Study on a Prophetic System for Real-time Ship Operation in Waves

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1 PROPHETIC SHIP OPERATION IN WAVES: BASIC IDEA

For a long time, marine hydrodynamics has relied on analytic methods based on mathematical modeling. In past decades, various numerical methods have been developed thanks to the development of computers. Currently, these theoretical and numerical techniques are used complementary to each other to analyze various marine hydrodynamics problems. Although CFD techniques are gradually expanding their application areas, physics-based analysis models still play an important role in studying various hydrodynamics problems and understanding physical phenomena in water waves and floating bodies.

Recently, dramatically expanding digital techniques are rapidly breaking into not only products of our daily lives such as AI-adopted machines and autonomous vehicles, but also the design, analysis, and operation of ships and offshore structures (Kim, 2021). This digital technique is expected to take its place as a new analysis technique comparable to mathematical and numerical analyses. In other words, a new area of analysis techniques is being created. Since these techniques do not require thorough physical understanding of engineering problems and most of them apply pure digital techniques, they may give a negative impression to those who are used to traditional physics-based analysis. These techniques clearly have weaknesses that are difficulties for physical understanding and explanation. However, if digital techniques can be combined with physics-based analysis techniques and mutually complementary applications are possible, it should be recognized that such a combination can provide more practical functions and can be applied to more complicated engineering problems.

In this study, an example of research that can link the traditional marine hydrodynamics and the concept of digital techniques is presented. The example is a prophetic digital twin for ship operation in waves. It is our dream to operate a marine vehicle or structure while presciently recognizing future situations in the ocean. If it is possible to foresee the motion, loads, and risk of the ship or offshore structure caused by the ocean waves occurring at sea, it is possible to avoid many dangers and also optimize operational costs. The real-time digital twin for ship operation has been introduced by Lee et al. (2022(a), 2022(b)), and this abstract introduces the main concept and key results of these studies.

Figure 1: Prophetic ship operation

2 KEY PROBLEMS AND THEORIES

The main goal of this study is to develop an integrated platform for ship operation in actual seaways, which can predict the wave and ship responses, particularly working in real time. To this end, we need three essential elements: 1) ocean wave prediction, 2) analysis of ship hydrodynamic performance, and 3) ship control algorithm. Those are mostly based on physics-based analysis. These three main parts must be integrated into one system, and the integrated system must have the ability to predict what the ship will experience in the near future during its voyage. Particularly the prediction must be possible in real time. Fig. 2 shows the main parts of this approach.

2.1 Wave reconstruction and prediction in real time

There are two main processes in ocean wave prediction: wave reconstruction using the sequence images measured by X-band wave radar, and wave prediction using the information of the reconstructed wave field.

The former was briefly introduced by Nam et al. at 36th IWWWFB(2022), and the details are described in their articles(Nam et al., 2023).

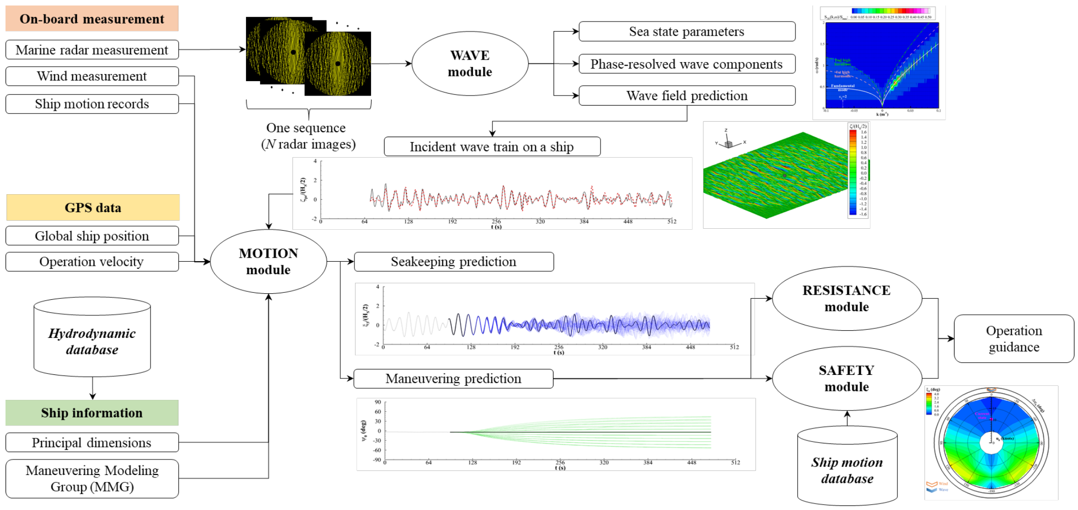

Figure 2: Concept and flowchart of real-time prediction system (Lee et al. 2022(a))

