Effect of Steady Disturbance on Free Surface Flow Around Slowly Moving Full Hull Forms in Waves

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Introduction

The linearized wave-making theory indicates that radiation or diffraction waves do not propagate upstream in the case that τ ($= U\omega/g$; U is the ship's velocity, ω the encounter frequency and g the acceleration of gravity) is larger than 0.25. However, Ohkusu observed that the diffraction waves in front of bow of a full hull form propagate obviously upstream even for τ much greater that 0.25, and those waves propagate some distance forward getting steep and break[1]. It is difficult to evaluate the complicated behavior of the waves in the framework of the ordinary linearized theory which does not take the effect of the deformation flow due to the presence of the ship hull (we shall call hereafter the deformed flow as the steady disturbance flow) into consideration.

In this paper, an approach of the theory based on double body flow[2] is introduced. The present approach can be regarded as an extension of the low speed steady wave resistance theory[3] to the ship motion problems. For better understanding of the free surface flow around slowly moving full hull forms in waves, the present theory applies to the evaluation of wave pattern generated by a pulsating source moving below the free surface taking the steady disturbance flow into account. As a result, it is found that in the region where local τ is close to 0.25, steep waves appear and the wave pattern shows the similar tendency to the diffraction waves observed by Ohkusu.

Outline of the Present Theory

Let us consider a slow ship with constant forward velocity U into a plane progressive wave of amplitude a, circular frequency ω_0, wave number K and the angle of wave incidence χ. By using the ship's velocity U which is assumed to be small, the orders of magnitude of a, K and ω_0 are assumed to be:

$$a = O(U^4),\ K = O(U^{-2}),\ \omega_0 = O(U^{-1})$$

The velocity potential ϕ_U representing the unsteady wavy motions is expressed as:

$$\phi_U(x,y,z,t) = \Re\left[\phi(x,y,z)e^{i\omega t}\right] \tag{1}$$

$$\phi = \frac{ga}{i\omega_0}(\phi_I + \phi_A + \phi_D) + i\omega\sum_{j=1}^{6}\xi_j\phi_{Rj} \tag{2}$$

In (1), $\Re$ means the real part of the complex value. ω is the encounter frequency($= \omega_0 - UK\cos\chi$). ξ_j denotes the oscillatory translation and rotation vector of j-th mode and is assumed to be the same order as a. ϕ_I is the velocity potential representing incident waves, and can be expressed as:

$$\phi_I = -e^{Kz}e^{-iK(x\cos\chi + y\sin\chi)} \tag{3}$$

ϕ_A is the velocity potential representing the deformation of the incident waves due to the effect of the steady disturbance(double body flow). ϕ_{Rj} is the velocity potential representing radiation flow due to the ship motion of j-th mode. ϕ_D is the velocity potential representing diffraction flow. Then, on assumptions about the order of magnitude for ϕ and double body flow potential referring to Ogilvie[4],

Baba[3] and Sakamoto[5], free surface and hull boundary conditions are represented as follows:
(a) radiation and diffraction problems:

$$[F] \quad -\omega^2\phi_j + 2i\omega(u_0\phi_{j_x} + v_0\phi_{j_y}) + u_0^2\phi_{j_{xx}} + 2u_0v_0\phi_{j_{xy}} + v_0^2\phi_{j_{yy}} + g\phi_{j_z} = 0 \qquad \text{on } z = 0 \tag{4}$$

$$[H] \quad \phi_{j_n} = n_j \ \text{ on } S \qquad (j = 1, 2, \ldots, 7) \tag{5}$$

where

$$\phi_j = \phi_{Rj} \ \ (j = 1, 2, \ldots, 6), \ \ \phi_7 = \phi_D$$

$$\left.\begin{array}{l}(n_1, n_2, n_3) = \mathbf{n} \\ (n_4, n_5, n_6) = \mathbf{r} \times \mathbf{n}\end{array}\right\} \tag{6}$$

$$n_7 = -\phi_{I_n} - \phi_{A_n} \tag{7}$$

Here, (u_0, v_0) denotes velocity components of double body flow on still water, $\mathbf{n}$ the normal vector of the hull, $\mathbf{r}$ the vector of the coordinate on the hull surface and S the submerged position of hull surface. Further, subscript of x, y, n means partial derivatives with respect to their variables. It is noted that (4) and (5) can be derived from the general boundary conditions in the linearized ship motion theory[6] under the assumptions employed in this paper.
(b) deformation problem of incident waves:

$$[F] \quad -\omega^2\phi_A + 2i\omega(u_0\phi_{A_x} + v_0\phi_{A_y}) + u_0^2\phi_{A_{xx}} + 2u_0v_0\phi_{A_{xy}} + v_0^2\phi_{A_{yy}} + g\phi_{A_z} = gI(x, y) \qquad \text{on } z{=}0 \tag{8}$$

where

$$I(x, y) = -\frac{gK - \{\omega - K(u_0\cos\chi + v_0\sin\chi)\}^2}{g} e^{-iK(x\cos\chi + y\sin\chi)} \tag{9}$$

