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Study on weakly nonlinear motions of ship advancing in waves and influences of steady ship wave

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ABSTRACT

Time domain Rankine source method incorporated with HOBEM is developed and applied to solve motion of ship advancing with steady forward speed in waves. Steady ship wave (SW) potential is solved beforehand and is applied in both boundary conditions of free surface and ship hull for solving time domain ship motion. m_j-terms in body boundary condition are computed with ship wave potential, time domain free surface conditions of radiation and diffraction problems are derived by use of ship wave potential. Since steady incoming flow has significant influences on ship motions, the two simplified steady flow models of uniform stream (US) and double body flow (DB) are also applied in time domain simulations for the comparative studies. In addition, nonlinear Froude-Krylov and restoring forces are used in ship motions equation.

A numerical program is originally coded by Fortran and is used to solve motions of four types of hulls, which are Series60 ship, Wigley-1, S-175 container ship and a full formed tanker, at various speeds. The results of added mass, damping coefficients, wave exciting forces and ship motions are in generally good agreement with related model tests data. It shows that both hydrodynamic coefficients and ship motions obtained by SW and DB are apparently more accurate than by US. The accuracy of motions is improved for ships with complex and full formed hulls by the present method, which takes SW as steady flow. Numerical results of ship motions are affected by both the different free surface conditions due to different steady flow models and m_j-terms, while added mass and damping coefficients are mainly influenced by m_j-terms. More physical phenomenon are detailedly investigated and discussed.

1. Introduction

Seakeeping analysis is significant in ship design. Prediction results of ship motions and hydrodynamic pressure are vital for hull form design, optimization and for structural strength checking. Potential flow method for zero speed seakeeping computation has been developed a lot since Hess and Smith (1967) came up with panel method. Until now, a variety of commercial software, such as Wamit, HydroD, Aqwa and etc. have been developed to solve wave-body interactions without forward speed. When it comes to the situation of forward speed case, numerical computation will be more complicated. Great efforts have been paid by researches in developing corresponding numerical methods. Among those, Strip theory was proposed in early stage (Ogilvie and Tuck, 1969). The theory has merit of high efficiency, while its applicability is limited by the low speed and high frequency assumption, as well as slender hull restriction. Therefore, the more advanced three dimensional method has been gradually developed with the development of computing hardware. 3D potential flow theory is usually classified into free surface Green's function method and Rankine source method.

With free surface Green's function method, the Green's function which satisfies Neumann-Kelvin (uniform stream) linearized free surface condition and radiation condition is used as the solution of Laplace's equation. So singularities are only required to be distributed on ship hull. Zero-speed pulsating source Green's function with speed correction is first applied to analyze seakeeping problem with forward speed. While this approach is only applicable in cases of low Froude numbers. To overcome the limitation, scholars including Kim and Shin (2007), Hong et al. (2016) used translating and pulsating source Green's function in place of zero-speed pulsating source Green's function and more accurate results were obtained. However, peak values of motions response amplitude operators (RAO) are usually overestimated. With respect to time domain analysis, Bingham (1994), Zhu (2009), Sengupta et al.

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Nomenclature

A_{ij}, H_{ij}	Influence coefficients
$a_{0i,j}, b_{0i,j}, c_{0i,j}$	Local added mass, damping and restoring coefficients
C_w	Wave drag coefficient
c_{ij}	Restoring coefficient
$\mathbf{F}_{F-K}, \mathbf{F}_L, \mathbf{F}_M, \mathbf{F}_R$	Force vectors. Subscripts denote Froude–Krylov force, time local, memory and restoring components, respectively
F_n	Froude number
$Ind(p,k)$	Global index of k-th node in p-th panel
$J(\xi,\eta)$	Jacobi matrix
k	Wave number
k_{yy}	radius of inertia for pitch
L	Ship length
$\mathbf{m}$	Mass matrix
Nb, Nf	Number of nodes on body and on free surface
$N_k(\xi,\eta)$	Bi-quadratic shape function
n_j, m_j	Normal vector and m-term in j-th mode
p	Hydrodynamic pressure
$S_b, \overline{S}_b$	Instantaneous and mean wetted body surface
S_f	Free surface
U	Sail speed
$\boldsymbol{\xi}$	Ship motion vector
ψ_{1j}, ψ_{2j}	Canonical potentials
ζ_a, λ, β	Incident wave amplitude, wave length, wave angle
ω, ω_e	Circular frequency, encounter frequency
ϕ, ζ	Total velocity potential and wave elevation
ϕ_I, ζ_I	Incident wave potential and wave elevation
ϕ_D, ζ_D	Disturbance potential and wave elevation of unsteady flow
Φ	Steady flow potential
ζ_S	Steady wave elevation
$\delta_{i,j}$	Kronerker delta function
α_i	Solid angle

