Numerical Analysis and Validation on Ship Springing

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INTRODUCTION

Hydroelastic behavior of hull-girder structure is getting more important as the size of modern ships becomes larger and voyage speed becomes faster. In the 24th IWWWFB, we introduced a new numerical method which adopts a fully coupled BEM-FEM in time domain. In the present study, this numerical method has been applied to real ship models, including large LNG carriers and containerships, and the computational results are compared with towing-tank experiment for validation. Furthermore, extension to nonlinear problem is introduced.

THEORETICAL BACKGROUND

Fluid domain

The velocity potential satisfying Laplace equation can be defined inside fluid domain and it is assumed that total potential can be decomposed into three components of basis potential, incident potential, and disturbed potential. Free surface elevation can also be decomposed into incident one and disturbed one as follows:

$$\nabla^2\phi(\mathbf{x},t)=0$$
$$\phi(\mathbf{x},t)=\Phi(\mathbf{x},t)+\phi_I(\mathbf{x},t)+\phi_d(\mathbf{x},t)$$
$$\zeta(\mathbf{x},t)=\zeta_I(\mathbf{x},t)+\zeta_d(\mathbf{x},t)0$$

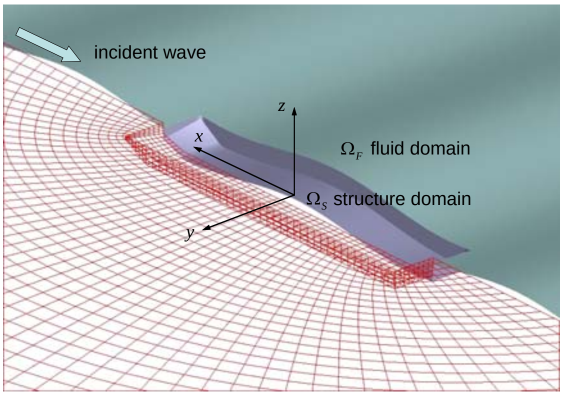


Fig.1 Coordinate system

When ship is moving with its forward speed of $\mathbf{V}$, kinematic and dynamic free-surface boundary condition after linearization can be written as follows:

$$\frac{\partial\zeta_d}{\partial t}-(\mathbf{V}-\nabla\Phi)\cdot\nabla\zeta_d=\frac{\partial^2\Phi}{\partial z^2}\zeta_d+\frac{\partial\phi_d}{\partial z}+(\mathbf{V}-\nabla\Phi)\cdot\nabla\zeta_I$$
$$\frac{\partial\phi_d}{\partial t}-(\mathbf{V}-\nabla\Phi)\cdot\nabla\phi_d=-\frac{\partial\Phi}{\partial t}-g\zeta_d+\left[\mathbf{V}\cdot\nabla\Phi-\frac{1}{2}\nabla\Phi\cdot\nabla\Phi\right]+(\mathbf{V}-\nabla\Phi)\cdot\nabla\phi_I$$

The motion of body in fluid domain requires the body boundary condition to be met on exact body location. Unlike rigid body case, the body boundary condition has to be treated separately for each panel due to the arbitrariness of deformation pattern of flexible hull. The body boundary condition after linearization at each panel is as follows:

$$\frac{\partial\phi_d}{\partial n}=\frac{\partial\mathbf{u}}{\partial t}\cdot\mathbf{n}-\frac{\partial\phi_I}{\partial n}+\Big[(\mathbf{u}\cdot\nabla)\mathbf{V}-(\mathbf{u}\cdot\nabla)\nabla\mathbf{\Phi}+\big((\mathbf{V}-\nabla\mathbf{\Phi})\cdot\nabla\big)\mathbf{u}\Big]\cdot\mathbf{n}\quad \text{on } \bar{S}_B$$

where $\mathbf{u}$ is the deformation of the panel induced by structural deformation.

Structure domain

For structure domain, a hill-girder structure is assumed to be Vlasov beam which can include warping effect. In this case, the kinetic energy of a beam element of length l and area A can be written as follows:

$$E_k = \frac{\rho}{2}\int \dot{\mathbf{u}}^T\dot{\mathbf{u}}dV = \frac{\rho}{2}\int_0^l\int_A\left(\dot{u}^2+\dot{v}^2+\dot{w}^2\right)dV$$
$$= \frac{\rho}{2}\int_0^l\left(I_{\omega\omega}\dot{\Theta}_{x,x}^2 + I_{xx}\dot{\Theta}_x{}^2 + A\dot{V}^2 + 2Az_s\dot{V}\dot{\Theta}_x + I_{zz}\dot{\Theta}_z{}^2\right)dx + \frac{\rho}{2}\int_0^l\left(A\dot{W}^2 + I_{yy}\dot{\Theta}_y{}^2\right)dx$$

where $I_{\omega\omega}$, I_{xx}, z_s are warping constant, the polar moment of inertia about shear center, and the vertical position of shear center, respectively. In addition, I_{yy}, I_{zz} are second moments of inertia about the centroid of the cross section. The first integral term of above equation is kinetic energy of torsion and horizontal bending coupled with torsion, and the second integral term is that of vertical bending.

Strain energy is stress times strain integrated over entire structural domain under the assumption of linear elasticity. Strain energy induced by the deformation of the beam under torsion and bending, which eventually will result in stiffness matrix of the system, can be obtained as follows:

$$E_s = \frac{1}{2}\int\left(E\varepsilon_{xx}^2 + G\gamma_{xy}^2 + G\gamma_{xz}^2\right)dV$$
$$= \frac{1}{2}\int_0^l\left(EI_{\omega\omega}\Theta_{x,xx}^2 + GJ\Theta_{x,x}^2\right)dx + \frac{1}{2}\int_0^l\left(EI_{zz}\Theta_{z,x}^2 + k_yGA(\dot{V}_{,x}-\Theta_z)^2\right)dx + \frac{1}{2}\int_0^l\left(EI_{yy}\Theta_{y,x}^2 + k_zGA(\dot{W}_{,x}-\Theta_y)^2\right)dx$$

where J is St. Venant torsional constant. G is shear modulus and k is shear factor for each bending direction. The first, second and third integral term of above equation correspond to the strain energy of torsion, horizontal bending and vertical bending respectively. The detailed theoretical background and coupling method of fluid field and structure field can be referred to Ref [1].

Numerical Method: Coupling Scheme

A time-domain Rankine panel method is applied to solve the boundary value problem in fluid domain. To this end, the fluid boundaries are discretized into panels and the following equation are solved also in discretized domain. The physical parameters, e.g. potential and elevation, are represented by using B-spline basis function.

$$\phi_d + \iint_{S_B}\phi_d\frac{\partial G}{\partial n}dS - \iint_{S_F}\frac{\partial\phi_d}{\partial n}GdS = \iint_{S_B}\frac{\partial\phi_d}{\partial n}GdS - \iint_{S_F}\phi_d\frac{\partial G}{\partial n}dS$$

It should be noted that the ship is not rigid anymore, therefore the ship surface is flexible and such flexible motion should be considered at all the collocation points.

On the other hand, the structural problem can be solved by using a finite element method. The discretized finite element equation obtained from the strain energy equation of Vlasov beam can be simplified into the following form:

$$[\mathbf{M}]\{\ddot{\mathbf{U}}\} + [\mathbf{C}]\{\dot{\mathbf{U}}\} + [\mathbf{K}]\{\mathbf{U}\} = \{\mathbf{f}\}$$

where $[\mathbf{M}],[\mathbf{C}],[\mathbf{K}]$ are the matrices of mass, damping, and stiffness. $\{\mathbf{f}\}$ indicates external force matrix.

Strong coupling of the two solvers can be achieved by fixed-point iteration method. Since the displacement and normal velocity of flexible body surface are needed for the fluid-domain solver and the nodal force due to fluid flow is needed for the structure solver, we can write the iteration equation in the following form:

$$\mathbf{f} = \mathbf{p} - \mathbf{F}(\dot{\mathbf{U}}, \mathbf{U}, \boldsymbol{\varphi}_f) = 0$$
$$\mathbf{s} = \dot{\mathbf{U}} - \mathbf{S}(\mathbf{p}) = 0$$

where $\mathbf{U}$ and $\dot{\mathbf{U}}$ are displacement and velocity of structural deformation, i.e. hull deformation, and $\mathbf{p}$ and $\boldsymbol{\varphi}_f$ are the pressure on the FEM node and velocity potential on free surface, respectively. At each time step, iteration should be done to make the above equations are satisfied.

NUMERICAL COMPUTATION AND VALIDATION

A few real ships are modeled for numerical test and validation. Fig.2 shows the FEM model of one of test ships, a large LNG carrier of 330m, and the corresponding hydrodynamic panels on hull surface. In the present method, the hydrodynamic panel should be distributed on free surface as well as the body surface. Fig.3 shows the RAOs of heave motion and vertical bending moment (VBM) at head sea. The Froude number in operation condition is 0.18, and the two-node vertical vibration model of hull structure has natural frequency around 3.78 rad/sec. The corresponding wave frequency is around 1.48rad/sec. Although the heave motion is not large at resonance frequency, the VBM RAO shows very dramatic increase at the resonance. This shows clearly why springing is important.

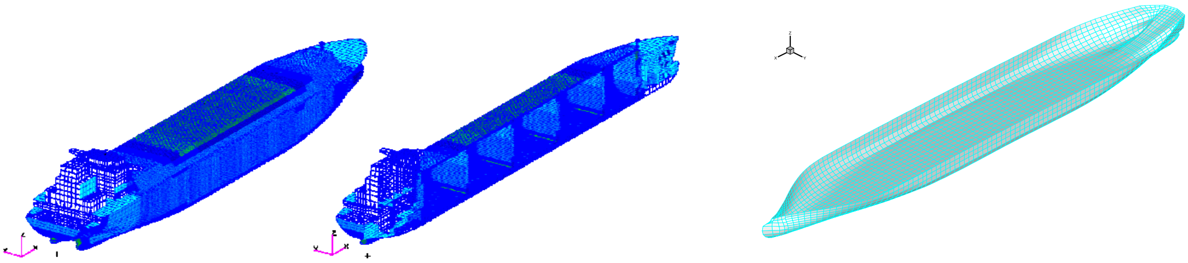


Fig.2 FEM modeling and hydrodynamic hull panels for a 330m LNG carrier

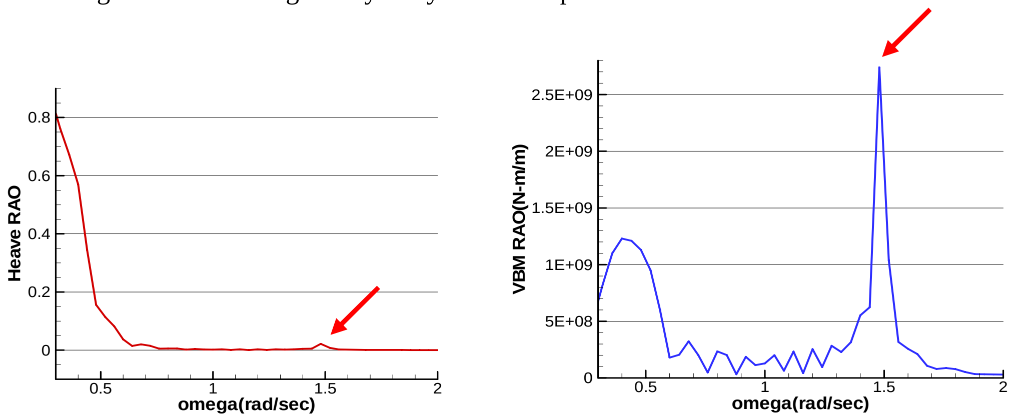
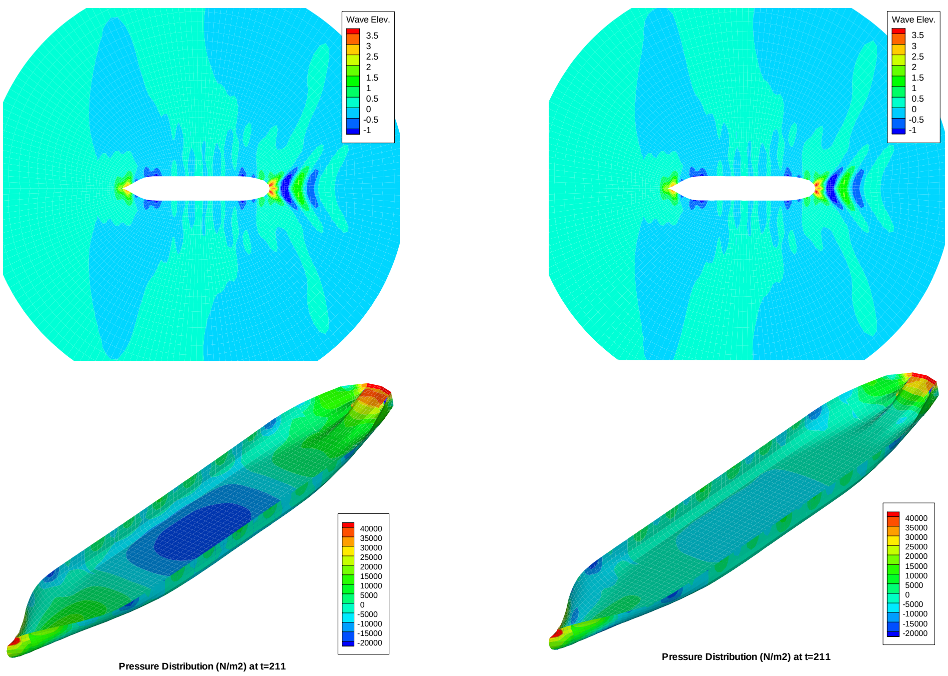


Fig.3 Heave RAO and VBM RAO at head sea: LNG carrier, Fn=0.18



(a) 0.5% (b) 2.0%

Fig.4 Effects of structural damping: LNG carrier, Fn=0.18, wave frequency at 1.48 rad/sec, instantaneous disturbed wave contour (top) and pressure contour (bottom)

Fig.4 compares the instantaneous disturbed wave elevation and hydrodynamic pressure near resonance when the structural damping coefficients are 0.5% and 2%. When the resonance between wave excitation and springing occurs, structural damping plays a key role to determine the magnitude of structural response. As this figure shows, the difference is not much in wave elevation around the body, however the dynamic pressure is not. This implies that the structural response is sensitive to structural damping as expected although the generated wave does not significantly change.

Fig.5 shows the segmented model tested by MOERI/KORDI as a part of WILS II project. The length of real ship is 321m, and it can carry 10,000TEU containers. For validation purpose, the numerical results are compared with experimental data of this model. Fig.6 shows two preliminary results at oblique sea. In the model test, two different connection structures have been applied, and the present computation are carried out to consider such difference as well as continuous(homogeneous) beam. The detailed results will be introduced in the workshop.

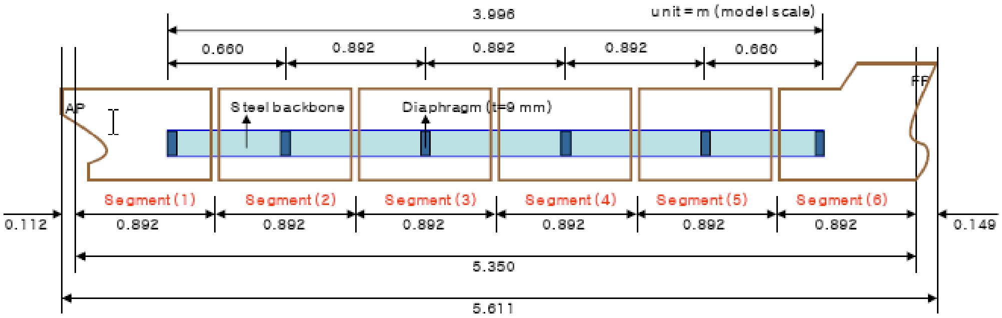
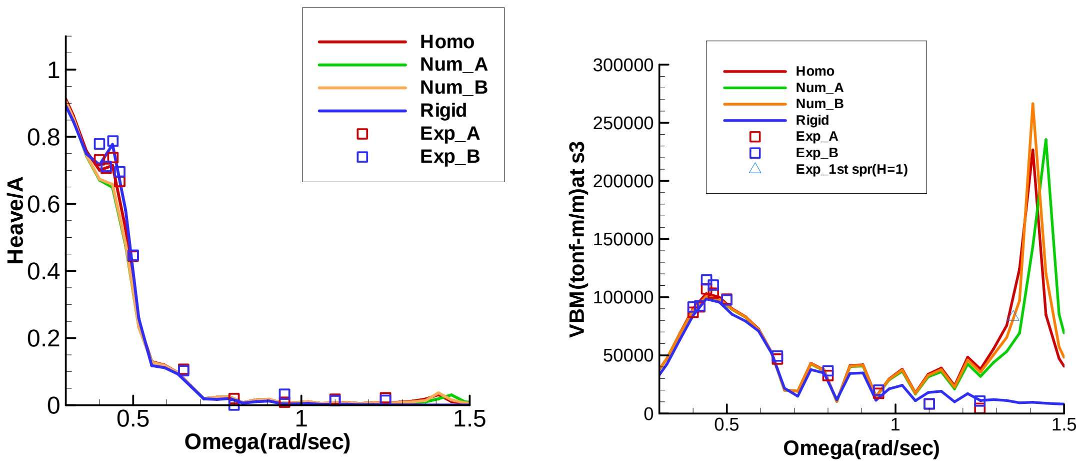


Fig.5 Segmented model for towing-tank springing test: 10,000-TEU containership, scaled for model test ([2])



(a) Heave RAO (b) VBM RAO

Fig.6 Heave and VBM RAOs of 10,000-TEU containership: 150deg heading, 20knots

References

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