, they are convenient to study various cases as a primary study. Thus, this paper applies a Reynolds-Averaged Navier–Stokes (RANS) method to achieve the

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