Particularly, they showed that the accuracy of significant wave height estimation, taking into account the shadowing effects in the radar images, is important in the overall accuracy of wave reconstruction. One of the key improvements of this study is the adoption of Smith function to estimate the probability of wave slope. The standard deviation of wave slope, w_{est}, was estimated by relating the illumination ratio of images (measurement) and the Smith function (theory), i.e.

$$S\left(\mu(r);w_{est}(\theta)\right)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\hat{S}\left(\zeta,q,\mu(r);\sigma,w_{est}(\theta)\right)\times\frac{1}{2\pi\sigma w_{est}(\theta)}\exp\left(-\frac{\zeta^2}{2\sigma^2}-\frac{q^2}{2w_{est}^2}\right)d\zeta\,dq=\frac{1}{T}\sum_t\Omega(r,\theta,t)\Delta t$$

where $\zeta(x,y,t)$ and $q(x,y,t)$ are wave elevation and slope, and σ is the standard deviation of wave elevation. μ is the angle of radar ray. $\hat{S}(\zeta_0,q_0,\mu(r);\sigma,w_{est}(\theta))$ is the shadowing probability density function which denotes the probability density for shadowing will not occur at the measurement point. The last term is the integration of visual function $\Omega(r,\theta,t)$ over a certain time window T. This term indicates the illumination ratio of radar images over a certain time window T. The visual function $\Omega(r,\theta,t)$ is 0 or 1, depending on the shadowed or non-showed area. Significant wave height H_S is obtained using the followings relation:

$$H_S=\frac{g w_{total} T_4^2}{\pi^2}\quad \text{where } w_{total}=\mathrm{RMS}\left\{\sqrt{w_{est}^2(\theta)+w_{est}^2(\theta+\pi/2)}\right\}\text{ and } T_4=2\pi\left(\frac{m_0}{m_4}\right)^{1/4}$$

Here, m_n means the n-th moment of wave spectrum which can be ontained from the 3D Fourier analysis of the measured images. In their study, more calibration techniques such as energy-level calibration are applied, and the details can be found in their articles.

The prediction using the reconstructed wave field was introduced by Lee et al. (2022(b)). The wave prediction zone is dependent on the group velocities (c_g) and heading of ocean wave components (χ) and ship speed (U). The predictable zone of ocean waves is defined when the Prediction Index (PI) at spatial locations is over 0.8. PI is defined as follows:

$$PI(x,y,t)=\frac{\sum\sum\sum S_{PR,mnj}\left(k_{x,m},k_{y,n},\omega_j\right)dk_x dk_y d\omega}{\sum\sum\sum S_{RC,mnj}\left(k_{x,m},k_{y,n},\omega_j\right)dk_x dk_y d\omega},\qquad for\ \left(x_{mnj}^*,y_{mnj}^*\right)\in\text{measuring region}$$

where $x^*_{mnj} = x + (t^* - t) C_{g,mn} \cos \chi_{mn}$ and $y^*_{mnj} = y + (t^* - t) C_{g,mn} \sin \chi_{mn}$. The subscripts m and n indicate the indices of wave components into x and y directions, and their wave numbers are $k_{x,m}$ and $k_{y,n}$. ω_j is wave frequency component, and the superscript * means the time when wave reconstruction is carried out. S_{PR} and S_{RC} are the 3D wave spectra of predicted and reconstructed zones. Therefore, PI represents the energy of predictable waves.

2.2 Prediction of ship responses in real time: SNU-SISO

The prediction of ship responses in waves requires all components of ship hydrodynamics, including resistance, propulsion, seakeeping, and manoeuvring. Table 1 summarizes the methods and sources of ship hydrodynamic analyses for such hydrodynamic components.

Table 1. Summary of hydrodynamic elements and analysis methods

Hydrodynamic problem		Theory and analysis methods
Seakeeping	Ship motion	Impulse response function method, hydrodynamic coefficients by slender-body theory or Rankine panel method
		Wave-induced mean force based direct pressure integration of Rankine panel method
Manoeuvring	4-DOF planar motion	MMG model, manoeuvring coefficients obtained from experimental or numerical PMM test
Seakeeping-Manoeuvring Coupling		Two-time scale for seakeeping-manoeuvring coupling analysis
Propulsion	Speed control	Body-force propellor model, PID control of RPM
Course control	Rudder control	Linear PID control of rudder angle
Resistance	Steady resistance	Experimental database or Holtrop-Mannen method
	Added resistance	Added resistance computation using Rankine panel method or combination of SNNM and SNU formulae
	Wind force	Wind force based on empirical formula (ITTC) or wind-tunnel test
Risk prediction	Extreme motion and loads	Weakly nonlinear simulation using nonlinear Froude-Krylov and restoring forces, statistical analysis

There are many candidates as the method of solutions for hydrodynamic analyses, but we need to solve all the problems in real time. Therefore, the total analysis and simulation time must be very fast with not much loss of accuracy. The methods in Table 1 require less CPU time compared to direct numerical methods. In this study, for each element of hydrodynamic solvers, the results are validated by comparing with experimental or other computational results.

