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Time-domain analysis of nonlinear motion responses and structural loads on ships and offshore structures: development of WISH programs

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ABSTRACT: *The present paper introduced a computer program, called WISH, which is based on a time-domain Rankine panel method. The WISH has been developed for practical use to predict the linear and nonlinear ship motion and structural loads in waves. The WISH adopts three different levels of seakeeping analysis: linear, weakly-nonlinear and weak-scatterer approaches. Later, WISH-FLEX has been developed to consider hydroelasticity effects on hull-girder structure. This program can solve the springing and whipping problems by coupling between the hydrodynamic and structural problems. More recently this development has been continued to more diverse problems, including the motion responses of multiple adjacent bodies, the effects of seakeeping in ship maneuvering, and the floating-body motion in finite-depth domain with varying bathymetry. This paper introduces a brief theoretical and numerical background of the WISH package, and some validation results. Also several applications to real ships and offshore structures are shown.*

KEY WORDS: WISH; Nonlinear Seakeeping; Nonlinear wave loads; Rankine panel Method; Time-domain method.

INTRODUCTION

Accurate prediction of motion responses and wave loads on ships is essential in ship structural design. Thanks to the recent trend of growing ship size, the demand of nonlinear analysis for ship motions and global hull-gird loads is getting higher. Furthermore, the seakeeping problems become more diverse to offshore engineering due to the construction of large floating structures. There are two main reasons of seakeeping analysis in marine hydrodynamics. First of all, the motion dynamics of marine vehicles or floating offshore structures is the primary interest. The motion response in ocean waves is important for the operation of vessels or offshore structures. Dynamic stability, passenger comfort, occurrence of slamming, and all similar problems belong to such category. On the other hand, the other important reason to carry out the motion analysis is to predict the structural loads. For instant, the vertical bending moment of global hull-structure can be predicted by carrying out the ship motion analysis. As long as ocean waves excite the floating body motion, the wave-induced loads on marine structure cannot be avoided.

Seakeeping analysis is one of classics in marine hydrodynamics. Therefore, there is no need to mention the details in this paper. The main objective of the present study is to develop a program package to predict the linear and nonlinear motion responses and structural loads on marine vehicles, and its extension to various engineering problems. To this end, the computer program called WISH(computer program for linear and nonlinear Wave-Induced loads and SHip motion) has been developed at the first stage, and it has been extended and applied to the seakeeping problems for cruise ships and offshore structures, hydroelasticity analysis such as springing, ship maneuvering, and so on. This paper introduces the theoretical and numerical background of WISH program, some validation results, and application examples.

The nonlinearity on the ship motion problem can be separated to two main characteristics. The first one is free-surface nonlinearity, and the other is body nonlinearity. The analytic or numerical analysis of the free-surface nonlinearity is not an easy task. On the other hand, the body nonlinearity, which is mostly due to the body geometry, is relatively easier to consider in numerical analysis than the free-surface nonlinearity. Fortunately, when the floating body is slender like ship, the disturbance due to body motion may not be very significant. When this is the case, more effort can be made to consider the effect of body nonlinearity. Many recent researches on nonlinear seakeeping analysis are based on such hypothesis.

A level of consideration of body nonlinearity can be classified to three steps (Singh and Sen, 2007). The first one is linear approach which has been widely applied in the ship motion problem for many years. This has been well studied

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by adopting strip theory, wave Green function method, Rankine panel method, etc. The second one is weakly-nonlinear approach, also called as blended approach, which applies nonlinear Froude-Krylov and restoring force obtained on the body surface actually wetted by incident wave and instantaneous body motion. This approach is an inconsistent method, since the wave disturbance is solved in the mean body surface as same as the linear approach. Recently, this method has got the popularity in the ship motion analysis, because computational burden is not much larger than that of linear computation and it is easily extendable from linear program. There have been many researches by using the weakly-nonlinear analysis, which were based on strip theory, wave Green function approach, or Rankine panel approach. Such research effort is well described by Watanabe and Soares (1999), and 14^{th} ISSC Committee (2000). Three-dimensional analysis programs such as LAMP2(NLOAD3D) and SWAN2(WASIM) developed by Lin et al. (1990, 1994), and Kring et al. (1996), are being used by DNV, ABS and other shipbuilding societies.

The last step to include body nonlinearity is the weak-scatterer approach, introduced by Pawlowski (1992). In this approach, nonlinear Froude-Krylov and restoring forces are applied as same as the weakly-nonlinear approach. However, free-surface boundary conditions are linearized not on the mean water level but on the instantaneous incident wave surface. This concept is based on the assumption that the scattered wave components are much smaller than the incident wave. Furthermore the body boundary condition is imposed on the exactly wetted ship surface. This approach takes much more computational time than the weakly-nonlinear approach, because computational grids and the boundary value problem should be newly set up on the exact-body surface and incident wave surface at every time-step. This is not an easy task, therefore there are few research cases yet. Huang (1998) developed a time-domain Rankine panel method program based on this approach, so called SWAN4, and LAMP4 is similar to SWAN4.

During last several years, five largest Korean shipbuilding companies and Korean Register have supported the development of WISH. Similar to SWAN and LAMP, WISH can apply three different levels of analysis, linear, weakly-nonlinear and weak-scatterer approaches for the analysis of ship motion responses and structural loads. This program is based on a three-dimensional Rankine panel method, and the time-domain formulation is applied (Kim et al., 2008; Kim and Kim, 2009c). During the development of WISH program, systematic verification and validation were performed by comparison with experimental data and/or other numerical results. Based on such study, the accuracy of WISH program has been evaluated, and it has been distributed to industry.

WISH program has been extended to the hydroelasticity problem of global ship structure. Very recently, springing and whipping are of great interest due to the potential risk of fatigue damage. As the size of ships or offshore structures is getting larger, the natural frequency of hull-girder vibration tends to move to lower frequency range. Moreover, faster forward speed makes the encounter excitation frequency of ocean wave to move much closer to its natural frequency of structural vibration, consequently leading to the higher chance of resonance between the two even under linear wave regime. The most critical situation is the case of ultra-large container carriers. Unlike other types of vessel, container carriers have very low torsional natural frequencies due to large hatch openings on deck.

From the foundation of WISH program as a kernel solver for seakeeping, many extensions and applications have been considered. One of the most representative extensions is WISH-FLEX which solves the hydroelasicity problem of ship structure in waves. Springing and whipping can be the main interests of this problem. Being motivated by recent demand of solving the hydroelasticity problem, WISH-FLEX has been developed by coupling with WISH and a sophisticated beam theory. Previous analysis of springing problem has been mostly relied on the frequency-domain approach and modal superposition method. Bishop and Price (1979) used the generalized coordinate approach, where the dynamic response of flexible hull was expressed in terms of the superposition of its basic natural modes, including six rigid body modes. These mode-shapes were considered as a new basis of the system, and all other physical quantities, such as added mass and damping coefficient as well as hydrodynamic excitation force, were expressed in this modal space. Later on such numerical scheme has been the main stream of many springing analyses, e.g. Price and Temarel (1982), Jensen and Dogliani (1996), Malenica et al. (2003), and Vidic-Perunovic (2005). The time-domain approaches has been also tried, mostly based on impulse-response function method, e.g. Wu and Moan (1996).

In the present extension to WISH-FLEX, a new approach is introduced for the analysis of springing problem in very large modern commercial ships. To this end, a hybrid BEM-FEM method has been developed as a method of solution. That is, WISH program is coupled with the finite element method which approximates the hull structure to a set of Vlasov beam element. During this development, a lot of effort has been made for the numerical tests of coupling scheme, time-marching method, and many other details. For the validation of WISH-FLEX, comparative studies with a frequency-domain program and comparison with experimental data have been performed for real commercial ships.

This paper introduces several other extensions and extensions of WISH program. Those include the motion control and comfort analysis of cruise ship, the motion responses of multiple adjacent floating bodies, the seakeeping problems of offshore structures, and ship maneuvering.

MATHEMATICAL FORMULATION

Boundary Value Problem

Let's consider a freely-floating body, e.g. ship or offshore structure, with a certain speed in the presence of incident waves. The body speed can be zero, constant, or even time-varying. A Cartesian coordinate system is defined at the body-fixed coordinate, as shown in Fig. 1.

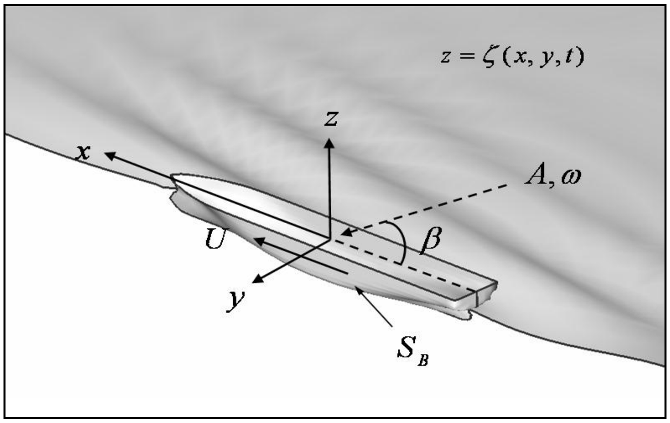


Fig. 1 Coordinate system.

The assumption of potential flow can lead the following initial boundary value problem:

$$\nabla^2\phi = 0 \quad \text{in fluid domain} \tag{1}$$

$$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\phi)\cdot\nabla\right]\left[z - \zeta(x,y,t)\right] = 0 \quad \text{on } z = \zeta(x,y,t) \tag{2}$$

$$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\phi)\cdot\nabla\right]\phi = -g\zeta + \frac{1}{2}\nabla\phi\cdot\nabla\phi \quad \text{on } z = \zeta(x,y,t) \tag{3}$$

$$\frac{\partial\phi}{\partial n} = \vec{U}\cdot\vec{n} + \frac{\partial\vec{\delta}}{\partial t}\cdot\vec{n} \quad \text{on body surface} \tag{4}$$

$$\frac{\partial\phi}{\partial n} = 0 \quad \text{on fluid bottom boundary} \tag{5}$$

$$\nabla\phi \to 0 \text{ at spatial infinity} \tag{6}$$

$$\phi = 0, \quad \frac{\partial\phi}{\partial t} = 0 \qquad \text{at } t = 0 \tag{7}$$

where $\vec{U}(t)$ is the body speed, and $\vec{\delta}$ is the displacement of the body motion. ζ and g are the wave elevation andgravity constant, respectively. In addition, $\vec{n}$ indicates the normal vector on the fluid boundary. The body motion can be written as $\vec{\delta} = \vec{\xi}_T + \vec{\xi}_R \times \vec{x}$ where $\vec{\xi}_T$ and $\vec{\xi}_R$ are the translational and rotational displacements.

