The Effect of Long-Period Components of Added Resistance in Irregular Waves on Ship Performance in Actual Seas

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Abstract. Added resistance in irregular waves is generally calculated in frequency-domain as the mean value. However, the mean value would be different from the averaged value in consideration of long-period components. Long-period components of added resistance in irregular waves have been rarely considered since tank tests method in irregular waves have not been established due to the effect by the appended restoring force, and the estimation method has not been verified. In this paper, long-period components are evaluated with Newman's approximation, and the correction for inertia force is employed for tank tests in order to eliminate the effect of appended restoring force. Through tank tests, the analysis method of tank tests data and the estimation method have been confirmed. The effect of long-period components on ship performance in actual seas are examined in a case example of PCC. As a result, it has been found that in consideration with the long-period components, the required power at the same speed might be different about 10% from that with the mean value calculated by the conventional frequency-domain method.

Keywords. restoring force, tank test, Newman's approximation

1. Introduction

Ship performance in actual seas has been commonly indicated by noon report data, which are recorded manually by ship crew. From the analysis with noon report data, the long-term evaluation on the fouling or the degradation can be conducted quantitatively[1], whereas they are not suitable for the verification of estimation methods or the factor analysis since the variation of wind and waves during a day could not be captured. Onboard monitoring systems have been developed recently and applied on actual ships increasingly. There are several kinds of monitoring systems developed (e.g.[2],[3]), and most systems equip the function for the measurement on ship performance, the function for the statistical analysis of measured data, and the function for the transmission of analyzed results via internet. The system enables the comprehensive evaluation of actual ship performance. Accordingly, high accuracy of the estimation of ship performance in actual seas is demanded.

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Added resistance in waves is one of major components of external forces acted on a ship in actual seas. The estimation accuracy of added resistance in waves influences the evaluation of ship performance in actual seas. Waves in actual seas are irregular waves which contain various frequencies, height and direction. Added resistance in irregular waves is generally evaluated by the frequency-domain calculation as a mean value. However the long-period components occur due to difference frequencies of component waves in irregular waves. Then the mean value by the frequency-domain calculation might be different from the averaged value in consideration of long-period components. The long-period components of added resistance in irregular waves have been rarely considered since the experimental technique as for an appended restoring force has not been established and the estimation method could not be validated[4]. In this paper, the long-period components of the added resistance in irregular waves is evaluated with Newman's approximation[5] that has been used for the estimation of the drifting force acted on an offshore structure. As for tank tests in irregular waves, the analysis method which employs the modification of inertia force is shown in order to eliminate the effect of the restoring force.

2. Theoretical Background

2.1. Estimation of added resistance in irregular waves

Added resistance in short-crested irregular waves R_{wave} acted on a ship in actual seas is derived from Eq. (1). Here, R_{AW} is the added resistance in regular waves, ζ_a is the wave amplitude, $E(\omega,\alpha)$ is the directional wave spectrum, ω is the wave angular frequency of components waves, α is the wave direction of components waves and V is the ship speed. The equation is in frequency-domain and the calculated results correspond to the mean value in short term.

$$R_{wave} = 2\int_0^{2\pi}\int_0^{\infty} \frac{R_{AW}(\omega,\alpha;V)}{\zeta_a^{\,2}} E(\omega,\alpha)\,d\omega\, d\alpha \tag{1}$$

In the case of long crested irregular waves, added resistance is calculated from Eq. (2). Here $S(\omega)$ is the wave frequency spectrum.

$$R_{AWL} = 2\int_0^{\infty} \frac{R_{AW}(\omega)}{\zeta_a^{2}} S(\omega)\,d\omega \tag{2}$$

The time history of added resistance in irregular waves is expressed with the quadratic transfer function on hydrodynamic force as shown in Eq.(4), where encountered long crested irregular waves ζ is expressed by the superposition of regular waves as shown in Eq. (3). Here, t is the time, $A_m^{\,r}$ is the complex amplitude with random phase, ω_{em} is the encountered angular frequency, $A_m^{\,r}$ and ω_{em} correspond to the m-th component of regular waves that consist irregular waves, $M_{mn}^{(2-)}(\omega_{em},\omega_{en})$ is the quadratic transfer function for sum frequencies, $M_{mn}^{(2-)}(\omega_{em},\omega_{en})$ is the quadratic transfer function for difference frequencies, and * denotes the conjugate.

$$\zeta(t) = \mathrm{Re}\sum_m A_m^r e^{i\omega_{em}t} \tag{3}$$

$$\begin{aligned}\Delta R^{\pm}(t) &= \mathrm{Re}\sum_m \sum_n A_m^r A_n^{r*} M_{mn}^{(2+)}(\omega_{em}, \omega_{en}) e^{i(\omega_{em}+\omega_{en})t} \\ &+ \mathrm{Re}\sum_m \sum_n A_m^r A_n^{r*} M_{mn}^{(2-)}(\omega_{em}, \omega_{en}) e^{i(\omega_{em}-\omega_{en})t}\end{aligned} \tag{4}$$

The long-period components are calculated by the second term of Eq.(4). For the estimation of the drifting force acted on an offshore structure, Newman's approximation has been applied for the long-period components. In the approximation, the contribution of the quadratic transfer function on the long-period components is assumed to be large in case the difference frequency is small[5]. The concept of Newman's approximation is applied to the calculation of added resistance in irregular waves, then the long-period components of added resistance in irregular waves is approximated by Eq. (6) on the assumption shown in Eq. (5).

$$M_{mn}^{(2-)}(\omega_{em}, \omega_{en}) = M_{mm}^{(2-)}(\omega_{em}) + O(\omega_{em} - \omega_{en}) \tag{5}$$

$$\Delta R(t) \cong \mathrm{Re}\sum_m \sum_n A_m^r A_n^{r*} M_{mm}^{(2-)}(\omega_{em}) e^{i(\omega_{em}-\omega_{en})t} \tag{6}$$

2.2. Experimental Method

For tank tests on resistance and vertical motions in head waves, the system as shown in Figure 1 is to be used. In the system, surge motion is not restricted to avoid the overload to load cells, and a longitudinal restoring force is appended by the torque motor or the spring. Then, the measured resistance data is influenced by the appended restoring force, and an amplitude of a linear response varies. For tank tests in regular waves, added resistance in waves is obtained as a mean value for a period, so that a variance of linear response could be ignored. Whereas for tank tests in irregular waves, long-period variance is affected by the appended restoring force.

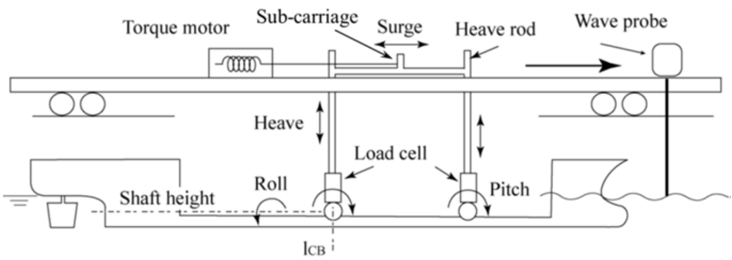


Figure 1. Measurement system for tests in head waves.

In the system shown in Figure 1, the force measured by load cells corresponds to the spring force given by the torque motor. Here the longitudinal equilibrium equation is expressed by Eq. (7), where m_M is the mass of model, m_c is the mass of sub-carriage, m_a is the longitudinal added mass, c_d is the damping coefficient, k_x is the coefficient of linear spring force, R is the resistance, and x is the longitudinal displacement (+ means forward).

$$(m_M + m_c + m_a)\ddot{x} + c_d\dot{x} + k_x x = R \tag{7}$$

The external force is obtained by the correction for the inertia term $(m_M + m_c + m\ )\ddot{x}$ on the assumption that the damping force $c_d\dot{x}$ related to ship speed is little. The inertia term can be calculated from the longitudinal acceleration obtained from the measured longitudinal displacement and the added mass estimated from the Motora's chart[6].

3. Tank Tests in Waves

3.1. Outline of Tank Tests

Tank tests in long-crested irregular waves have been carried out for the purpose of the verification of experimental method and estimation method of the long-period components of added resistance in irregular waves. The object ship is shown in Table 1. Tank tests have been conducted in Mitaka No.2 ship model basin (length: 400m, width: 18.0m, depth: 8.0m, plunger-type wave maker). The model has been installed to the system shown in Figure 1, and the resistance R, heave displacement z, pitch angle θ, surge displacement x, and encountered waves ζ are measured. In order to examine the effect of appended longitudinal restoring force, tests have been conducted with several kinds of longitudinal spring coefficients k_x. To ensure the encountered wave number, measurement of 41 seconds are carried out for 4 times for each condition of k_x. The natural angular frequency ω_x and the natural period T_x have been derived from free surge tests as shown in Table 2.

Table 1. Principal dimensions of PCC models.

Item	Ship	Model
Length between perpendiculars L_{pp} [m]	190.0	4.675
Breadth B_{max} [m]	32.26	0.794
Draft d_m [m]	9.0	0.221
Longitudinal radius of gyration k_{yy}/L_{pp}	0.245	0.245
Froude number F_n	0.239	0.239

Table 2. Longitudinal restoring coefficient.

	k_x [N/m]	ω_x [rad/s]	T_x [s]
kx1	81	0.43	14.6
kx3	225	0.70	9.0
kx5	382	0.90	7.0
kx7	570	1.06	5.9
kx10	833	1.26	5.0

3.2. Results of Tank Tests

Frequency spectrum of measured waves are shown in Figure 2 and Table 3. It is indicated that there are little difference among k_x, and that the natural angular frequency would not affect the frequency wave spectrum. In full scale range, $H_{1/3}$ and T_{01} correspond to 3.9 m and 7.6 s, which are close to Beaufort scale 7. In Figure 2, λ is the wave length, K_{AW} is the coefficient of added resistance in regular waves expressed by Eq. (8), R_{AW} is the added resistance in regular waves, ρ is the fluid density, and g is the gravitational acceleration. R_{AW} is calculated by the method based on Maruo's theory combined with the practical correction parameter obtained from tank tests in short waves[7]. Figure 2 indicates the good agreement of added resistance in regular waves between the calculation (KAW:cal) and the experiment (KAW:Exp).

$$K_{AW} = \frac{R_{AW}}{4\rho g \zeta_a^2 \left(B_{max}^2 / L_{pp}\right)} \tag{8}$$

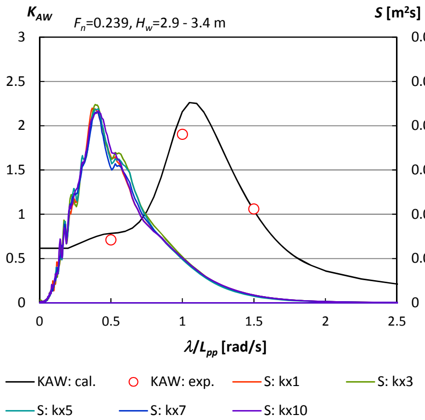
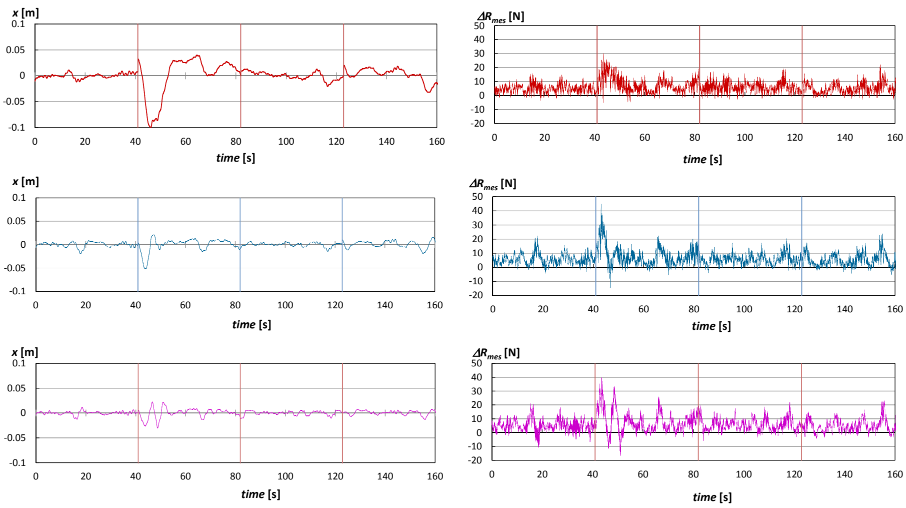


Figure 2. Frequency spectrum of measured waves and added resistance in regular waves.

