ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Prediction of Power Increase in Irregular Waves from Model Tests

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Prediction of Power Increase in Irregular Waves from Model Tests

1. PURPOSE OF PROCEDURE

The purpose of this procedure is to provide guidelines on how to obtain accurate predictions of power increase in irregular waves based on responses curves obtained from routine model tests in regular, irregular waves and in still water.

2. INTRODUCTION

For the purpose of predicting the power increase in realistic sea conditions, conducting resistance or self-propulsion tests in irregular waves is the most direct and simplest approach. However, this is not in general a satisfactory solution, because the results only apply only to the particular wave spectra for which the experiments were carried out. In order to design ships or to analyze the measured data of ships at sea, it is necessary to be able to predict ships' power performance in various irregular wave conditions. The common approach relates to the application of linear spectral analysis, for which purpose it is necessary to have the basic data on ship's response amplitude operators (RAOs) in regular waves. In particular, by using these data and the irregular wave spectra, power increase in various kinds of irregular waves can be predicted and evaluated.

Several methods have been proposed and are in broad use at various laboratories to predict the power increase in irregular waves by combining response amplitude operators from model tests in regular waves with results from performance tests in still water.

The Seakeeping Committee of 25th ITTC made a comparison of four different methods to obtain the power increase in waves, namely:

Direct Power Method	DPM
Torque & Revolution Method	QNM
Thrust and Revolution Method	TNM
Resistance & Thrust Identity M.	RTIM

The results show that, three of four methods give almost the same results in the case of full load conditions. (See Figures 1 and 2, 25th ITTC (2008))

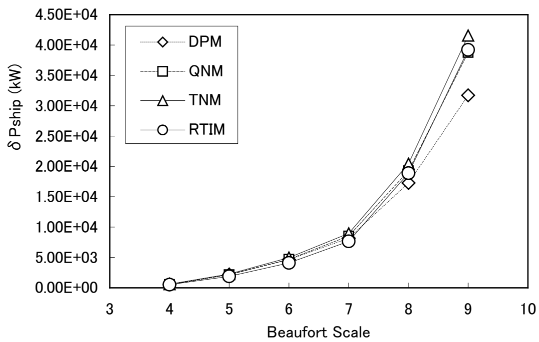

Figure 1: Power increase in irregular waves, Container ship (FULL)

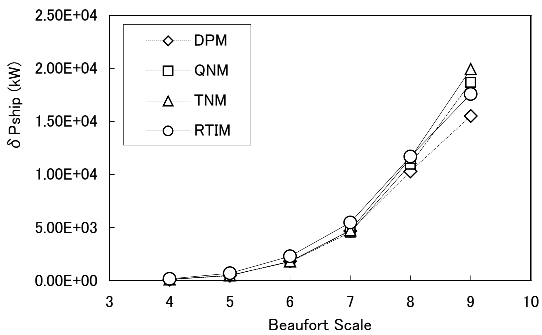

Figure 2: Power increase in irregular waves, VLCC (FULL)

The predicted results by these three methods should also be compared with the measured power increase in irregular wave obtained from the direct irregular wave tests, i.e. resistance tests or self-propulsion tests in irregular waves.

But the data used for comparing and evaluating the above three methods do not contain the test results in irregular waves. Therefore as the secondary measure, the resistance increase δR, propeller torque and revolution increase δQ and δn in irregular waves are compared between their predicted values and the measured values, whose data are referred from Takahashi (1987) and Nakamura *et al.* (1975) for a tanker model and a container ship model, and also voluntary in-house data for two VLCCs that are not available in the open literature.

The papers, which contain data, do not include still water performance and the propeller open water characteristics. Therefore, a full power prediction cannot be performed, but instead of that the three parameters δR, δQ and δn are compared between their predicted and measured values. The predicted values here mean those obtained multiplication of the measured response functions in regular waves and the measured wave spectra obtained from the irregular wave tests.

