Time-Domain Simulation of KVLCC2 Motions and Mean Drift Forces in Oblique Waves using Hybrid Green Function Method

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1 INTRODUCTION

Seakeeping performance is a critical issue in naval architecture. Among various evaluation methods, the numerical simulation based on the potential flow theory is widely used due to its efficiency. However, the application of the time-domain Green function method faces significant challenges. As noted in previous studies[1], when both the field and source points approach the free surface, the traditional point source Green function exhibits significant oscillatory behavior. This characteristic leads to poor calculation accuracy and low efficiency, requiring dense grids and small-time steps to maintain stability.

To overcome the limitations of traditional methods, the authors recently proposed a Vertical Line Source Green Function (VLSGF) method combined with a hybrid boundary element scheme [2]. In this approach, the point source is integrated along a vertical line segment, which analytically improves the spatial singularity. To further improve the computational efficiency, Chebyshev approximation algorithms are originally extended from point source to the vertical line source for small time parameters, while asymptotic expansions and polynomial approximations are derived for large time parameters. This new method has been proven to be stable and accurate for simplified ship models (such as Slender and Blunt Wigley ships) in head waves[2].

However, the validation of this method for practical hull forms with complex geometry in oblique waves remains to be fully demonstrated. In this abstract, we extend the application of the VLSGF to the standard KVLCC2 tanker. The primary objective is to investigate the numerical robustness and accuracy of the proposed method in predicting both ship motions and second-order mean drift forces in oblique wave conditions by comparing the results with benchmark experimental data.

2. MATHEMATICAL FORMULATIONS

2.1 Governing Equations and Hybrid Model

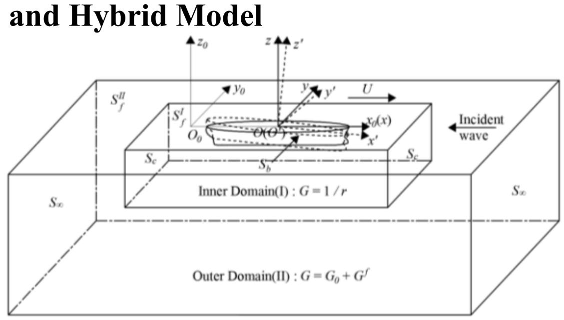


Figure 1: Definition of coordinate systems and divided flow domain

The total velocity potential Ψ is decomposed as $\Psi(x,y,z,t)=-Ux+\Phi_s+\phi_I+\phi_d$, where U is the forward speed, Φ_s is the double-body basis flow, ϕ_I is the incident wave potential, and ϕ_d is the disturbed potential. Based on the previous work[2], the flow domain is divided into an inner part and an outer part by an artificial control surface S_c, as shown in Figure 1. For the inner domain, the first-order partial Taylor Expansion Boundary Element Method (PTEBEM) based on the Rankine panel distribution is applied. For the outer domain, the singularities are only distributed on the control surface S_c, and the BIE of the velocity potential is summarized as,

$$2\pi\phi(p,t)=\iint_{S_c}\left[\phi\frac{\partial G_0}{\partial n}-\frac{\partial\phi}{\partial n}G_0\right]dS+\int_0^t d\tau\iint_{S_c}\left[\phi\frac{\partial G^f}{\partial n}-\frac{\partial\phi}{\partial n}G^f\right]dS+L_\Gamma \tag{1}$$

where L_Γ denotes the waterline integral terms along the intersection of S_c and the free surface (see Eq. 11 in [2] for the explicit form). G^f denotes the memory part of the Green function. In traditional methods, the integral over panel of G^f is evaluated based on point sources, which oscillate violently near the free surface. In present study, we utilize the Vertical Line Source Green Function, obtained by integrating the point source along a vertical segment $z \in [z_1, z_2]$.
Furthermore, the mean wave drift forces are evaluated by the direct pressure integration method over the mean wetted body surface. Following the near-field formulation, the time-averaged second-order force $\vec{F}^{(2)}$ is expressed as:

