Numerical Study on the Influence of the Steady Flow Field in Seakeeping

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1 Introduction

3-D methods for estimating seakeeping of ships have become popular with the wide availability of high-speed computers and sophisticated numerical techniques. Some finite element analyses of the ship structure require improved estimations of the unsteady wave forces on the hull. Especially fatigue analysis involving repeatedly imposed unsteady forces is quite interesting for ship yards. In this respect, computations should take into account forward-speed effects and three-dimensional effects. Two-dimensional computations, e.g. strip methods, are insufficient for this purpose, [1], [2].

Forward-speed effects include more than just the change of the frequency of encounter, [3]. The degree of approximation for the steady flow is important in the unsteady calculations. Iwashita et al. applied their 3-D Green function method to a blunt tanker, [1], and a catamaran, [2], demonstrating this not only for the unsteady hydrodynamic forces, but also for the unsteady pressures on the hull. These calculations included the steady disturbance effect through the body boundary condition approximating the steady flow by double-body flow. This approximation is adequate if the steady waves generated by the ship are small. The validity of this approximation should be confirmed by investigating how the steady wave field affects the unsteady wave field. The discrepancy between experimental and computational pressure distributions near the bow of the tanker in [1] suggests a significant effect of the steady wave field in some cases and motivated the present numerical study.

We study numerically the influence of the steady flow to the unsteady wave field, using a 3-D Green function method (GFM) and a Rankine panel method (RPM) taking the steady disturbance effect into account. Three approximations of the steady flow are employed for the input of the unsteady problem: uniform flow ignoring the steady disturbance, double-body flow, and linear (Kelvin) wave field. m-vector, steady velocity field and its derivatives evaluated from those steady flows are commonly used both in the GFM and the RPM. The GFM includes the steady flow only through the body boundary condition and the free-surface boundary condition by necessity includes only the uniform flow. The RPM can include the steady flow both in the body boundary condition and the free-surface boundary condition. We can therefore observe the influence of the body boundary condition and the free-surface boundary condition separately or together. Results are shown here for a Series-60($C_b = 0.6$) for the hydrodynamic forces and the unsteady pressures on the hull.

2 Boundary Conditions

We consider a ship advancing at constant forward speed U in oblique regular waves encountered at angle χ, Fig.1. The ship motion $\xi_j e^{i\omega_e t}(j = 1 \sim 6)$ around its equilibrium position and the wave amplitude A of the incident wave are assumed to be small. ω_0 is the circular frequency and K the wave number of the incident wave. The encounter circular frequency is $\omega_e(= \omega_0 - KU\cos\chi)$. The linear theory is employed for this problem assuming ideal (potential) flow.

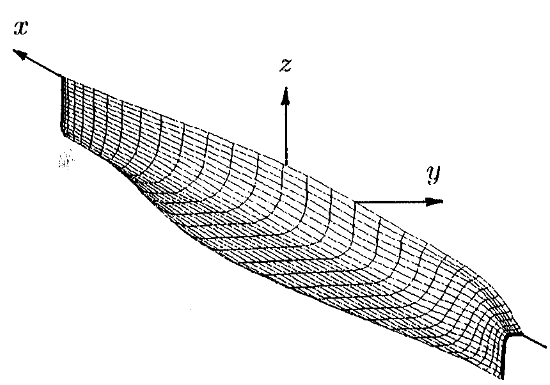

Fig.1 Coordinate system

The velocity potential Φ governed by Laplace's equation can be expressed as

$$\Phi(x,y,z;t) = U[-x+\phi_s(x,y,z)] + \Re[\phi(x,y,z)e^{i\omega_e t}] \tag{1}$$

where

$$\phi = \frac{gA}{\omega_0}(\phi_0+\phi_7) + i\omega_e \sum_{j=1}^{6} \xi_j \phi_j\,, \quad \phi_0 = ie^{Kz-iK(x\cos\chi+y\sin\chi)} \tag{2}$$

ϕ_s is the steady potential, ϕ the unsteady velocity potential including the incident wave potential ϕ_0, scattering potential ϕ_7 and radiation potential $\phi_j(j=1\sim 6)$.

