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An integrated empirical manoeuvring model for inland vessels

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ABSTRACT

Ship manoeuvrability is important for navigation safety. However, few studies have been specifically carried out for inland vessels. Since most of the empirical methods were generated based on databases of seagoing ships, the usability of these methods for inland vessels is doubtful. The objective of the present work is to assess the existing manoeuvrability models and find the most suitable ones for inland vessels. Furthermore, these models are integrated into a single new model that can predict the manoeuvring behaviour of benchmark inland vessels without extensive experimental tests. The method aims at inland ships of typical dimensions in the Yangtze River (inland ships on European waterways have different dimensions), which is characterised by a large water depth. After preselecting the most promising methods through reviewing literature, a selection of the empirical methods for hull forces and moments is performed by comparing simulation results to model-scale free-running experiments of various turning and zigzag manoeuvres. Considering the large variety of rudder configurations for inland vessels, this paper describes a procedure of using 2D open-water RANS results to calculate the rudder forces and moments. Accordingly, hydrodynamic coefficients of benchmark rudder profiles are provided to apply the proposed procedure for different rudder configurations.

1. Introduction

An inland vessel, in this paper, is a self-propelled motor ship that sails in inland waterways, such as rivers, canals, and lakes. The design and navigation environment of inland vessels are different from those of seagoing ships. The impacts of these differences should be carefully considered when prediction methods that are based on or intended for seagoing ships are used for inland vessels (Liu et al., 2015). Unlike seagoing ships that commonly equip a single propeller and a single rudder (SPSR), inland vessels commonly feature multiple propellers and multiple rudders (MPMR). Typical MPMR configurations of inland vessels are single-propeller twin-rudder (SPTR), twin-propeller twin-rudder (TPTR), and twin-propeller quadruple-rudder (TPQR). This paper focuses on manoeuvring modelling of the TPTR system for inland vessels as it is widely used on both the Rhine and the Yangtze River.

Normally, TPTR ships have better course keeping and course changing abilities but worse turning abilities than SPSR ships (Kim et al., 2007). Yoshimura and Sakurai (1989) showed that a wide-beam TPTR ship may have an improved turning ability in shallow water instead of a customarily worsened one for conventional SPSR ships. In general, the TPTR system is preferred in shallow water due to the possibility to have restricted draught. To analyse the manoeuvrability of TPTR inland vessels, the mathematical model needs to consider the particulars of the inland vessels and the twin-rudder configurations. The objective of the present work is to formulate an integrated model, which is based on available knowledge and easy to use at the initial design stage without requiring extensive model tests.

Besides studies on the mathematical modelling of MPMR ships (Yoshimura and Sakurai, 1989; Lee and Fujino, 2003; Hasegawa et al., 2006; Khanfir et al., 2008; Di Mascio et al., 2011), several attempts have been made to model the interaction between the hull and the rudder (Khanfir et al., 2011), the interaction between the propeller and the rudder (Nakatake et al., 1989), and the flow straightening effect of the hull and the propeller on the rudder (Molland and Turnock, 2002). Additionally, a number of studies have been published on the asymmetric manoeuvring behaviour of MPMR ships (Kang et al., 2011; Coraddu et al., 2013; Dubbioso et al., 2015). However, the above-mentioned studies were carried out for seagoing ships, very few manoeuvrability studies have been performed for inland vessels. This paper presents studies based on two standard TPTR inland vessels in the Yangtze River. One is a 6700 t TPTR bulk carrier, and the other one is a 3500 t TPTR tanker.

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Nomenclature

Abbreviations

COG	Centre of gravity
MPMR	Multiple-propeller multiple-rudder
SPSR	Single-propeller single-rudder
RANS	Reynolds-Averaged Navier-Stokes
TPTR	Twin-propeller twin-rudder

Greek symbols

α	Angle of attack (rad)
β	Ship drift angle (rad)
β_P	Drift angle at propeller position (rad)
Δ	Relative deviation of the parameter (%)
δ	Rudder angle (rad)
δ_h	Hydrodynamic inflow angle of the rudder (rad)
$\dot{\delta}$	Rudder turning rate ($°s^{-1}$)
η_R	Ratio of propeller diameter to rudder span, $\eta_R = D_P/B_R$ (–)
ϵ_R	Ratio of the wake fraction of the propeller to the wake fraction of the rudder (–)
k_P	Impact factor of the propeller slipstream on the rudder hydrodynamics (–)
k_R	Impact factor of the end plates on the rudder hydrodynamics (–)
γ_R	Flow straightening coefficient of the rudder (–)
κ_R	Experimental constant for expressing u_R (–)
λ	Model scale (–)
Λ_G	Rudder geometric aspect ratio (–)
Λ_E	Rudder effective aspect ratio (–)
∇	Ship displacement volume (m^3)
ψ	Ship heading angle (rad)
ψ_{O1}	First overshoot angle (deg)
ψ_{O2}	Second overshoot angle (deg)
ρ	Water density (kgm^{-3})
σ_T	Average absolute deviation of the turning criteria (%)
σ_Z	Average absolute deviation of the zigzag criteria (%)