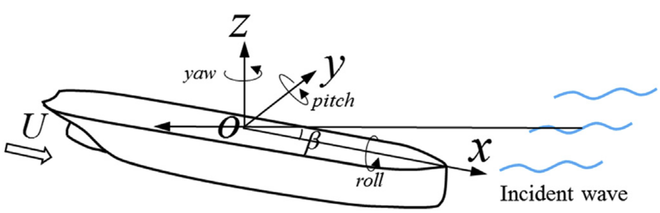

Fig. 1. Coordinate system.

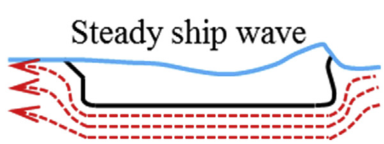

Fig. 2. Steady ship wave.

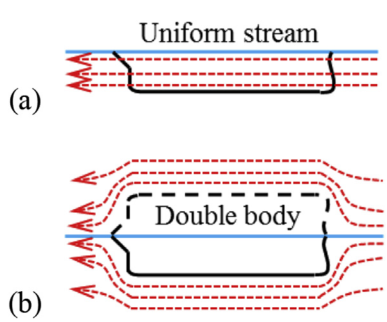

Fig. 3. Approximated steady flow: (a) Uniform stream; (b) double body flow.

(2016) studied on transient Green's function method and applied the method to compute hydrodynamic coefficients, forces and motions of ship. Numerical results in relatively high Froude numbers are also not quite satisfactory. It indicates forward speed effects are significant for unsteady seakeeping computation. Nuemann-Kelvin linearized free surface condition adopted in the derivation of Green's function restricts steady incoming flow to be uniform stream. Thus, in order to concern influences of steady flow on unsteady flow more precisely, researchers imposed complex m_j-term in body boundary condition to replace simplified ones. Numerical results of added mass, damping coefficients and motions are obviously improved. To solve m_j-term, many researches like Nakos (1990), Kring (1994), Kim and Shin (2007), Song et al. (2011), Kim et al. (2011) and etc used double body flow potential. Kim and Shin (2007) in further employed more reliable steady ship wave potential to compute m_j-term.

Numerical evaluation of free surface Green's function is difficult and time consuming. Green's function oscillates severely near free surface (Chen and Wu, 2001). For ship with large flare, integral of Green's function on panel would be singular near free surface. Rankine source method can avoid these obstacles, as elementary solution $1/r$ of Laplace equation is used as Green's function. This method can also be applied to any form of free surface condition. For problem with forward speed, the method will not be restricted with Neumann-Kelvin linearized free surface condition. Based on Rankine source method, Nakos (1990), Kring (1994), Kim and Kim (2010), Zhang et al. (2010), Song et al. (2011) and so many other researchers applied double body linearized free surface condition to compute ship motions in waves of both frequency domain and time domain. Generally, the predicted results would agree well with experiments. Liu and Papanikolaou (2011) solved ship motions with forward speed in earth fixed coordinate to avoid computing spatial differential of velocity potential and m_j-terms, while the moving mesh should be used in their method and consequently computational cost would increase a lot. Huang (1997), Kim et al. (2011) developed a nonlinear method according to weak scatter assumption, and double body flow is also employed as steady flow. In the theory, body boundary condition is satisfied on instantaneous wetted hull under incident wave surface, so m_j-terms are avoided. While computation time increases a lot as coefficient matrix of boundary integral equation should be reassembled and solved at each time step. Although double body flow linearized method has been successfully used in computation of ship seakeeping for a long time, double body flow is actually an approximation of steady flow as Froude number approaches to zero. So the method is just applicable for slow ships.

In this paper, three dimensional time domain Rankine source method is applied to compute ship seakeeping with forward speed. Ship wave is evaluated and is taken as steady flow in hydrodynamic calculation. Accordingly, free surface condition of time domain radiation and diffraction problems is derived by taking into consideration of ship wave potential, and m_j-term in body boundary condition is also computed with ship wave potential. Further comparative studies are conducted by applying the two conventional steady flow models of uniform stream (US) and double body flow (DB) in time domain simulations, for that steady incoming flow has significant influences on unsteady ship motion.