The linearization of the free-surface boundary condition and the body boundary condition yields two set of the boundary condition for ϕ_s and $\phi_j(j=1\sim 7)$.

$$\frac{\partial^2\phi_s}{\partial x^2} - \mu\frac{\partial\phi_s}{\partial x} + K_0\frac{\partial\phi_s}{\partial z} = 0 \quad \text{on } z=0\,, \quad \frac{\partial\phi_s}{\partial n} = n_1 \quad \text{on } S_H \tag{3}$$

$$\left.\begin{aligned} &\left[\left(i\omega_e - U\frac{\partial}{\partial x}\right)^2 + \mu\left(i\omega_e - U\frac{\partial}{\partial x}\right) + g\frac{\partial}{\partial z}\right]\phi_j = 0 && \text{on } z=0 \\ &\frac{\partial\phi_j}{\partial n} = n_j + \frac{U}{i\omega_e}m_j \quad (j=1\sim 6)\,, \quad \frac{\partial\phi_7}{\partial n} - \frac{\partial\phi_0}{\partial n} && \text{on } S_H \end{aligned}\right\} \tag{4}$$

where

$$\begin{aligned} &(n_1,n_2,n_3) = \boldsymbol{n}\,, && (m_1,m_2,m_3) = -(\boldsymbol{n}\cdot\nabla)\boldsymbol{V}\,, \\ &(n_4,n_5,n_6) = \boldsymbol{r}\times\boldsymbol{n}\,, && (m_4,m_5,m_6) = -(\boldsymbol{n}\cdot\nabla)(\boldsymbol{r}\times\boldsymbol{V})\,, \\ &\boldsymbol{r} = (x,y,z)\,, && \boldsymbol{V} = \nabla(-x+\phi_s)\,, \quad K_0 = g/U^2 \end{aligned}$$

μ in the free-surface boundary conditions is the Rayleigh's artificial viscosity introduced to satisfy the radiation condition at infinity, and $\boldsymbol{n}$ is a normal vector inward to fluid. ϕ_s and ϕ_j also subject to the condition at infinite depth.

3 Solution Methods

The GFM using the spline element described in [1] and [2] is applied to solve the unsteady problem subject to (4). The direct method solves the integral equation to avoid the irregular-like solutions and the steepest descent integration method proposed by Iwashita & Ohkusu [4] evaluates the wave term of the Green function.

The unsteady pressure distribution on the hull is estimated by an expression derived by Timman and Newman [5]:

$$p(x,y,z) = -\rho(i\omega_e + U\boldsymbol{V}\cdot\nabla)\phi - \rho\frac{U^2}{2}\sum_{j=1}^{6}\xi_j(\boldsymbol{\beta}_j\cdot\nabla)(\boldsymbol{V}\cdot\boldsymbol{V})\,, \quad \boldsymbol{\beta}_j = \begin{cases} \boldsymbol{e}_j & (j=1,2,3) \\ \boldsymbol{e}_{j-3}\times\boldsymbol{r} & (j=4,5,6) \end{cases} \tag{5}$$

ρ is the density of the fluid, $\boldsymbol{e}_j(j=1,2,3)$ are the unit vectors of x,y,z axes.

The right hand second term of eq.(5) indicates the dynamical restoring force due to the unsteady motion in the steady flow. The second derivatives of the steady flow in this term are determined by solving the steady problem (3). We solve the steady problem by using the RPM explained in the subsequent paragraph. For the double-body flow, the same method can be applied omitting the second derivative of ϕ_s in the free-surface boundary condition in (3).

The hydrodynamic forces are calculated by integrating the unsteady pressure (5) over the hull up to the calm-water level.

The RPM described in [6] is used. The unsteady velocity potential is represented by source distributions on the hull and the free surface. The radiation condition is numerically satisfied by the staggered grid technique which is approximately equivalent to the condition $\phi_x = \phi_{xx} = 0$ at upstream. This method therefore is applicable only for $\tau > 1/4$.

Several kinds of free-surface boundary condition are possible by the RPM. Among them we employed the following unsteady free-surface boundary condition derived under the assamption of the small unsteady disturbance of the free surface, [6]:

$$-\omega_e^2\phi + 2i\omega_e B\phi + 2\overline{\nabla}\phi_s\overline{\nabla}\phi + (B\overline{\nabla}\phi_s + \boldsymbol{a}^{(0)} + \boldsymbol{a}^g)\overline{\nabla}\phi + \overline{\nabla}\phi_s(\overline{\nabla}\phi_s\cdot\overline{\nabla})\overline{\nabla}\phi = 0 \quad \text{on } z=\zeta_s \tag{6}$$

where

$$\boldsymbol{a}^{(0)} = (\overline{\nabla}\phi_s\overline{\nabla})\overline{\nabla}\phi_s\,, \quad \boldsymbol{a}^g = \boldsymbol{a}^{(0)} - (0,0,g)^T\,, \quad B = -\frac{1}{a_3^g}\frac{\partial}{\partial z}(\overline{\nabla}\phi_s\cdot\boldsymbol{a}^g)$$

This free-surface boundary condition is satisfied on the steady wave surface $z = \zeta_s$. It includes the influence of the steady flow completely.

