Application of Digitalization Scheme for Ship Performance Prediction in Waves: Combination of Physics-Based Simulation and Digital Technique

Yonghwan Kim(1), **Jae-Hoon Lee**(1), **Yuming Liu**(2), **Yoonseo Nam**(1), **Jae-Hak Lee**(1), **Heesuk Yang**(1)
(1) Seoul National University, Seoul, Korea
(2) Massachusetts Institute of Technology, Cambridge, USA
(corresponding author: yhwankim@snu.ac.kr)

INTRODUCTION

Digitalization has stood out most in engineering trends around the world over the past few years. Digital technology, the so-called Fourth Industrial Revolution, is now permeating all over our lives, and this trend is also progressing in the academic field. It is clear that various technologies related to ships and offshore structures are being developed in a digitalized and eco-friendly trend, and will be affected by such an influence in the traditional marine fluid dynamics field.

Sometimes digital technology is somewhat reluctant to be accepted in the traditional engineering approach and by researchers who interpret physical models using mathematical or numerical techniques. This is because there is a strong perception that the fundamental approach is different from the physics-based or the mathematical model in the application of digital technology. For example, let's say that the motion of a ship is interpreted as a machine learning technique. The machine learning technique was not originated from seakeeping theory, nor is it based on mathematical models such as slender-body theory or Neumann-Kelvin theory. Because it predicts the ship's motion based on learning various data, this digital technique may not be convincing to traditional researchers.

However, these digital technologies can be presented as a method of improving the accuracy of existing theories or overcoming their limitations by combining with mathematical or numerical methods. For example, it can be used as a method of complementing nonlinear components by combining it with the linear theory of a ship, or it can be used as a method of reducing the number and cost of experiments by predicting the results that are already expected before performing expensive experiments.

In this abstract, an example of applying digitization techniques is introduced: the development of the digital twin for predicting the operational performance of ships in waves, showing how the digital technology can be applied and combined with the traditional marine hydrodynamic analyses.

CONCEPT OF DIGITAL TWIN FOR SHIP OPERATION IN OCEAN WAVES

Basic Concept

If it is possible to predict the future conditions that a ship or offshore structure will experience due to anticipated ocean waves, this will enable people who operate the ship or offshore structure to optimize operational efficiency and predict the future risks due to waves and motions. To this end, it is necessary to implement a system, a so-called digital twin, that predicts the ocean waves and corresponding hydrodynamic and structural performance related to the motion and navigation of ships in the future in the digital domain. For example, the flow chart in Fig.1 can be the concept of a digital twin of a ship's navigation.

Prediction of Ocean Waves in Ship Route

If the accurate prediction of future ocean waves is impossible, we cannot predict the operation of ships at sea. Therefore, in the digital twin, the prediction of ocean waves is a problem that must precede and is the most difficult element. The currently-occurring ocean wave data can be grasped from the measurement data of a X-band wave radar installed on the ship, but it is not easy to accurately perform wave reconstruction from such measurement data. For the accurate reconstruction of the wave field, some critical problems such as shadow effect, filtering non-physical dispersion component, and wave energy, and modulation effects. The details will be introduced in the presentation.

Fig. 2(a) is an example of synthetic data of a X-band wave radar. Due to shadow effects, noise, and other effects, the measured data is not like a 3D wave profile in the ocean. Using some techniques, this data must be reconstructed to 3D wave profiles like Fig.2(b). Fig.3 shows an actual example of wave measurement and analysis. It shows the images of a X-band wave radar, measured at Jeju Island in 2008 in the range of 3 km. The corresponding wave spectrum can be obtained after the reconstruction of the wave profile. The reconstructed wave information can be used for the prediction of waves in the domain of ship operation.

