Ocean Engineering 137 (2017) 367–381

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng

A study on prediction of ship maneuvering in regular waves

Wei Zhang[a,b], Zao-Jian Zou[b,c,*], De-Heng Deng[b]

[a] School of Petroleum Engineering, China University of Petroleum (East China), Qingdao 266580, China
[b] School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China
[c] State Key Laboratory of Ocean Engineering, Shanghai Jiao Tong University, Shanghai 200240, China

ARTICLE INFO

Keywords:
Ship maneuvering in waves
Wave drift force
Two-time scale model
Rankine panel method
Time domain analysis

ABSTRACT

A simulation method is developed for predicting ship maneuvering in regular waves. Based on a two-time scale model, the total ship motion is divided into the low frequency maneuvering motion and the high frequency wave-induced motion. The maneuvering analysis is based on a MMG model which takes the mean second-order wave loads into account. In order to evaluate the second-order wave loads, a velocity potential is introduced and decomposed into a basic part and a perturbation part, which are related to the maneuvering motion and the wave-induced motion, respectively. The basic part is evaluated based on the double-body model with a trailing vortex sheet, while the perturbation part is solved via a time domain Rankine panel method. The effects of maneuvering motion on the wave forces are considered through the m-terms as well as the leading-order terms kept in the boundary conditions on the free surface. By using the proposed method, turning and zig-zag maneuvers of the S-175 container ship in regular waves are simulated. The predicted turning trajectories and 10°/10° and 20°/20° zig-zag maneuvers are compared with the experimental data, which show fairly good agreements. The drift forces and moment on the ship turning in waves are also discussed.

1. Introduction

Prediction of ship maneuverability is typically carried out under calm water condition. This provides valuable information at the ship design stage. However, an actual seagoing ship usually maneuvers in the presence of waves. From the viewpoint of ship navigation safety, it is meaningful to understand the maneuvering behavior of a ship in waves. According to the report of ITTC Maneuvering Committee (2011) and the literature review given by Tello Ruiz et al. (2012), the existing methods for investigating ship maneuvering in waves can be generally classified as experimental methods, simulation methods based on two-time scale models, simulation methods based on hybrid approach, and simulation methods using CFD.

Experiment methods are supposed to be the most reliable method to investigate ship maneuvering in waves. Several experimental investigations have been published. For example, Ueno et al. (2003) carried out turning, zig-zag and stopping tests in regular waves using a VLCC model, and discussed the effects of wave length and encounter angle to waves as well as the effect of loading condition on maneuvering motion based on the experimental data. Lee et al. (2009) investigated the effects of the wave amplitude and wave length on the maneuverability of a ship, with tests on a KVLCC model. The results showed that second-order wave force has a dominant influence on the trajectory for turning and zig-zag maneuvers. Yasukawa (2006, 2008) conducted turning tests as well as zig-zag and stopping maneuvers with the SR108 ship model, and compared the model test results with their numerical results.

CFD methods in principle provide an adequate description of all physics. However, this approach is still considered as a subject of the state-of-the-art research rather than application in engineering practice. On one hand, these methods require large computational resources and long CPU time. On the other hand, according to Skejic (2013), a lot of technical difficulties concerning the analysis of ship maneuvering in waves are still unsolved, such as the adequacy of the selected turbulence models, the adequacy of the propeller and rudder models under large angle of attack, the appearance of the crossflow shed vortices and so forth.

Compared with CFD methods, the hybrid methods and the two-time scale methods are much more widely applied in numerical simulation of ship maneuvering in waves. Both of these two methods are based on the potential flow theory but they are different in specific treatments:

The hybrid approach integrates maneuvering motion and wave-induced motion into a generic set of rigid body motion equations to describe the ship maneuvering in waves. Several works falling into this category can be found in the literature, for instance, Bailey et al.

---

[*] Corresponding author at: School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, Shanghai 200240, China.
E-mail address: zjzou@sjtu.edu.cn (Z.-J. Zou).

http://dx.doi.org/10.1016/j.oceaneng.2017.03.046
Received 28 November 2015; Received in revised form 1 January 2017; Accepted 24 March 2017

