Multi-step Force Correction Method for Prediction of Ship Parametric Roll Motions in Irregular Waves

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1 INTRODUCTION

Parametric roll events can occur due to significant variations in transverse stability when a vessel encounters head or following waves. To ensure vessel stability, it is crucial to evaluate both the occurrence and magnitude of parametric roll in irregular waves. Numerical approaches for evaluating parametric roll in irregular waves have been developed at various levels of fidelity [1, 2, 3]. Although these numerical approaches generally capture similar trends in the occurrence of parametric roll, their quantitative accuracy in predicting roll responses in irregular waves remains limited.

In this study, a neural network-based hybrid force correction model is developed to predict parametric roll behavior in irregular waves, employing a modified multi-step force correction framework that incorporates temporal ensembling. The deep-learning model compensates for the limitations of a low-fidelity approach by predicting the correction forces required to reproduce motion responses observed in experiments. The neural network is trained using irregular wave test data and is subsequently applied to predict roll responses under different wave conditions. This study aims to investigate the feasibility of the proposed multi-step force correction method for predicting parametric roll motion in irregular waves through direct comparison with experimental observations.

2 METHODS

Multi-step Force Correction with Temporal Ensembling

The force correction method has been employed to compensate for discrepancies between methods of different fidelity levels [4, 5]. In this study, a multi-step force correction model with temporal ensembling is newly developed to improve prediction accuracy and simulation stability. Two low-fidelity methods are considered: the linear impulse response function (IRF) method for the "IRF–based force correction model", and a restoring force (RS) model including a mooring system for the "RS–based force correction model". The governing equations are formulated by introducing a correction force term, denoted as δ, as expressed in Eqs. (1) and (2).

$$\sum_{j=1}^{6}\left[m_{ij}\ddot{\xi}_J(t)\right] = F_{Res,i}^{lin.} + \delta_i(\xi_j; t) \tag{1}$$

$$\sum_{j=1}^{6}\left[\left(m_{ij} + a_{ij}(\infty)\right)\ddot{\xi}_j(t) + \int_0^t R_{ij}(t-\tau)\dot{\xi}_j(\tau)d\tau\right] = F_{Res,i}^{lin.} + F_{D,i}^{lin.} + F_{F.K.,i}^{lin.} + F_{visc,i} + \delta_i(\xi_j; t) \tag{2}$$

The correction force is trained by a neural network composed of MLP (Multi-Layer Perceptron) and LSTM (Long Short-Term Memory) layers, using motion responses observed in experiments, which serve as the high-fidelity reference. The input and output variables of the neural network are defined in Eq. (3). The neural network outputs multi-step 6-DoF correction forces. Here, $\hat{\delta}_{i,k|n}$ denotes the correction force at time step k predicted by the model initialized at time step n. As input variables, the time series of wave elevations at the midship, AP, and FP, together with the time series of six DoF (degrees of freedom) motions, are employed, as shown in Eq. (4). During the inference process, temporal ensembling is performed by averaging multiple correction force predictions corresponding to the same time step, as expressed in Eq. (5).

$$\hat{Y}[n] = f_\theta\big(X_\eta[n], X_\xi[n]\big) = \begin{bmatrix} \hat{\delta}_{1,n|n} & \cdots & \hat{\delta}_{6,n|n} \\ \vdots & \ddots & \vdots \\ \hat{\delta}_{1,n+L_\delta|n} & \cdots & \hat{\delta}_{6,n+L_\delta|n} \end{bmatrix} \in R^{(L_\delta+1)\times 6} \tag{3}$$

$$X_\eta[n] = \begin{bmatrix} \eta_1[n-L_\eta] & \cdots & \eta_3[n-L_\eta] \\ \vdots & \ddots & \vdots \\ \eta_1[n] & \cdots & \eta_3[n] \end{bmatrix}, \qquad X_\xi[n] = \begin{bmatrix} \xi_1[n-L_\xi] & \cdots & \xi_6[n-L_\xi] \\ \vdots & \ddots & \vdots \\ \xi_1[n] & \cdots & \xi_6[n] \end{bmatrix} \tag{4}$$

$$\bar{\delta}_\iota[k] = \begin{cases} \dfrac{1}{k+1}\displaystyle\sum_{n=0}^{k} \hat{\delta}_{i,k|n}, & if\ k < L_\delta \\[2em] \dfrac{1}{L_\delta+1}\displaystyle\sum_{n=k-L_\delta}^{k} \hat{\delta}_{i,k|n}, & else \end{cases} \tag{5}$$

