The Wave Correction Method for Speed Trial Analysis: Simple-NMRI method

by

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Abstract

When speed trial data is analyzed, wave correction is performed to remove the effect of added resistance caused by waves. The wave correction methods used in the analysis are prescribed in ISO 15016 or ITTC Recommended procedures. They include a simplified method as an alternative to the other methods that require more input data. The simplified method, however, does not take the speed effect into account, even though it is used for speed trial analysis. In this paper, we propose the Simple-NMRI method, a simplified wave correction method for speed trial analysis based on the theoretical method for the purpose of solving the issue for the current simplified method. Through validation by a comparison with tank test results, it is found that the Simple-NMRI method enables to evaluate the added resistance in waves appropriately.

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原 稿 受 付　令和 ５年 ４月 ２５日
審　査　日　令和 ５年 ５月 ２６日

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1. Introduction

An attempt to standardize the procedure of speed trials internationally has been carried out in ISO (International Organization for Standardization), and ISO15016:2002[1)] was established firstly. For the implementation of EEDI (Energy Efficiency Design Index) [2)] in 2013, the revision of ISO15016:2002 in view of limitation of optional methods was required. The revised version ISO15016:2015[3)] has been published. ITTC (International Towing Tank Committee) has also been in charge of technical study and developing the Recommended Procedures[4)]. In the current guidelines on survey and certification of EEDI[5)], ISO15016:2015 and the latest ITTC Recommended Procedures are referred, and according to which the reference speed V_{ref} for the calculation of EEDI is to be determined. The reference ship speed V_{ref} corresponds to the ship speed in EEDI calculation condition, that is, in a calm sea condition, in maximum summer load condition and at 75%MCR, and is to be finalized by the speed trials. Therefore, correction methods for environmental effects are prescribed in ISO 15016 and ITTC Recommended Procedures. In this paper, a new wave correction method is presented and the validation studies are shown.

2. Wave correction methods for speed trials

Wave correction of speed trials of a ship is conducted with the aim of removing the effect of added resistance due to waves. There are several correction methods presented in the standard procedures depending on the level of the input data, in case the hull data, such as sectional data and waterplane data, cannot be obtained and only the principal dimensions can be obtained.

The following 5 methods for the wave correction of the speed trials are prescribed in ISO 15016 or ITTC Recommended Procedures; 1) Seakeeping model tests, 2) Theoretical method with simplified tank tests in short waves or empirical formula (NMRI method), 3) Semi-empirical method for predicting the added resistance of a ship advancing in waves of arbitrary directions (SNNM method), 4) Empirical correction method with frequency response function for ships with heave and pitch during the speed runs (STAWAVE-2) and 5) Simplified correction method for ships with limited heave and pitch during the speed runs (STAWAVE-1).

Comparison for the wave correction methods of 2) to 5) is shown in Table 1. It summarizes difference of input of ship data, consideration of speed effects / ship motion and application range of wave direction for clarity.

1) Seakeeping model tests

Frequency response of added resistance in regular waves obtained by tank tests can be used. Tank tests have to be conducted for the specific ship geometry and at the trial loading condition. The tank tests should be conducted not only in head and following waves but also in oblique waves. The test set-up procedure and procedure are to be followed by ITTC RP 7.5-02-07.02.2[6].

Table 1 Comparison for the wave correction methods.

Correction methods	Empirical/Theoretical	Ship data	Speed effects	Ship motion effects	Wave direction
NMRI method	Theoretical	Principal dimensions, Sectional data, Waterplane data, Speed	Yes	Yes	All directions
SNNM method	Empirical	Principal dimensions, Speed	Yes	Yes	All directions
STAWAVE-2	Empirical	Principal dimensions, Speed	Yes	Yes	Head ± 45 deg.
STAWAVE-1	Empirical	Breadth, Length of the bow on the water line to 95% of maximum breadth	No	No	Head ± 45 deg.

2) Theoretical method with simplified tank tests in short waves or empirical formula (NMRI method)[7]

Frequency response of added resistance is calculated by applying the theoretical method. In the method, the added resistance in regular waves R_{AW} is calculated from the components of the added resistance based on Maruo's theory R_{AWM} and its correction term which is primarily valid in short waves R_{AWR}.

$$R_{AW} = R_{AWM} + R_{AWR} \tag{1}$$

R_{AWM} is the added resistance in regular waves mainly induced by ship motion, and calculated based on Maruo's theory[8]. For the calculation of R_{AWM}, sectional data and waterplane data are used as well as basic ship full form parameters. R_{AWR} is the added resistance due to wave reflection for correcting R_{AWM}. Since R_{AWR} is the base of the method presented in section 3 in this paper, the calculation procedures are described below[9] and the method has been validated by tank tests and sea trial data[10].

The expression of R_{AWR} is given by the Eq. (2). Here, ρ_s is the fluid density, g is the gravitational acceleration, ζ_A is the wave amplitude, B is the ship breadth, B_f is the Bluntness coefficient, α_T is the effect of draught and encounter frequency, C_U is the coefficient of advance speed, F_r is the Froude number, ω is the wave circular frequency, and V_s is the ship speed.

$$R_{AWR} = \frac{1}{2}\rho_s g \zeta_A^2 B B_f \alpha_T \left(1 + C_U F_r\right) \tag{2}$$

with

$$\alpha_T = \frac{\pi^2 I_1^2 (k_e T_{deep})}{\pi^2 I_1^2 (k_e T_{deep}) + K_1^2 (k_e T_{deep})} \tag{3}$$

$$k_e = k\left(1 + \Omega \cos\alpha\right)^2 \tag{4}$$

$$\Omega = \frac{\omega V_S}{g} \tag{5}$$

$$B_f = \frac{1}{B}\left\{ \int_I \sin^2(\alpha + \beta_w) \sin\beta_w dl + \int_{II} \sin^2(\alpha - \beta_w) \sin\beta_w dl \right\} \tag{6}$$

Where, I_1 is the modified Bessel function of the first kind of order 1, K_1 is the modified Bessel function of the second kind of order 1, k is the wave number, T_{deep} is the deepest draught, α is the wave direction, β_w is the slope of the line element dl along the water line and domains of the integration (I & II) are shown in Fig. 1.

