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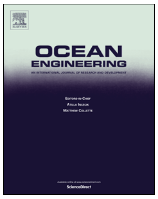

Numerical prediction of parametric roll in oblique waves

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ABSTRACT

Numerical prediction of parametric roll in head and following waves has been intensively investigated so that the requirements for a reasonably good prediction are almost entirely known. However, prediction of parametric roll in oblique waves has not yet been sufficiently investigated owing to the unavoidable coupling with sway and yaw motions. Since parametric roll for actual ships occurs with almost zero forward velocity, accurate prediction of the sideways drift of the ship in waves is difficult. Therefore, in this study, the authors present a numerical model of parametric roll in oblique waves by considering low-speed manoeuvring forces. The numerical predictions are compared with newly performed free-running model experiments of a hypothetical ship, in which the maximum roll amplitude was about 20°. The obtained results show that the present model captures some qualitative tendencies in the experiment but the estimated amplitudes are larger than the experiment by about 7°. This information can be used to identify the minimum requirements for good prediction of parametric roll in oblique waves.

1. Introduction

While the danger of parametric roll has been long discussed among the scientific community (e.g. Watanabe, 1934), the recent extensive studies of this phenomenon have been motivated by an accident involving a C11 class post Panamax container ship, which resulted in the loss of about 400 containers and the damage of about 400 containers (France et al., 2003). As a result, several numerical models for parametric roll were developed with some of them being well validated with model experiments in head and following waves (Spanos and Papanikolaou, 2009; Reed, 2011). These models treat coupled heave-pitch-roll motions by solving simultaneous non-linear differential equations with the hydrodynamic coefficients used in these equations calculated by potential theories and empirical viscous force estimation. Inclusion of time dependence of roll restoring coefficients, including coupling from other modes and diffraction moment depending on heel angle, is vital for the accuracy of these models.

Stability criteria for preventing parametric roll based on the results of the recent research are now under development at the International Maritime Organization (IMO) (Umeda, 2013). These consist of three levels: the first and second levels use simplified estimation of occurrence and magnitude of parametric roll in head and following waves with the averaging method applied to uncoupled roll model with restoring variation and the third level involves the direct use of time-domain numerical simulation of coupled roll model in irregular waves. For the latter case, the numerical models mentioned above could be used. Here, it is important to note that the third level requires calculation not only in head and following waves but also in oblique waves in order to evaluate safety for ship courses. For oblique waves, validation efforts for existing numerical models (Sanchez, Nayfeh, 1990; Neves and Valerio 2000) have not been sufficient so far, partly because a model experiment requires a seakeeping and manoeuvring basin and partly because coupling with manoeuvring motion including rudder actions are unavoidable.

Based on this understanding, in this study, we attempt to validate a numerical simulation model using a low-speed manoeuvring model in oblique waves with a newly executed model experiment in a seakeeping and manoeuvring basin. This numerical model is an extension of that developed by Hashimoto and Umeda (2010) for head and following waves, which was well validated with model experiments of container ships and a car carrier in the towing tank of Osaka University. The ship used in this study is a typical ship with large flare and transom stern, i.e. a hypothetical ship known as the ONR flare topside vessel, for which the hull form is publicly available. The comparison between the