Weakly-nonlinear IRF method

The weakly nonlinear IRF method was introduced for comparison with the force correction method and experimental results. While linear radiation and diffraction forces were considered, the nonlinear restoring ($F_{Res,i}^{nl}$) and Froude–Krylov forces ($F_{FK,i}^{nl}$) were calculated by integrating over the instantaneous wetted surface, as shown in Eqs. (6) and (7). Wheeler stretching was applied to model the velocity potential on the instantaneous free surface.

$$\sum_{j=1}^{6}\left[\big(m_{ij} + a_{ij}(\infty)\big)\ddot{\xi}_j^*(t) + \int_0^t R_{ij}(t-\tau)\dot{\xi}_j^*(\tau)d\tau\right] = F_{Res,i}^{nl} + F_{D,i}^{lin.} + F_{FK,i}^{nl} + F_{visc,i} \tag{6}$$

$$F_{FK,i}^{nl} = -\rho \iint_{S_B} \left\{\frac{\partial\phi_I}{\partial t} - U_k\frac{\partial\phi_I}{\partial x_k}\right\} n_i dS \tag{7}$$

Experiment

Model tests are conducted in the towing tank at Seoul National University with a scale ratio of 1:166.8. Figure 1 shows the side view of the model ship, and Table 1 lists its principal dimensions. The model has a length of 1.8 m, a beam of 24.2 cm, and a draft of 7.9 cm. The natural roll period is 2.08s and tests are performed under zero-speed conditions. Model tests were conducted under head wave conditions for a duration corresponding to 30 min in full-scale time. Nine wave conditions, composed of three significant wave heights ($H_s = 6.5, 8.5, 10.5\ m$) and three peak

periods ($T_z = 10.5, 12.5, 14.5\ s$), were used for training, while the developed method was tested under ten different irregular wave conditions.

Figure 1: Side view of model ship

Table 2: Principal dimensions for model ship

Item	Full-scale	Model
Scale ratio	1	1/166.8
Length overall	300.25 m	1.8 m
Beam	40.3 m	24.2 cm
Draft	13.2 m	7.9 cm
GM	1.084 m	0.65 cm
Roll natural period	26.86 s	2.08 s

3 RESULTS

To investigate the prediction performance of the numerical methods, the predicted time series of motion responses are directly compared with the experimental results for the training wave conditions in Figure 2. For the training dataset, it is found that the multi-step force correction models successfully predict the parametric roll behavior, which the weakly nonlinear IRF model fails to capture.
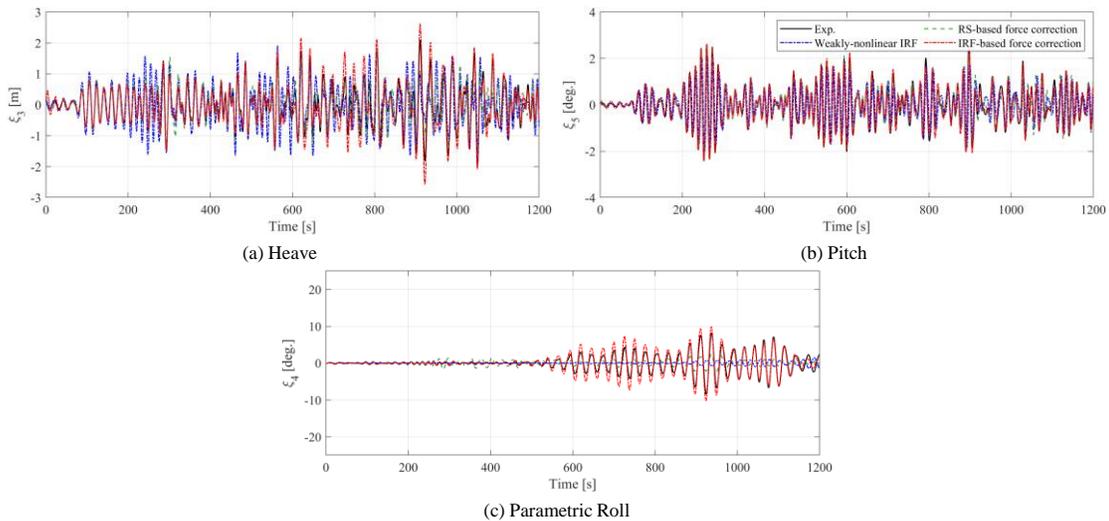