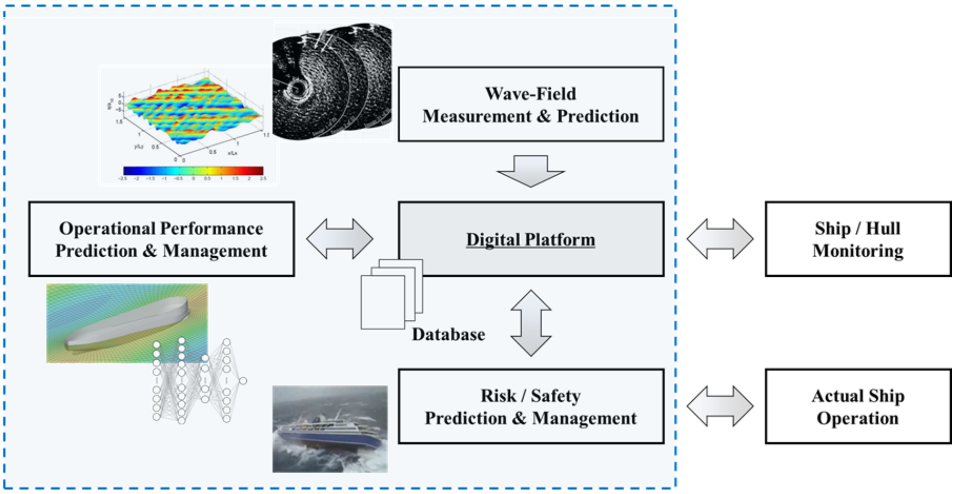
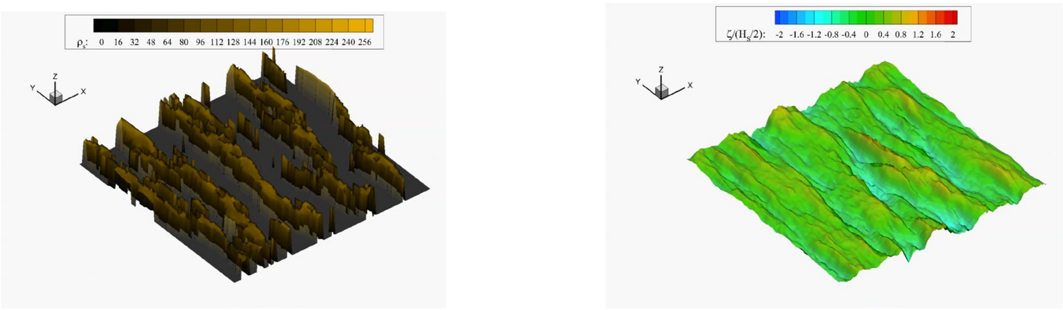
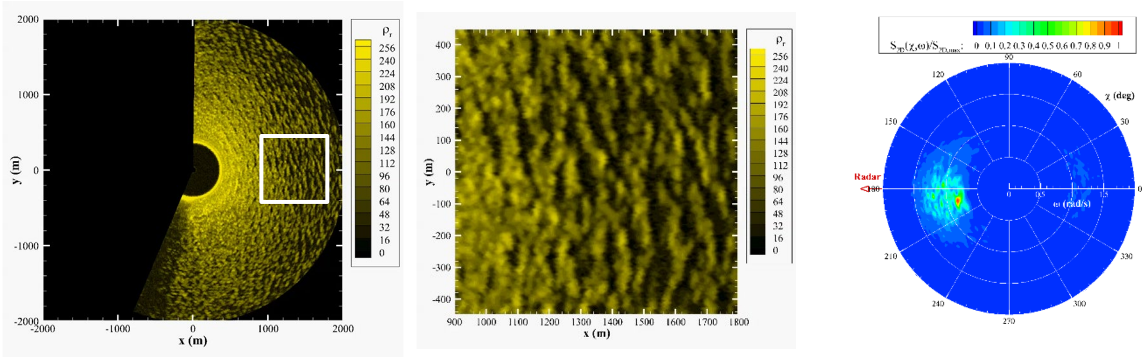


Fig.1 Brief concept of digital twin for ship operation in ocean waves



(a) Measured wave profile of X-band wave radar (b) Reconstructed wave profile

Fig.2 Example of the measured wave profile of wave radar and reconstructed wave profile



(a) Radar image of total domain (b) Radar image of local domain (c) Analyzed Wave spectrum

Fig.3 Actual data of X-band wave radar (instantaneous wave images) and wave spectrum analyzed: Jeju Island, June, 2018

Real-time Simulation of Ship Motion and Maneuverability in Waves

In order to predict and navigate the ship's future performance at sea, it is necessary to be able to predict the motion and maneuvering of the ship in real time. Therefore, numerical methods such as panel method or CFD which require a lot of computation time cannot be used with current computational capability. In this study, we analyze the motion and control performance of ships for real-time changing sea conditions by adopting an impulse-response-function (IRF) approach. That is, the motion of the ship is interpreted by the following equation applying the retardation function *R(t)*, but the hydrodynamic characteristics in the frequency domain must be calculated in advance for a wide range of sea conditions.

$$\sum_{k=1}\left(M_{jk}+M_{jk}^{\infty}\right)\ddot{\xi}_k+\int_0^t R_{jk}(t-\tau)\dot{\xi}_k(\tau)\,d\tau+\left(C_{jk}+C_{jk}^{R}\right)\xi_k=F_{ext,j} \qquad (1)$$

The ship manoeuvring analysis is performed in real time, based on the MMG model as shown in the following equations. The ship motion program is combined with this MMG model and the mean wave-induced drifting force is included in the MMG model. In this process, the operation of a ship can be simulated as much as possible in the actual situation when all factors including various control functions such as propeller, rudder and autopilot are considered.

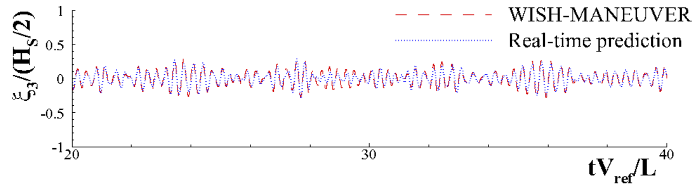
$$
\begin{aligned}
&m(\dot{u}-vr) = X_H + X_R + X_P + X_{WDF}, \qquad && m(\dot{v}+ur) = Y_H + Y_R + Y_{WDF} \\
&I_{xx}\dot{p} = K_H + K_R, && I_{zz}\dot{r} = N_H + N_R + N_{WDF}
\end{aligned}
\tag{2}
$$

where the subscripts *H, R, P, WDF* indicate the components due to hull, rudder, propellor, and wave-induced force and moment. For example, the followings are the hull force components in Eq.(2).

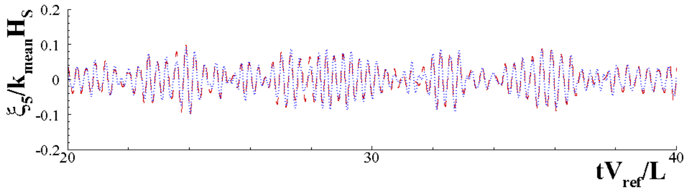
$$
\begin{aligned}
X_{Hull} &= -R_C(u) + X_{\dot{u}}\dot{u} + X_{vv}v^2 + (X_{vr} - Y_{\dot{v}})vr + X_{rr}r^2 \\
Y_{Hull} &= Y_{\dot{v}}\dot{v} + Y_v v + (Y_r + X_{\dot{u}}u)r + Y_{vvv}v^3 + Y_{vvr}v^2 r + Y_{vrr}vr^2 + Y_{rrr}r^3 \\
K_{Hull} &= -z_{Hull}Y_{Hull} \\
N_{Hull} &= N_{\dot{r}}\dot{r} + N_v v + N_r r + N_{vvv}v^3 + N_{vvr}v^2 r + N_{vrr}vr^2 + N_{rrr}r^3
\end{aligned}
\tag{3}
$$

Here, *X*, *Y*, *K*, and *N* denote the surge, sway, roll, and yaw directional force and moment; $R_c(u)$ and z_{Hull} indicate the calm water resistance and vertical moment arm, respectively. In the case of the MMG model, most manoeuvring coefficients are obtained mostly by PMM test.

Fig.4 shows the example results of seakeeping analysis in real time, compared with the results of a computer program WISH-MANEUVER which is based on a time-domain Rankine panel method. It should be noted that the ship speed varies in time. It is obvious that the real-time simulation provides an acceptable correspondence with the Rankine panel method.



(a) Heave



(b) Pitch

Fig.4 Example of heave and pitch motion simulation during in real-time free-running simulation: KVLCC2 in short-crested waves of Beaufort scale 8 (significant wave height 5.5m, mean period 9.1sec)

Prediction of Future Performance and Risk

If we can predict the ocean waves and ship motions in the near future, it is possible to predict the ship's operational efficiency and future risks, and from this, a safer and efficient operation can be expected. For example, if a serious ocean wave occurrence such as a freak wave is predicted, the ship can avoid such risk by changing the course or speed slightly. In addition, if the captain of containership or passenger ship can be aware the risk of extreme motions such as parametric roll a few minutes or tens of minutes in advance, the captain can change operating conditions to avoid serious exercise. Such functions will make a remarkable contribution to improving the safety of ships during operation.