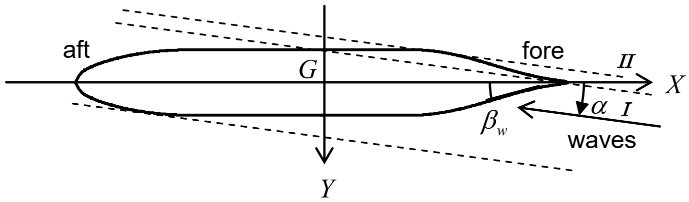


Fig. 1 Coordinate system for wave reflection.

The coefficient of advance speed C_U is determined by tank tests which should be carried out in short waves ($0.5L_{pp}$ or less) with at least three different Froude numbers. Fig. 2 shows the relation between the coefficient of advance speed C_U and the bluntness coefficient B_f based on tank tests for various type of ships in head and oblique waves. When C_U in head waves is obtained by tank tests, the empirical line for C_U and B_f are shifted parallel to C_U in head waves, and the shifted line used for the calculation of C_U in oblique waves. The empirical line is also used for obtaining C_U in head waves when tank tests are not carried out. In this case, C_U for arbitrary wave directions is calculated by Eq. (7).

$$C_U(\alpha) = \mathrm{sgn}\big(B_f(\alpha)\big) \cdot C_U^{\,+}(|\,B_f(\alpha)\,|) \tag{7}$$

with

$$C_U^{\,+}(B_f(\alpha)) = \mathrm{Max}[F_C, F_S] \tag{8}$$

(i) $B_f(\alpha = 0) < B_{fc}$ or $B_f(\alpha = 0) < B_{fs}$

$$F_S = C_U(\alpha = 0) - 310\{B_f(\alpha) - B_f(\alpha = 0)\} \tag{9}$$

$$F_C = \mathrm{Min}[C_U(\alpha = 0), 10] \tag{10}$$

(ii) $B_f(\alpha = 0) \geq B_{fc}$ and $B_f(\alpha = 0) \geq B_{fs}$

$$F_S = 68 - 310 B_f(\alpha) \tag{11}$$

$$F_C = C_U(\alpha = 0) \tag{12}$$

where $B_{fc} = \dfrac{58}{310} \approx 0.187$ and $B_{fs} = \dfrac{68 - C_U(\alpha = 0)}{310}$.

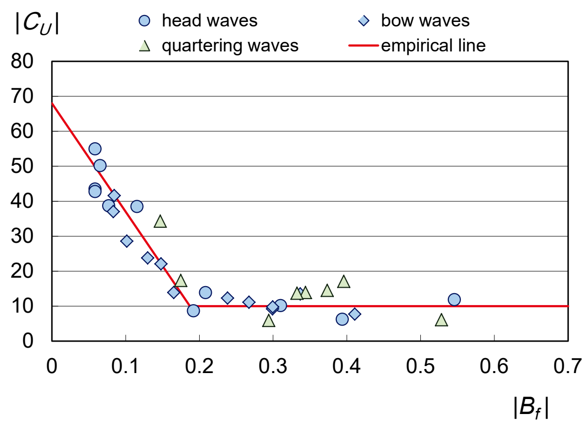


Fig. 2 Relation between the coefficient of advance speed on added resistance due to wave reflection and the bluntness coefficient for conventional hull form above water.

3) Semi-empirical method for predicting the added resistance of a ship advancing in waves of arbitrary directions (SNNM method)[11]

The method approximates the transfer function of the added resistance in arbitrary wave directions. The added resistance in regular waves is calculated by the empirical formulas consisting of ship hull form parameters, that is, the ship length between perpendiculars, the ship breadth, the draft at midship/F.P./A.P., the entrance length, the run length, the block coefficient, the longitudinal radius of gyration and the ship speed.

4) Empirical correction method with frequency response function for ships with heave and pitch during the speed runs (STAWAVE-2) [12]

The method approximates the transfer function of the added resistance in head waves. In this method, the added resistance in regular head waves is calculated by the empirical formulas consisting of ship hull form parameters, that is, the ship length between perpendiculars, the ship breadth, the block coefficient, the draft at midship, the longitudinal radius of gyration and the ship speed. Since the method is only applicable for head waves, it has the application restriction for wave direction: wave direction within 0 to ±45deg. from bow.

5) Simplified correction method for ships with limited heave and pitch during the speed runs (STAWAVE-1) [12]

The method estimates the added resistance in head waves with limited input data provided that heave and pitch motions are small. The effect of wave induced motions are neglected here, and only the effect of the wave reflection of the hull on the waterline is considered. The bow shape is expressed by parameter L_{BWL} which is the length of the bow on the water line to 95% of maximum beam (See Fig. 4).

The added resistance in head waves for STAWAVE-1 (R_{AWL}) is estimated by Eq. (13). This expression is for the long crested irregular head waves and it can be derived by the linear superposition of regular waves shown as Eq. (14) where $S(\omega)$ is the frequency spectrum. Since the added resistance in regular waves (R_{AW}) is the constant for STAWAVE-1, R_{AWL} is express as Eq. (15) by using ITTC spectrum[13].

The added resistance in head waves (R_{AWL}) is estimated by Eq. (14), where R_{AWL} is the added resistance due to long crested irregular head waves and $H_{1/3w}$ is the significant wave height of wind waves

Since the wave reflection only in the bow sector is taken into account, the application is restricted for the wave direction: wave direction within 0 to ±45deg. from bow.

$$R_{AWL}=\frac{1}{16}\rho_s g H_{1/3w}^2 B\sqrt{\frac{B}{L_{BWL}}} \tag{13}$$

$$R_{AWL} \simeq 2\int_0^\infty \frac{R_{AW}}{\zeta_A^2} S(\omega)\mathrm{d}\omega \tag{14}$$

$$R_{AWL} = \frac{173}{691} H_{1/3w}^2 R_{AW} \simeq \frac{1}{4} H_{1/3w}^2 R_{AW} \tag{15}$$

3. Simple-NMRI method

3.1 Concept of the simplified method

The current simplified method: STAWAVE-1 is positioned at the alternative method to other methods requiring more input data. Therefore, the application conditions are limited in head waves and without ship motion. Based on the conditions, the calculation method considers only the wave reflection component that is dominant in short waves where ship motion is small. The background of the formulation of STAWAVE-1 has not been disclosed unfortunately. From the formulation, a problem can be raised that the effect of ship speed on added resistance in waves is not taken into account in STAWAVE-1. Because the speed trials are conducted at the different ship speed, the lack of the consideration of the ship speed is the critical matter and should be improved.

3.2 Outline of the Simple-NMRI method

The update of a simplified method was considered based on the following concepts for the simplified method:

- Easiness: calculate with a calculator,
- Simplicity: calculate with a small number of ship dimension,

and also based on the concept of STAWAVE-1:

- Considering the component of the added resistance due to wave reflection in head waves which is primary in the short-waves.
- The same input as STAWAVE-1.

For the purpose of solving the issue for STAWAVE-1 that the ship speed is not taken into account, the update of the simple method is considered with the calculation method of R_{AWR} shown by Eq. (2), which is introduced in the theoretical calculation method.

In Eq. (2) for R_{AWR}, parameters except for ship's dimension are the Bluntness coefficient B_f, the effect of draught and encounter frequency α_T and the coefficient of advance speed C_U. α_T is the parameter for the wave reflection by ship hull and it is calculated with the draught and the wave number as shown in Eq. (3). The calculation example of α_T is shown in Fig. 3. Here, λ is the wave length. Fig. 3 indicates that α_T tends to 1 for short waves. According to the concept of considering the short waves where ship motion is small, $\alpha_T = 1$is assumed in the simple method.

Using the empirical relation between C_U and B_f shown in Eqs. (7) to (12) and Fig. 2, C_U can be calculated with B_f.

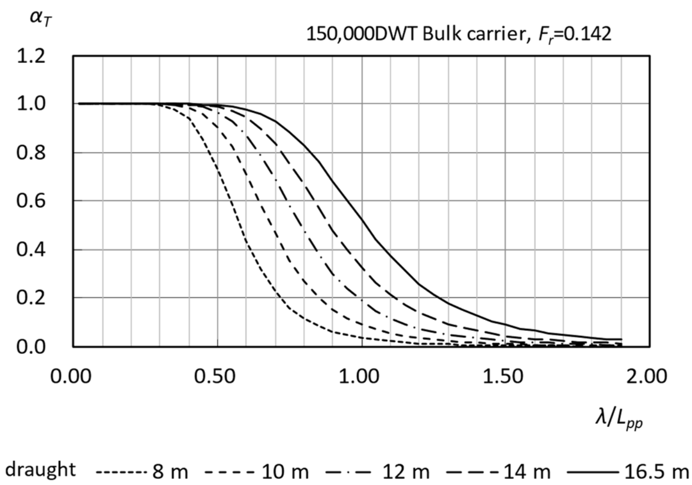


Fig. 3 Calculation example of the effect of draught and encounter frequency for 150,000DWT bulker (JBC).

In head waves, the bluntness coefficient can be expressed by Eq. (16). In order to calculate B_f with ship dimension, the bow shape is approximated to a triangle as the same way as for STAWAVE-1 shown in Fig. 4. With a parameter L_{BWL}, the bluntness coefficient for a triangle bow B_{ftri} is derived as Eq. (17).

$$B_f(\alpha = 0) = \frac{1}{B}\int_{-B/2}^{B/2} \sin^2 \beta_w dy \tag{16}$$

$$B_{ftri} = \frac{(B/2)^2}{L_{BWL}^2 + (B/2)^2} \tag{17}$$

The actual waterline shape is blunter than a triangle. Therefore, the relation between B_{ftri} and B_f is investigated for various types of ships and the estimation formula is derived expressed as Eq. (18). The relation between B_{ftri} and B_f is shown in Fig. 5. Dashed lines in Fig. 5 indicate ±10% of the approximation by Eq. (18). It is found that most of the points except are within ±10% range of the approximation line.

$$B_f \simeq \frac{1.3(B/2)^2}{L_{BWL}^2 + (B/2)^2} = 1.3B_{ftri} \tag{18}$$

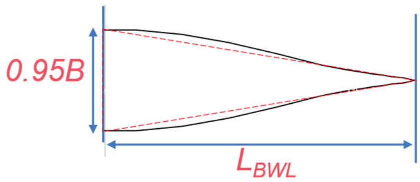


Fig. 4 Approximation of bow water plane to a triangle.

