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Seakeeping 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 power increase in realistic seas, 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 are less precise than those obtained in regular waves and 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 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 power increase in irregular waves from response amplitude operators obtained from model tests in regular waves and using basic results from performance tests in still water.

The Seakeeping Committee of 25th ITTC made comparison of four methods, and the results obtained for various ships show that three of four methods explained below give almost the same results in the case of full load conditions. (See Figures 1 and 2, 25th ITTC (2008))

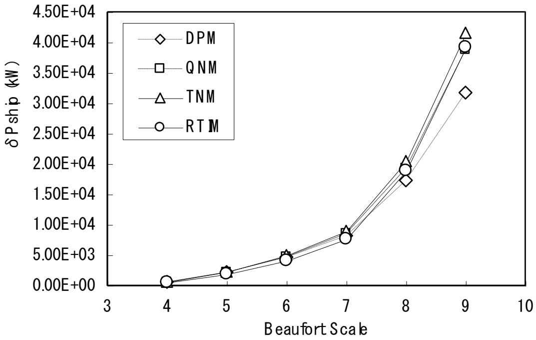


Figure 1: Power increase in irregular waves, Container ship (FULL)

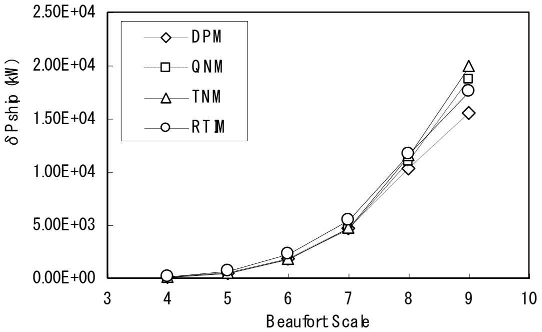


Figure 2: Power increase in irregular waves, VLCC (FULL)

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 open literature.

The papers, which contain data, do not include still water performance and the propeller open 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)

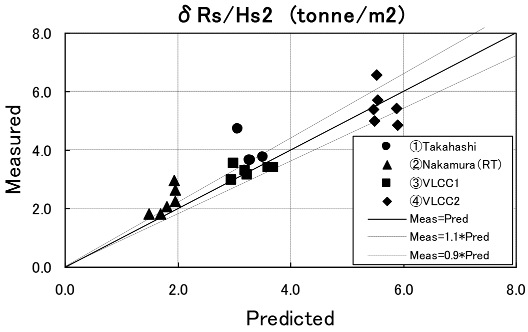


Figure 3: Resistance increase in irregular waves

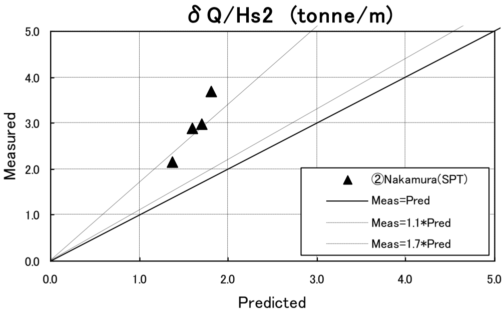


Figure 4: Torque increase in irregular waves

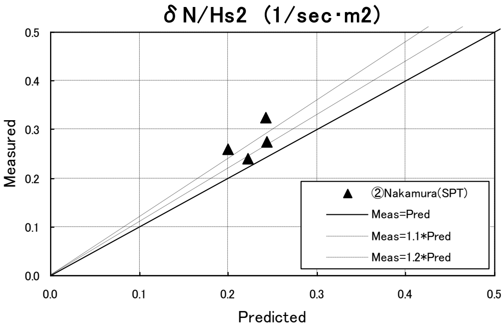


Figure 5: Revolution increase in irregular waves

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

3. IRREGULAR WAVES

Symbols

D : Angular distribution function

E : Directional spectrum

H : Significant wave height

S : Frequency spectrum

T : Mean wave 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

As ocean waves are characterized as short crested irregular ones, the directional spectrum should be considered. The directional spectrum E is composed of frequency spectrum S and angular distribution function D. For example, directional spectrum is given as follows.