There are a few different manners for the decomposition of velocity potential and wave elevation. In the present study, the following decompositions are adopted.

$$\phi(\vec{x},t) = \Phi(\vec{x},t) + \phi_I(\vec{x},t) + \phi_d(\vec{x},t) \tag{8}$$

$$\zeta(\vec{x},t) = \zeta_I(\vec{x},t) + \zeta_d(\vec{x},t) \tag{9}$$

where Φ, ϕ_I, ϕ_d are the basis, incident, and disturbance potentials. In addition, $\zeta_I(\vec{x},t)$ and $\zeta_d(\vec{x},t)$ are the elevations of incident and disturbance waves. It is assumed that the orders of the basis and disturbance components are as below:

$$\Phi \sim O(1),\ \phi_d \sim O(\varepsilon),\ \zeta_d \sim O(\varepsilon) \quad (\varepsilon << 1) \tag{10}$$

Linear and Weak-Scatterer Formulations for Free Surface

For a body with zero or non-zero speed, the linear free-surface boundary condition has been widely used.

Table 1 Linear and weak-scatterer formulations for free surface boundary conditions.

Formulation	Linear	Weak-scatterer
Order assumption	$\phi_I \sim O(\varepsilon)$, $\zeta_I \sim O(\varepsilon)$	$\phi_I \sim O(1)$, $\zeta_I \sim O(1)$
Kinematic condition	$\frac{\partial\zeta_d}{\partial t} - (\vec{U} - \nabla\Phi)\cdot\nabla\zeta_d = \frac{\partial^2\Phi}{\partial z^2}\zeta_d + \frac{\partial\phi_d}{\partial z} + (\vec{U} - \nabla\Phi)\cdot\nabla\zeta_I$ (11)	$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I)\cdot\nabla\right]\zeta_d = -\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I - \nabla\phi_d)\cdot\nabla\right]\zeta_I + \frac{\partial\Phi}{\partial z} + \frac{\partial\phi_I}{\partial z} + \frac{\partial\phi_d}{\partial z} + \zeta_d\left[\frac{\partial^2\Phi}{\partial z^2} - \nabla\left(\frac{\partial\Phi}{\partial z} + \frac{\partial\phi_I}{\partial z}\right)\cdot\nabla\zeta_I\right]$ (13)
Dynamic condition	$\frac{\partial\phi_d}{\partial t} - (\vec{U} - \nabla\Phi)\cdot\nabla\phi_d = -\frac{\partial\Phi}{\partial t} - g\zeta_d + \left[\vec{U}\cdot\nabla\Phi - \frac{1}{2}\nabla\Phi\cdot\nabla\Phi\right] + (\vec{U} - \nabla\Phi)\cdot\nabla\phi_I$ (12)	$\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I)\cdot\nabla\right]\phi_d = -\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I)\cdot\nabla\right]\phi_I + \frac{1}{2}\nabla\phi_I\cdot\nabla\phi_I - \left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi)\cdot\nabla\right]\Phi + \frac{1}{2}\nabla\Phi\cdot\nabla\Phi - g(\zeta_I + \zeta_d) - \zeta_d\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I)\cdot\nabla\right]\frac{\partial\phi_I}{\partial z} - \zeta_d\left[\frac{\partial}{\partial t} - (\vec{U} - \nabla\Phi - \nabla\phi_I)\cdot\nabla\right]\frac{\partial\Phi}{\partial z}$ (14)
Surface to be applied	on $z = 0$	on $z = \zeta_I(\vec{x},t)$

In the present study, two different conditions are considered. The both formulations are based on the assumption that the disturbance due to the body motion is not very large. This assumption is not valid when the body motion is so large that flow disturbance in fluid domain is very strong. However, for slender bodies, this assumption has been widely accepted for seakeeping analysis. The two formulations are summarized in Table 1.

The fully nonlinear free-surface boundary conditions can be also considered. However, a proper numerical modeling for fully nonlinear conditions is not an easy task in the potential theory, particularly when free surface becomes very violent.

Nowadays, the fully nonlinear conditions can be treated by using CFD programs, but it is beyond our present study. It should be mentioned that the dynamic conditions include the time-difference terms of the basis flow. When the body speed is a function of time, these terms should be considered. Furthermore, even for the case which the body speed is steady, the basis flow in the weak-scatterer formulation is not steady since the body surface is varying depending on the exact wetted surface. This will be mentioned later.

Rigid-Body Motion with Constant Forward Speed

The body boundary condition can be also formulated into two manners. In the case of linear formulation, the body motion can be considered as a summation of 6-DOF components. Then, the body boundary conditions for the basis and disturbance flow can be written as follows:

$$\frac{\partial \Phi}{\partial n} = \vec{U} \cdot \vec{n}, \quad \frac{\partial \phi_d}{\partial n} = \sum_{j=1}^{6} \left(\frac{\partial \xi_j}{\partial t} n_j + \xi_j m_j \right) - \frac{\partial \phi_I}{\partial n} \qquad \text{on } \bar{S}_B \tag{15}$$

where $\bar{S}_B$ means the mean body surface below still-water level, and

$$\begin{aligned} &(n_1, n_2, n_3) = \vec{n}, \quad (n_4, n_5, n_6) = \vec{x} \times \vec{n} \\ &(m_1, m_2, m_3) = (\vec{n} \cdot \nabla)(\vec{U} - \nabla \Phi), \\ &(m_4, m_5, m_6) = (\vec{n} \cdot \nabla)(\vec{x} \times (\vec{U} - \nabla \Phi)) \end{aligned} \tag{16}$$

The subscript notation indicates the direction of motion, i.e. 1, 2, 3 implies *x, y, z*, respectively.

The other pair of body boundary condition can be written as follows:

$$\frac{\partial \Phi}{\partial n} = \vec{U} \cdot \vec{n}, \quad \frac{\partial \phi_d}{\partial n} = \frac{\partial \vec{\delta}}{\partial t} \cdot \vec{n} - \frac{\partial \phi_I}{\partial n} \qquad \text{on } S_B \tag{17}$$

Here, S_B means the body surface wetted by incident waves. Therefore, the body condition for the basis flow as well as the disturbed flow should be applied on S_B.

The equation of motion can be simply written as

$$[M]\{\ddot{\xi}\} = \{F_{Res.}\} + \{F_{F.K.}\} + \{F_{H.D.}\} + \{F_{others.}\} \tag{18}$$

where $[M]$ and $\{\ddot{\xi}\}$ are the mass matrix and acceleration vector of the body motion. $\{F_{Res.}\}$, $\{F_{F.K.}\}$, and $\{F_{H.D.}\}$ are the restoring, Froude-Krylov(FK) and hydrodynamic forces, respectively. Furthermore, $\{F_{others.}\}$ means all other external and/or internal forces such as force due to appendage(s) or sloshing-induced force in liquid cargo.

Linear pressure on the body surface can be written as follows:

$$\begin{aligned} p = &-\rho \left(\frac{\partial}{\partial t} - (\vec{U} - \nabla \Phi) \cdot \nabla \right) \Phi - \rho \left(\frac{\partial}{\partial t} - (\vec{U} - \nabla \Phi - \nabla \phi_I) \cdot \nabla \right) \phi_I \\ &- \rho \left(\frac{\partial}{\partial t} - (\vec{U} - \nabla \Phi - \nabla \phi_I) \cdot \nabla \right) \phi_d + \frac{1}{2} \rho \nabla \Phi \cdot \nabla \Phi \\ &+ \left(\frac{1}{2} \rho \nabla \phi_I \cdot \nabla \phi_I \quad \text{in weak-scatterer} \right) \end{aligned} \tag{19}$$

The last term is valid when the weak-scatterer formulation is applied. The hydrodynamic force can be obtained from the integration of disturbed pressure on the body surface either under still-water level, i.e. $\bar{S}_B$, or wetted by incident wave, i.e. S_B, depending on the type of the free-surface boundary conditions. On the other hand, the Froude-Krylov force can be obtained by integrating the pressure terms of only incident wave. Restoring force can be obtained by integrating hydrostatic pressure. It should be mentioned that both FK and restoring forces can be considered either with or without the correction of instantaneous body motion. That is, the change of wetted body geometry can be considered in the computation of restoring and FK forces, providing nonlinear effects on the total force.

For the basis flow, two candidates are the most popular: double-body flow and uniform flow. Using the potential of uniform flow is so called Neumann-Kelvin approach. The Neumann-Kevin formulation can be defined simply by substituting $\Phi = \vec{U} \cdot \vec{x}$, however an extra effort is needed for the double-body flow to solve the first boundary condition of Eq. 15 or 17.

Flexible-Body Motion: Hull-Girder Hydroelasticity

When the body structure is flexible not rigid, the boundary value problem becomes more complicated. Moreover, structural response should be considered and coupled with hydrodynamic problem. Recently this has been introduced by Kim et al. (2009b, 2010b) by using the present hydrodynamic formulation and a sophisticated beam approximation for ship structure. In this paper, the detailed description and methodology for structural analysis are not introduced, and only the hydrodynamic solutions are mentioned. If the body flexibility is not ignorable, the equation of motion for the 6-DOF global body motion, i.e. Eq. 18 cannot be directly applied. The equation of motion should be considered at each segment or part of the body structure and hull surface. For instant, the body boundary condition defined in Eq. 4 should be used at each surface location.

When the fluid flow is coupled with structural response, the coupled boundary value problem should be solved. The following compact equations are a set of typical coupled equation:

$$\begin{aligned} \mathrm{f} &= \mathrm{p} - \mathrm{F}\left(\mathrm{d}, \dot{\mathrm{d}}, \varphi_{\mathrm{f}}\right) = 0 \qquad \text{in } \Omega_F \cup \partial\Omega_F \\ \mathrm{s} &= \dot{\mathrm{U}} - \mathrm{S}\left(\mathrm{p}\right) = 0 \qquad \text{in } \Omega_S \cup \partial\Omega_S \end{aligned} \tag{20}$$

Here, the fluid and structure problems in computational domains Ω_F and Ω_S are notated as f and s respectively. p represents the surface pressure or local force on the structural surface, i.e. $\partial\Omega_B$, and $\mathrm{d}, \dot{\mathrm{d}}$ are the deformation displacement and deformation velocity at a node. φ_{f} indicates the velocity potential on free surface.