$$\frac{1}{\rho}\vec{F}^{(2)}=\vec{I}_{S_B}+\vec{I}_{WL}=\vec{I}_{S_B}+\int_{WL}\left\{\frac{1}{2}g\left(\eta-\xi_z\right)^2\vec{n}^{(0)}-\left\{\nabla\Pi\cdot\vec{\xi}\right\}\left(\eta-\xi_z\right)\vec{n}^{(0)}-\Pi\cdot\left(\eta-\xi_z\right)\cdot\vec{n}^{(1)}\right\}dl \tag{2}$$

where $\Pi=-\vec{W}\cdot\nabla\Phi+\nabla\Phi\cdot\nabla\Phi/2$. The full expansion of the surface integral $\vec{I}_{S_B}$ involves complex body-nonlinear interaction terms and will be presented in detail at the workshop.

2.2 Vertical Line Source Green Function

In traditional point-source methods, the evaluation of G^f suffers from strong numerical oscillations near the free surface. To address this, we perform an analytical integration of the point source along a vertical segment $z\in[z_1, z_2]$. As derived in our previous work[2], the resulting vertical line integral I_z effectively mitigates these oscillations and can be expressed as:

$$I_z=\int_{z_1}^{z_2}G^f dz=2g^{1/2}r_1^{-1/2}\left[\int_0^\infty k^{-1/2}\sin\left(\tau k^{1/2}\right)e^{-k\cos\theta}J_0\left(k\sin\theta\right)dk\right]_{z_1}^{z_2}=2g^{1/2}r_1^{-1/2}G_5\Big|_{z_1}^{z_2} \tag{3}$$

where the kernel function G_5 involves the first-kind Bessel function J_0. To achieve fast evaluation, distinct approximation strategies are applied based on the parameter space (τ,θ):
(i) For small time parameter ($\tau\leq 12$):
The kernel function exhibits high-frequency oscillations and singular behavior as $\theta\to\pi/2$. Direct approximation is inefficient. Following the strategy [2], we decompose the kernel into a singular part (residual function f_{res}) and a smooth part G_5^*

$$G_5=G_5^*+f_{res}(\tau,\theta) \tag{4}$$

The residual function f_{res} captures the asymptotic singular trend analytically. The remaining smooth part G_5^* is then efficiently expanded using double Chebyshev polynomials:

$$G_5^*(\tau,\theta)\approx\sum_{i=0}^{N}\sum_{j=0}^{M}c_{ij}T_i(\tau)T_j(\theta) \tag{5}$$

where T_n are Chebyshev polynomials of the first kind. The truncation orders are determined based on convergence tests, ensuring sufficient accuracy with minimal computational cost.
(ii) For large time parameter ($\tau>12$):
Asymptotic expansions are derived by applying the stationary phase method. The integral is transformed to involve the Dawson integral F_{Daw}. The final expression is reduced to a rational polynomial series[2]:

$$I_z=\sqrt{\frac{g}{r_1}}\left[\frac{4}{\tau}+\frac{8\mu}{\tau^3}+\frac{24}{\tau^5}(3\mu^2-1)+\frac{240}{\tau^7}(5\mu^3-3\mu)+\frac{840}{\tau^9}(35\mu^4-30\mu^2+3)+4F\right] \tag{6}$$

where $\mu=\cos\theta$, the complex correction term F and the partial derivative $\partial I_z/\partial\mu$, $\partial I_z/\partial\tau$ and $\partial I_z/\partial t$

can be get as the previous work[2]. This semi-analytical formulation effectively eliminates the numerical singularity at the free surface and accelerates the evaluation of the convolution integral by orders of magnitude compared to traditional methods.

(iii)For special case:

When the field and source points are close to the free surface, the asymptotic expansion loses accuracy. An alternative series expansion based on the vertical line integral limit is derived to ensure convergence[2].