Here, $I(x, y)$ stands for the residual term where ϕ_I does not satisfy the present free surface condition.
For expression of the velocity potentials with respect to the above problems, a function which satisfies the present free surface condition (4) is introduced. Referring to Baba[3] and Wehausen[7], the function $G(x, y, z; x_1, y_1, z_1)$ can be derived as follows:

$$G(x, y, z\ ;\ x_1, y_1, z_1) = \frac{1}{r} - \frac{1}{r_1} + \frac{g}{\pi}\left[\int_0^\gamma\int_0^\infty + \int_\gamma^{\frac{\pi}{2}}\int_{L_1} + \int_{\frac{\pi}{2}}^{\pi}\int_{L_2}\right] d\theta\, dk \times \frac{k\ \exp(kz)[\exp(-ik\varpi_1) + \exp(-ik\varpi_2)]}{gk - (\omega + kU_0\cos\theta)^2} \tag{10}$$

where

$$r = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z - z_1)^2}, \quad r_1 = \sqrt{(x - x_1)^2 + (y - y_1)^2 + (z + z_1)^2}$$

$$U_0^2 = u_0^2 + v_0^2, \quad \theta_0 = \tan^{-1}\left(\frac{-v_0}{-u_0}\right), \quad \theta_1 = \theta + \theta_0, \quad \theta_2 = \theta - \theta_0$$

$$\varpi_1 = (x - x_1)\cos\theta_1 + (y - y_1)\sin\theta_1, \quad \varpi_2 = (x - x_1)\cos\theta_2 - (y - y_1)\sin\theta_2$$

$$\gamma = \begin{cases} 0 & \tau_0 < 0.25 \\ \cos^{-1}\left(\frac{1}{4\tau_0}\right) & \tau_0 > 0.25 \end{cases}$$

$$\tau_0 = \frac{U_0\omega}{g}$$

Here, (x, y, z) is the field point, (x_1, y_1, z_1) the singular point. U_0 means the magnitude of velocity of the double body flow and θ_0 the direction of the flow. It should be noted that this function $G(x, y, z; x_1, y_1, z_1)$ can not be called Green's function because U_0 and θ_0 vary with the position of P. In the far field, however, the function G coincides with ordinary Green's function[7] since the double body flow around the ship hull tends toward uniform flow, namely, $U_0 \cong U, \theta_0 \cong 0$. The velocity potentials can be represented by distributions of G on the hull and still water surfaces.

In the ordinary linearized theory, τ is the parameter for determining the characteristics of radiation or diffraction waves and the waves never propagate upstream in the case that τ is larger than 0.25. In the present theory, however, τ_0 which varies with the position of field point becomes a new parameter for the wave propagation. This means that the waves can propagate upstream in the region where τ_0 is smaller than 0.25 even if τ is much greater than 0.25.

Effect of Steady Disturbance on Wave Pattern

For better understanding of the free surface flow around slowly moving full hull forms in waves, calculation is made of wave pattern generated by a pulsating source moving below the free surface taking the steady disturbance flow into account by applying the present theory. The calculation is carried out for $f = 1.0, K_0(= g/U^2) = 4.0$ and $\tau = 0.274$ where f denotes the immersion of the source point. Fig.1 shows τ_0 contour and wave patterns at $t = 0$ by the present theory and the ordinary linearized theory. In the wave pattern calculated by the present theory, waves propagate upstream in the region where τ_0 is smaller than 0.25, and half-circular shaped steep waves appear along a contour line of $\tau_0 = 0.25$ which is limit of the wave propagation. On the contrary, such steep waves can not be observed in the wave pattern calculated by the ordinary linearized theory. Thus, it is found that the wave pattern near the source point by the present theory is quite different from that by the ordinary theory.

It seems that the present wave pattern resembles the tendency of the waves observed by Ohkusu[1]. Here, we try to explain Ohkusu's observation by applying the present theory. For the full hull forms, the region where τ_0 is smaller than 0.25 always exists near the stagnation point of the bow. In the region the diffraction waves can propagate upstream. Then, as shown in the present wave pattern of Fig.1, steep waves appear near the line of $\tau_0 = 0.25$ in front of the bow, which may get too steep and break. The present theory can explain the tendency of the diffraction waves observed by Ohkusu.