The comparison results (Figures 3, 4, and 5, 26th ITTC (2011)) show that the predicted results are scattered around the measured values in the range mostly of 10 or 20% for the resistance increase. For torque and revolution increase, though, measured values are larger than predicted values. The above discrepancies and scatter between predicted and measure values are estimated to be due to that:

1. response amplitude operators in regular waves may not be proportional to the square of incident wave amplitude, which is the assumption of linear spectral analysis.
2. the accuracy of measurements and analysis of the values in irregular waves may be less than those in regular waves including the effect of the time duration of the measurements in irregular waves. (See section 4.3)

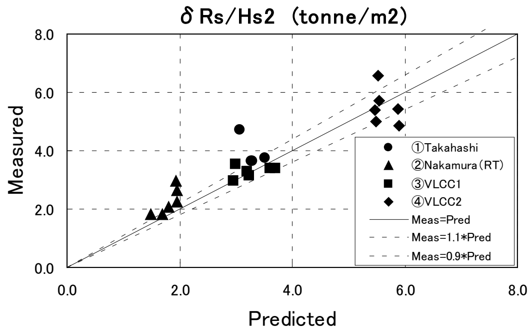

Figure 3: Resistance increase in irregular waves

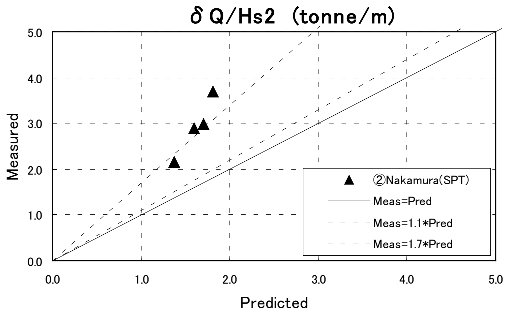

Figure 4: Torque increase in irregular waves

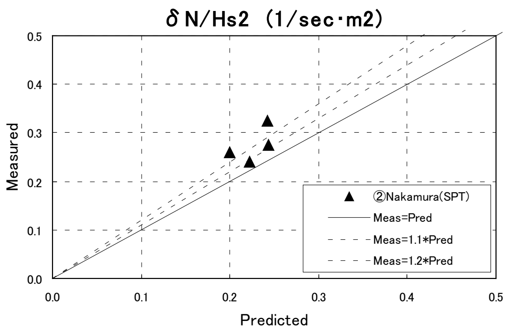

Figure 5: Revolution increase in irregular waves

However, the amount of data for the above evaluation is limited and further investigation is necessary.

3. IRREGULAR WAVES AND THE EFFECT OF DIRECTIONAL SPREADING ON POWER PREDICTIONS

Ocean waves are normally short crested and irregular. This should be taken into account when predicting the power increase in waves and can be achieved by use of a directional spectrum. The directional spectrum *E* is composed of frequency spectrum *S* and angular distribution function *D*. For open ocean environments for example, a directional spectrum can be formulated as follows (see also ITTC guideline 7.5-02-07-01.1).

$$E\left(\omega; H_{W1/3}, T, \alpha, \theta\right) = S\left(\omega; H_{W1/3}, T\right) D(\alpha, \theta) \quad (1)$$

$$S\left(\omega; H_{W1/3}, T\right) = \frac{A_S}{\omega^5} e^{-\frac{B_S}{\omega^4}} \quad (2)$$

where T can be T_1 or T_2, depending on the formulation used:

$$A_S = 173 H_{W1/3}^2 / T_1^4 \approx \frac{H_{W1/3}}{4\pi}\left(\frac{2\pi}{T_2}\right)^4$$
$$B_S = 691 / T_1^4 \approx \frac{1}{\pi}\left(\frac{2\pi}{T_2}\right)^4 \quad (3)$$

with the significant wave height $H_{W1/3}$ and the spectral peak period T_0, the average period T_1 and the average zero crossing period T_2 and their approximate relations:

$$T_1 = 2\pi m_0 / m_1$$
$$T_2 = 2\pi\sqrt{m_0 / m_2} \quad (4)$$
$$T_0 \approx 1.296 T_1 \approx 1.408 T_2$$

and the directional spreading function:

$$D(\alpha, \theta) = \begin{cases} \frac{2^{2s-1}}{\pi} \frac{\Gamma^2(s+1)}{\Gamma(2s+1)} \cos^{2s}\left(\frac{\theta-\alpha}{2}\right) & \text{for } |\theta - \alpha| \leq \pi \\ 0 & \text{otherwise} \end{cases} \quad (5)$$

with *s* the directional spreading parameter (a positive integer) and Γ the Gamma function. For long crested irregular waves *D* is given as:

$$D(\alpha, \theta) = \delta(\theta - \alpha) \quad (6)$$

where δ is Dirac's delta.