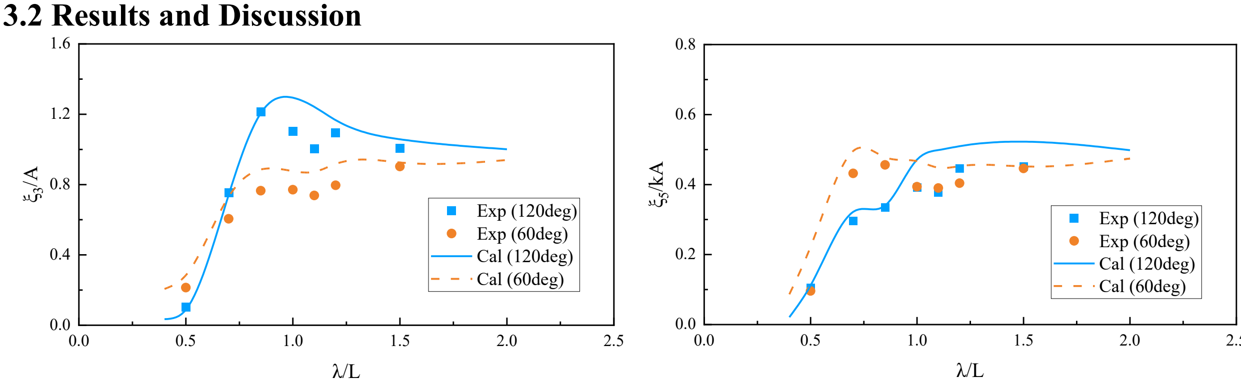
This semi-analytical approach ensures that the vertical line source Green function and its derivatives remain bounded and smooth even when the panel is located directly on the free surface, which is critical for the stability of simulations in oblique waves.

3. NUMERICAL RESULTS AND DISSCUSSION

3.1 Ship Model and Simulation Setup

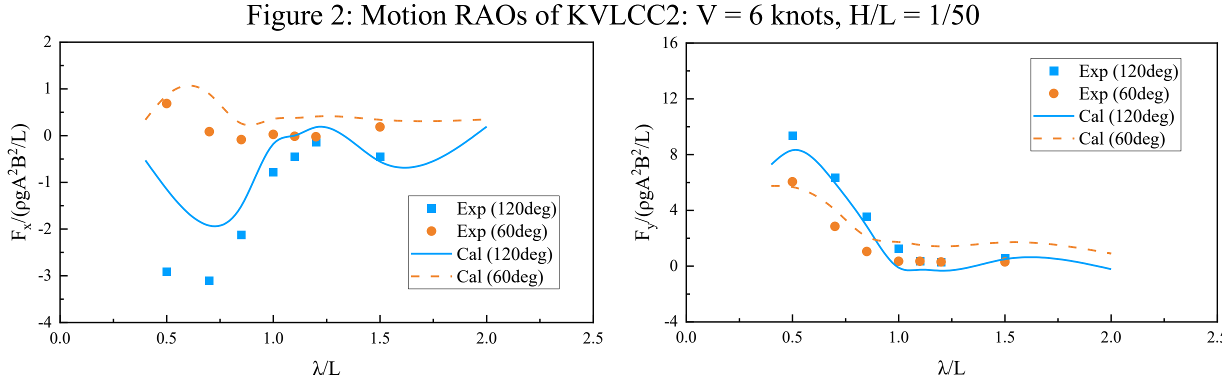
The KVLCC2 tanker is selected for validation, the main parameters refer to Seo et al[3]. The simulation is conducted at a forward speed 6kn (corresponding to full scale model). The wave heading is set to bow quartering sea ($\beta = 120°$) and stern quartering sea ($\beta = 60°$), which is known to cause significant coupling between vertical and lateral motions.