$$E(\omega,\alpha;H,T,\theta) = S(\omega;H,T)D(\alpha;\theta) \tag{1}$$

$$S(\omega;H,T) = \frac{A_S}{\omega^5}\mathrm{e}^{-\frac{B_S}{\omega^4}} \tag{2}$$

where,

$$A_S = \frac{H^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4, \quad B_S = \frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4, \quad T_z = 0.920T$$

$$D(\alpha,\theta) = \begin{cases} \frac{2^{2n}}{\pi}\frac{\Gamma^2(n+1)}{\Gamma(2n+1)}\cos^{2n}(\theta-\alpha), \\ \quad for \quad |\alpha-\theta| \leq \frac{\pi}{2} \\ \\ 0, \quad for\,(others) \end{cases} \tag{3}$$

where n is directional spreading parameter in positive integer and Γ is Gamma function.

For long crested irregular waves, D is given as,

$$D(\alpha,\theta) = \delta(\theta-\alpha) \tag{4}$$

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 brief description of their advantages and disadvantages for each method.

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 (5) and (6), at assumption that propeller torque increase and revolution increase in regular waves are proportional to the square of the incident wave amplitude

$$\delta Q_M = 2\int_0^{2\pi}\int_0^{\infty} \frac{\delta Q(\omega)_M}{\zeta_A^2} E(\omega, \alpha; H, T, \theta) d\omega d\alpha \tag{5}$$

$$\delta n_M = 2\int_0^{2\pi}\int_0^{\infty} \frac{\delta n(\omega)_M}{\zeta_A^2} E(\omega, \alpha; H, T, \theta) d\omega d\alpha \tag{6}$$

The mean power increase in irregular waves is then calculated by using these mean torque and revolution increases according by the equation (7):

$$dP_{\mathrm{M}} = \times\frac{2p}{75}\left\{\left(Q_{\mathrm{SW}} + dQ_{\mathrm{M}}\right)\left(n_{\mathrm{SW}} + dn_{\mathrm{M}}\right) - Q_{\mathrm{SW}}.n_{\mathrm{SW}}\right\} \tag{7}$$

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)

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

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 (8) and (9) separately:

$$\delta T_M = 2\int_0^{2\pi}\int_0^{\infty} \frac{\delta T(\omega)_M}{\zeta_A^2} E(\omega, \alpha; H, T, \theta) d\omega d\alpha \tag{8}$$

$$\delta n_M = 2\int_0^{2\pi}\int_0^{\infty} \frac{\delta n(\omega)_M}{\zeta_A^2} E(\omega, \alpha; H, T, \theta) d\omega d\alpha \tag{9}$$

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:

$$T_{\mathrm{M}} = T_{\mathrm{SW,M}} + \delta T_{\mathrm{M}} \tag{10}$$

$$n_{\mathrm{M}} = n_{\mathrm{SW,M}} + \delta n_{\mathrm{M}} \tag{11}$$

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 chart in still water.

First, the thrust coefficient K_T is calculated by:

$$K_T = \frac{T_M}{\rho \cdot n_M^2 \cdot D^4} \tag{12}$$

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

$$J = \frac{(1-w)\cdot V}{n \cdot D} \tag{13}$$

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

$$K_P = \frac{K_Q}{J^3} = \frac{Q}{\rho n^2 D^5 J^3} = = \frac{nQ}{\rho(1-w)^3 V^3 D^2} \tag{14}$$

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

$$P_S = \frac{2\pi}{75} nQ = \frac{2\pi}{75} K_P \rho (1-w)^3 V^3 D^2 \tag{15}$$

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

$$\delta P_S = P_S - P_{SW,S} \tag{16}$$

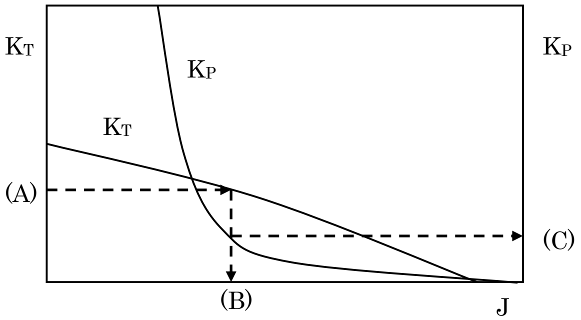
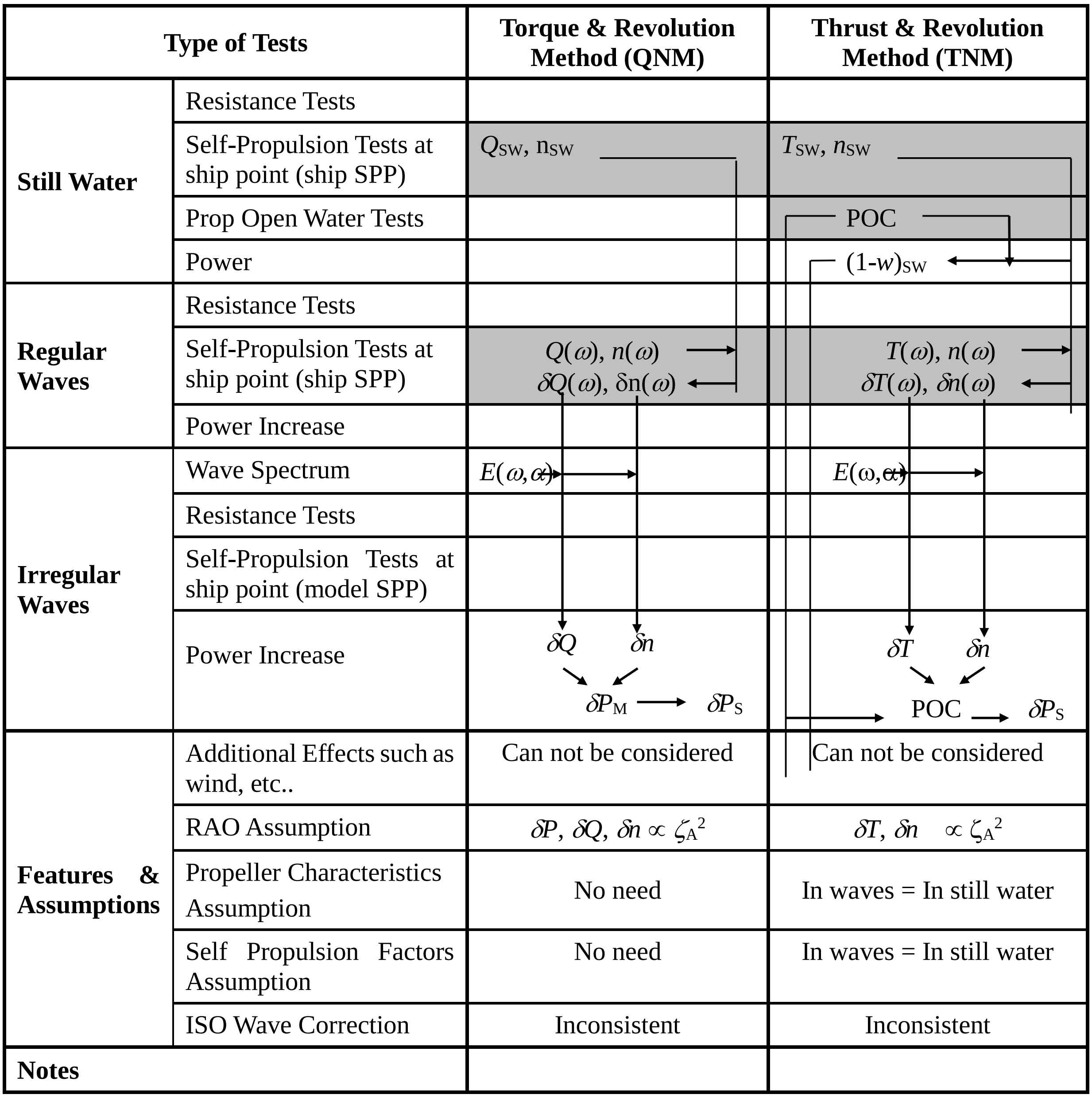


Figure 6: Propeller Open Chart (TNM)

To apply this method, besides self-propulsion tests in still water and in regular waves, propeller open water performance data in still water are also necessary, but these tests have basically been conducted previously for predicting power in still water in general.

