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Development of a 3D-NWT for simulation of running ship motions in waves

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1 Introduction

Numerical Wave Tank (NWT) is a generic name of numerical simulators for nonlinear free surface waves, hydrodynamic forces and floating body motions. In the past two decades, a lot of efforts have been made to develop theories and numerical techniques for NWT.

The first pioneer work was the development of well known mixed Eulerian and Lagrangian method (MEL) by Longuet-Higgins and Cokelet (1976). In MEL method, as its name shows, Eulerian field equations are solved to obtain fluid velocity, and obtained velocity is used to track fluid particles on the free surface in Lagrangian way. The development of MEL enabled us to compute fully nonlinear free surface motions in time domain.

The second pioneer work was the development of modal decomposition method by Vinje and Brevig (1981). They introduced acceleration field and showed how to determine pressure distribution and resulting floating body acceleration simultaneously. This was the first consistent method to simulate nonlinear floating body motions in time domain. Cointe et al.(1990) used this method in their NWT. Following these works, other three consistent methods were developed in rapid succession. Tanizawa (1995) developed implicit boundary condition method. Berkvens (1998) developed 3D-NWT based on this method. Recently, Ikeno (2000) and Shirakura (2000) also developed 3D-NWT based on implicit boundary condition method. Cao et al.(1994) developed iterative method. Wu and Eatock-Taylor (1996) extended the modal decomposition method and proposed a new indirect method. Kashiwagi (1998) used this method as faster solver of floating body motions.

By these research efforts, theories and numerical techniques were developed and prepared as necessary parts of NWT. Nowadays, using these parts, we can develop practical 2D-NWT as we wish. On the other hand, development of practical 3D-NWT is still tough work. We have to develop additional theories and various numerical techniques for 3D-NWT. Desktop computers are still not powerful enough to run 3D simulations. However, development of 3D-NWT is present hot topic. Many challenging works are on going and overcoming the difficulties.

The authors are also developing 3D-NWT. The target of our 3D-NWT is simulation of running ship motions in waves. In this abstract, the basic formulations of our 3D-NWT and simulated results of running modified Wigley hull motions are presented.

2 Formulation

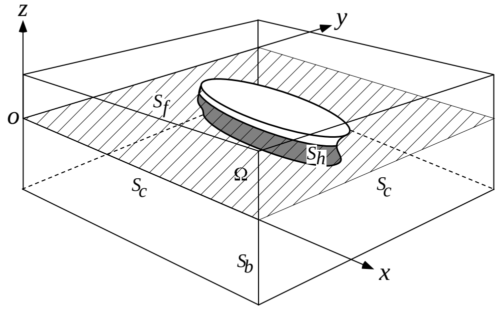

Fig.1 Computational domain

Fig.1 shows the computational domain bounded by free surface S_f , four vertical control surface S_c , a bottom S_b and hull surface S_h . Reference frame $o-xyz$ is a inertial system advancing with ship in constant velocity. The fluid is assumed to be homogeneous, incompressible, inviscid and its motion irrotational. All variables are nondimensionalized using fluid density ρ , gravitational acceleration g and hull length L . Velocity potential ϕ is used to describe the ideal fluid motion. In the fluid domain, the velocity potential satisfies Laplace's equation $\nabla^2\phi = 0$. Applying Green's theorem, boundary integral equation (BIE)

$$c(Q)\phi(Q) = \int_S \phi(P)u_n(P,Q) - u(P,Q)\phi_n(P)ds \quad (1)$$

is obtained, where P and Q are points on the boundary S , $c(Q)$ is solid angle of the boundary at point Q , $u(P,Q) = 1/||P-Q||$ is kernel function. Subscript n denotes the operation $\boldsymbol{n}\cdot\nabla$ in

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which $\boldsymbol{n}$ is the unit surface normal vector. This BIE is valid also for $\partial\phi/\partial t \equiv \phi_t$.

Originally, NWT is developed for nonlinear time domain simulation. However, 3D-NWT requires large amount of computation. Capacity and speed of desktop computers are still not enough to simulate practical problems. Therefore, as the first step, the authors developed a linearized 3D-NWT to test various ideas by trial and error. In the linear NWT, the boundary shape is fixed to the mean position of oscillation and following boundary conditions (BC) for velocity field and acceleration field are imposed on it.