Table 3. Wave parameters of measured irregular waves.

	kx1	kx3	kx5	kx7	kx10	average
Significant wave height $H_{1/3}$ [m]	0.0948	0.0963	0.0952	0.0945	0.0954	0.0952
Mean wave period T_{01} [s]	1.20	1.20	1.20	1.20	1.20	1.20

The time history of measured surge displacement and measured longitudinal force for kx1, kx5 and kx10 are shown in Figure 3. From Figure 3, it is found that the surge displacement would be large in the case of small spring coefficient and the longitudinal force would be large in case of large spring coefficient.

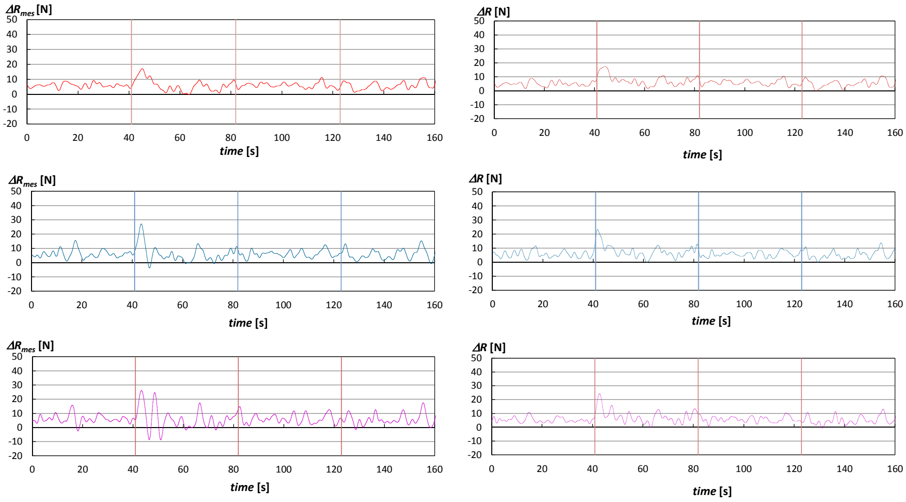


(a) surge displacement (b) longitudinal force

Figure 3. Time history of measured surge displacement and longitudinal force.

3.3. Correction for Inertia Force

The correction method described in section 2.2 is applied to measured results and the long-period components of added resistance in irregular waves are obtained. The longitudinal components extracted from measured force and that after the correction are shown in Figure 4. It is found that the difference between the spring coefficient k_x is decreased by the correction for inertia force.



(a) measured longitudinal force (b) added resistance in irregular waves

Figure 4. Long-period components of measured longitudinal force and added resistance in long-crested irregular waves.

3.4. Comparison with estimated results

The long-period components of added resistance in irregular waves calculated by the method described in section 2.1 and experimental results are shown in Figure 5. It is indicated that the calculated results well expresses the long-period components of added resistance in irregular waves obtained by the experiment.

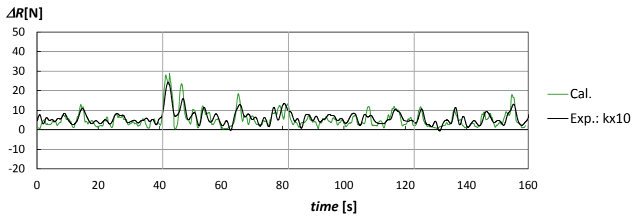
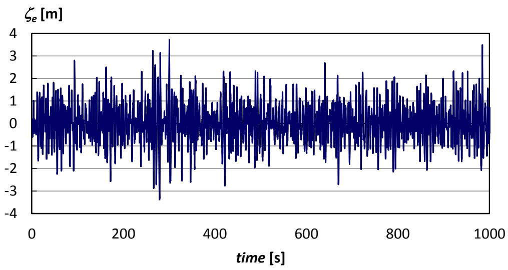


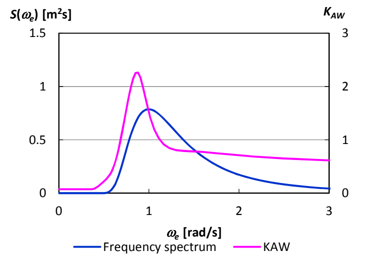
Figure 5. Comparison between experimental results and calculated results for added resistance in long-crested irregular waves.