Eq. 20 means that the deformation and deformation velocity are a set of input for the fluid field equation, while structural responses is dependent on the dynamic loads due to fluid flow. Therefore, in this approach, the fluid flow problem requires the kinematic boundary condition on the common boundary of fluid and structure, i.e. $\partial\Omega_B$. When dynamic pressure is obtained, this pressure should be used as input for the structural analysis which provides the kinematic responses as a part of solution. This coupling scheme is an essence of most of the fluid-structure interaction problems.

A special care should be given to the restoring force when the hydroelastic response of hull structure is a part of solution. Since the body surface is flexible, normal vector on the body surface varies. In the case of linear formulation, the leading order component of the change of normal vector should be considered. For instant, the restoring force can be written as

$$\vec{F}_{restoring} = -\rho g \iint_{\bar{S}_B} \left\{ \bar{Z}\delta\vec{n} + \delta Z\vec{n} \right\} ds \tag{21}$$

where $\bar{Z}$ is water head on the body surface at its mean position, and $\delta\vec{n}$ and δZ denote the leading order variations of the normal vector and water head.

Ship Maneuvering Coupled with Ship Motions in Waves

When the body motion is advancing with a non-constant speed, e.g. ship maneuvering problem, the problem becomes more complicated. A technical difficulty is that the BVP should include the temporal and spatial variations due to the change of heading speed and angle. Another difficulty comes from the strong influence of nonlinear and/or viscous components during the change of the body speed and heading.

To solve the unsteady ship maneuvering problem, two different Cartesian coordinates are adopted: one for the body-fixed system which seakeeping problem is defined, and the other for global coordinate. The relationship of these two coordinates is as follows:

$$\begin{aligned} X &= x\cos\psi_0(t) - y\sin\psi_0(t) + X_0(t) \\ Y &= y\sin\psi_0(t) + y\cos\psi_0(t) + Y_0(t) \\ Z &= z \end{aligned} \tag{22}$$

where $X_0(t)$, $Y_0(t)$, $\psi_0(t)$ indicates the coordinate and heading angle of the ship motion center at time *t*. For instant, by using this, the velocity potential of regular incident wave of heading angle χ can be written as

$$\begin{aligned} \phi_I = \frac{gA}{\omega} e^{kz} \sin\{ & kx\cos(\chi - \psi_0(t)) + \\ & ky\sin(\chi - \psi_0(t)) + kX_0(t)\cos\theta + kY_0(t)\sin\theta - \omega t\} \end{aligned} \tag{23}$$

Particularly, in this problem, the difficulty on the treatment of basis flow can be slightly reduced by applying the following decomposition of the velocity potential:

$$\phi(\vec{x},t) = -\vec{U}(t)\cdot\vec{x} + \phi_I(\vec{x},t) + \phi_d(\vec{x},t) \tag{24}$$

In the ship maneuvering problem, 4-DOF motions are of primary interest in the global coordinate system, i.e.

$$\begin{aligned} m\left(\dot{u}_0 - v_0 r_0\right) &= F_{X,H} + F_{X,P} + F_{X,R} + F_W \\ m\left(\dot{v}_0 + u_0 r_0\right) &= F_{Y,H} + F_{Y,R} + F_{Y,W} \\ I_{xx}\dot{p}_0 &= F_{K,H} + F_{K,R} + F_{K,W} \\ I_{zz}\dot{r}_0 &= F_{N,H} + F_{N,R} + F_{N,W} \end{aligned} \tag{25}$$

where the subscripts *X, Y, K, N* represent each directional component, and *H, P, R* indicate the force on hull, propeller and rudder. In addition, *W* means the mean drift force which should be obtained from seakeeping analysis. The hull force consists of many linear and nonlinear components due to motion, turning, resistance and so on. The boundary value problem described above can take care of only a part of the hull force. Therefore, more force components should be considered for the hull force. Such component can be obtained from some empirical formulae or model test. Module-type model (MMG) is one of the most popular models for such purpose.

In the presence of incident wave and resultant body motion, a ship can experience planar drift motion during turning motion. An accurate prediction of such drift motion is one of crucial element in the prediction of motion trajectory. In the present study, the following equation is introduced for the mean drift force due to the incident wave and ship motion under unsteady motion:

$$\begin{aligned}\vec{F}_W &= \rho g \int_{WL} \frac{1}{2}\left(\eta-(\xi_3+\xi_4 y-\xi_5 x)\right)^2 \cdot \vec{n} dl \\ &-\rho \iint_{S_B} g(\vec{z}+Z_0)\cdot \vec{n}_2 dS \\ &-\rho \iint_{S_B} \frac{1}{2}\nabla(\phi_I+\phi_d)\cdot\nabla(\phi_I+\phi_d)\cdot \vec{n} dS \\ &-\rho \iint_{S_B} g(\xi_3+\xi_4 y-\xi_5 x)\cdot \vec{n}_1 dS \\ &-\rho \iint_{S_B} \left(\frac{\partial(\phi_I+\phi_d)}{\partial t}-\vec{U}\cdot\nabla(\phi_I+\phi_d)\right)\cdot \vec{n}_1 dS \\ &-\rho \iint_{S_B} \vec{\delta}\cdot\nabla\left[\frac{\partial(\phi_I+\phi_d)}{\partial t}-\vec{U}\cdot\nabla(\phi_I+\phi_d)\right]\cdot \vec{n} dS\end{aligned} \tag{26}$$

where $\vec{n}_1$ and $\vec{n}_2$ are the first-order and second-order components of normal vector on the ship surface. In the case of the Neumann-Kelvin linearization scheme, all terms which contain Φcan be ignored.

DEVELOPMENT OF WISH PACKAGE

Global Scope of WISH Development

There are two main common goals in seakeeping analysis. One is the analysis of motion dynamics in actual sea conditions. Besides the prediction of motion RAOs and spectra in voyage condition, many other engineering issues are of interests in recent marine engineering. For instant, a significant amount of effort is made for study on dynamic stability such as parametric rolling, capsizing, motion dynamics of multiple adjacent bodies, the effects of finite depth with varying bathymetry, and the coupling effects of sloshing and mooring lines. The other goal of seakeeping analysis is to predict or analyze the structural responses due to dynamic body motion. For instant, FE analysis of hull structure requires a set of input, i.e. dynamic loads, on hull surface.

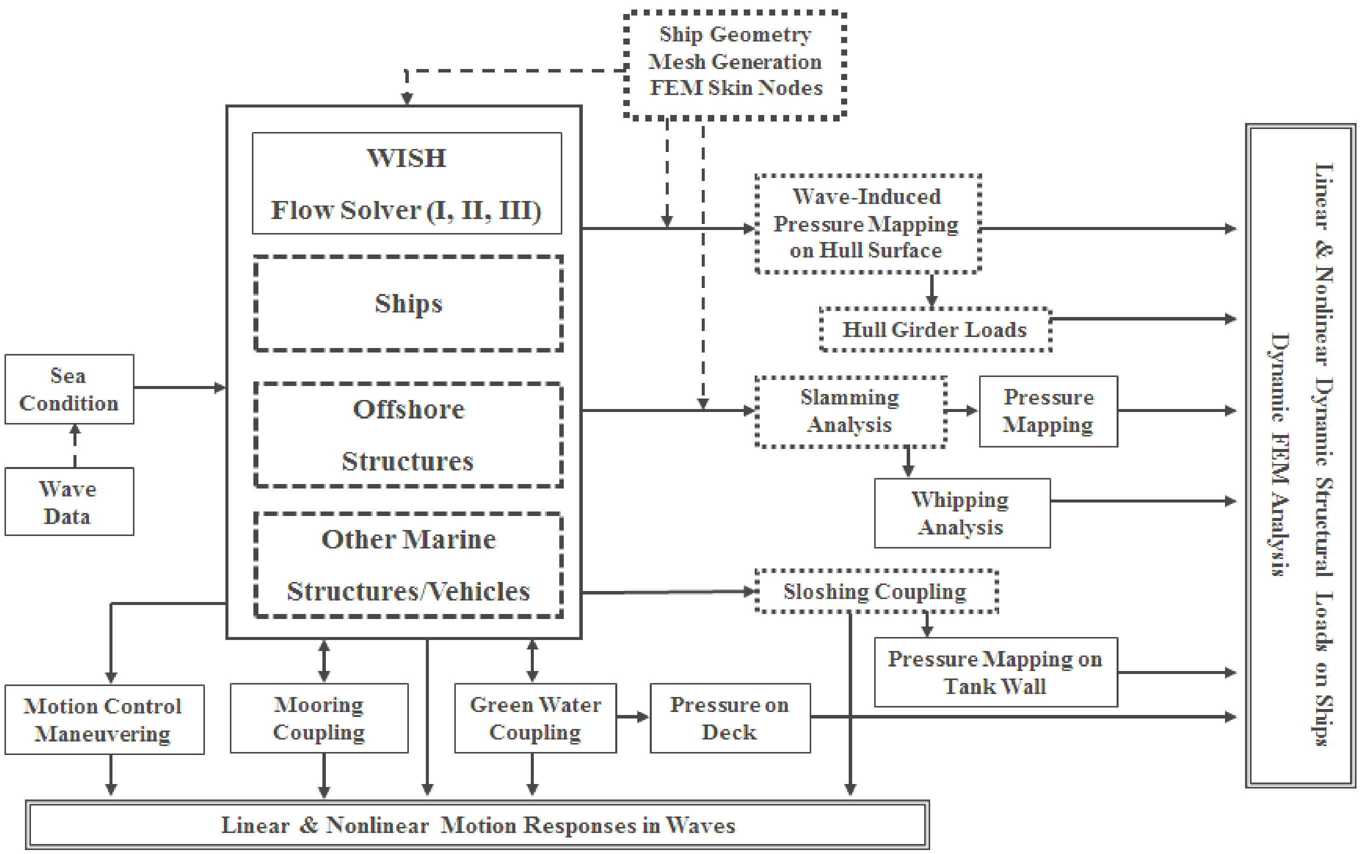


Fig. 2 Overall scope of WISH development.

For this purpose, an extra work is needed for transferring the solution of hydrodynamic problem to structural solver. Pressure mapping is a good example of such extra work. Sometimes the two problems, hydrodynamics and structure dynamics, should be solved simultaneously, e.g. springing problem.