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.

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		$(1-w)_{SW}$
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 $\delta P_M \longrightarrow \delta P_S$	δT δn POC $\longrightarrow \delta P_S$
Features & Assumptions	Additional Effects such as wind, etc..	Can not be considered	Can not 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

continued …..

▨

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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	Can not 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 ▨

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 ▨

4.3 Resistance and Thrust Identity Method (RTIM)

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

$$\delta R_S{=}2\int_0^{2\pi}\int_0^{\infty}\frac{\delta R(\omega)_M}{\zeta_A^2}E(\omega,\alpha;H,T,\theta)d\omega d\alpha \qquad (17)$$

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 (17).

Total resistance in irregular waves is calculated by:

$$R_S = R_{SW,S} + \delta R_S \qquad (18)$$

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

$$T_S = \frac{R_S}{1-t_{SW}} \qquad (19)$$

$$K_T / J^2 = \frac{T}{\rho_s D^2 V^2 (1-w_{SW})^2} \qquad (20)$$

$$J = \frac{(1-w)V}{nD} \qquad (21)$$

$$K_p = \frac{K_Q}{J^3} \qquad (22)$$

(See Figure 7 (A) to (C))

where the total power in waves is calculated as:

$$P_S = 2\pi/75\ nQ = 2\pi/75\ K_P\ \rho(1\text{-}w)^3\ V^3\ D^2 \qquad (23)$$

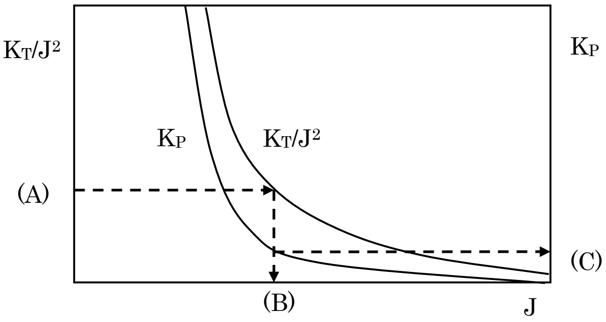

Figure 7: Propeller Open Chart (RTIM)

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

$$\delta P_S = P_S - P_{SW,S} \qquad (24)$$

The advantage of this method is that only resistance tests in regular waves are to be conducted, which is easier to perform rather than self-propulsion tests in regular waves. Resistance tests, self-propulsion tests and propeller open test in still water are also necessary to be conducted, but they are principally 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 due to wind and maneuver, in ship design and/or analysis of the ship performance at sea. For instance, the same procedure is used by ISO 15016 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)”, which is 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, mean propeller torque and revolution increase in irregular waves, δQ_M and δn_M, can be obtained directly. The mean power increase will be calculated by equation (7) with the above values and those in still water.

4.5 Resistance test in irregular waves

Mean resistance increase in irregular waves, δR, can be obtained directly by performing resistance test in irregular waves. The mean power increase will be calculated by equation (18) to (25) with the above values δR, self-propulsion factors and propeller open water characteristics.

5. BRIEF DESCRIPTION OF MODEL EXPERIMENTS NECESSARY FOR THE PROCEDURE

Usually, added resistance (or power increase) in waves is measured in the process of basic seakeeping tests, along with motions and motion related effects. Thus, general recommendations outlined in the ITTC RP&G 7.5-02-07-02.1 “Seakeeping Experiments” hold. Some specific details are described below.

5.1 Resistance test in regular waves

5.1.1 Procedure in general

Experimental estimation of added resistance in waves is performed in two steps:

a) measurement of still water resistance, Rsw, at speeds of interest
b) measurement of total resistance in waves, R_T, at same speeds

Both measurements give values of resistance force averaged over run time. Then, the added resistance is obtained as a difference between the two measured values:

$$Raw = Rt - Rsw \tag{25}$$

5.1.2 The model

Runs in still water and in waves should be performed using preferably one and the same model at one and the same loading condition and the same model outfit. The model should be equipped with all appendages, fixed rudder and propeller hub, but without propeller. If relative motions are to be measured in the course of testing in waves, the probes should be installed during still water tests as well, at presumption that they do not create additional force in waves. However, in specific cases of multiple probes or massive holders, their influence on added resistance should be specially addressed by duplicate testing with and without probes.

5.1.3 Towing technique

Two methods of towing could be possibly applied:

a) Constant thrust (model free to surge)
b) Constant speed (surge restricted)

It has been proven by Journee (1976) that both methods give compatible results for added resistance and do not influence motion measurements. Application of specific towing technique thus depends on towing apparatus available. In principle, constant thrust method gives more freedom to model motions and less oscillations of instantaneous resistance force about its average, but it requires more complicated construction of towing apparatus. Constant speed method is easy for realization, but it results in large oscillations of resistance force and eventual loss of accuracy at instant overshooting of force gauge limits, especially in high waves.

5.1.4 Test conditions

Measurement of added resistance in regular waves does not require larger samples than these in case of regular seakeeping (motion) experiments and is thus performed within one test run (20 – 25 encounters).

5.2 Self-propulsion test in regular waves

5.2.1 Procedure in general

Analogously to 4.1.1, the procedure consists of two sets of runs, as follows:

a) estimation of self-propulsion point (RPM, torque, thrust or power) in still water at certain speed
b) estimation of corresponding self-propulsion point in waves

Then the increase in propulsive characteristics (added RPM, added torque, added thrust or power increase) are obtained as a difference between average values measured in still water and in waves.

5.2.2 Model preparation

Principles for model preparation correspond to those outlined in 4.1.2, but drive engine and propeller are installed in addition. If the model is autonomous (see 4.2.3), rudder control machine must be installed as well.

5.2.3 Testing technique

Two techniques for model guidance are commonly applied:

a) captive model (model connected to carriage by a force gauge, zero force correspond to the self-propulsion point). Several runs at various RPM are to be performed to get SPP at any speed of interest, speed being controlled by the towing carriage.
b) free-running (autonomous, radio-controlled) model. Several runs at various RPM are to be performed to get SPP at any speed of interest, average speed being controlled by a tracking system.

It should be noted that both methods are accurate enough approximation to real ship operation condition, where both RPM and speed vary even slightly within one wave period (i.e. Grande et. Al (1992)). Principally it could be modelled by application of special engine controllers but the effect on accuracy will be minor, confronted against complication of experimental set-up.

Selection of target self-propulsion point regime depends on adopted method for power prediction as described in para. 3, Table 1 respectively. In case of modelling at ship SPP, additional force to account for skin-friction effects must be applied both in still water and waves, at presumption that the average friction per wave period remains equal to the friction in still water. This force is considered steady and can be applied by additional weights or, more correctly, by a fan installed on-board model. In a similar way, other steady forces, like wind forces on superstructure, can be modelled.

5.2.4 Test conditions

3-4 successive runs at various RPM are required at average to access the SPP at certain speed of advance. In case of a captive model the transition time is shorter and measurement could be completed within a single run. Transition time for free-running models is larger and it may take more runs until steady motion regime is reached.

5.3 Tests in irregular waves

There is no practical difference in performing resistance tests or self-propulsion tests in regular or irregular seas, except the time duration of experiment.

It is a common practice to collect resistance data in parallel with seakeeping (motions) tests. Statistics set a minimum limit of 20-30 minutes full scale for a representative sample for motions. Considering added resistance (power) as a second-order force, however, some resent studies (i.e. Naito & Kihara (1993) and Kim & Kim, (2010)) arrived at a time span of 1-1,5 hours necessary to ensure convergence of resistance estimates. Repetitive runs are normally conducted to accumulate necessary full scale run duration.

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

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

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

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