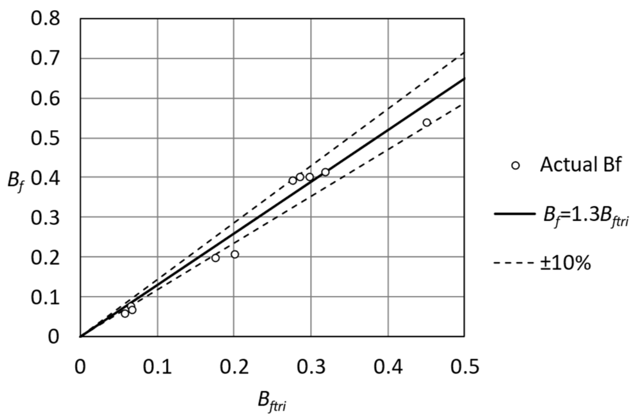


Fig. 5 Relation between the bluntness coefficient approximated for a triangle bow and the actual bluntness coefficient.

From the above, the added resistance due to wave reflection in head waves is expressed by Eq. (19).

$$R_{AWR} \simeq \frac{1}{2}\rho_s g \zeta_A^2 B \frac{1.3(B/2)^2}{L_{BWL}^2+(B/2)^2}(1+C_{Ue}F_r) \quad (19)$$

$$C_{Ue} = \begin{cases} 10 & \text{for } \dfrac{L_{BWL}}{B} \le 1.22 \\ 68-310\dfrac{1.3(B/2)^2}{L_{BWL}^2+(B/2)^2} & \text{for } \dfrac{L_{BWL}}{B} > 1.22 \end{cases} \quad (20)$$

In case heave and pitch motions are small, R_{AW} can be approximated by R_{AWR}. Consequently, the added resistance due to long crested irregular head waves can be obtained by Eq. (21).

$$R_{AWL} \simeq \frac{1}{16}\rho_S g H_{1/3w}^2 B \frac{1.3(B/2)^2}{L_{BWL}^2+(B/2)^2}(1+C_{Ue}F_r) \quad (21)$$

The Simple-NMRI method is applicable for head waves ± 45 deg. The method is valid for all ship types with the following restrictions; $50\text{m} \le L_{pp}$, $4.0 \le L_{pp}/B \le 9.0$, $2.2 \le B/T_{mid} \le 9.0$, $0.39 \le C_B \le 0.90$, which is the same restrictions for NMRI method. Here, T_{mid} is the draft at midship, and C_B is the block coefficient.

3.3 Effect of the approximation of the bluntness coefficient

In order to examine the difference between approximated B_f by Eq. (18) and the actual B_f, the added resistance in waves is compared for PXBC shown in Table 2. The value of B_{ftri} is 0.277 where the actual B_f is 0.393. The value of $1.3B_{ftri}$ becomes 0.360 and it is 10% smaller than the actual B_f. The estimated results using $1.3B_{ftri}$ and the actual B_f are shown in Fig. 6, where K_{AW} is defined by Eq. (22). From Fig. 6, it is found that K_{AW} using $1.3B_{ftri}$ is 10% larger than that using the actual B_f.

$$K_{AW} = \frac{R_{AW}}{4\rho_s g \zeta_A^2 B^2/L_{pp}} \quad (22)$$

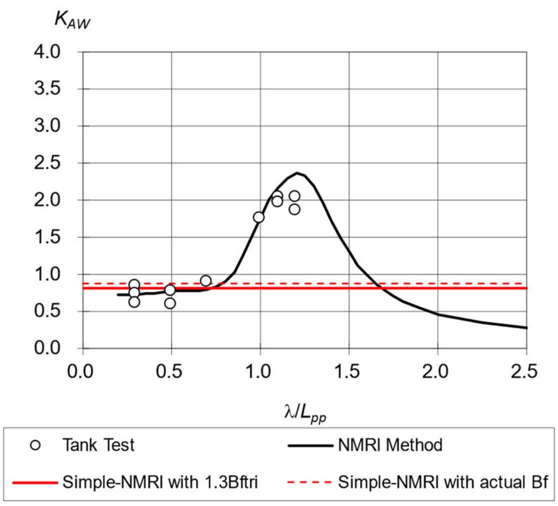


Fig. 6 Comparison for the approximation of the bluntness coefficient (PXBC, F_r = 0.167)

The desired target accuracy for the speed trial prescribed in ISO15016:2015 is set as 2% in shaft power. If the added resistance in waves is 20% of the total resistance, the error of 2% is allowed. Since the added resistance in waves is less than 20% of the total resistance considering the wave height at the actual speed trial, the 10% difference does not matter.

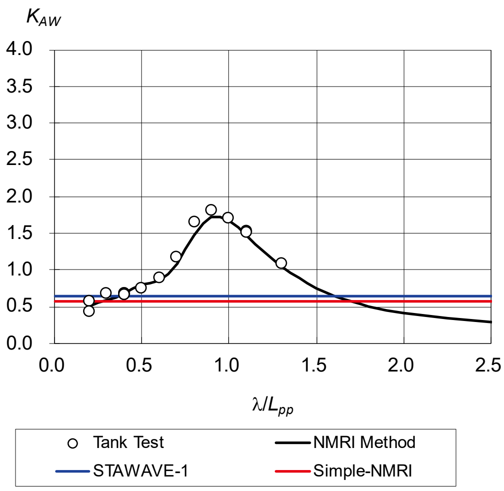
3.4 Trial calculations and validations

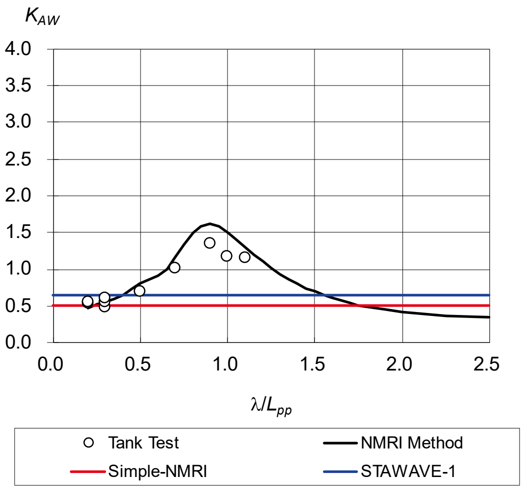
For object ships shown in Table 2, the Simple-NMRI method is applied and results are compared with tank test results in the references[14), 15), 16), 17), 18)] with the results of STAWAVE-1 and NMRI method.

Results of the added resistance in regular head waves are shown in Fig. 7. In Fig. 7, values of STAWAVE-1 is converted from the added resistance in long crested irregular waves by Eqs. (13) and (15). Tank test results are interpolated according to the reference[19)]. From the reference, the frequency response is extrapolated by a constant value at end points, and natural spline is used for the interpolation of the measured points. From the figures it is found that the Simple-NMRI method shows good agreement with tank tests in short waves range and various ship speed.

Table 2 Principal parameters of object ships.

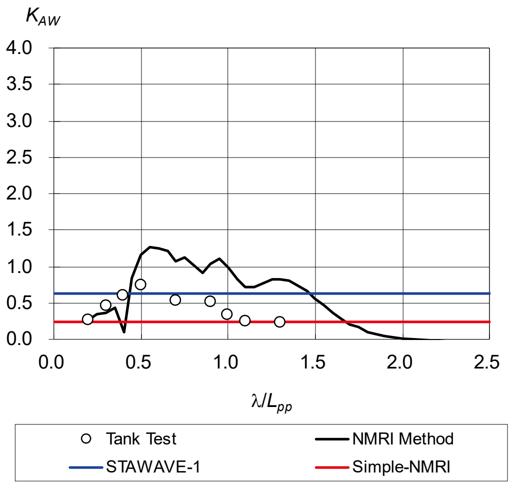
Items	Unit	DTC[14)]	CONT[15)]	PCC[15)]	JBC[16)]	PXBC[15)]	VLCC	Domestic cargo ship1	Domestic cargo ship2
Ship type	-	Container ship	Container ship	PCC	Bulker	Bulker	Tanker	Cargo ship	Cargo ship
Ship size	-	14,000TEU	6,500TEU	5,000 cars	15,000DWT	73,000DWT	300,000DWT	499GT	199GT
Length between perpendiculars (L_{pp})	m	355.000	300.000	190.000	280.000	217.000	324.000	69.000	51.300
Breadth (B)	m	51.000	40.000	32.260	45.000	32.260	60.000	12.000	9.600
Draft at midship (T_{mid})	m	14.500	14.000	9.000	16.500	14.000	20.500	4.124	3.278
Stern trim (τ)	m	0.000	0.000	0.000	0.000	0.000	0.000	1.380	0.000
Length of the bow on the water line to 95% of maximum beam (L_{BWL})	m	94.424	80.72	60.450	34.439	25.780	33.080	19.584	9.567
Froude number (F_r)	-	0.157, 0.139, 0.052, 0.000	0.247, 0.200	0.249, 0.200	0.142, 0.059, 0.000	0.167, 0.135	0.121	0.227	0.203

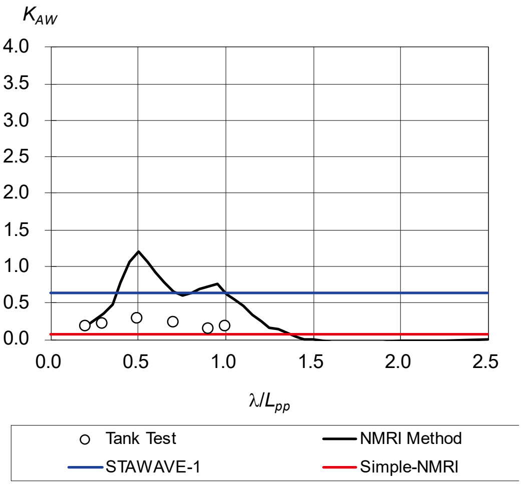




(a) DTC ($F_r = 0.157$)

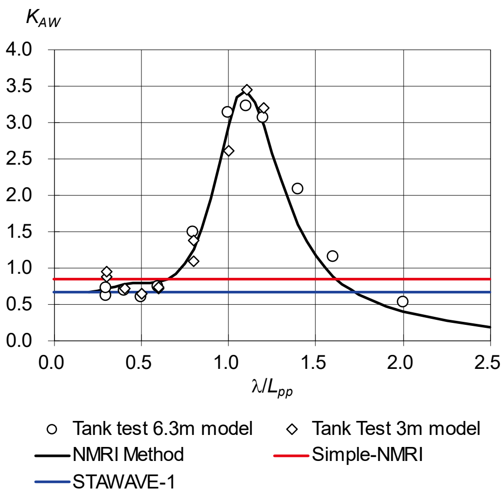
(b) DTC ($F_r = 0.139$)