The present study aims the development of a program package which is applicable to some representative seakeeping problems. When a main flow solver is developed, it can be extended to many seakeeping problems. In our research, a computer program called WISH has been developed as the main solver of fluid flow and floating body motion. Then WISH has been applied and extended to many problems for ships and offshore structures.

Fig. 2 shows the overall scope of WISH development. The key functions of current WISH package includes:

- linear ship motion analysis in time domain (WISH 1)
- weakly nonlinear ship motion analysis in time domain (WISH 2)
- weak-scatterer-based nonlinear ship motion analysis in time domain (WISH 3)
- wave-induced hull-girder hydroelasticity analysis including springing (WISH-FLEX)
- motion control and passenger comfort analysis (WISH-CRUISE)
- motion analysis of multiple adjacent floating bodies in waves with and without forward speed (WISH-NBODY)

Fluid Flow Solver: Three-Dimensional Rankine Panel Method

The main flow solver for the boundary value problems described above is based on a three-dimensional Rankine panel method. Particularly a time-domain analysis is applied in this development. The body geometry is discretized into a set of flat panels, but the physical variables, i.e. velocity potential, wave elevation, and normal flux along fluid boundary, are approximated by using B-spline basis function, as follows:

$$\begin{aligned} \phi_d(\vec{x},t) &= \sum_j (\phi_d)_j(t)B_j(\vec{x}) \\ \zeta_d(\vec{x},t) &= \sum_j (\zeta_d)_j(t)B_j(\vec{x}) \\ \frac{\partial \phi_d}{\partial n}(\vec{x},t) &= \sum_j \left(\frac{\partial \phi_d}{\partial n}\right)_j (t)B_j(\vec{x}) \end{aligned} \tag{27}$$

where, $B_j(\vec{x})$ is the basis function and $(\phi_d)_j$, $(\zeta_d)_j$ and $(\partial\phi_d / \partial n)_j$ are the potential coefficient, wave elevation coefficient and normal flux of potential coefficient, respectively. This combined technique has been used in the development of SWAN (Kring *et al.*, 1996). This representation can be substituted in the boundary value problem described above along with the Green second identity such that

$$\phi_d + \iint_{S_B} \phi_d \frac{\partial G}{\partial n} dS - \iint_{S_F} \frac{\partial \phi_d}{\partial n} G dS = \iint_{S_B} \frac{\partial \phi_d}{\partial n} G dS - \iint_{S_F} \phi_d \frac{\partial G}{\partial n} dS \tag{28}$$

In time-marching, the kinematic free-surface boundary condition is solved explicitly to obtain the disturbed wave elevation, while the dynamic condition is solved implicitly to predict the velocity potential in the next time step.

$$\frac{\zeta_d^{n+1} - \zeta_d^n}{\Delta t} = P(\vec{U}^n, \zeta_d^n, \phi_d^n) \tag{29}$$

$$\frac{\phi_d^{n+1} - \phi_d^n}{\Delta t} = Q(\vec{U}^{n+1}, \zeta_d^{n+1}, \phi_d^{n+1}) \tag{30}$$

where *P* and *Q* are the forcing function of all other terms in the free-surface boundary condition explained above. In addition, the equation of motion can be solved by applying a multi-step time integration method. A popular 4th-order predictor-corrector is applied in this study.

In Rankine panel method, the source potential doesn't satisfy the radiation condition. The present study applies the concept of artificial damping zone in which the numerical damping terms are added into the kinematic free-surface boundary condition as follows:

$$\frac{d\zeta_d}{dt} = \frac{\partial \phi_d}{\partial z} - 2\nu\zeta_d + \frac{\nu^2}{g}\phi_d \tag{31}$$

where ν is so called damping strength.

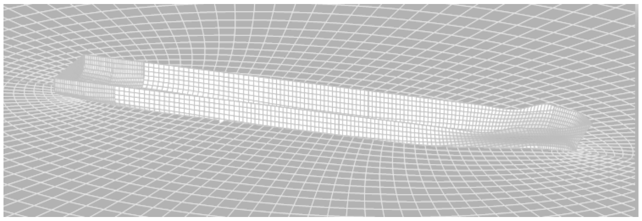
Rigid Body Motion: WISH 1,2,3

Like LAMP or SWAN packages, the different levels of nonlinear formulation are considered in WISH development. These formulations are summarized in Table 2. As the nonlinear level becomes higher, many more difficulties should be overcome in numerical implementation. The CPU time is also the major difference of these formulations. The computational times are very compatible between the linear and weakly-nonlinear formulations, i.e. WISH 1 and 2, but the weak-scatterer formulation requires a dramatic increase of computational time.

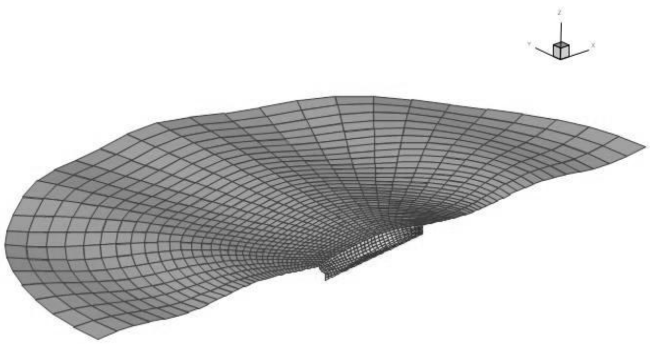
Table 2 Summary of formulations of WISH 1, 2, and 3

	WISH 1	WISH 2	WISH 3
Free-surface BC	Eq. 11, 12 on still-water level	Eq. 11, 12 on still-water level	Eq. 13, 14 on incident wave elevation
Body BC	Eq. 17 on mean surface	Eq. 17 on mean surface	Eq. 17 on wetted surface
Disturbance force	On mean surface	On mean surface	On wetted surface
Froude-Krylov force	On mean surface	On wetted surface	On wetted surface
Restoring force	On mean surface	On wetted surface	On wetted surface

In the Rankine panel method, panel generation is also different from each formulation. Solution grids in linear and weakly nonlinear formulations are basically the same. Once they are distributed on fluid boundary, they don't need to move or redistributed. However, for computing nonlinear restoring and Froude-Krylov forces, an extra effort is needed to obtain the instantaneous pressure integration on the body surface wetted by incident wave and body motion. For instant, Fig. 3(a) shows an extra set of fine meshes on the body surface above still water level. At each time step, these meshes can be checked if they are wetted, and the nonlinear force can be calculated by integrating hydrostatic and Froude-Krylov pressure quantities on these meshes. In the case of WISH 3 based on the weak-scattered formulation, the solution panels are redistributed at each time step. Therefore, a significant amount of effort is required to handle the hull geometry and incident wave profiles (Kim and Kim, 2009c).



(a) Extra surface meshes for weakly-nonlinear method(WISH 2).



(b) Solution grids for weak-scatterer formulation (WISH 3).

Fig. 3 Example of panels for WISH 2 and 3.

Modeling of Global Ship Structural Response: WISH-FLEX

When the flexibility of the body structure should be considered, the structure response can be obtained by using either 3D FE analysis or beam approximation. The former method is not enough efficient in the viewpoint of CPU time, therefore the present development is based on the latter method. The displacement $\mathbf{U}$ and velocity $\dot{\mathbf{U}}$ of the body structure can be solved by using a finite element method. The discretized finite element equation obtained from the beam approximation can be simplified into the following form:

$$[\mathrm{m}]\{\ddot{\mathbf{U}}\}+[\mathrm{c}]\{\dot{\mathbf{U}}\}+[\mathrm{k}]\{\mathbf{U}\}=\{\mathbf{f}\} \qquad (32)$$

where $[\mathrm{m}],[\mathrm{c}],[\mathrm{k}]$ are the matrices of mass, damping, and stiffness, and $\{\mathbf{f}\}$ means the external force matrix. In real engineering problems, structural damping is a very critical factor to dictate the motion amplitude in resonance condition. In this study, the damping is written as follows:

$$[\mathrm{c}]=\alpha[\mathrm{m}]+\beta[\mathrm{k}] \qquad (33)$$

Parameters α,β are determined depending on the damping ratio which is the ratio between critical damping factors to the considered one.

The coupled equation of fluid flow and beam motion, i.e. Eq. 20, can be solved by an iteration method. In this study, a fixed-point iteration scheme is used to solve the coupling equation. First, solve the structural problem with initially guessed or previously converged pressure field and obtain the structural deformation and deformation velocity, subsequently tossing it to fluid field equation. Then the new pressure field can be obtained from this equation. Note that it is assumed that linearized free-surface boundary condition is implicitly included in the fluid field equation so that the update of potentia2096l on free surface can be made at each iteration step. This is to be repeated until the solution converges, i.e. $\left|\dot{\mathrm{U}}^{\mathrm{k}}_{\mathrm{t+\Delta t}}-\dot{\mathrm{U}}^{\mathrm{k+1}}_{\mathrm{t+\Delta t}}\right|/\left|\dot{\mathrm{U}}^{\mathrm{k}}_{\mathrm{t}}\right|\prec\varepsilon$.

$$\begin{aligned}\dot{\mathrm{U}}^{\mathrm{k+1}}_{\mathrm{t+\Delta t}} &= \mathrm{S}(\mathrm{p}^{\mathrm{k}}_{\mathrm{t+\Delta t}})\\ \mathrm{p}^{\mathrm{k+1}}_{\mathrm{t+\Delta t}} &= \mathrm{F}(\dot{\mathrm{U}}^{\mathrm{k+1}}_{\mathrm{t+\Delta t}},\mathrm{U}^{\mathrm{k+1}}_{\mathrm{t+\Delta t}},\varphi^{\mathrm{k+1}}_{\mathrm{f,t+\Delta t}})\end{aligned} \qquad (34)$$

The details on numerical scheme can be found in the recent papers of Kim et al. (2009b, 2010b).

Application and Extensions

Once the main flow and structural solvers are developed, many applications and extensions are possible. For instant, any external and/or internal forces can be included to couple with the body motions. Coupling with mooring line(s), appendage effects, sloshing inside cargo, and wind force is not a difficult tasks as long as the mechanism of external and/or internal forces are given.

For example, a modular-type model(MMG) for ship maneuvering can be combined with seakeeping routine (see Fig.4). Another example can be an application to cruise vessels which have active fins for motion control. WISH can be easily coupled with the control algorithm of active fins. Furthermore the results of seakeeping analysis can be used to predict passenger comfort during voyage. This simulation-based comfort analysis can be applicable in the detailed design stage of a cruise ship, and WISH program can be the kernel program in this whole procedure.