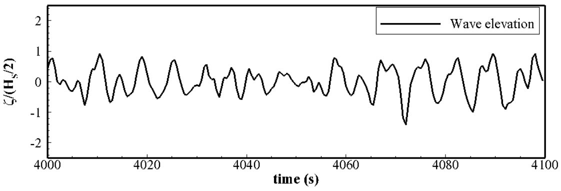
Application of Machine Learning Scheme for Ship Response

The application of machine learning scheme can be combined with the seakeeping and manoeuvring simulation. Obviously, there are limitations and lack of theories and computational methods. For example, even fully nonlinear seakeeping theory and computation methods like CFD show some discrepancy of ship motion in actual seaways. Such discrepancies can be reduced by using digital schemes such as machine learning method.

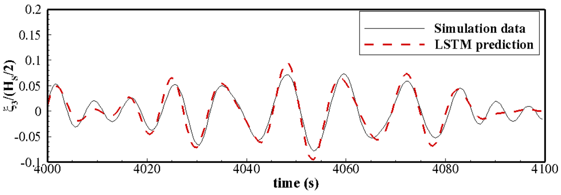
Fig.5 shows the tentative results of ship motion prediction in irregular waves, which is predicted by using a machine learning scheme. In this simulation, as the first trial, linear ship motion is obtained based on a recursive neural network (RNN) and long short-term memory (LSTM) scheme. A lot of motion signals generated by the IRF-based analysis described above are used for the machine learning process. As Fig.5 shows, the motion signals predicted by the machine learning scheme show a fair agreement with numerical simulation.

The data measured during the actual voyage of a ship can be collected and used as the data for digital techniques. For instance, the manoeuvring coefficients in Eq.(3) can be corrected more accurately as the collected data are more. Then, eventually such voyage data will improve the accuracy of ship operation and control.

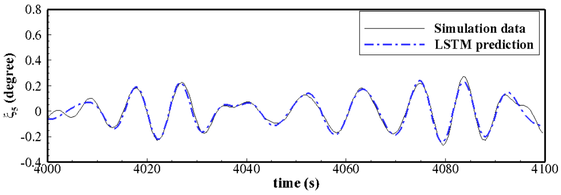
It should be stated that the machine learning scheme is not based on any physics-based model or theory. It is a pure digital technique. Therefore, we should be very careful to apply this scheme for actual seakeeping analysis. However, if we combine this digital technique with a physics-based method, the accuracy of the solution can be improved. For example, the discrepancy between numerical method and actual measurement can be modeled by a digitalization scheme, and it can be a complementary method of the physics-based model.



(a) Predicted wave elevation



(b) Heave



(b) Pitch

Fig.5 Comparison of ship motion signals between numerical simulation and machine learning method: KVLCC2

ACKNOWLEDGEMENT

This research is supported by Daewoo Shipbuilding and Marine Engineering(DSME) as a long-term project of Future Ocean Cluster(FOC). Their financial and administrative support is highly acknowledged.

REFERENCES

- Cummins, W.E. 1962, “The impulse response function and ship motions,” *Schiff-stechnik*, 47(9), pp. 101-109.
- Lee, J.H. and Kim, Y. 2020, "Study on ship operation performance in actual seaways using time-domain free-running simulation," *Journal of Engineering for the Maritime Environment,* https://doi.org/10.1177/1475090220944108 (online publish).
- Nieto Borge, J.C., Reichert, K. and Dittmer, J. 1999, "Use of nautical radar as a wave monitoring instrument," *Coastal Engineering*, Vol. 37(3-4), pp. 331-342.
- Nieto Borge, J., RodrÍguez, G.R., Hessner, K. and González, P.I. 2004, “Inversion of marine radar images for surface wave analysis,” *Journal of Atmospheric and Oceanic Technology*, Vol. 21(8), pp. 1291-1300.
- Wijaya, A.P. and van Groesen, E. 2016, "Determination of the significant wave height from shadowing in synthetic radar images," *Ocean engineering,* Vol. 114*,* pp. 204-215.
- Zinchenko V., Vasukyev L. and Liu Y. 2021, "An improved algorithm for phase-resolved sea surface reconstruction from X-band marine radar images," (under review).