2.3 Course control and risk prediction

Ship speed and/or direction can be changed for course correction, risk avoidance, or fuel-consumption reduction. In such cases, two possible cases can be considered: control of propeller RPM (change in the speed over ground, SOG) and control of rudder (change in the course over ground, COG). For both cases, linear PID control algorithms are applied. Many scenarios must be considered to predict the optimum or alternative path of ship operation. The methods presented in Table 1 can provide analysis results in a short time so that decisions can be made based on various scenarios.

3 APPLICATION EXAMPLES

Fig. 3 shows an example of results for KVLCC2, a very large tanker, in the sea state of Beaufort scale 8. Ship speed is 15.5 knots (Froude number is 0.142). Head sea is considered, and the wave prediction zone becomes the smallest due to ship speed. 64 sequential wave radar images of 2.56km and 5.12km ranges with 1-sec interval are imposed for wave-field analysis, and wave predictions in the domain of PI>0.8 are imposed for the prediction of future ship responses. When a wider range of wave radar is measured, prediction of a longer future is possible. It is obvious that the predicted wave elevation agrees well with the exact solution, and the predicted ship motions based on IRF approach show good agreement with a time-domain Rankine panel solver, WISH-MANEUVER.

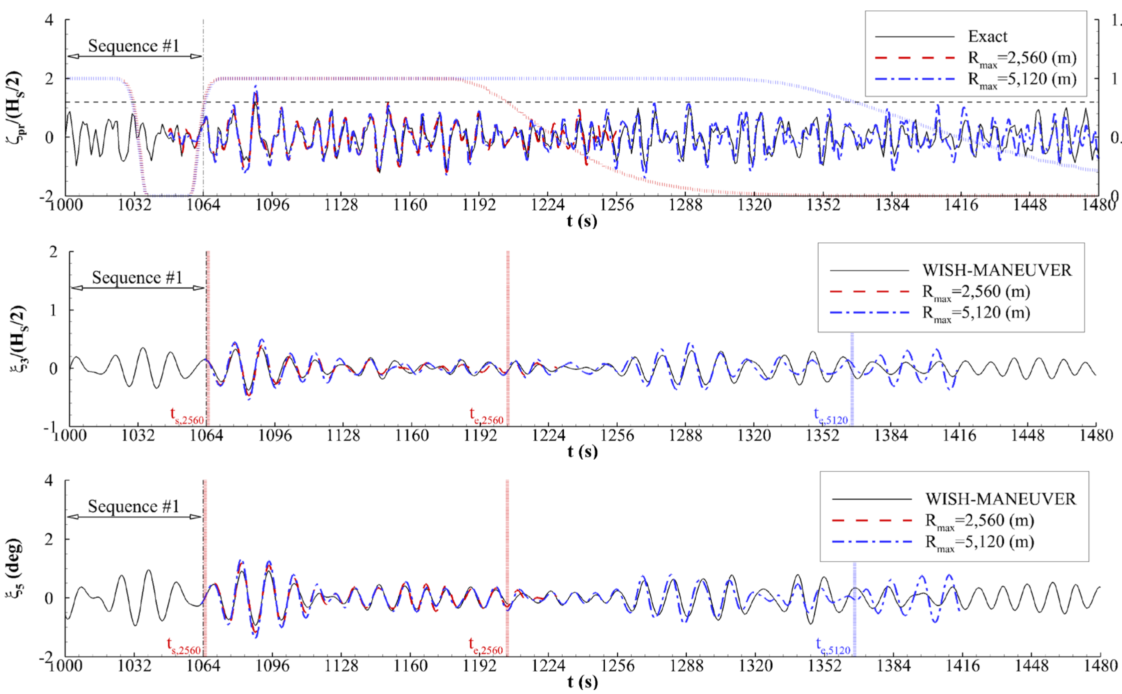

Figure 3: Validation of the predicted incident waves(top), heave(middle) and pitch(bottom) motions: KVLCC2, Fn=0.142, head sea condition, prediction based using 64 radar images

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