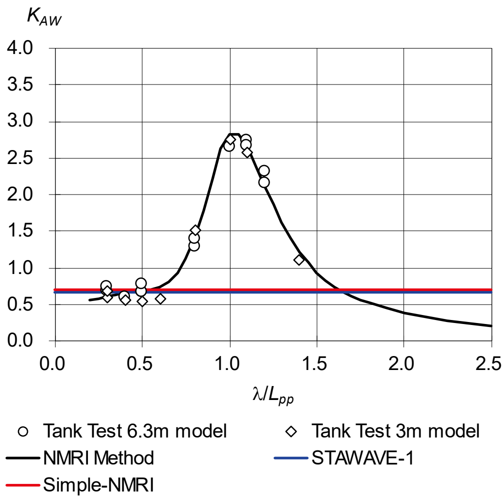




(c) DTC ($F_r = 0.052$)

(d) DTC ($F_r = 0.000$)

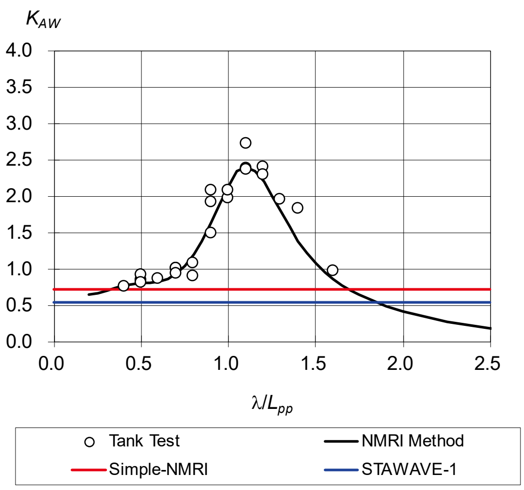


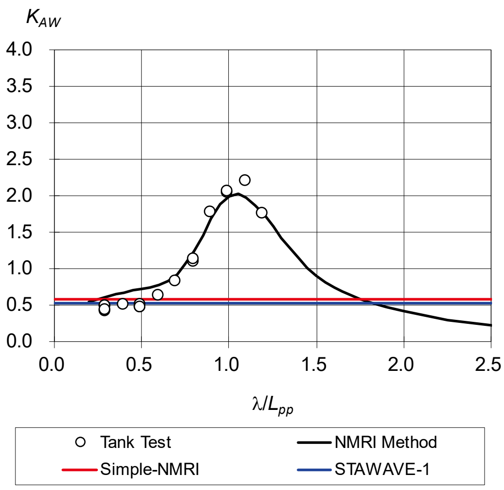


(e) CONT ($F_r = 0.247$)

(f) CONT ($F_r = 0.200$)

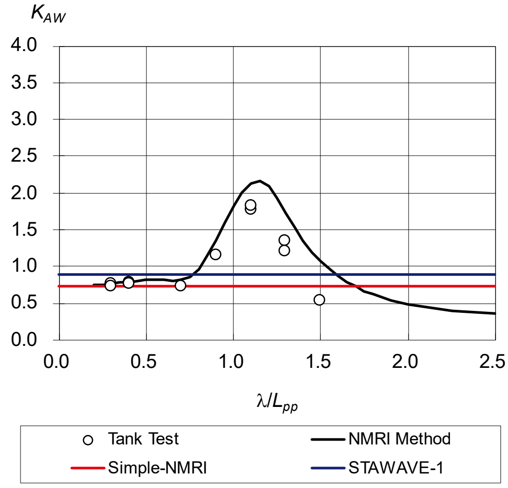
Fig. 7 Frequency response of added resistance in head waves (*continued*).



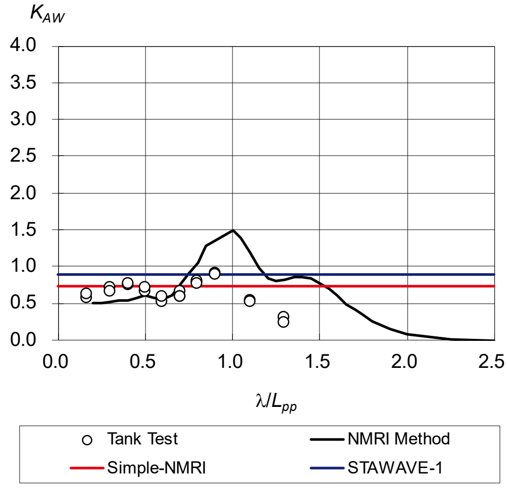


(g) PCC ($F_r = 0.249$)

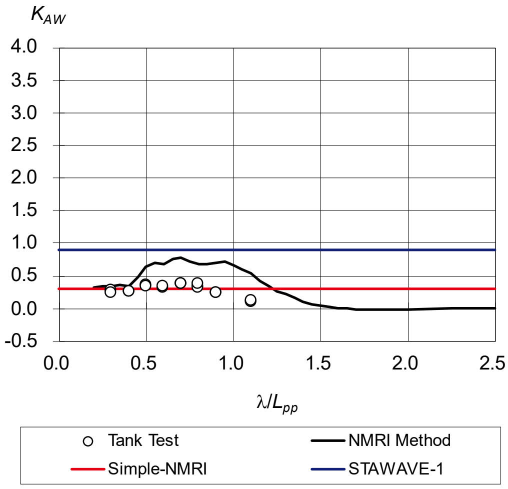
(h) PCC ($F_r = 0.200$)