References

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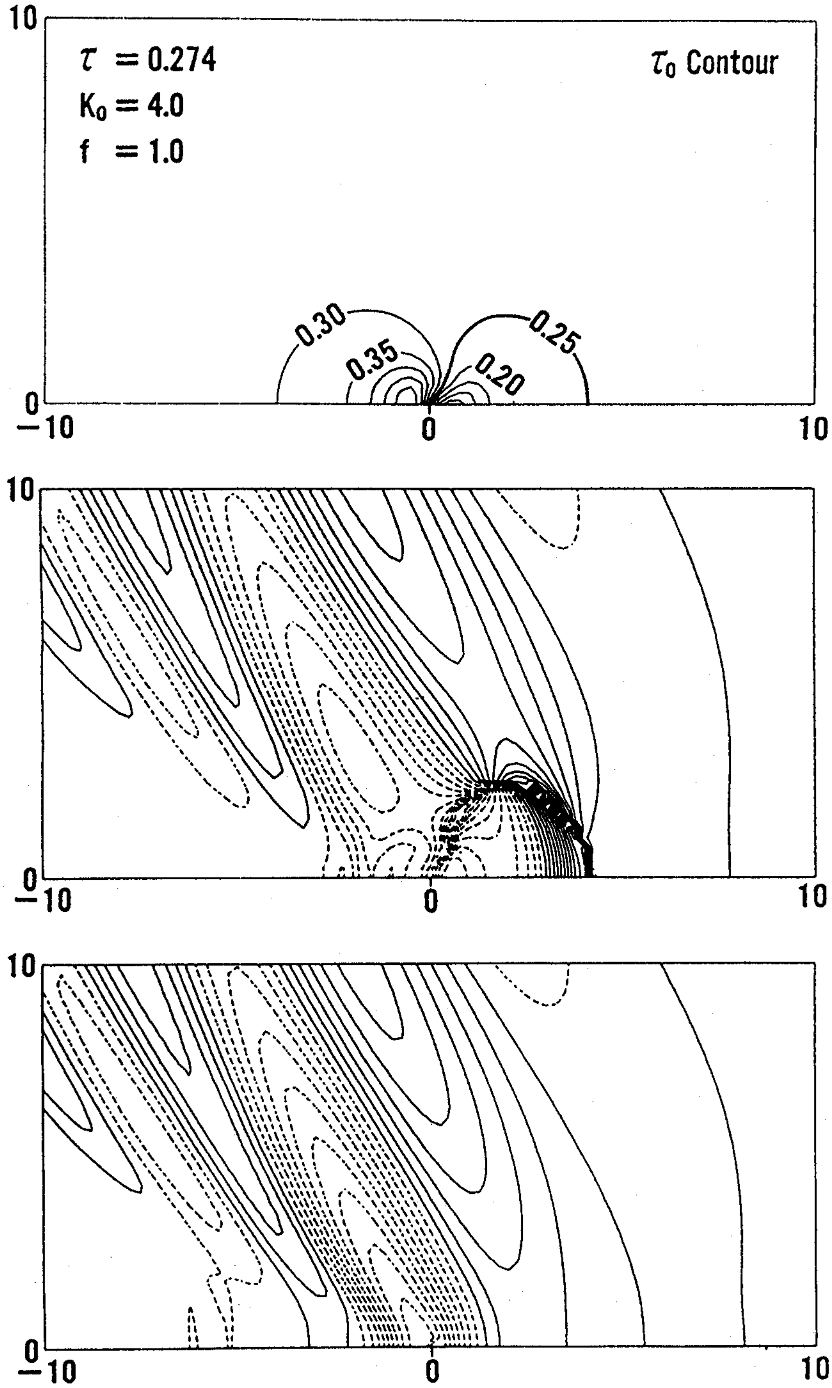

Figure 1: τ_0 contour and wave patterns($\tau = 0.274, f = 1.0, K_0 (= g/U^2) = 4.0$), upper: τ_0 contour on $z = 0$, middle: present theory, lower: ordinary linearized theory

DISCUSSION

Kagemoto H.: From the point of consistency of the theory, should the free surface conditions be imposed on the undisturbed free surface or on the surface of a double model flow?

Yasukawa H.: We deal with three problems such as radiation, diffraction and deformation of incident waves as mentioned in the presentation. Then, we derive consistently the free surface conditions under some assumptions about the order of magnitude for the potentials. As a result, the free surface condition in the radiation and diffraction problems should be employed on $z = \zeta_0$ which means wave height due to double body flow. Also the condition in the deformation problem of incident waves should be imposed on $z = 0$ because the hull surface condition is not necessary in our formulation. You can see the detailed derivation of the conditions in the paper presented in JSNA, Japan, 1991.

Tulin M.: In the case of the pulsating source for $\tau = 1/4$, what is the wavelength of the radiated waves in comparison to the beam of the body. In particular, are the wave lengths small enough to satisfy by the requirements of ray theory?

Yasukawa H.: The present function G depends on local τ based on double body flow. This means that the present approach include the change of the wavelength due to the effect of steady disturbance. So we can basically evaluate the wave pattern of the pulsating source for gloval $\tau = 1/4$. In the far field, however, the wavelength becomes larger. Therefore, our approach may be regarded as an improvement of the ordinary linearized theory.