4 Results

Fig.1 shows the grid system of Series-60($C_b = 0.6$) container ship employed in this calculation. 990 elements are used on the body surface and 1500 elements on the free surface in the RPM.

Fig.2 shows the distributions of the m_3-vector on the hull calculated assuming the double-body flow and the linear (Kelvin) solution for the steady flow. We can see an influence of the Kelvin wave near the free surface. Two different computations, based on a desingularized constant strength panel and a higher-order panel, were previously tested for a half-immersed prolate spheroid in double body flow and we found good agreement with the analytical solution for both approaches. A significant difference between them, however, was observed at the bow and stern parts when we applied them for the Series-60. Then the higher-order panel was adopted in Fig.2 and following calculations, as the computed results appeared more plausible.

Fig.3 shows the wave pressure distribution on some hull sections at $F_n = 0.2$, $\lambda/L = 0.3$, $\chi = 180°$. The influence of the steady flow seems remarkable especially in the bow part. It is confirmed that the approximation of the exact steady flow tends to underestimate the wave pressure.

Fig.4 shows heave exciting force and pitch exciting moment obtained by integrating this pressure over the hull surface. The influence of the steady flow is less significant here due to the integration effect.

Calculations for a tanker with blunt bow are in progress and should be finished in time for the workshop.

References

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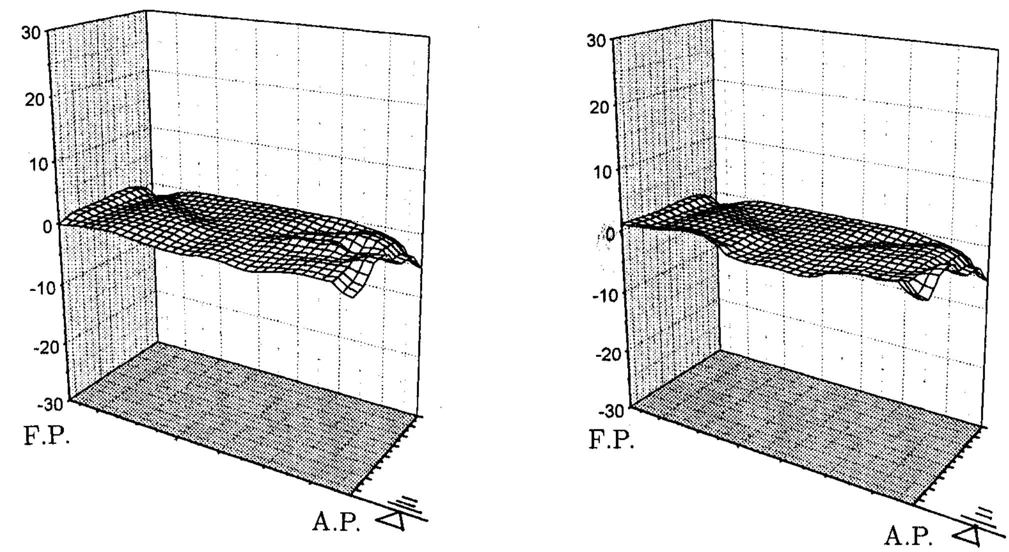

Fig.2 Comparison of m_3 distribution on the ship hull surface
[left: Double body flow, right: Linear Kelvin wave($F_n = 0.2$)]