- Free surface

$$\frac{\partial \zeta}{\partial t} = \phi_z - \frac{\partial \phi}{\partial x}\frac{\partial \zeta}{\partial x} - \frac{\partial \phi}{\partial y}\frac{\partial \zeta}{\partial y} \ , \qquad (2)$$

$$\frac{\partial \phi}{\partial t} = -\zeta - \frac{1}{2}(\nabla\phi \cdot \nabla\phi) \ , \qquad (3)$$

where ζ is wave elevation. Value of ϕ on $z = 0$ is given by time integral of eq.(3). The second order term $(\nabla\phi \cdot \nabla\phi)/2$ is left to consider the steady wave field by running ship.

- Hull surface

$$\frac{\partial \phi}{\partial n} = \boldsymbol{n} \cdot (\boldsymbol{V} + \boldsymbol{\omega} \times \boldsymbol{r}) \qquad (4)$$

$$\frac{\partial \phi_t}{\partial n} = \boldsymbol{n} \cdot (\dot{\boldsymbol{V}} + \dot{\boldsymbol{\omega}} \times \boldsymbol{r}) \qquad (5)$$

where $\boldsymbol{V}$, $\boldsymbol{\omega}$ are velocity and angular velocity of the hull respectively, $\boldsymbol{r}$ is position vector of hull surface from the center of gravity.

- Bottom

$$\frac{\partial \phi}{\partial n} = \frac{\partial \phi_t}{\partial n} = 0 \qquad (6)$$

- Vertical control surface

$$\frac{\partial \phi}{\partial n} = \frac{\partial \phi_o}{\partial n}, \quad \frac{\partial \phi_t}{\partial n} = \frac{\partial \phi_{ot}}{\partial n} \qquad (7)$$

where ϕ_o is velocity potential of linear propagating waves observed from $o - xyz$ system.

To determine the acceleration of the hull $\dot{\boldsymbol{V}}, \dot{\boldsymbol{\omega}}$, we need pressure distribution $p = -\phi_t - (\nabla\phi)^2/2 - z$ on the hull. Therefore, the acceleration is unknown before we solve BIE of ϕ_t . This means we can not use BC(5) explicitly and some implicit methods are indispensable to solve the acceleration field. As explained in the introduction, implicit methods were studied in the past two decades and following four methods were available now.

(1) Iterative method
(2) Modal decomposition method
(3) Indirect method
(4) Implicit boundary condition method

In the present linear 3D-NWT code, the authors use modal decomposition method to save memory and CPU time. Above four methods are reviewed by Tanizawa(2000).

3 Simulation

3.1 Target of the simulation

For test trials of the newly developed 3D-NWT, motions of a modified Wigley hull were simulated. The modified Wigley hull form is defined as

$$\eta = (1-\xi^2)(1-\zeta^2)(1+0.2\xi^2) + \zeta^2(1-\zeta^8)(1-\xi^2)^4 \ , \qquad (8)$$

where $\xi = 2x/L, \ \eta = 2y/B, \ \zeta = z/d$. The principle dimensions are shown in Table 1.

Table 1 Principle dimensions of ship

Length: L	$1L$
Breadth: B	$0.15L$
Draft: d	$0.0625L$
Displacement: ∇	$0.56LBd$
Water-Plane Area: A_w	$0.693LB$
Center of Gravity: OG	$0.012L$
Gyrational Radius: k_{yy}	$0.2325L$

The 3D-NWT is bounded by $4L \times 4L$ square free surface area, four vertical control surfaces and a bottom at the depth L . Wave damping zone, used by Cointe(1990), is allocated at the border of the free surface. Since the breadth of the damping zone is L , the effective free surface is $2L \times 2L$ square area. Boundary panels of the hull and NWT are shown in Fig.3 and Fig.4. On the damping zone, larger panels are used. At the location where flux is discontinuous such as intersection lines of free surface and hull, corner points on NWT and etc., double nodes and triple nodes are collocated. For this NWT, a higher order BEM (HOBEM) is newly developed. This HOBEM supports mixed use of triangular element (linear and quadratic) and rectangular element (linear, quadratic and Lagrangian). For the following simulation, linear triangular and linear rectangular elements are used. Total number of elements and collocation points are 4560 and 4827, respectively.

3.2 Simulated results

Using the 3D-NWT, motions of the running modified Wigley hull were simulated in regular waves. Parameters of simulations were 1) $\chi = 180deg.$ (head sea), 2) $Fn = 0.2$ and 3) $\lambda/L = 0.5 \sim 3.0$. Fig.5 shows simulated wave field around the hull at an instant of the periodical motion. Diffraction and radiation wave by hull is significant for shorter waves. We can observe small amplitude Kelvin wave pattern, too. However, the present code is still unstable for high speed simulation and convergence of Kelvin wave may be insufficient. The results presented in this paper is obtained by short simulation of about 10 wave encounter periods.