(a) Heave

(b) Pitch

(c) Parametric Roll

Figure 2: Predicted time series of roll responses in training wave condition ($H_s = 8.5m, T_z = 10.5s$)

To further examine the generalization ability of the developed method, the motion prediction of the weakly nonlinear IRF and the multi-step force correction methods was evaluated for test data. Figure 3 shows the envelopes of the predicted roll responses for test irregular wave conditions, compared with those from experiments. Among the force correction methods, the IRF-based force correction model exhibited superior prediction performance. Even under test wave conditions, the force correction model produces roll envelopes that are in good agreement with the experimental results. This demonstrates that the force correction approach enables deterministic predictions of parametric roll by accurately evaluating the nonlinear forces acting on the vessel.

(a) Test wave condition 1
$(H_s = 10.5m, T_z = 14.5s)$

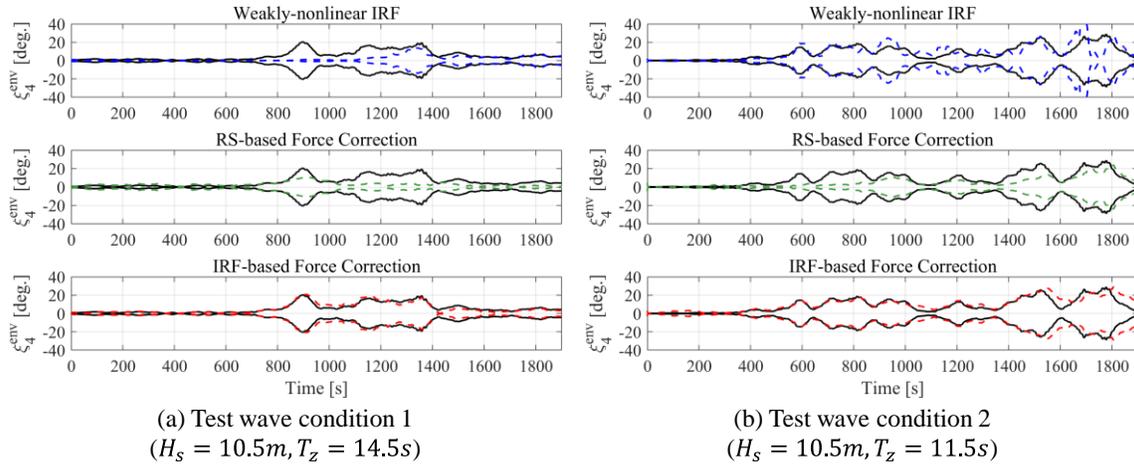(b) Test wave condition 2
$(H_s = 10.5m, T_z = 11.5s)$

Figure 3: Envelopes of time series of parametric roll responses in test wave conditions. (The solid black line denotes the experimental results, while the dashed lines indicate each numerical result.)

REFERENCES

[1] Reed, A. M., 2019, "26th ITTC parametric roll benchmark study," Contemporary Ideas on Ship Stability: Risk of Capsizing, pp 619-636.

[2] Park, D. M., Kim, Y., and Song, K. H., 2013, "Sensitivity in numerical analysis of parametric roll," *Ocean Engineering*, 67, pp 1-12.

[3] Kapsenberg, G., Wandji, C., Duz, B., & Kim, S., 2020, "A comparison of numerical simulations and model experiments on parametric roll in Irregular Seas," Journal of Marine Science and Engineering, 8(7), 474.

[4] Marlantes, K. E., Bandyk, P. J., and Maki, K. J., 2024, "Predicting ship responses in different seaways using a generalizable force correcting machine learning method," *Ocean Engineering*, 312, 119110.

[5] Marlantes, K. E., & Maki, K. J., 2024, "A hybrid data-driven model of ship roll," Ocean Engineering, 303, 117821.