Superposition can be used to handle the case of two directional sea conditions, e.g. sea and swell with different directions and significant wave heights.

4. SUMMARY OF PREDICTION METHODS

In the following sections 4.1 to 4.3, three different methods for prediction of power increase in irregular waves based on regular wave test results, mostly used in model basin's practice worldwide, are described. Power increase prediction methods from direct irregular wave tests are also described in sections 4.4 and 4.5. Table 1 summarizes successive steps in application of these methods, including a brief description of their advantages and disadvantages.

4.1 Torque and Revolution Method (QNM)

In this method, model tests in still water and in regular waves are carried out at the ship SPP (Self-Propulsion Point), applying SFC (Skin Friction Correction) force, and response amplitude operators of torque and revolutions in regular waves are obtained. The mean propeller torque increase and revolution increase in irregular waves are calculated by equations (7) and (8), assuming that propeller torque increase and revolution increase in regular waves are proportional to the square of the incident wave amplitude

$$\delta Q_{\mathrm{M}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{\delta Q(\omega)_{\mathrm{M}}}{\zeta_A^2}E(\omega,\alpha,H,T,\theta)d\omega d\alpha \quad (7)$$

$$\delta n_{\mathrm{M}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{\delta n(\omega)_{\mathrm{M}}}{\zeta_A^2}E(\omega,\alpha,H,T,\theta)d\omega d\alpha \quad (8)$$

The mean power increase in irregular waves is then calculated by using these mean torque and revolution increases according to equation (9):

$$\delta P_{\mathrm{M}} = 2\pi\cdot\{(Q_{\mathrm{SW}}+\delta Q_{\mathrm{M}})(n_{\mathrm{SW}}+\delta n_{\mathrm{M}}) - Q_{\mathrm{SW}}.n_{\mathrm{SW}}\} \quad (9)$$

The mean power increase of the ship in irregular wave, then, is obtained under the assumption that the result in model scale can be simply scaled by $\lambda^{3.5}$.

The advantage of this method is that only self-propulsion tests in still water and in regular waves are to be conducted, and that consideration of propeller performance is not necessary.

4.2 Thrust and Revolution Method (TNM)

In this method, preliminary SPT (Self-Propulsion Test) are carried out in still water at the ship SPP, measuring the thrust and revolutions, and then estimating the wake fraction, $(1\text{-}w)_{\mathrm{SW}}$.

From the self-propulsion test results in regular waves, analogously to 4.1, the mean thrust increase and propeller revolution increase in irregular waves are calculated by equations (10) and (11) separately:

$$\delta T_{\mathrm{M}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{\delta T(\omega)_{\mathrm{M}}}{\zeta_A^2}E(\omega,\alpha,H,T,\theta)d\omega d\alpha \quad (10)$$

$$\delta n_{\mathrm{M}} = 2\int_0^{2\pi}\int_0^{\infty}\frac{\delta n(\omega)_{\mathrm{M}}}{\zeta_A^2}E(\omega,\alpha,H,T,\theta)d\omega d\alpha \quad (11)$$

The assumption is that thrust increase and revolution increase in regular waves are proportional to the square of the incident wave amplitude.

The total thrust and propeller revolution in irregular waves are given as the sum of those in still water and mean added values in irregular waves:

$$T_{\mathrm{M}} = T_{\mathrm{SW,M}} + \delta T_{\mathrm{M}} \quad (12)$$

$$n_{\mathrm{M}} = n_{\mathrm{SW,M}} + \delta n_{\mathrm{M}} \quad (13)$$

Once thrust and propeller revolution in irregular waves are obtained as above, the power increase in irregular waves is calculated according to the following procedure using the propeller open water chart in still water.