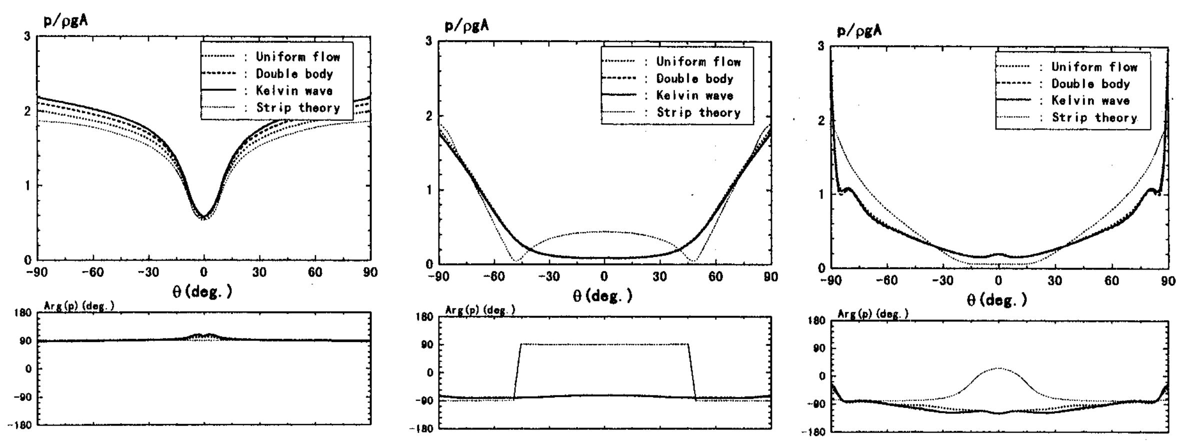

Fig.3 Wave pressure distribution at $F_n = 0.2$, $\lambda/L = 0.3$, $\chi = 180$(deg.)
[left: Ord.9.5, middle: Ord.5, right: Ord.3]

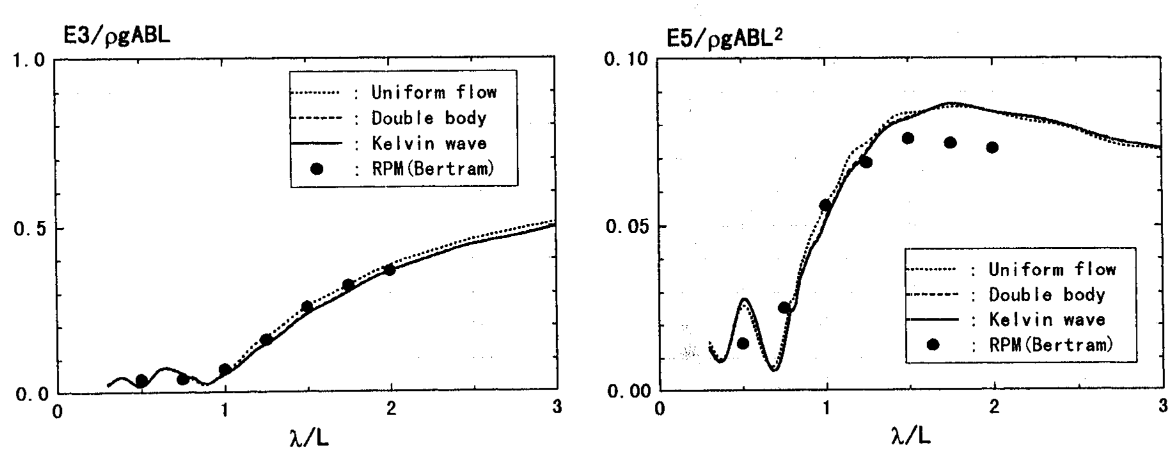

Fig.4 Wave exciting force for heave and pitch at $F_n = 0.2$, $\chi = 180$(deg.)

DISCUSSION

Yeung R.W.: I think this is a nice investigation to understand the role played by the steady flow potential. From the results your showed, it is not surprising that the diffraction potential does not have a strong dependence on $\varphi^{(s)}$. Afterall, the only role that $\varphi^{(s)}$ plays is in the convective derivative of the pressure equation. The much stronger dependence of radiation potentials on $\varphi^{(s)}$ is however to be expected because of the m_j terms.

Iwashita H., Bertram V.: The influence of the steady flow field is concluded to be important only on the estimation of the wave pressure near the bow part for the diffraction problem, and to be always strong for the radiation problem not only on the force estimation but pressure estimation, due to the m_j-term on the body boundary-condition.

Ohkusu M.: You did not discuss your results in terms of the experimental data of the pressure distribution at the bow of a ship presented in your second slide. Your results on Kelvin wave field seem not to agree with the measured pressure distribution close to the free surface in particular.

Iwashita H., Bertram V.: The measurement of the wave pressure along the water line includes some error relating ot the experimental analysis. Near the bow part the pressure gage is sometimes exposed outside the free surface due to large steady waves and Fourier analysis breaks down. The numerical results therefore should be compared with experiments excluding such points near the free surface. Then we can see an improvement of the numerical results by taking the Kelvin wave field into account.

Rainey R.C.T.: I believe this work is of great practical importance, and deserves every encouragement. The authors' conclusion that steady-flow effects are seen mainly at the bow is consistent with the long history of ship structural failures in this region. A ship Classification Society not a million miles from the Institut für Schiffbau, for example, will be familiar with the case of the 100,000 tonne tanker *"Kirki"*, whose whole bow section fell off in the Indian Ocean, in 1991. See my discussion of Faulkner and Williams' paper *The Design for Abnormal Waves*, in the Transactions of the Royal Institution of Naval Architects, Vol 139, 1997.