3.2 Results and Discussion



(a) Heave motion RAOS (b) Pitch motion RAOs

Figure 2: Motion RAOs of KVLCC2: V = 6 knots, H/L = 1/50

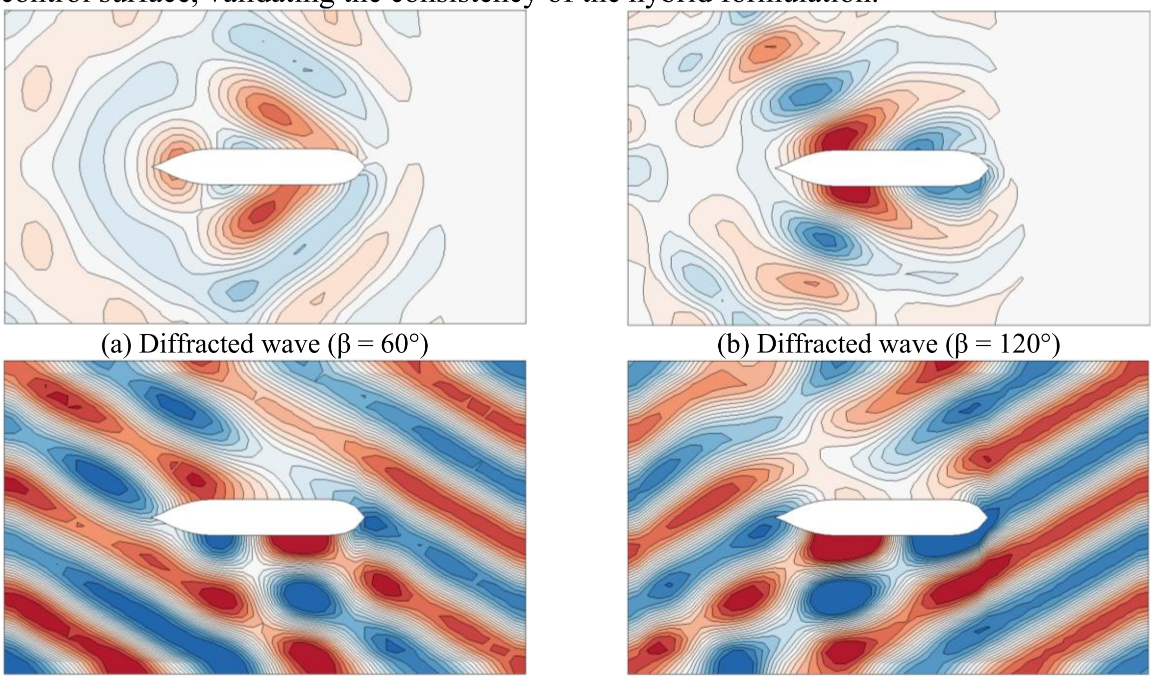


(a) Surge drift force (b) Sway drift force

Figure 3: Mean wave drift forces on KVLCC2: V = 6 knots, H/L = 1/50

Figure 2 compares the computed Heave and Pitch Response Amplitude Operators (RAOs) with experimental data[3]. Numerical results from the hybrid method based on the VLSGF method (lines) show excellent agreement with the experimental measurements (dots) across the entire frequency range. It is worth noting that the present method maintains stable predictions not only in the long-wave region but also in the resonance frequency region, where the coupling effects between vertical and lateral motions are significant.

Figure 3 presents the mean wave drift forces in surge and sway. The evaluation of second-order forces involves the second order gradient of the velocity potential, which is highly sensitive to numerical oscillations. As observed, the calculation results agree well with the experimental data, even in the resonance frequency region. This demonstrates that the VLSGF method not only provides accurate first-order motion predictions but also yields a high-quality velocity field on the hull surface, which is essential for mean second order drift force and moment analysis.
Figure 4 illustrates the diffracted wave and total wave around the KVLCC2 hull at $\lambda/L=0.5$, $\beta=60°$ and $120°$. A key indicator of numerical quality is the continuity of wave elevation across the matching boundary between the inner TEBEM domain and the outer Green function domain. The contours show seamless propagation of the Kelvin wave system without reflection or distortion at the control surface, validating the consistency of the hybrid formulation.



(a) Diffracted wave ($\beta = 60°$) (b) Diffracted wave ($\beta = 120°$)

(c) Total wave ($\beta = 60°$) (d) Total wave ($\beta = 120°$)

Figure 4: Wave fields near the KVLCC2: V = 6 knots, $\lambda/L = 0.5$

4. CONCLUSION

The Vertical Line Source Green Function method has been successfully applied to the time-domain simulation of the KVLCC2 tanker in oblique waves. The study demonstrates that:
(i) The analytical integration along the vertical line effectively suppressess free-surface oscillations, thereby enhancing numerical stability in numerical simulations.
(ii) The method accurately predicts coupled motions in oblique seas, showing good agreement with benchmark experimental data.
(iii) The proposed approach is robust for various wave conditions, making it a promising tool for complex seakeeping and maneuvering analysis.

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