First, the thrust coefficient K_T is calculated as:

$$K_T = \frac{T_{\mathrm{M}}}{\rho_{\mathrm{M}}\cdot n_{\mathrm{M}}^2\cdot D_{\mathrm{M}}^4} \quad (14)$$

On the K_T curve, the advance ratio J is obtained as: (See Figure 6 (A) and (B))

$$J = \frac{(1-w)\cdot V}{n\cdot D} \quad (15)$$

At this J value, power coefficient K_P is obtained on the K_P curve: (See Figure 6(C))

$$K_P = \frac{K_Q}{J^3} = \frac{Q}{\rho n^2 D^5 J^3} = \frac{nQ}{\rho(1-w)^3V^3D^2} \quad (16)$$

By using this K_P value, the power in irregular waves is calculated by:

$$P_S = 2\pi \cdot nQ = 2\pi \cdot K_P \rho (1-w)^3 V^3 D^2 \quad (17)$$

The mean power increase in irregular waves can be obtained by subtracting the power in still water:

$$\delta P_S = P_S - P_{SW,S} \quad (18)$$

In order to use this method, propeller open water tests are required in addition to self-propulsion tests in still water and in regular waves. However, such propeller tests will normally already have been conducted previously for predicting power in still water.

The main assumption of this method is that the propeller characteristics and the self-propulsion factors such as wake fraction factor (1-*w*) in waves are identical to those in still water. This assumption seems valid only for mild wave conditions. Further investigation on this issue seems desirable.

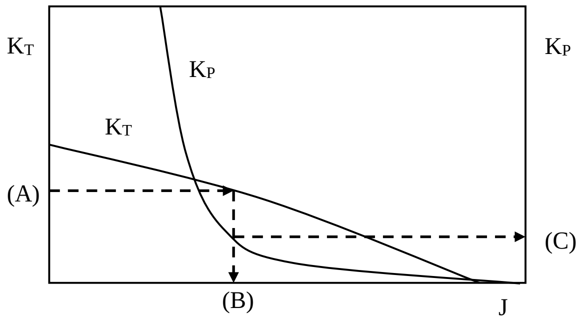

Figure 6: Propeller Open Water Chart (TNM)

Table 1 Summary of prediction methods

Type of Tests		Torque & Revolution Method (QNM)	Thrust & Revolution Method (TNM)
Still Water	Resistance Tests		
	Self-Propulsion Tests at ship point (ship SPP)	Q_{SW}, n_{SW}	T_{SW}, n_{SW}
	Prop Open Water Tests		POC
	Power		$(1\text{-}w)_{SW}$
Regular Waves	Resistance Tests		
	Self-Propulsion Tests at ship point (ship SPP)	$Q(\omega)$, $n(\omega)$ $\delta Q(\omega)$, $\delta n(\omega)$	$T(\omega)$, $n(\omega)$ $\delta T(\omega)$, $\delta n(\omega)$
	Power Increase		
Irregular Waves	Wave Spectrum	$E(\omega,\alpha)$	$E(\omega,\alpha)$
	Resistance Tests		
	Self-Propulsion Tests at ship point (model SPP)		
	Power Increase	δQ δn δP_M δP_S	δT δn POC δP_S
Features & Assumptions	Additional Effects such as wind, etc..	Cannot be considered	Cannot be considered
	RAO Assumption	$\delta P, \delta Q, \delta n \propto \zeta_A^2$	$\delta T, \delta n \propto \zeta_A^2$
	Propeller Characteristics Assumption	No need	In waves = In still water
	Self Propulsion Factors Assumption	No need	In waves = In still water
	ISO Wave Correction	Inconsistent	Inconsistent
Notes			

Tests to be conducted	(grey)

continued …..

Table 1 (continued)

Type of Tests		**Resistance & Thrust Identify Method (RTIM)**	***Self-Propulsion Test In Irregular Waves***
Still Water	Resistance Tests	R_{SW}	
	Self-Propulsion Tests at ship point (ship SPP)	T_{SW}, Q_{SW}, n_{SW}	Q_{SW}, n_{SW}
	Prop Open Water Tests	POC	
	Power	$(1\text{-}w)_{SW}$, $(1\text{-}t)_{SW}$	
Regular Waves	Resistance Tests	$R(\omega)$ $\delta R(\omega)$	
	Self-Propulsion Tests with SFC (ship SPP)		
	Power Increase		
Irregular Waves	Wave Spectrum	$E(\omega,\alpha)$	$E(\omega,\alpha)$
	Resistance Tests		
	Self-Propulsion Tests with SFC (model SPP)		Q, n δQ, δn
	Power Increase	δR POC → δP_S	δP_M δP_S
Features & Assumptions	Additional Effects such as wind, etc..	Can be considered	Cannot be considered
	RAO Assumption	$\delta R \propto \zeta_A{}^2$	
	Propeller Characteristics Assumption	In waves = In still water	No need
	Self Propulsion Factors Assumption	In waves = In still water	No need
	ISO Wave Correction	Consistent	Inconsistent
Notes		24th ITTC AC comment	

Tests to be conducted	(grey)

continued …..

Table 1 (continued)

Type of Tests		***Resistance Test In Irregular Waves***
Still Water	Resistance Tests	R_{SW}
	Self-Propulsion Tests at ship point (ship SPP)	T_{SW}, Q_{SW}, n_{SW}
	Prop Open Water Tests	POC
	Power	$(1\text{-}w)_{SW}$, $(1\text{-}t)_{SW}$
Regular Waves	Resistance Tests	
	Self-Propulsion Tests with SFC (ship SPP)	
	Power Increase	
Irregular Waves	Wave Spectrum	$E(\omega,\alpha)$
	Resistance Tests	R δR
	Self-Propulsion Tests with SFC (model SPP)	
	Power Increase	POC → δP_S
Features & Assumptions	Additional Effects such as wind, etc..	Can be considered
	RAO Assumption	
	Propeller Characteristics Assumption	In waves = In still water
	Self Propulsion Factors Assumption	In waves = In still water
	ISO Wave Correction	Consistent
Notes		

Tests to be conducted	(grey)

4.3 Resistance and Thrust Identity Method (RTIM)

This method requires detailed information about the model performance in still water, including resistance and Self-propulsion test at ship SPP and their resultant self-propulsion factors. Towing tests are performed in regular waves to obtain the response amplitude operator of the resistance increase, $\delta R(\omega)_M/\zeta_A{}^2$. Then the resistance increase in irregular waves δR_S for a given wave energy spectrum $E(\omega,\alpha)$ is calculated as:

$$\delta R_S = 2\int_0^{2\pi}\int_0^{\infty}\frac{\delta R(\omega)_M}{\zeta_A^2}E(\omega,\alpha,H,T,\theta)d\omega d\alpha \tag{19}$$

where the mean resistance increase in irregular waves in ship scale δR_S is assumed to be given by multiplying the ship scale wave energy spectrum $E(\omega,\alpha)$ in equation (19).

Total resistance in irregular waves is calculated by:

$$R_S = R_{SW,S} + \delta R_S \tag{20}$$

The mean power increase in irregular waves is calculated as follows:

$$T_S = \frac{R_S}{1 - t_{SW}} \tag{21}$$

$$K_T /J^2 = \frac{T}{\rho_S D^2 V^2 (1 - w_{SW})^2} \tag{22}$$

$$J = \frac{(1 - w) V}{n D} \tag{23}$$

$$K_p = \frac{K_Q}{J^3} \tag{24}$$

See Figure 7. The total power in waves is then calculated as:

$$P_S = 2\pi nQ = 2\pi K_P \rho(1\text{-}w)^3 V^3 D^2 \tag{25}$$

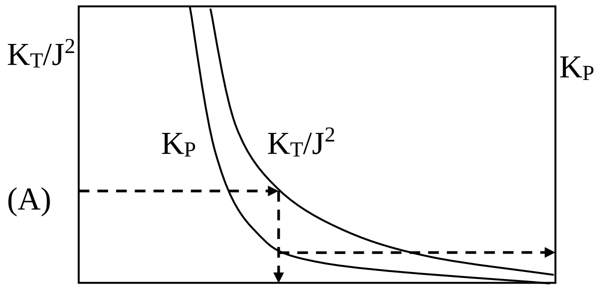

Figure 7: Propeller Open Water Chart (RTIM)

Finally, the mean power increase in irregular waves is obtained by subtracting the power in still water from the above power in irregular waves:

$$\delta P_S = P_S - P_{SW,S} \tag{26}$$

The advantage of this method is that only resistance tests in regular waves have to be conducted, which are easier to perform rather than self-propulsion tests in regular waves. Resistance tests, self-propulsion tests and propeller open water test in still water are also necessary, but they usually will have been carried out previously for power prediction in still water, as mentioned above.