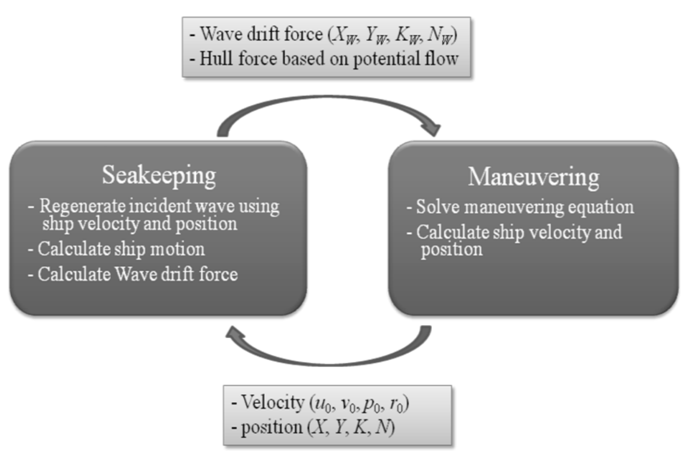


Fig. 4 Ship maneuvering analysis coupled with ship motion in waves: WISH-MANEUVER.

COMPUTATIONAL RESULTS

Validation of WISH 1, 2, 3

During WISH development, many cases have been considered for the validation of the developed program. In this paper, two representative results are introduced. At first, the computational results of WISH 1 and 2 are compared with experimental data for a 6500 *TEU* containership. The other model is a well-known S175 hull, showing the comparison between the results of WISH 1, 2, and 3.

Fig. 5 shows the motion RAOs of linear solution obtained by using WISH 1, comparing with experimental data in a wide range of frequency. Overall agreement is very obvious, but yaw motion has slight difference in low frequencies due to implementation of an artificial restoring mechanism. In the time-domain approach, a proper mechanism for non-restoring motion should be included in the motion simulation. Sometimes this mechanism can cause the difference of motion results with experimental data.

Fig. 6 compares the time-histories of vertical bending moment at different wave heights. The nonlinear solution is dependent on wave slope. The agreement is very acceptable, validating the accuracy of WISH program.

The comparisons between WISH 1, 2, and 3 are shown in Figs. 7 and 8 for S175 hull. The result of weak-scatterer approach shows best agreement with the experimental data, and the results of linear and weakly-nonlinear show reasonable correspondences, too. Particularly, Fig. 8 shows the heave and pitch motion responses at *Fn* = 0.2 for different wave slopes. The computational results of WISH are compared with the experimental data obtained by O'Dea (1992). The results of weakly-nonlinear and weak-scatterer approaches show reasonable correspondences with experimental data. Particularly the agreement of heave motion is good. This implies that the nonlinear analysis is essential to evaluate the wave-load in design wave condition. It should be mentioned that, according to the present computational experiment, the weak-scatterer formulation does not provide the best agreement with experiment in all the cases. Sometimes, it is found that the weakly-nonlinear formulation predicts nonlinear motion responses in a fair agreement range. It also should be noted that the CPU times of the weakly-nonlinear and weak-scatterer formulations are very different.

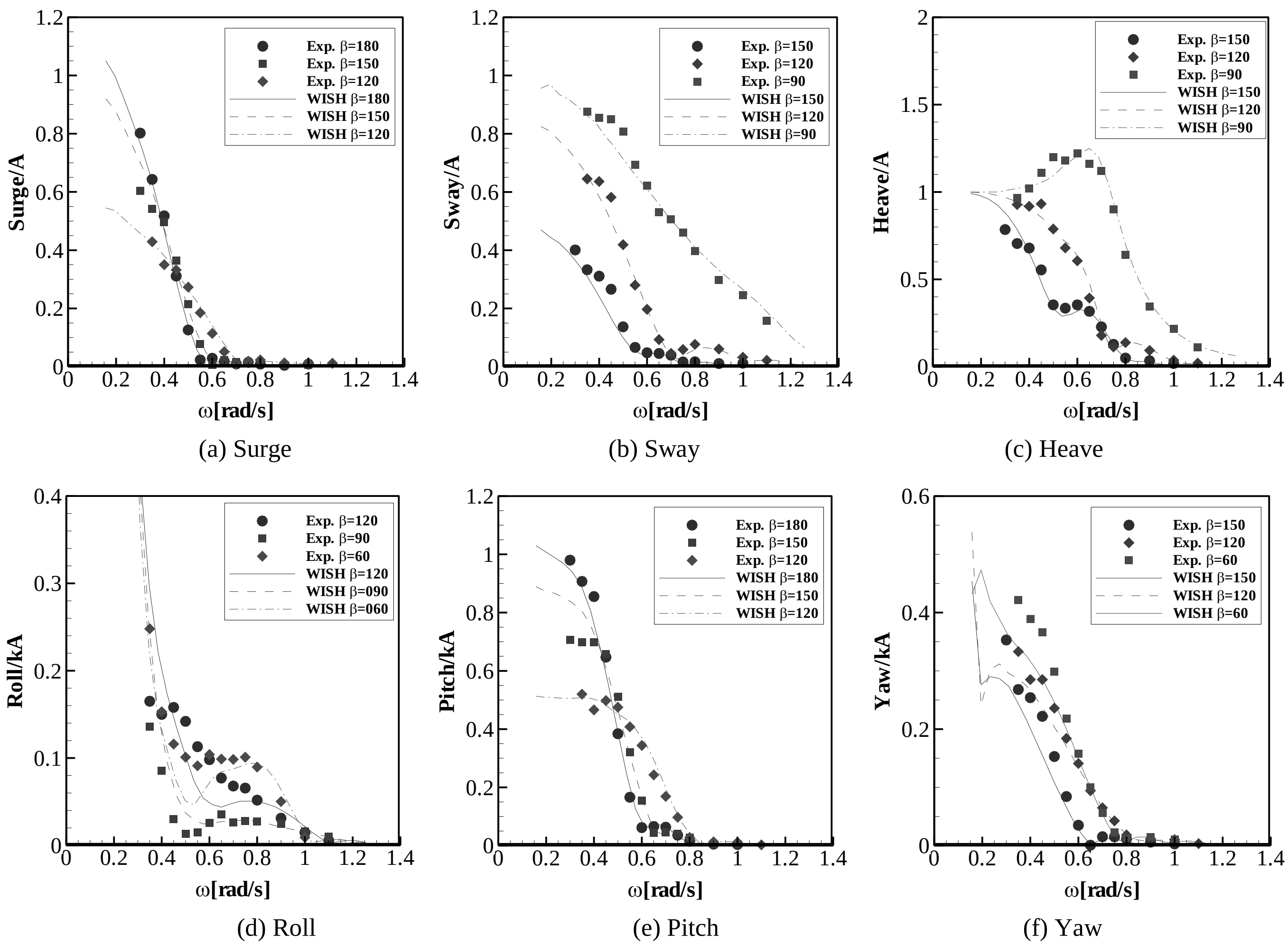
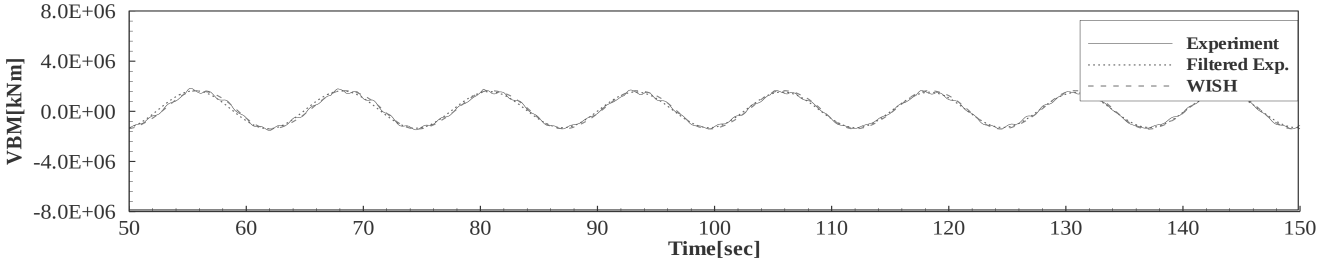
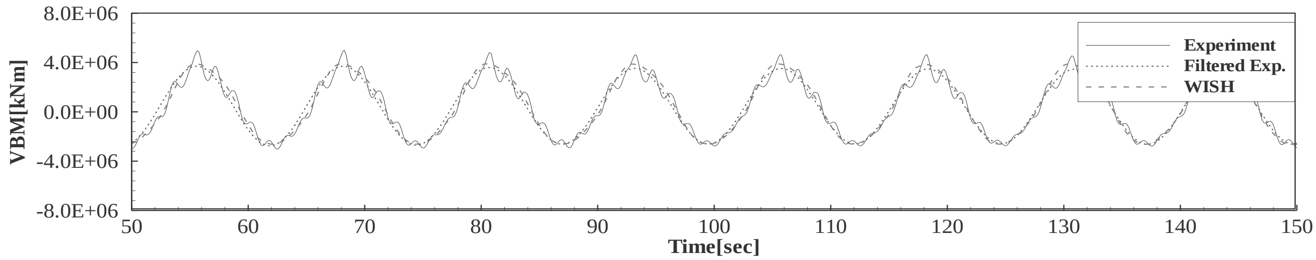


Fig. 5 RAOs of 6-DOF motions, *Fn* = 0.0485, WISH 1 (Song et al., 2011).

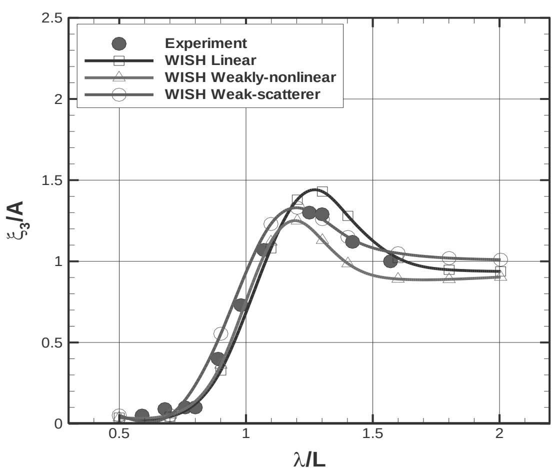


(a) H=5*m*

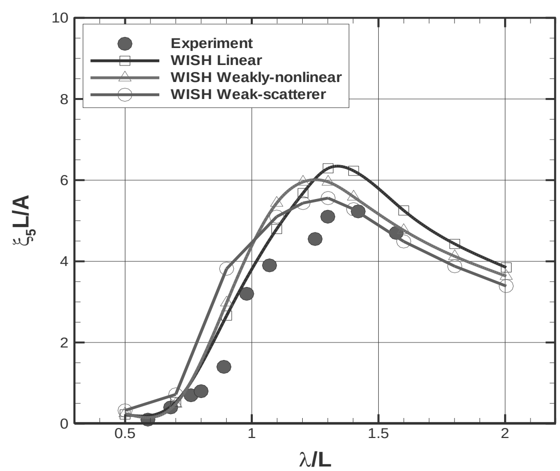


(b) H=10*m*

Fig. 6 Time-histories of vertical bending moment at mid-ship, *Fn* = 0.0485, WISH 2 (Song et al., 2011).