Next, simulated heave and pitch responses are shown in Fig.6. The thick solid line with black circle shows the result of simulation by 3D-NWT. The thin solid line, broken line and white circle shows the result of enhanced unified theory (EUT), NSM and experiment by Kashiwagi et al.(2000). In comparison with heave responses, you see a gap in resonant frequency between NWT and others. The reason of this gap is under investigation and not clear now. In comparison with pitch responses, agreement between NWT and others are good. NWT gives a little larger response which looks nearer to experiment than EUT and NSM. Looking at phase, agreement between NWT and others is good in longer wave range. However in short wave range, $\lambda/L < 1.0$, the agreement is not enough. Since the panel size is fixed for entire wave range, lack of resolution may be the reason of this disagreement in shorter wave range.

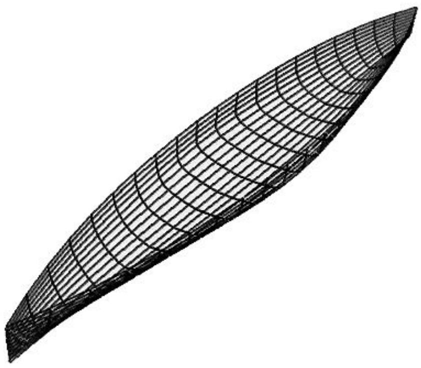

Fig.3 Boundary panels on the ship hull

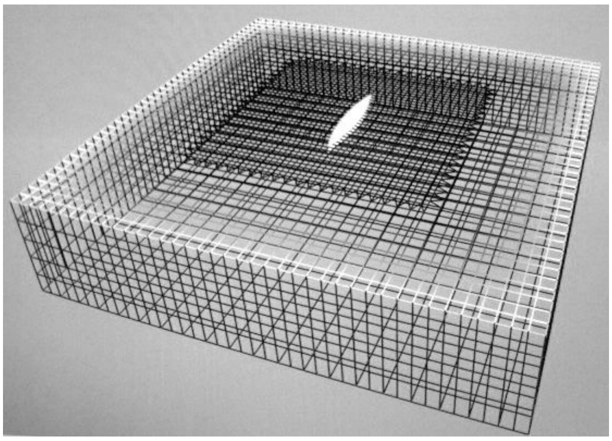

Fig.4 Boundary panels on NWT

4 Conclusion

In this short paper, a newly developed 3D-NWT is introduced and simulated running modified Wigley hull motions are reported promptly. The results qualitatively agree with EUT, NSM and experimental data of Kashiwagi. However, the accuracy and numerical stability are still insufficient. To make this 3D-NWT practicable, we have to stabilize the free surface simulation around hull and check the accuracy of hydrodynamic force and motions precisely. Diffraction problem, radiation problem and radiation-diffraction problem should be simulated step by step for systematic accuracy check. Result of these systematic accuracy check will be reported at the workshop.

Our final goal is development of fully nonlinear 3D-NWT for simulation of running ship motions in waves. After we complete linear 3D-NWT, we intend to extend it to body surface nonlinear code and fully nonlinear code step by step.