The main advantage of this method is that it allows consideration of additional resistance components such as forces due to wind or as a result of manoeuvring. The same procedure is used by ISO 15016 (2015) to correct the wave effect on the ship speed trial results.

The main assumption of this method is the same as in “Thrust and Revolution Method (TNM)”, i.e. that the propeller characteristics and the self-propulsion factors such as wake fraction factor (1-w) and thrust deduction factor (1-t) in waves are identical to those in still water.

4.4 Self-propulsion test in irregular waves

By conducting self-propulsion test in irregular waves, the mean increase in propeller torque and revolution, δQ_M and δn_M, can be obtained directly. The mean power increase will be calculated by equation (9) with the above values and those in still water.

4.5 Resistance test in irregular waves

The mean resistance increase in irregular waves, δR, can also be obtained directly by performing resistance test in irregular waves. The mean power increase will be calculated by equation (19) to (26) with the above values δR, self-propulsion factors and propeller open water characteristics.

5. MODEL TESTS

The ITTC recommended procedure 7.5-02-07-02.1 on seakeeping experiments describes the various model tests and their requirements to obtain the added resistance or the Self Propulsion Point in regular and in irregular waves.

6. PARAMETERS TO BE TAKEN INTO ACCOUNT

D	Propeller diameter
Q_{SW}	Propeller Torque in still water
n_{SW}	Propeller revolution in still water
T_{SW}	Thrust in still water
R_{SW}	Resistance in still water
w	Wake fraction
t	Thrust deduction ratio
ζ_A	Regular wave amplitude
ω	Wave frequency
$S(\omega)$	Wave energy spectrum
$H_{W1/3}$	Significant wave height
T_0	Zero-up-crossing wave period
$Q(\omega)$	Propeller Torque in regular waves
$n(\omega)$	Propeller revolution in regular waves
$T(\omega)$	Thrust in regular waves
$R(\omega)$	Resistance in regular waves
$\delta Q(\omega)$	Propeller Torque increase in regular waves
$\delta n(\omega)$	Propeller revolution increase in regular waves
$\delta T(\omega)$	Thrust increase in regular waves
$\delta R(\omega)$	Resistance increase in regular waves
δQ	Mean propeller torque increase in irregular seas
δn	Mean propeller revolution increase in irregular seas
δT	Mean thrust increase in irregular seas
δR	Mean resistance increase in irregular seas
δP	Mean power increase in irregular seas
λ	Model scale
D	Angular distribution function
E	Directional spectrum
$H_{W1/3}$	Significant wave height
S	Frequency spectrum
T_1	Mean wave period
T_2	Mean wave zero (up-)crossing period
α	Angle between ship course and regular waves (angle 0(deg.) is defined as the head waves direction)
θ	Mean wave direction
ω	Circular frequency of incident regular waves

Subscript:

S	ship scale
M	model scale
SW	still water

Abbreviations:

POC	Propeller Open Water Characteristic
RT	Resistance Test
SPT	Self-Propulsion Test
SPP	Self-Propulsion Point
SFC	Skin Friction Correction
RAO	Response Amplitude Operator

QNM Torque & Revolution Method
DPM Direct Power Method
TNM Thrust and Revolution Method
RTIM Resistance & Thrust Identity Method

7. VALIDATION

7.1 Uncertainty Analysis

Uncertainty analysis of methods outlined above has to be done, following ITTC Recommended Procedure 7.5-02-02-02.1 – Example for Uncertainty Analysis of Resistance tests in Towing Tank

8. REFERENCES

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