Roman symbols

A_D	Advance in the turning manoeuvre (m)
A'_D	Non-dimensional advance in the turning manoeuvre, $A'_D = A_D/L$ (–)
a_H	Rudder force increase factor (–)
A_R	Rudder lateral area without the horn part (m^2)
A_{RP}	Rudder lateral area in the propeller slipstream (m^2)
T_D	Tactical diameter of turning circle test (m)
T'_D	Non-dimensional tactical diameter of turning circle test, $T'_D = T_D/L$ (–)
B	Ship width at the water level (m)
B_R	Rudder span (m)
C_b	Block coefficient (–)
C_D	Drag coefficient (–)
C_L	Lift coefficient (–)
C_R	Rudder chord length (m)
C_{D_0}	Drag coefficient at zero angle of attack (–)
C_{L_0}	Lift coefficient at zero angle of attack (–)
D_P	Propeller diameter (m)
F_D	Rudder drag force (N)
F_L	Rudder lift force (N)
F_N	Rudder normal force (N)
F_R	Rudder resultant force (N)
F_T	Rudder tangential force (N)
F_X	Longitudinal component of rudder induced forces (N)
F_Y	Lateral component of rudder induced forces (N)
I_z	Moment of inertial (km^2)
J_z	Added moment of inertial (km^2)
k_A	Impact factor of the rudder aspect ratio on the rudder hydrodynamics (–)
K_T	Propeller thrust coefficient (–)
L	Ship length between perpendiculars (m)
L_{oa}	Ship length over all (m)
m	Ship mass (kg)
m_x	Added mass due to motion in x-direction (kg)
m_y	Added mass due to motion in y-direction (kg)
N	Total hydrodynamic moment acting on midship around the z-axis (Nm)
n	Propeller revolution rate (s^{-1})
N_H	Hydrodynamic moment due to hull acting on the ship around z-axis (Nm)
N_P	Hydrodynamic moment due to propeller acting on the ship around z-axis (Nm)
N_R	Hydrodynamic moment due to rudder acting on the ship around z-axis (Nm)
n_T	Number of performed turning manoeuvres (–)
n_Z	Number of performed zigzag manoeuvres (–)
$\dot{r}$	Yaw acceleration around midship ($rads^{-2}$)
r	Yaw rate around midship ($rads^{-1}$)
r_C	Yaw rate in steady turn ($rads^{-1}$)
S	Wetted surface (m)
T	Ship draught (m)
T_P	Propeller thrust (N)
t_P	Propeller thrust deduction (–)
t_R	Steering resistance deduction factor (–)
t_{O1}	Time to the first overshoot angle (s)
t_{O2}	Time to the second overshoot angle (s)
$\dot{u}$	Ship acceleration in x-direction (ms^{-2})
u	Forward speed in x-direction, $u = V\cos\beta$ (ms^{-1})
u_R	Longitudinal velocity of the inflow to rudder (ms^{-1})
$\dot{v}$	Ship acceleration in y-direction (ms^{-2})
V	Ship velocity on midship, $V = \sqrt{u^2 + v^2}$ (ms^{-1})
v	Sway speed in y-direction on midship, $v = -V\sin\beta$ (ms^{-1})
V_A	Propeller advance speed (ms^{-1})
V_C	Speed in steady turn (ms^{-1})
V_R	Rudder inflow velocity (ms^{-1})
v_R	Lateral velocity of the inflow to rudder (ms^{-1})
V_S	Service speed (ms^{-1})
w_P	Wake factor at propeller position in manoeuvring (–)
w_R	Wake factor at rudder position in manoeuvring (–)
w_{P_0}	Wake factor at propeller position in straight moving (–)
X	Total hydrodynamic force acting on midship in the x-direction (N)
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)
$X_H(\beta, r')$	Longitudinal hull force due to manoeuvring motions expressed by β and r' on midship in x-direction (N)
$X_H(u)$	Longitudinal hull force due to straight moving on midship in x-direction (N)
$X_H(v', r')$	Longitudinal hull force due to manoeuvring motions expressed by v' and r' on midship in x-direction (N)
X_P	Hydrodynamic force due to propeller acting on midship in