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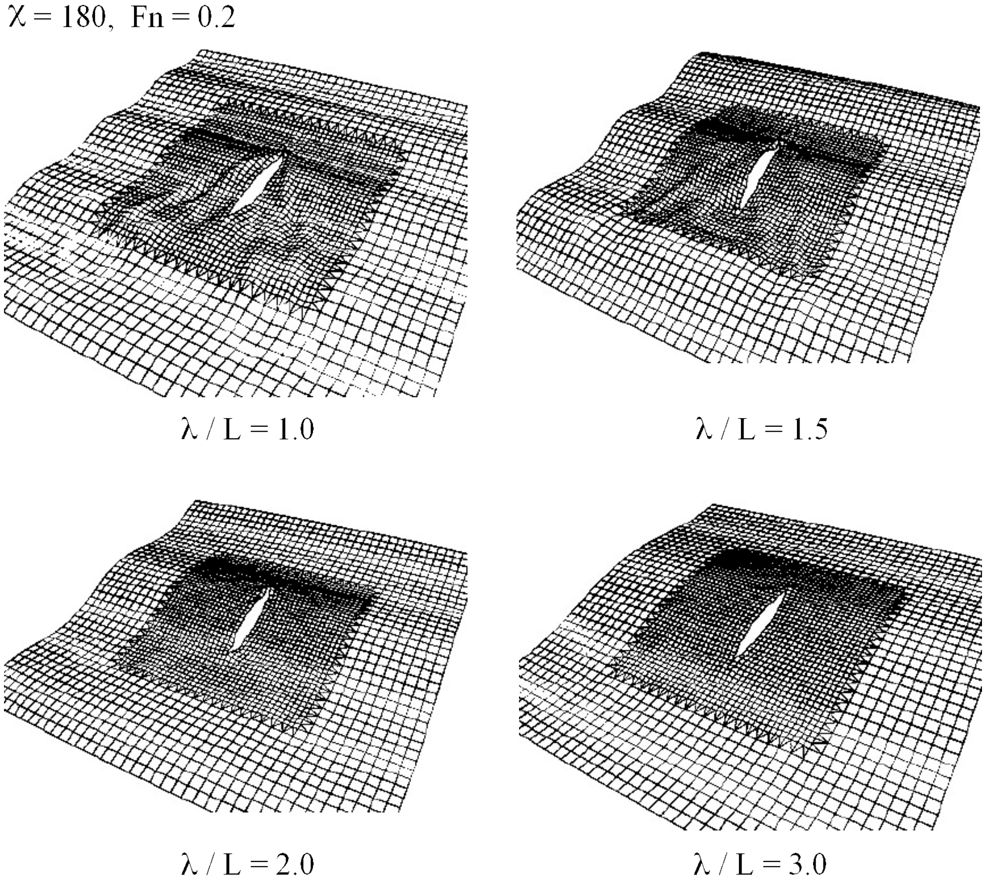

Fig.5 Wave Field around running ship hull

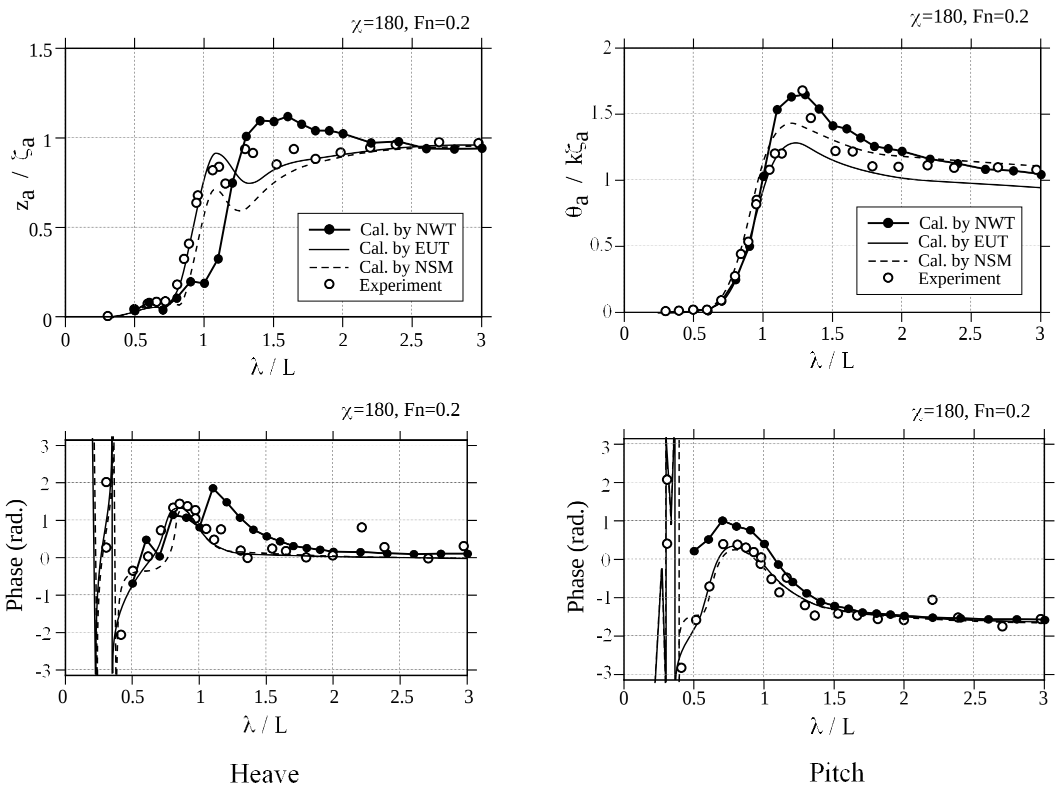

Fig.6 Simulated heave and pitch responses