4. Effect on ship performance in actual seas

The long-period components of added resistance in long-crested irregular head waves ($H_{1/3}$ =3.5m, T_{01}=7.7s) are calculated for full-scale PCC by the method described in section 2.1. Time history and frequency spectrum of assumed waves are shown in Figure 6.



(a) Time history.

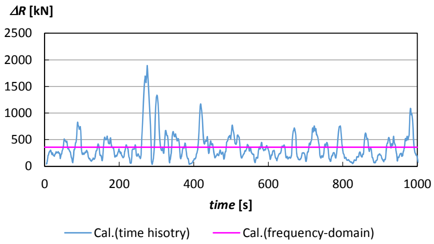


(b) Frequency spectrum.

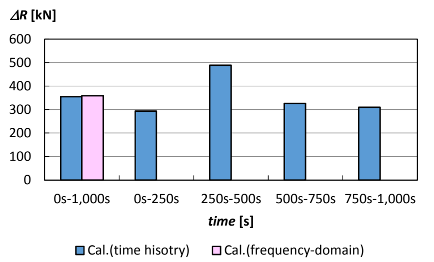
Figure 6. Assumed long-crested irregular waves.

Time history of added resistance in long-crested irregular waves is calculated by the method described in section 2.1 as shown in Figure 7(a). To examine the effect of time length for the evaluation, mean values per 250 seconds as well as the total mean value are calculated as shown in Figure 7(b). The mean value is also calculated from the conventional frequency-domain method.

A time history of encountered waves varies even if the frequency spectrum is the same. In an example case, mean values of added resistance in irregular waves vary from about -8% to +38% against the total mean value, which is almost the same with the value by the conventional frequency-domain calculation. To examine the effect of the difference in added resistance due to waves on ship performance in actual seas, power curves are derived and shown in Figure 8. Here, head wind of mean wind speed U_{wind} = 15.7 m/s is also assumed. From the comparison at 19.9 knot (F_n=0.239), the required power calculated with added resistance in irregular waves of each 250 seconds



(a) time history



(b) mean value

Figure 7. Added resistance in long-crested irregular waves (Full scale PCC, F_n=0.239).

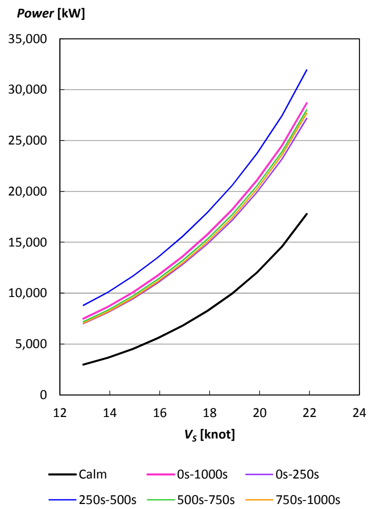


Figure 7. Speed-power curves (Full scale PCC).

is different by -5.6% ~ +12.0% from that calculated with added resistance in irregular waves of entire time range. It has been found that in case that the time length for the evaluation would be limited, ship performance might be different about 10% from that with added resistance in irregular waves calculated by the conventional frequency-domain method.

5. Conclusions

Followings have been found from the consideration on the long-period components of added resistance in irregular waves:

- The effect of the appended restoring force as for tank tests in irregular waves could be decreased by the correction for the inertia force;
- The long-period components of added resistance in irregular waves could be estimated with Newman's approximation which has been used for the calculation of the drifting force on an offshore structure through the comparison with tank tests' results;
- The required power in actual seas in consideration with the long-period components might be different about 10% against that calculated by the conventional frequency-domain calculation in case the time length for the evaluation is limited.

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