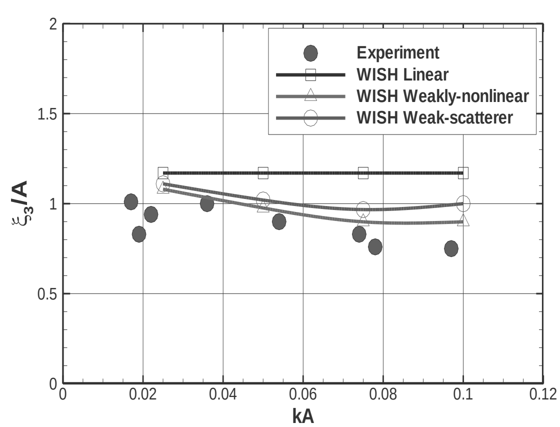


(a) Heave motion

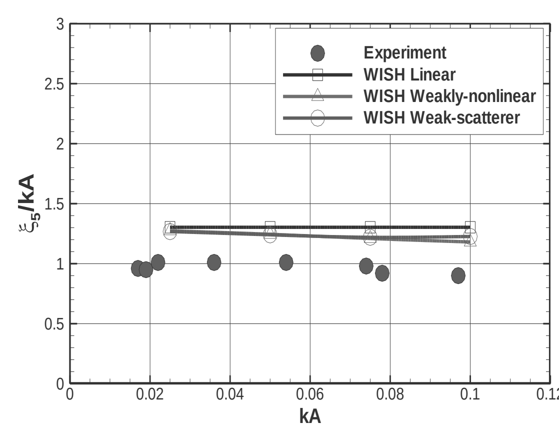


(b) Pitch motion

Fig. 7 Heave and pitch motion RAOs of S175 containership, *Fn* = 0.275, wave heading angle = 180 *deg*, A/L = 0.015



(a) Heave motion



(b) Pitch motion

Fig. 8 Heave and pitch motion RAOs of S175 containership with regard to the wave steepness, *Fn* = 0.2, wave heading angle = 180 *deg*, λ/L = 1.2.

WISH-FLEX

The computational results of WISH-FLEX have been introduced by Kim et al. (2009b, 2010b). Those papers include many test cases for verification and validation of the developed numerical scheme and program. Therefore many results are not introduced in this paper. Figs. 10 and 11 show two representative results for a 10,000 TEU containership which its solution panels are shown in Fig. 9. This vessel was tested as the industrial joint project, called WILS II JIP. The experiment was carried out at MOERI/KOREDI in 2009.

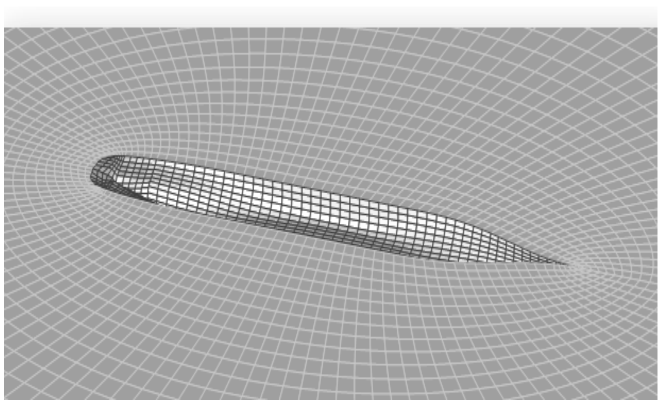


Fig. 9 Solution panels for a 10,000 TEU containership.

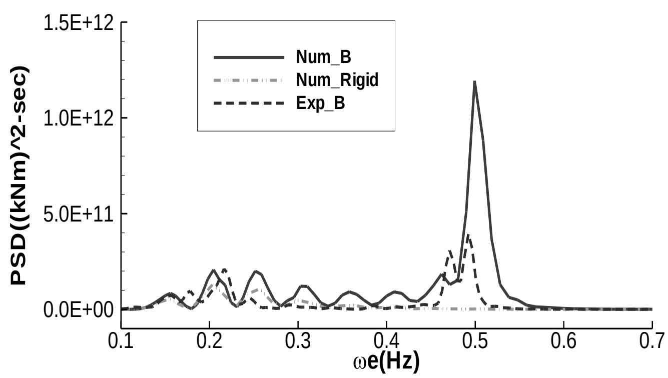


Fig. 10 Spectral density of VBM in irregular wave condition for 2nd order springing, T_p = 7.271sec, H_s = 2.1*m*, ship speed = 20 *knots*, wave heading = 150 *deg* (Kim et al., 2010b).

In Figs. 10 and 11, the spectral density of vertical bending moment in irregular wave conditions are compared, comparing the computational results for a rigid body and a flexible body with experimental observation. Particularly, these figures show the cases when the second- and third-order springing occurred. As shown in the figures, a big difference is obvious in response spectrum between rigid body and flexible body. In the case of flexible body, the difference is significant in the case of the second-order springing resonance, but a better agreement is shown in the third-order springing resonance. It is hard to make any conclusion from the present comparison with experimental data, and more comparison is essential to judge if such agreement and disagreement is meaningful.

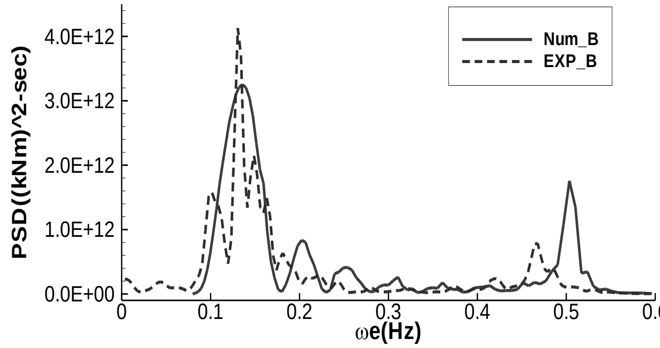


Fig. 11 Spectral density of VBM in irregular wave condition for 3rd order springing, T_p = 9.704*sec*, H_s = 3.8*m*, ship speed = 20 *knots*, wave heading = 150 *deg* (Kim et al., 2010b).

WISH-Cruise

Two major tasks are of primary interest in this application: motion control and passenger comfort analysis. In the present paper, computational results for the motion control using active stabilizing fins are introduced. The cruise ship was designed by Daewoo Shipbuilding and Marine Engineering Co., and its length is 242*m*. Fig. 12 shows the solution panels on and around the ship with a pair of stabilizing fin.

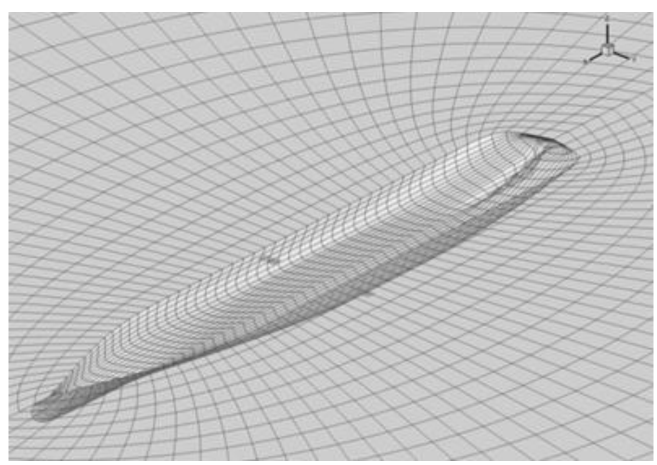
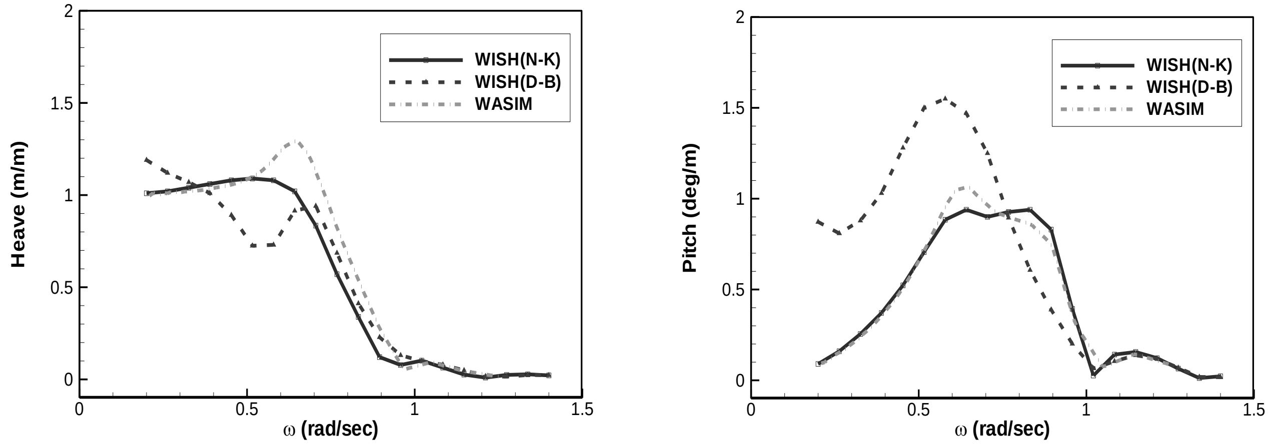


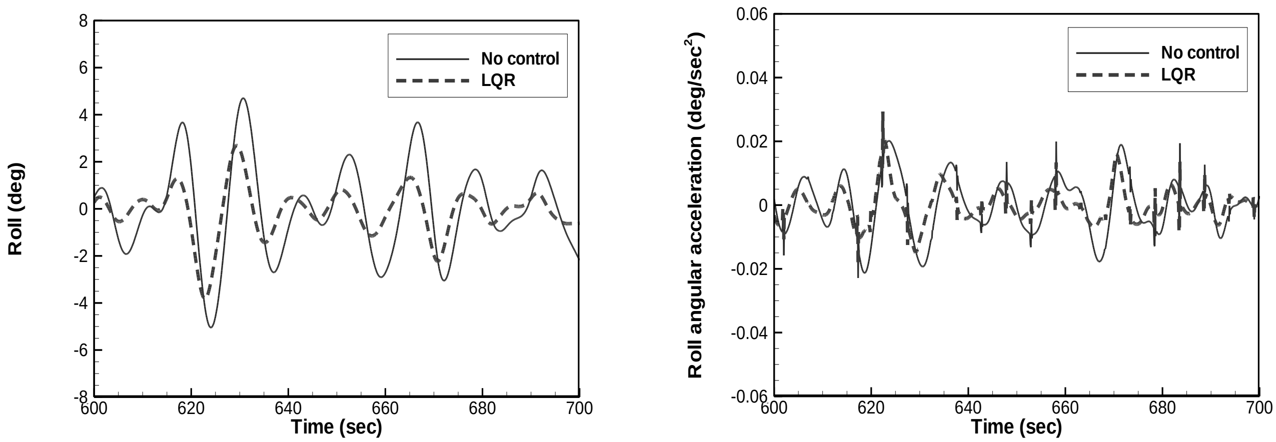
Fig. 12 Cruise ship with active control fins.

Fig. 13 shows the heave and pitch RAOs computed by two different formulations and WASIM, the computer program of DNV. In the present study, numerical computation has been carried out by applying two different basis flows: double-body flow and uniform flow. The latter is so called Neumann-Kelvin (NK) formulation. As shown in Fig. 18, the NK formulation provides more reasonable solutions than the double-body formulation. The hull forms of cruise ships are slightly different from other commercial ships, and it seems that the NK formulation is suitable for cruise ships. This observation is important in the application aspect. More systematic study for the different linearization has been introduced by Kim and Kim (2010a).



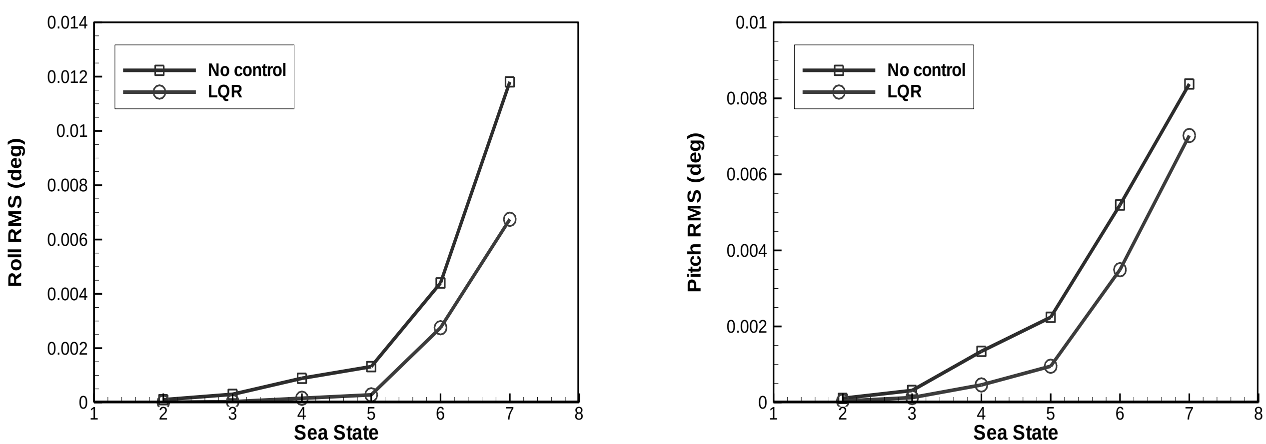
(a) Heave (b) Pitch

Fig. 13 Heave and pitch RAOs of DSME cruise ship, *Fn* = 0.316, wave heading angle =150 *deg*.



(a) Roll angle (b) Roll angular acceleration

Fig. 14 Roll motion of DSME cruise ship equipped with one pair of active fins, *Fn* = 0.211, Sea state 6, wave heading angle = 90 *deg*, fin control using LQR algorithm.



(a) Roll motion (b) Pitch motion

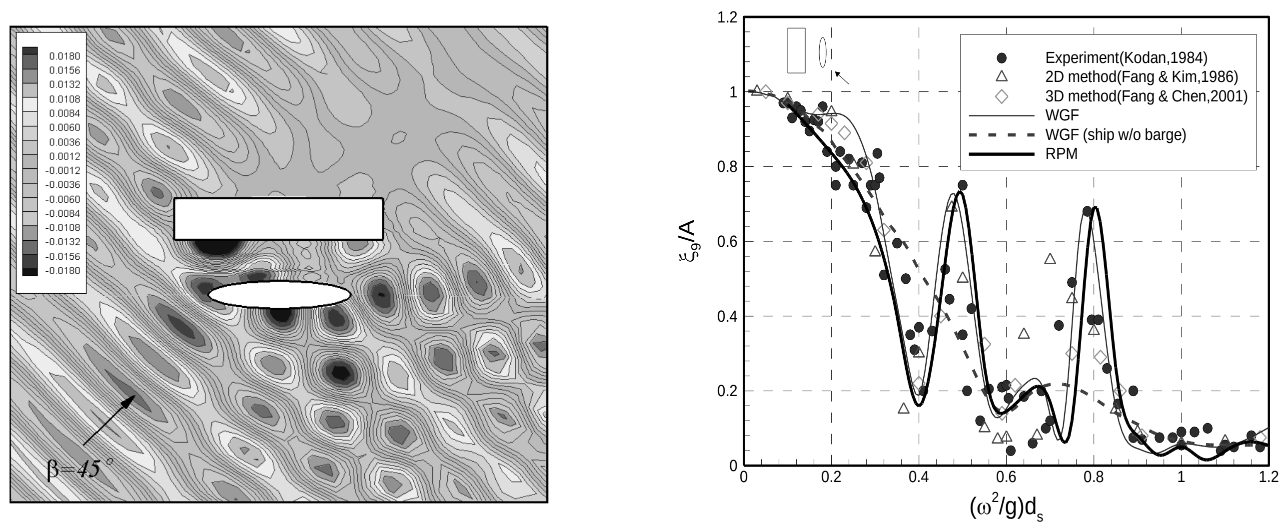
Fig. 15 Root-mean-square(RMS) of roll and pitch motion when two pairs of fins are equipped, ship speed, *Fn* = 0.211, wave heading angle = 135 *deg*, fin control using LQR algorithm.

Fig. 14 shows the roll motion control by using a pair of active stabilizing fin. In this computation, the fins are controlled to reduce the roll motion. Each fin has NACA 0012 section with 7*m* span and 3.5*m* chord. The maximum operation angle and angular velocity of each fin are ±20 *deg* and ±20 *deg/sec*, respectively. The most popular control scheme is PID control, but LQR algorithm is applied in this study. In general, the roll reduction is dramatic when the sea condition is mild. As ocean waves roughs and motion amplitude becomes large, the roll reduction ratio is not high, but still the stabilizing fins are effective as long as the ship is moving with a forward speed. Such trend is clear in Fig. 15 which shows the RMS of roll and pitch at irregular sea. In this case, it is assumed that two pairs of active fins are equipped to control both the roll and pitch motions. Generally the active fins in cruise ships are installed to reduce roll amplitude only. However, a ship with two pairs of active fins is considered to the possibility of the control of the two motions at the same time. The control of pitch motion requires a lot of power, since the pitch moment inertia is much larger than that of roll. In this study, a physically reasonable constraints and size of fins are applied, and the results are very encouraging for engineering application.

WISH-Offshore

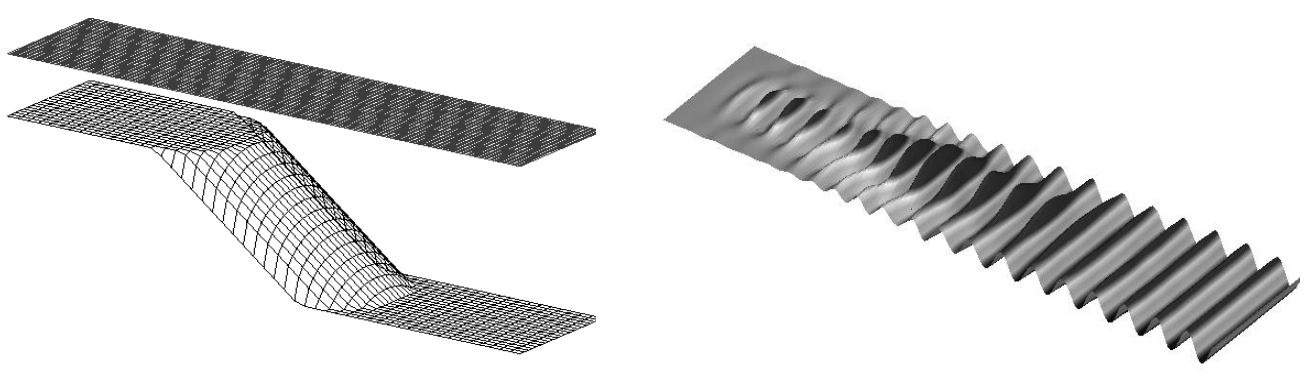
One of strong advantages of Rankine panel method is the flexibility to consider the topology of fluid boundary. Taking such merit, WISH program has been extended to the seakeeping analysis for floating bodies in finite depth, and also to the motion responses of multiple adjacent floating bodies.

The latter problem has been introduced by Kim et al. (2009a). For example, Fig. 16 shows their results by using the present Rankine panel method. More recently, WISH program has been extended to the seakeeping problem in the fluid domain with finite depth or varying bathymetry. One difficulty in this problem is how to consider incident waves. Since bottom is not constant, the incident waves should be solved as a part of solution or obtained prior to seakeeping analysis. In this study, incident waves are numerically generated as a part of solution. Fig. 17 shows an example of such wave generation in a domain with varying bottom.



(a) Instantaneous wave contour (b) Heave RAO of the ship in weather-side

Fig. 16 Instantaneous wave contour and heave motion RAOs of barge-ship model, wave heading angle = 45 *deg* (Kim et al., 2009a).



(a) Panel model of sloping bottom for shoaling (b) Wave elevation

Fig. 17 Linear shoaling in varying bottom domain: wave generation by WISH-OFFSHORE.

Fig. 18 shows a computational model for varying bathymetry. The ship is a LNG carrier of 274*m* length. This LNG carrier is assumed to be installed above sloping bottom which lies beneath two flat bottoms as shown in Fig. 25. In the upstream and downstream domains, constant water depths are considered. The sloping bottom is 300-meter long and its slope is 1/20. According to recent researches, simulating wave propagation over sloping bottom requires special treatments because nonlinear low frequency component could be generated by reflection and shoaling (Voogt, 2005; Waals, 2009). Fig. 19 shows the motion RAOs of surge, heave, and pitch, comparing the results for three different constant depths. As shown in this result, motion responses in the sloping bottom region are similar to that in constant water depth corresponding to mid-ship. In this case, mild slope does not give significant influence on floating body motion. A little difference is observed in pitch response at low frequency.

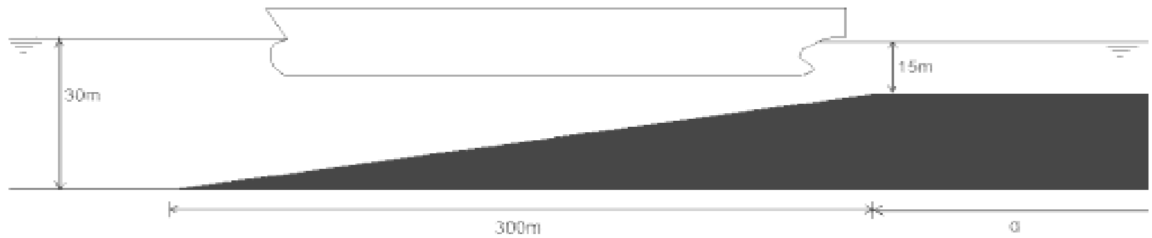
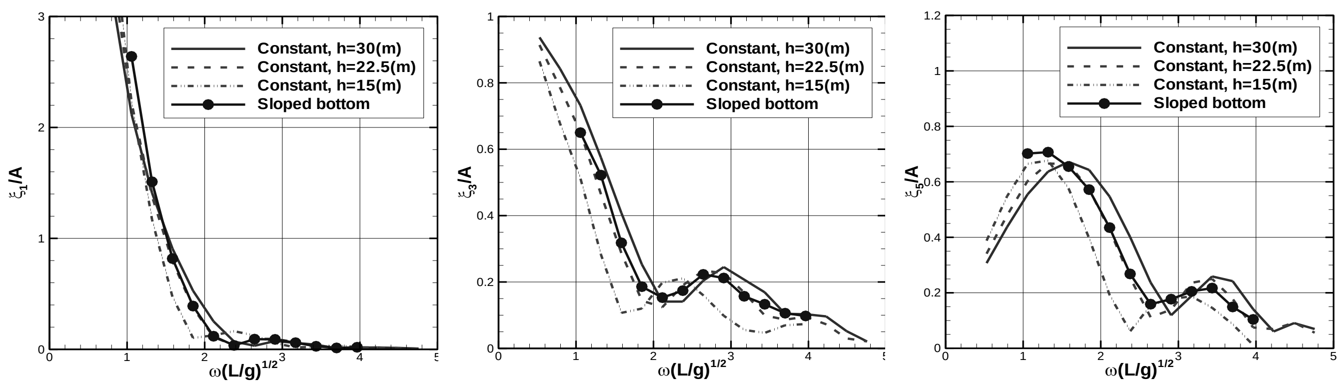


Fig. 18 Computational model for a LNG carrier in varying bathymetry.



(a) Surge (b) Heave (c) Pitch

Fig. 19 Motion RAOs of the LNG carrier in head sea.

WISH-MANEUVER

WISH-MANEUVER is the most recently developed part of WISH program for predicting ship maneuvering performance in the presence of incident wave and resultant ship motion responses. In the presence of incident wave and wave-induced floating ship motion, the hydrodynamic forces on body become different from those in calm water, so does the resultant maneuvering trajectory. Fig. 20 shows some snapshots of wave contour around of S175 under turning motion in regular incident waves. The diffraction wave contours are significant in all the snapshots. In Fig. 21, the turning trajectories at three different waves are compared with experimental data. The experiment data shown here is from the paper of Yasukawa and Nakayama(2009). The agreement of motion trajectories with experimental data is very encouraging.

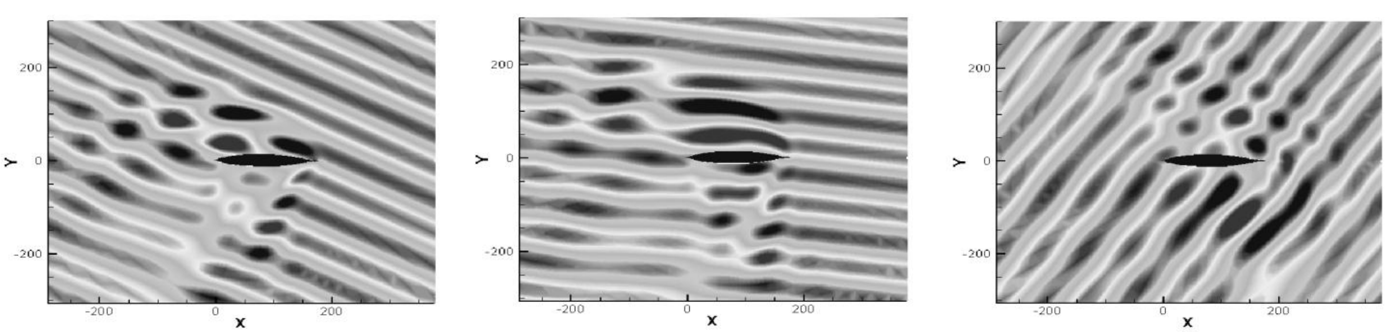
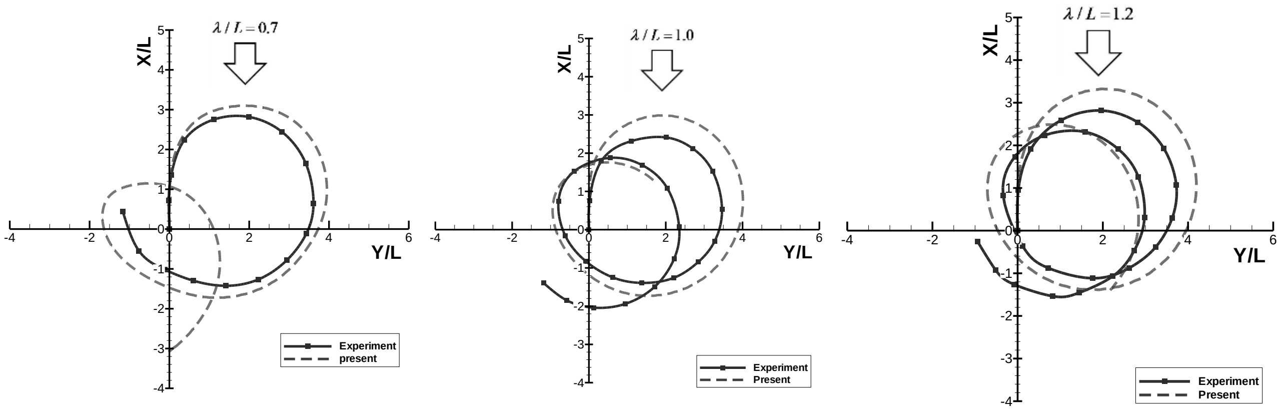


Fig. 20 Instantaneous wave contours around S175 hull: turning starts at head sea, *Fn* = 0.15, λ/L = 0.7, *A/L* = 0.01 (Seo and Kim, 2011).



(a) λ/L = 0.7 (b) λ/L = 1.0 (c) λ/L = 1.2

Fig. 21 Motion trajectories at three different wave conditions: S175 hull, turning starts at head sea, *Fn* = 0.15, *A/L* = 0.01 (Seo and Kim, 2011).

CONCLUSIONS

In the present study, a set of computer program has been developed for several different problems related to seakeeping analysis. For this development, WISH program has been developed as the kernel program for different applications and extensions. Based on the present study, the following conclusions are made:

- According to our observation during validation and applications, a higher-level nonlinear formulation provides generally the better correspondence with experimental data, particularly in rough wave condition. However, it is not the case for every ships and wave conditions. Sometimes, the linear and/or weakly nonlinear formulation provides very compatible results as long as the incident wave is not extremely high.
- The accuracy of the kernel program, i.e. WISH in our case, is very important in its extension and application. The verification and validation of flow solver and coupled routine is an essential process in the development of computer program. Particularly, the computational efficiency and the limitation of application should be well defined.
- So far, the boundary element method using Rankine panel can be a good candidate as a method of solution for many engineering problems. In the long run, CFD programs may replace the potential theory. However, most physical phenomena related to seakeeping problems have strong memory effects due to free surface flows, and the potential theory is still valid in such cases.
- The developed program, WISH, has been very successfully extended to various seakeeping problems and applied to real ships. Most of such extension and application are possible by means of coupling with internal and/or external forces. As long as a coupling system can communicate with WISH in the form of kinematics or dynamics, the coupling is not very difficult. In some cases, like hull-girder hydroelasticity, the coupling requires some modification of flow solver. Then some technical difficulties should be overcome.
- The motion RAOs and global hull-structure loads are well predicted by WISH 1, 2, 3 and other WISH programs and showed very acceptable correspondence with experimental data for many validation models. In the case of WISH-FLEX, the solution is strongly dependent on structural damping and beam modeling.
- A control system to reduce the roll and pitch motions at the same time is embedded in WISH-CRUISE. Furthermore, it is proposed to predict the passenger comfort by using WISH-CRUISE, replacing experimental measurement.
- It is expected that WISH-MANEUVER can be extended to other seakeeping problems with transient behavior. This program can handle the both seakeeping and maneuvering, not limited to a steady ship speed. To expand its capability, more effort is needed for viscous effect and an accurate prediction of lifting force.
- WISH-OFFSHORE is under development for seakeeping analysis in varying bottom topology. More validation is needed for wave making and motion response.

ACKNOWLEDGEMENTS

WISH package has been developed through several research projects, including WISH JIP Phase 1 and 2, WISH-FLEX JIP, ONR NICOP Project, and so on. The strong supports by Korean industry(HHI, SHI, DSME, STX, Hanjin, KR), ONR and ONRG, and The Lloyd's Register Education Thrust are very much appreciated.

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