Nomenclature

A	Amplitude of the incident wave
a_H	Rudder force increase factor
C_f	Frictional resistance coefficient
C_r	Residuary resistance coefficient
C_{Rr}, C_{Rrrr}, C_{Rrrv}	Experimental constants for expressing the inflow velocity to rudder
$[C_{ij}]$	Matrix of hydrostatic restoring coefficients
D_p	Propeller diameter
F_i	High frequency hydrodynamic components
$\vec{F}^{(2)}$	Generalized second-order wave force vector
F_N	Normal rudder force
G	Rankine source
I_{zz}	Moment of inertia about z axis
J_P	Propeller advance ratio
J_{zz}	Added moment of inertia about z axis
k_f	Form factor
k	Wave number of the incident wave
K_T	Thrust coefficient
L	Ship length
m	Ship mass
m_x, m_y	Added masses in x-axis direction and y-axis direction, respectively
m_i	m-terms
$[M_{ij}]$	Inertial matrix for the hull
n	Propeller revolution
$\vec{n}^{(0)}$, $\vec{n}^{(1)}$, $\vec{n}^{(2)}$	Zero-, first- and second-order components of the normal vector on the hull surface, respectively
n_i	Component of the generalized normal vector
N_t	Ratio of τ_L to τ_H
$o-xyz$	Reference frame with the origin at midship
$O-XYZ$	Global frame fixed in space
$p^{(1)}$	First-order hydrodynamic pressure
r	Yaw rate of the low frequency motion
r'	Non-dimensional yaw rate of the low frequency motion
$R(u)$	Ship resistance
S	Wetted hull surface
$\bar{S}_B$	Mean wetted hull surface
t	Time
t_p	Thrust deduction fraction
t_R	Steering thrust deduction factor
u	Forward speed of the low frequency motion
U_R	Relative inflow velocity to rudder
v	Transverse speed of the low frequency motion
v'	Non-dimensional transverse speed
w_{P0}	Wake fraction in straight moving
w_P	Wake fraction
$\vec{W}$	Velocity vector due to the low frequency motion
x_G	x-coordinate of the center of gravity
x'_P	Non-dimensional longitudinal coordinate of propeller
x_R	Longitudinal coordinate of the rudder
x_H	Longitudinal coordinate of acting point of the additional lateral force induced by steering
X_H, Y_H, N_H	Low frequency hydrodynamic surge force, lateral force, yaw moment acting on ship hull except added mass components
X_P	Surge force due to propeller
X_R, Y_R, N_R	Surge force, lateral force, yaw moment by rudder
X_W, Y_W, N_W	Wave drift forces and moment
α_R	Relative inflow angle to rudder
β_P	Geometrical inflow angle to the propeller
χ	Incident angle of wave defined in the global frame
δ	Rudder angle
ε, κ, τ, γ	Coefficients representing the interaction among the hull, propeller and rudder
$\phi(\vec{x}, t)$	Perturbation potential
$\Phi(\vec{x}, t)$	Basic potential
η	Wave elevation
λ	Wave length
$\varphi_I(\vec{x}, t)$	Incident wave potential
$\varphi(\vec{x}, t)$	Perturbation potential except incident wave potential $\varphi_I(\vec{x}, t)$
Λ	Rudder aspect ratio
ρ	Water density
τ_L	Time step for the maneuvering computation
τ_H	Time step for the seakeeping computation
υ	Damping strength of the numerical damping beach
ω	Frequency of the incident wave
ω_e	'Local' encounter frequency during maneuvering process
$\vec{\xi}_T$	Translational displacements due to high frequency motion
$\vec{\xi}_R$	Rotational displacements due to high frequency motion
ψ	Ship heading angle
$\Psi(\vec{x}, t)$	Total velocity potential
$\zeta(x, y, t)$	Wave elevation except incident wave elevation $\zeta_I(x, y, t)$
$\zeta_I(x, y, t)$	Incident wave elevation
ξ_z	Vertical displacement of point (x, y) due to high frequency motion

(1997), Fang et al. (2005), Sutulo and Guedes Soares (2006), and Lin et al. (2006). A defect common to all these works is that none of them incorporated the effects of second-order wave forces. The omission of the steady components of the second-order wave forces will heavily decrease the accuracy of the maneuvering predictions. Recently, Subramanian and Beck (2015) developed a body-exact strip theory based model to simulate maneuvering of a ship in a seaway. In their methodology, the second-order wave effects are considered approximately via the square of the velocity potential's gradient.

Different from the hybrid approach, the two-time scale methods separate the total ship motion into two parts: the one for high frequency wave-induced motion and the other for the low frequency maneuvering motion, based on the fact that the wave-induced motions are generally much faster than the maneuvering motion. The motion separation brings in a favorable merit that the second-order wave forces can be evaluated in a more accurate manner. Within the framework of the two-time scale model, Skejic and Faltinsen (2008) carried out a unified seakeeping and maneuvering analysis of ships in regular waves and compared the wave drift forces obtained by using four different approaches based on strip theory. Yasukawa and Nakayama (2009) conducted the 6-DOF motion simulations of a turning ship in regular waves. The high-frequency wave forces in their study were estimated based on the strip theory, while the wave drift forces were evaluated by Maruo's method. It should be noted that the seakeeping analysis in these two works was carried out based on the quasi-steady assumption, which means the memory effects due to the ship motion were not considered. Seo and Kim (2011) conducted the numerical analysis of the coupled maneuvering and seakeeping problem. In their study, two different time scales were used in solving the maneuvering and seakeeping problems, respectively; while the wave forces were solved directly in time domain by a 3D Rankine panel method.

In this paper, a numerical model for investigating ship maneuvering in waves is developed. The simulation method is based on the procedure suggested by Seo and Kim (2011), i.e. the maneuvering motion is predicted using MMG model, whereas the wave effects are