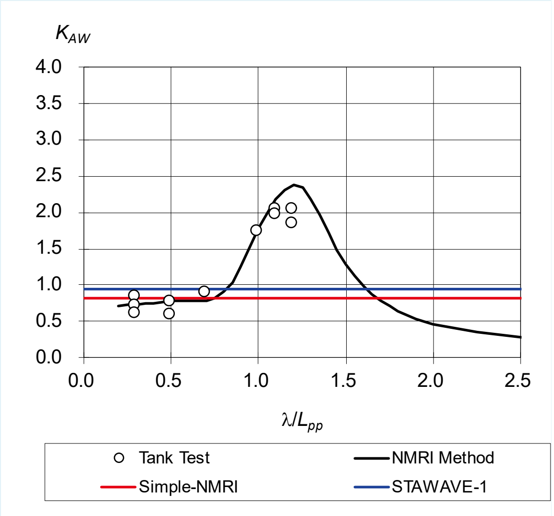
(i) JBC (F_r = 0.142)



(j) JBC (F_r = 0.059)

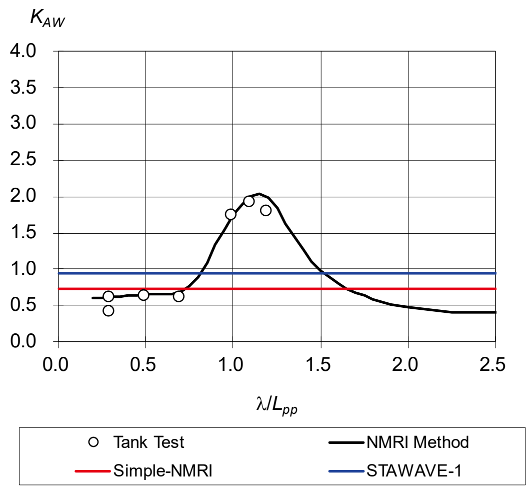


(k) JBC (F_r = 0.000)

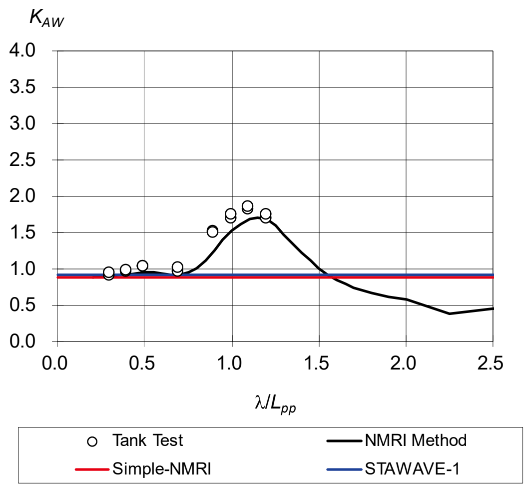


(l) PXBC (F_r = 0.167)

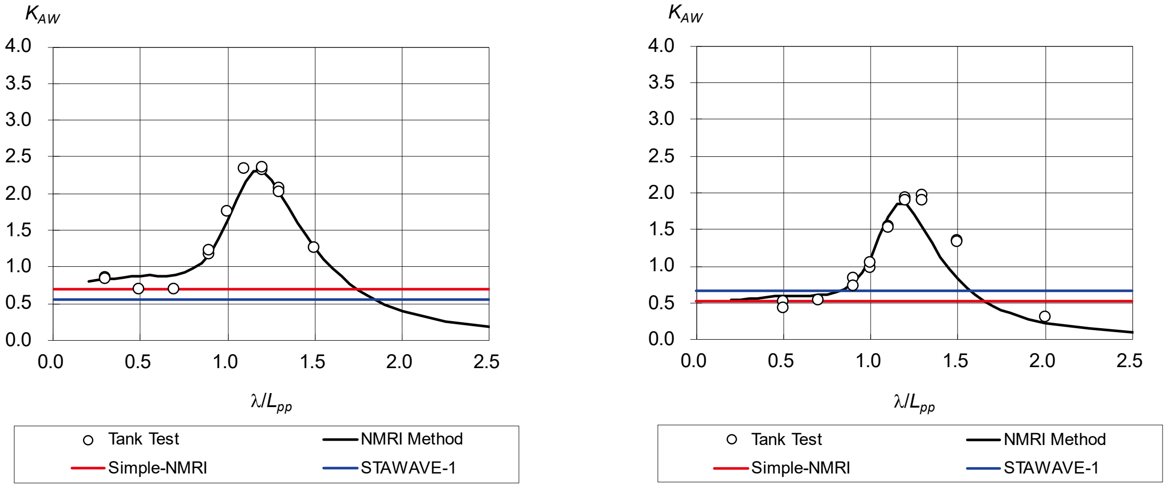
Fig. 7 Frequency response of added resistance in head waves (*continued*).



(m) PXBC (F_r = 0.135)



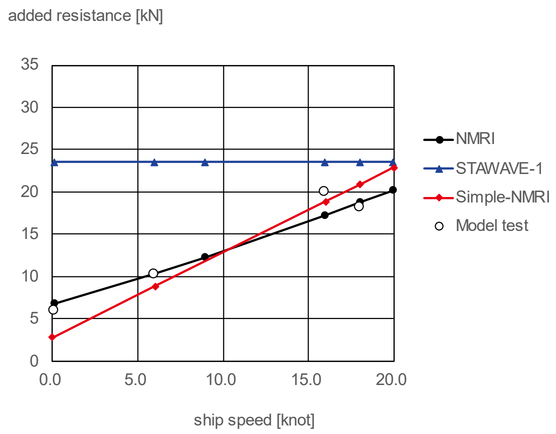
(n) VLCC (F_r = 0.121)



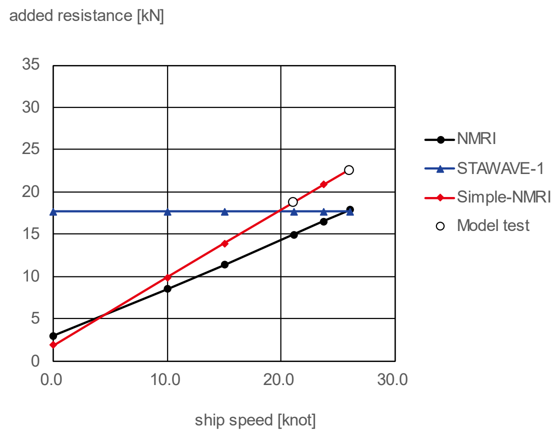
(o) Domestic cargo ship1 (F_r =0.227)　　(p) Domestic cargo ship2 (F_r =0.203)

Fig. 7 Frequency response of added resistance in head waves.

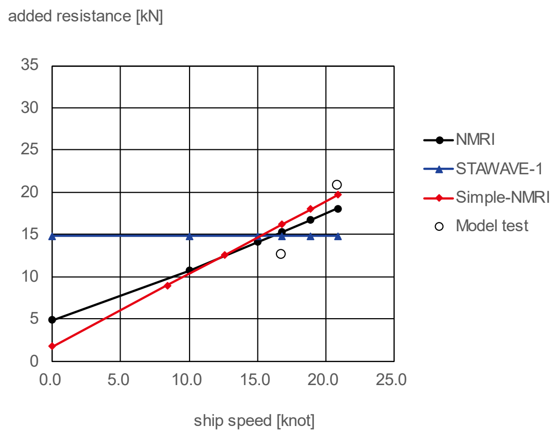
Results for the added resistance in long crested irregular head waves where the significant wave height is 1 m and the mean wave period is 3.9 s, which is rather mild wave conditions and common for the speed trial condition, are shown in Fig. 8. Here, ITTC spectrum[13)] is used as wave frequency spectrum. It can be found that the Simple-NMRI method shows the same tendency with NMRI method and model test, despite STAWAVE-1 is constant for the ship speed and overestimates the added resistance for low load conditions, which leads to the inappropriate verification of the reference ship speed V_{ref} and EEDI value.



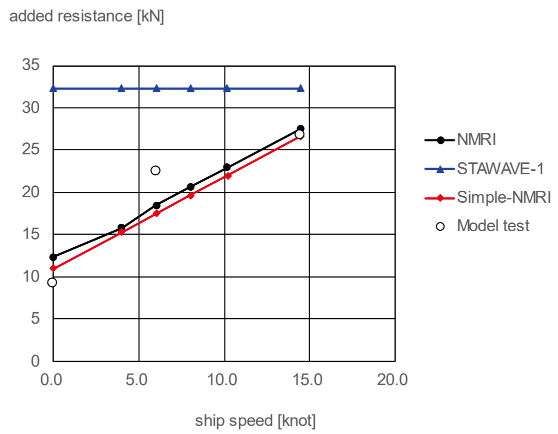
(a) DTC



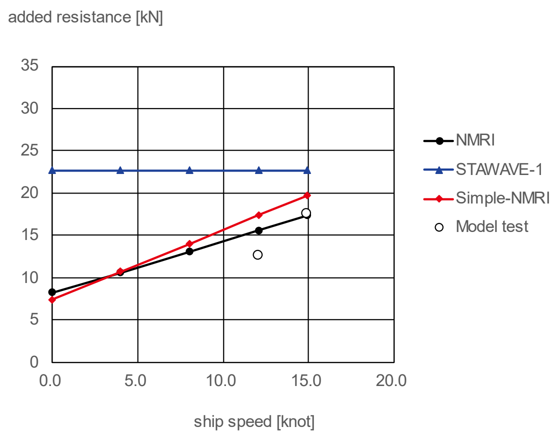
(b) CONT



(c) PCC



(d) JBC



(e) PXBC

Fig.8 Added resistance in long crested irregular head waves (significant wave height: 1 m, mean wave period: 3.9 s).

From the above, the Simple-NMRI method has been confirmed to be in good agreement with tank test results in short waves with the limited input data as the same as STAWAVE-1, and to lead the similar expression of the speed effect to the theoretical method or tank test results.

4. Conclusions

In this paper, the simplified wave correction method for speed trial analysis; Simple-NMRI method derived based on the theoretical method shows the merits for the application against the current STAWAVE-1;

- the Simple-NMRI method uses of the same input of the ship data as STAWAVE-1,
- the Simple-NMRI considers the speed effect more properly than STAWAVE-1.

Through the validation by the comparison with tank test results, it is found that the Simple-NMRI method enables to evaluate the added resistance in waves appropriately. Applying the Simple-NMRI method leads to the accurate wave correction with the limited data of the ship with the restricted application condition.

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