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Nomenclature

a_H	interaction factor for rudder force between hull and rudder
A_{Hij}	sectional added mass coefficient in the ith direction due to the jth motion mode
A_{ij}	added mass coefficient in the ith direction due to the jth motion mode
a_n	Fourier coefficients of cosine wave component
A_n	amplitude of nth order frequency in Fourier series expansion
A_R	rudder area
B	ship breadth
B_{BK}	bilge keel breadth
B_{Hij}	sectional wave damping coefficient in the ith direction due to the jth motion mode
B_{ij}	wave damping coefficient in the ith direction due to the jth motion mode
b_n	Fourier coefficients of sine wave component
C_b	block coefficient
C_D	cross-flow drag coefficient when the ship is laterally towed
C_{ij}	restoring coefficient in the ith direction due to the jth motion mode
d	ship draught
D	ship depth
D_P	propeller diameter
g	gravitational acceleration
G	centre of ship mass
GM	transverse metacentric height
G-xyz	body-fixed coordinate system
k	ship aspect ratio
K_P	rudder gain
K_T	thrust coefficient
K_{yy}	radius of gyration in pitch
F_j	force or moment in the j direction
F_j^B	force or moment due to hydrostatic pressure
F_j^D	diffraction component of force or moment
F_j^{DEL}	force or moment due to rudder action
F_j^{EG}	force or moment due to gravity
F_j^{FK}	force or moment due to incident wave pressure
F_j^{MLS}	force or moment due to manoeuvring motion
F_j^R	radiation component of force or moment
f_α	hydrodynamic rudder lift slope
I_{xx}	moment of inertia of ship mass in roll
I_{yy}	moment of inertia of ship mass in pitch
I_{zz}	moment of inertia of ship mass in yaw
J	propeller advance coefficient
L_{BK}	bilge keel length
LCB	longitudinal position of centre of buoyancy from the midship
L_{pp}	ship length between perpendiculars
m	ship mass
n	propeller revolution number
n_j	vector normal to the hull surface
N_v, N_r	coefficients of terms proportional to v or r included in N_L
O_1-$\xi\eta\zeta$	space-fixed coordinate system
O_2-XYZ	coordinate system moving with a constant speed and on a consistent course
p	wave pressure
r	ship angular velocity around z axis
S_H	sectional submerged hull contour
t	time
T_ϕ	natural roll period
u	ship velocity in x direction
U	speed of the moving coordinate system
u_P	propeller inflow velocity
u_R	rudder inflow velocity
v	ship velocity in y direction
W	buoyancy force due to displacement weight of a ship
w_P	wake fraction coefficient
x_f, x_a	position of fore/aft section from midship
x_H	longitudinal position of rudder force due to interaction between hull and rudder
x_i	ship motion (1: surge, 2: sway, 3: heave, 4: roll, 5: pitch, 6: yaw)
x_R	longitudinal rudder position
Y_C, N_C	non-linear cross-flow drag components of manoeuvring force and moment
Y_L, N_L	linear lift components of manoeuvring force and moment
Y_v, Y_r	coefficients of terms proportional to v or r included in Y_L
Y_v', N_v', Y_r',Y_r'	non-dimensionalized values of Y_v, N_v, Y_r and Y_r
α, β, γ	roll damping coefficients
δ	rudder angle
ε	wake ratio between propeller and rudder
ζ_a	wave amplitude
ζ_w	wave profile
ρ	water density
ϕ_D	diffraction velocity potential of two-dimensional flow under hull and linear free surface conditions in incident waves
ϕ_j	velocity potential of two-dimensional flow under hull and linear free surface conditions
χ	azimuth angle of the moving coordinate
ω_e	wave encounter frequency
ω_k	wave circular frequency
ω_ϕ	natural roll frequency

model and experiment for regular oblique waves is performed, while that between the model and experiment in irregular oblique waves will be the subject of future work. In this paper, details of the numerical model are described for facilitating development of the guidelines for the direct assessment of safety at the IMO.

2. Numerical model for parametric roll in oblique waves

2.1. Coordinate systems and equations of coupled motions

The coordinate systems used in this work are shown in Fig. 1. The space-fixed coordinate system is denoted by O_1-$\xi\eta\zeta$, the coordinate system moving with a constant speed of U and course of χ is denoted by O_2-XYZ and the body-fixed coordinate system is denoted by G-xyz. Here, we assume that a wave propagates in the direction of the $O_1\xi$ axis and the ship oscillates around O_2-XYZ. G indicates the centre of ship mass and O_1G_0 indicates the initial depth of the centre of ship mass. The ship's motions around O_2-XYZ are denoted by x_i: *surge* ($i = 1$), *sway* ($i = 2$), *heave* ($i = 3$), *roll* ($i = 4$), *pitch* ($i = 5$) *and yaw* ($i = 6$)..

The coupled sway-heave-roll-pitch-yaw motions are modelled as follows: