ITTC Quality System Manual

Recommended Procedures and Guidelines

Procedure

Calculation of the weather factor f_w for decrease of ship speed in wind and waves

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Updated / Edited by	Approved
Seakeeping Committee of the 29th ITTC	29th ITTC Executive Committee
Date 12/2017	Date 01/2018

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Calculation of the weather factor f_w for decrease of ship speed in wind and waves

1. PURPOSE OF PROCEDURE

The purpose of the recommended procedure and guideline for calculating the speed reduction coefficient f_w is to provide the recommended method in compliance with the 2014 Guidelines on the method of calculation of the attained energy efficiency design index for new ships (EEDI), adopted by MEPC.212 (63) (IMO, 2012a) and later refined by MEPC.245 (66) (IMO, 2014).

f_w is a non-dimensional coefficient indicating the decrease of speed in representative sea conditions of wave height, wave frequency and wind speed for a ship sailing at constant engine power.

2. PARAMETERS AND SYMBOLS

A_V	Transversal projected area of the ship above the waterline (m^2)
CFD	Computational fluid dynamics
D	$D(\alpha,\vartheta)$, Angular distribution function
DWT	Capacity of ship in deadweight tons
E	$E(\omega,\alpha,H_{W1/3},T,\theta)$, Directional wave spectrum
EEDI	Energy Efficiency Design Index
f_w	Weather factor, a non-dimensional coefficient indicating the decrease in speed in a representative sea condition of wave height, wave frequency and wind speed
$H_{W1/3}$	Significant wave height
IMO	International Maritime Organization
LNG	Liquefied natural gas
MCR	Maximum Continuous Rating of engine
MEPC	Marine Environment Protection Committee (of the IMO)
P_B	Brake power
P_{Bw}	Brake power in representative sea condition
RAO	Response Amplitude Operator
R_T	Calm water resistance
R_{Tw}	Total resistance in wind and waves
ΔR_{wind}	Added wind resistance
ΔR_{wave}	Added wave resistance
S	$S(\omega,H_{W1/3},T)$, Wave amplitude energy density spectrum
T	Wave period
T_z	$=2\pi\sqrt{m_0/m_2}=0.920T$, Zero-up crossing period
U_{10}	Wind speed 10 m above sea surface
V	Ship speed
V_{ref}	Design ship speed when the ship is in operation in a calm sea condition (no wind and waves)
V_w	Design ship speed when the ship is in operation under the representative sea condition
α	Angle between ship course and regular waves ($\alpha = 0$ [deg] is defined as the head waves direction)
θ	Mean wave direction
μ	Wave encounter angle. Angle between ship positive x-axis and positive direction of dominant wave direction (short crested)
ω	Circular frequency of incident regular waves

3. OVERALL PROCEDURE FOR f_w PREDICTION

3.1 Introduction

In order to cap greenhouse gas emissions, the International Maritime Organization (IMO) passed a resolution on the Energy Efficiency Design Index (EEDI). This index is a measure of the amount of carbon dioxide a ship emits in relation to its cargo capacity and speed.

Simplified, the EEDI is computed as:

$$EEDI = \frac{CO_2 \text{ Emissions}}{\text{Cargo Capacity } f_w V_{ref}} \quad (1)$$

where V_{ref} is the speed of the ship in calm water achieved at a brake power P_B consistent with the value used in the EEDI calculation guidelines (IMO, 2014). f_w is the so-called 'weather factor' taking into account the influence of wind and waves. Using V_w to denote the speed of the vessel in 'representative sea conditions' achieved at a brake power P_{Bw}, then f_w is defined as:

$$f_w = \frac{\text{speed in wind and waves}}{\text{speed in calm water}} = \frac{V_w}{V_{ref}} \quad (2)$$

for the point where:

$$P_B(\text{ at } V_{ref}) = P_{Bw}(\text{ at } V_w) \quad (3)$$

In most cases this brake power is taken as the brake power achieved at 75% MCR, but a number of exceptions are defined in IMO (2014). Figure 1 illustrates this definition of f_w by means of a speed-power plot, in this case using 75% MCR to determine the available brake power.

The speed reduction is dependent on wave environment condition, e.g. wave, wind and current. IMO resolution MEPC.245(66) (IMO 2014) stipulates that the wave conditions for f_w evaluation are Beaufort 6.

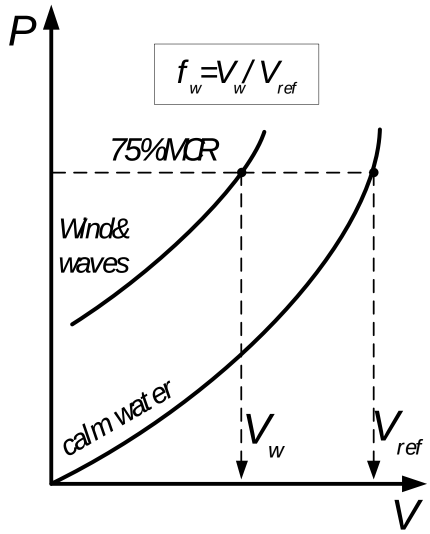

Figure 1: Finding the weather factor f_w

This ITTC-Procedure considers an overall process to determine f_w. Both, experimental and numerical methods will be presented and explained. Since many variations of the methods are possible, this procedure defines the general procedure rather than specifying a specific methodology.

Additionally, the IMO Interim Guidelines for the Calculation of the Coefficient f_w (IMO, 2012b) contains a very simple evaluation method based on 'Standard Curves'. This method only requires ship type and cargo capacity as input to provide a rough estimate of f_w but it is unable to capture ship specific details.

3.2 Representative sea conditions

Table 1 summarizes the 'representative sea conditions' for calculating f_w as defined by IMO (IMO 2012). It should be noted that f_w is a measure that represents the 'involuntary' speed reduction of a vessel underway in wind and waves with respect to calm water conditions without wind and waves.

The conditions listed in Table 1 may result in ‘voluntary’ speed reduction by the ship’s master for smaller sized ships to avoid excessive motions and loads on the vessel. This can be related to smaller sized vessels having a lower natural period for particularly pitch, more closely matching the zero crossing (encounter) period of the representative sea condition defined in Table 1. Although clear limits are difficult to determine, depending on ship type and slenderness, this may occur for ship lengths below 150 m.

Further research is necessary to confirm and refine these limits and if possible define more appropriate representative sea conditions for this class of vessels.

Table 1: Representative sea conditions based on IMO 2012b

Significant wave height $H_{W1/3}$	3.0 m
Mean wind speed 10m above sea surface U_{10}:	12.6 m/s
Zero-up crossing period T_z	6.16 s
Wave spectrum	Eqn. (4)
Wind and Wave Headings	Head sea condition or the direction which results in *largest* speed reduction

Following IMO (2012b) the wind and wave encounter angle for the f_w calculation should be taken as the direction which results in the largest speed loss; i.e. yields the smallest f_w value. Should this require too much computational or experimental effort then the head sea condition can be used to represent the ocean environmental condition for computing f_w.

The wave spectrum $S(\omega)$ for f_w computation is defined by IMO (2012b) as:

$$S(\omega, H_{W1/3}, T) = \frac{A_S}{\omega^5} e^{\frac{B_S}{\omega^4}} \tag{4}$$

with:

$$A_S = \frac{H_{W1/3}{}^2}{4\pi}\left(\frac{2\pi}{T_Z}\right)^4, B_S = \frac{1}{\pi}\left(\frac{2\pi}{T_Z}\right)^4 \tag{5}$$

More information regarding such a type of wave amplitude energy density spectrum can be found in ITTC-procedures 7.5-02–07–02.1 “Seakeeping Experiments” and 7.5-02–07–02.2 “Predicting of Power Increase in Irregular Waves from Model Tests”.

The long-crested wave energy spectrum from Equation (4) using the parameters from Table 1 is plotted in Figure 2.

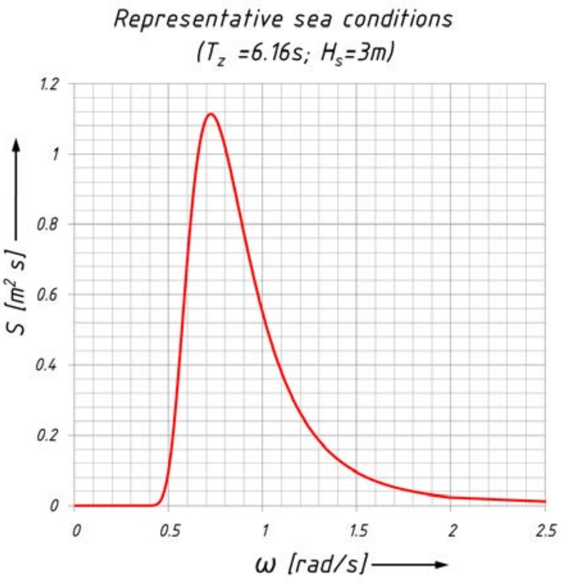

Figure 2: Wave energy spectrum $S(\omega)$

To take into account that ocean waves are usually short-crested, the wave spectrum S is multiplied by the distribution function *D*. The result is the directional spectrum *E*.

$$E(\omega,\alpha,H_{W1/3},T,\theta)=S(\omega,H_{W1/3},T)D(\alpha,\theta) \quad (6)$$

with:

$$D(\alpha,\theta)=\begin{cases}\frac{2}{\pi}\cos^2(\theta-\alpha);|\alpha-\theta|\le\frac{\pi}{2}\\ 0 \text{ for others}\end{cases} \quad (7)$$

3.3 Ship condition

According to IMO (2014), the following ship conditions are assumed when calculating the EEDI in general and f_w in particular:

- Ship operating at maximum summer load draught, except for a container ship, which draught is defined at a displacement corresponding to a loading condition at 70% of the deadweight;
- Constant engine output as percentage MCR, usually 75%, but with some exceptions as specified in IMO (2014);
- Steady navigating conditions on a fixed course.

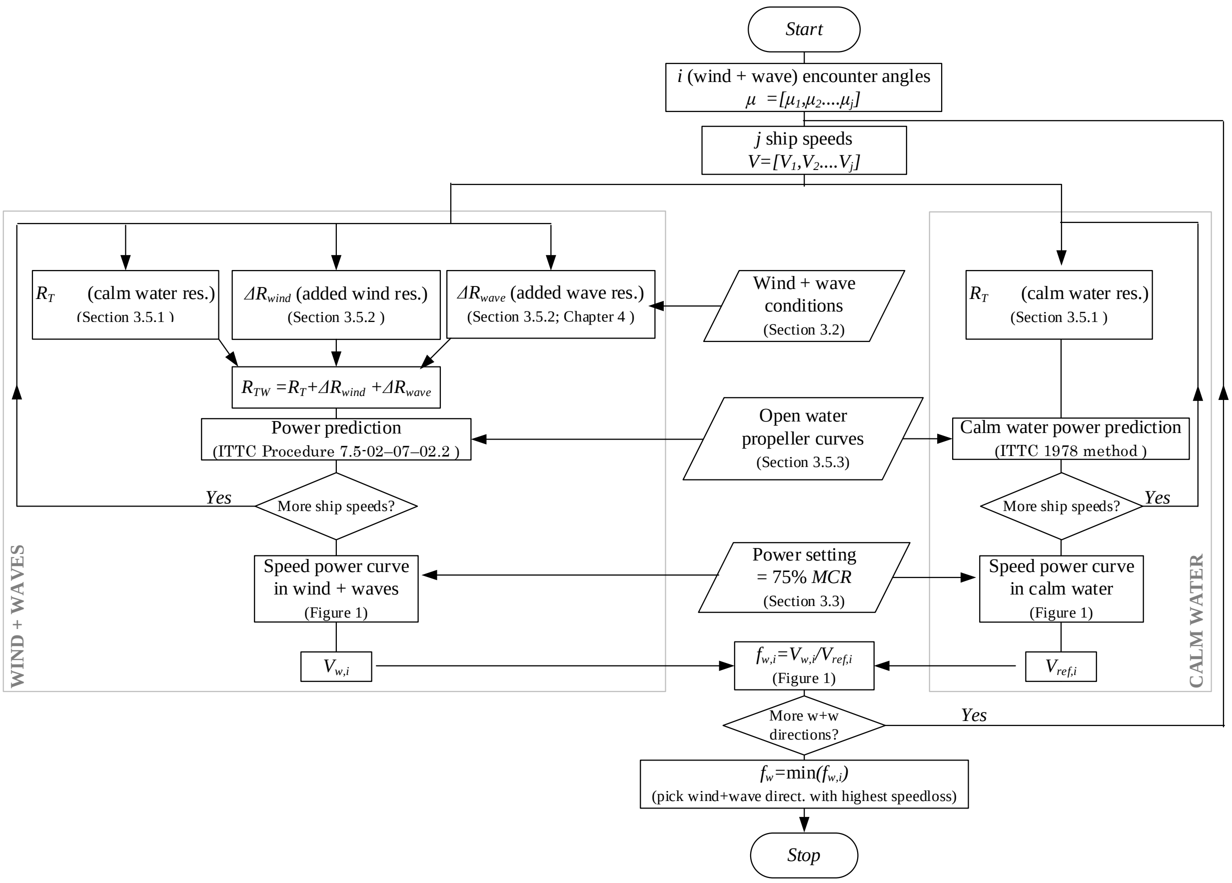

Figure 3: Outline of calculation method for f_w

3.4 Obtaining f_w by physical testing and/or simulations

Figure 3 illustrates the overall method of obtaining f_w. The calculation of f_w requires V_{ref} and V_w, i.e. the ship speeds in calm water and in representative sea conditions. These speeds are calculated separately as shown in Figure 3. Finding the calm water speed at the specified MCR value (here 75% is used) is illustrated in the right-hand part of the figure while the left-hand side explains how to determine V_w. Finally, the lower part of Figure 3 shows how to calculate f_w from the two speeds V_{ref} and V_w.

3.5 Components of Total Resistance

The total resistance under the representative sea condition, R_{Tw}, is calculated by adding ΔR_{wind}, which is the added resistance due to wind, and ΔR_{wave}, which is the added resistance due to waves, to the total resistance in a calm sea condition R_T:

$$R_{Tw} = R_T + \Delta R_{wind} + \Delta R_{wave} \tag{8}$$

The individual resistance components can be determined by several methods of different complexity and accuracy, Figure 4 provides an overview. The simpler, mostly semi-empirical methods can be found on the right hand side of the Figure, while the more advanced methods are depicted on the left.

3.5.1 Calm-water resistance

As illustrated in Figure 4, the calm-water resistance R_T can be found experimentally (ITTC Procedures 7.5-02-02-01 "Seakeeping Experiments" and 7.5-02-03-01.4 "1978 ITTC Performance Prediction Method", numerically (ITTC Procedures 7.5-03-02-03 "Practical Guidelines for Ship CFD Applications" and 7.5-03-02-04 "Practical Guidelines for Ship Resistance CFD") or by simple empirical methods such as the one by Holtrop and Mennen (1982). Normally calm-water resistance curves will be known from the pre-verification towing tank tests that are mandatory under the EEDI-regulations

3.5.2 Added resistance due to wind

This resistance component is calculated in accordance with ITTC Procedure 7.5-04-01-01.1 "Preparation, Conduct and Analysis of Speed /Power Trials" as the difference between the total wind resistance in waves and waves and the air resistance force in calm water due to the ship speed:

$$\Delta R_{wind} = \frac{1}{2}\rho_a A_V C_{DA}(\beta_{WRref}) V_{WRref}^2 - \frac{1}{2}\rho_a A_V C_{DA}(0) V_{ref}^2 \tag{9}$$

where the wind force coefficient C_{DA} is a function of the apparent wind angle β_{WRref} at the reference height, A_V is the area of maximum transverse section exposed to the wind and ρ_a is the density of air. V_{WRref} denotes the apparent wind speed at the reference height and is determined from the vector sum of ship speed V_w and 'true' wind speed V_{WTref} at the reference height and the true wind angle β_{WT}:

$$V_{WRref} = \sqrt{V_{WTref}^2 + V_w^2 + 2 \cdot V_{WT} \cdot V_w \cos\beta_{WT}} \tag{10}$$

$$\beta_{WRref} = \arccos\left(\frac{V_{WTref}\cos\beta_{WT} + V_w}{V_{WRref}}\right) \tag{11}$$

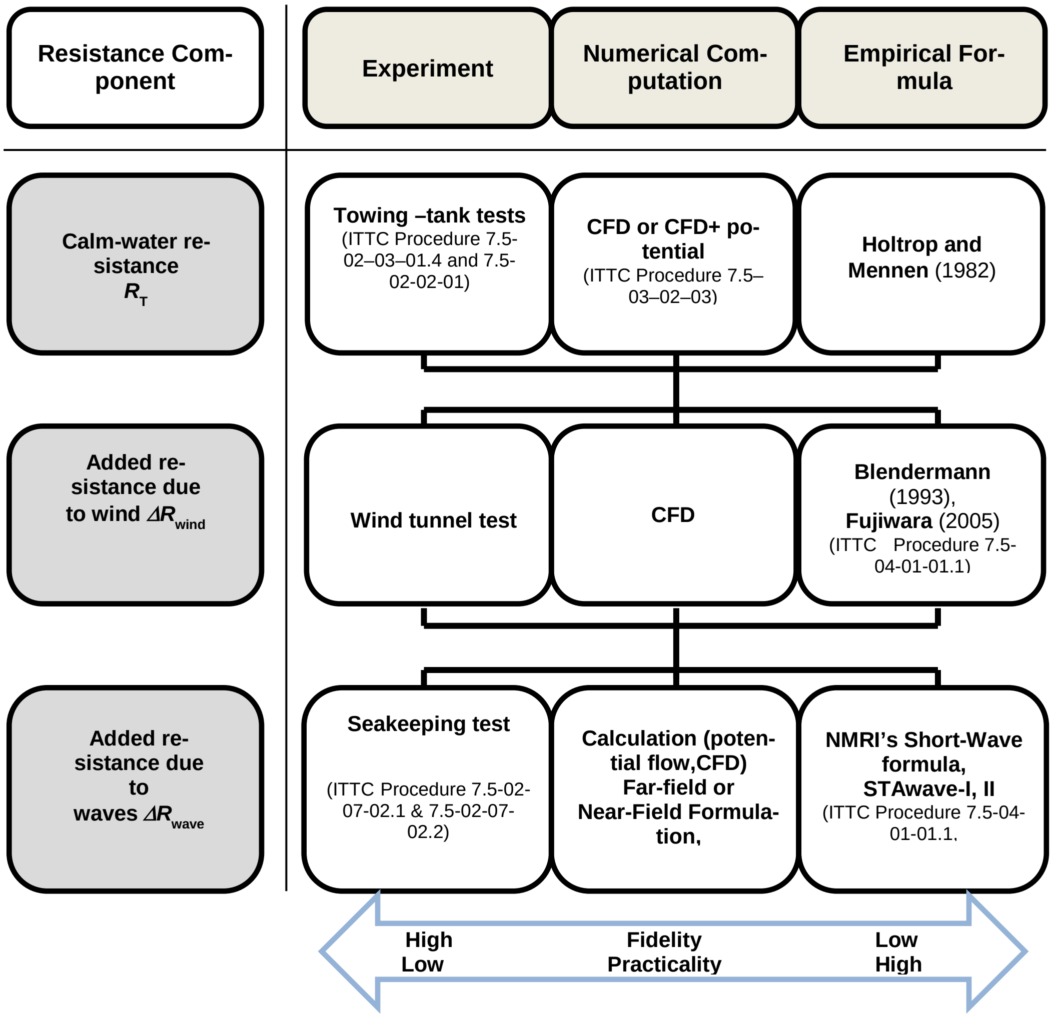

Figure 4: Methods to determine resistance components

The true wind angle β_{WT} is the angle between the ship's x-axis and the incident wind. A wind angle of 0 signifies head wind. Here the wind angle is set at $\beta_{WT} = 180 - \mu$ i.e. wind and waves come from the same direction. The reference height for the wind resistance coefficients, Z_{ref}, is selected as the corresponding height for the wind resistance coefficient from wind tunnel tests (usually 10 m). The wind speed at the reference height can be obtained from the wind speed at 10 m (as given in Table 1) as follows:

$$V_{TWref} = U_{wind} \left(\frac{Z_{ref}}{10} \right)^{\frac{1}{9}} \qquad (12)$$

In order to obtain a realistic and ship specific f_W-value, the wind-force coefficient C_{DA} in Eqn. (9) is best found by testing in a boundary layer wind tunnel. In this case it should be remembered that $C_{DA} = -C_X$. In the absence of dedicated wind tunnel tests C_{DA} values for similar ships can be taken from wind tunnel tests of similar ships, see e.g. Blendermann (1993), Fujiwara (2005) or from viscous flow CFD simulations. Wind force coefficients of typical ship types and the details of Fujiwara's method are summarized in ITTC Procedure 7.5-04-01-01.1 "Preparation, Conduct and Analysis of Speed Power Trials"

3.5.3 Added resistance due to waves

This key-component of the total resistance force can be obtained in a number of ways that will be explained in Chapter 4.

3.5.4 Power prediction and f_w evaluation

Once the individual resistance components are known the total resistance R_{Tw} in wind and waves is calculated (Eqn. 8) and the corresponding engine power is established by the principles outlined in ITTC procedure 7.5-02–07–02.2 "Prediction of Power Increase in Irregular Waves from Model Test". The propeller open water curves that are required for the power prediction are known from the calm water analysis described in paragraph 3.5.1.

As illustrated by the inside loop in Figure 3 such power predictions are carried out for several ship speeds and a speed-power curve in wind and waves is plotted, see Figure 1. The f_w value for the wind and wave direction under investigation is found as shown at the bottom of Figure 3. As illustrated by the outside loop in the figure several such 'preliminary' f_w values are calculated for a number of wind and wave directions. The final f_w value, corresponding to the largest speed reduction, is the minimum of these 'preliminary' f_w values.

Depending on the exact method to obtain the predicted speed-power curve in wind and waves (as outlined in ITTC procedure 7.5-01-07-02.2 "Prediction of Power Increase in Irregular Waves from Model Test"), the prediction may be carried out under the assumption that the calm water nominal wake fraction and thrust deduction factor can be directly applied to the ship operating in the representative sea conditions. It should be noted that this assumption, although widely applied, is only valid for mild sea conditions. Further investigation may be needed into this assumption.

4. DETERMINATION OF ADDED RESISTANCE DUE TO WAVES

4.1 Overview

The added resistance due to irregular waves can be determined using numerical or experimental methods. The columns in Table 2 provide details of the available methods.

Seakeeping experiments to evaluate added resistance can either directly be conducted in irregular waves of the spectrum defined in section 3.2 or may be carried out in regular waves to obtain the Response Amplitude Operator (RAO) of added resistance. In either case, the experiments may be conducted with a captive or a free sailing model. Details of experimental methods are given in section 4.2 of this guideline.

Seakeeping simulations can also be carried out for irregular waves (a spectrum) or for a number of regular waves to obtain the RAO. The latter method is more common because the approach of irregular wave simulations usually requires longer time than a combination of added resistance tests/simulations in regular waves in combination with linear superposition theory. Details regarding numerical methods can be found in section 4.3 of this guideline.

Table 2. Summary of prediction methods for added resistance due to waves

Type of Methods		**Slender-body Theory**	**3D Panel Method: Frequency Domain**	**3D Panel Method: Time Domain**	**CFD**	**Experiments**
ITTC Reference Procedures		7.5-02-07-02.5 7.5-04-01-01.2			7.5-03-02-03	7.5-02-07-02.1
Approach		2D Strip Method	Green Function		Euler Equation Based	Captive Test Regular or irregular wave
		Enhanced Unified Theory EUT	Rankine Panel Method		Navier-Stokes Equation Based	Free sailing Regular or irregular wave
Formulation	**Far-field Method**	Maruo’s Formula	Momentum Conservation Method		*None*	*None*
	Near-field Method	*None*	Direct Pressure Integration Method		Direct Pressure / Shear Stress Integration	Total Force Measurements
	Short-wave Approximation	NMRI Formula	NMRI formula can replace diffraction components		*No need*	*No need*
Fidelity		Low	Good		Excellent	Excellent
Typical requirements: Hardware; Time		Personal Computer; Minutes	Computer Cluster or PC; Hours-days		Cluster; Days	Seakeeping basin; Days

4.2 Experimental methods for added resistance

The added resistance in waves is usually measured during basic seakeeping tests, along with motions and related effects. Thus, the general recommendations outlined in ITTC procedure 7.5-02-07-02.1 "Seakeeping Experiments" can be used for added resistance tests. Additional information can be found in procedure 7.5-02-07-02.2 "Prediction of Power Increase in Irregular Waves from Model Test".

Figure 5 shows an overview of how to determine added resistance for the example of captive model tests. Equivalent ideas hold for free-sailing test. Some specific details of added resistance tests are described below.

Selection of model scale, tank dimension, equipment and general set-up considerations are similar to standard seakeeping tests, see ITTC guideline 7.5-02-07-02.1 "Seakeeping Experiments". During the test, the same model with the same appendages, and the same measurement apparatus and systems should be used for all tests that are related to the quantification of f_w to reduce uncertainty. Typical execution conditions can be decided based on a general seakeeping test and resistance tests, except for time waiting time between consecutive test runs. Longer waiting times than those for motion measurement or 1st order forces are required to provide more stable conditions for the added resistance measurements.

Experimental and data reduction techniques are described in ITTC procedure 7.5-02-07-02.2 "Predicting of Power Increase in Irregular Waves from Model Tests". Only a brief summary is given below. The estimation of added resistance in waves is performed in two steps:

1. The measurement of the still water resistance, R_T, at speeds of interest;
2. The measurement of the total resistance in waves, R_W, at same speed, with same loading condition, model outfit and measurement system.

The added resistance is obtained as a difference between the mean values of the two measured forces:

$$\Delta R_{wave} = R_W - R_T \tag{13}$$

Two methods to tow the ship model in waves can be distinguished:

1. Constant thrust (model free to surge);
2. Constant speed (surge restricted).

Both methods show compatible results for added resistance, however, by allowing surge motion using soft-springs or similar methods, smaller oscillation of instantaneous forces will be measured. Therefore, the load cell capacity can be reduced and an improvement of the measurement accuracy can be achieved.

The overall procedures for tests in regular and irregular waves are similar, except for the time duration. Convergence tests are recommended for test time duration considering added resistance as a 2nd order force. More detailed information including above paragraph is listed in ITTC procedure 7.5-02-07-02.2 "Predicting of Power Increase in Irregular Waves from Model Tests".

It is recommended to record the following parameters during the tests: time, motion amplitude, longitudinal force, incident wave amplitude and period.

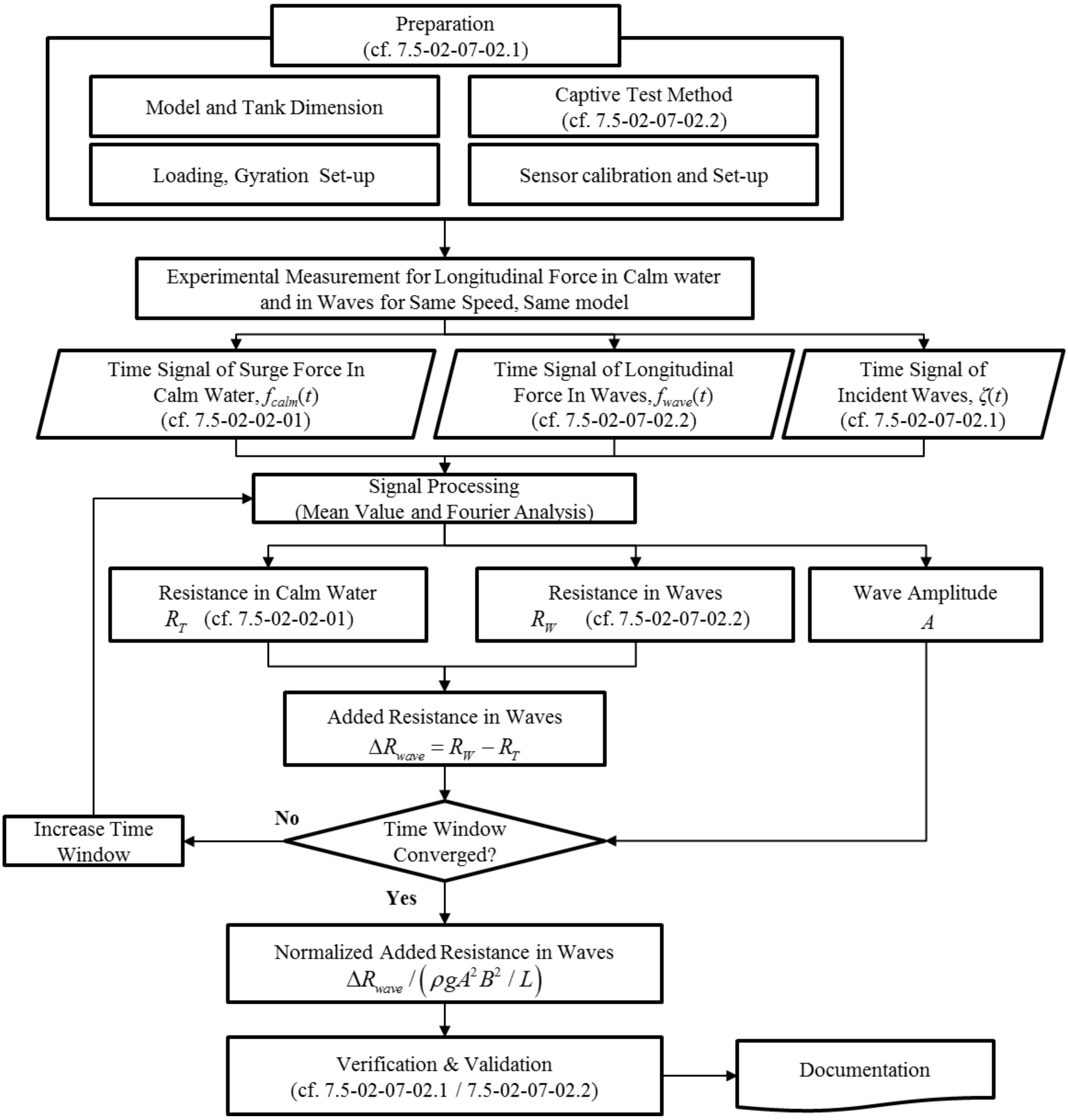

Figure 5: Flow chart for measuring added resistance due to waves based on captive model test

The data-sampling rate and filter details should be determined based on the wave encounter frequency and considerations of the primary noise frequencies. Sampling rates may vary between 50 and 200 Hz or above. The measured real time data should be recorded. It is recommended to inspect the measured signals in the time domain immediately after each test run, to check possible errors during the test, sensor failures, unexpected noise, unwanted transient behaviour, etc.

For stationary tests, the mean value of the measured data should be calculated over the time interval. For the analysis of dynamic tests, it is required to use techniques such as Fourier or regression analysis. Convergence tests for the time windows used in the analysis is necessary to obtain reliable results.

At least the following, but not restrictively, should be documented and included in the test report: hull size and model set-ups, model tank dimension, parameters measured, signal recordings, calibration information, analysis procedures and results. Tabulation of data for dimensional or non-dimensional values together with an appropriate description of measured parameters are recommended.

The uncertainty analysis of the added resistance based on captive model tests can be carried out using ISO-GUM (ISO/IEC 2008) or ITTC procedure 7.5-02-07-02.2 "Predicting of Power Increase in Irregular Waves from Model Tests". The detailed procedure of uncertainty analysis following the principles behind the ISO-GUM is shown in ITTC procedure 7.5-02-07-02.1 "Seakeeping Experiments".

4.3 Computational methods for added resistance

The prediction of the added in regular waves has been widely studied in the past. The general recommended procedure for validation of a numerical analysis of added resistance due to waves is ITTC 7.5-02-07-02.5 "Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes". The general method for linear superposition of the components of regular waves is outlined in ITTC 7.5-04-01-01.1 "Preparation, Conduct and Analysis of Speed/Power Trials". The next sub-sections describe the various available numerical methods from Table 2 in more detail.

4.3.1 Slender-body theory

For this method, strip theory or enhanced unified theory (EUT) is the general approach. Slender-body theory provides engineering accuracy of added resistance in waves. Maruo's theory (Maruo, 1960), which is based on momentum conservation and a correction term which is primarily valid for short waves could be used for the prediction of added resistance in regular waves. The formulae are presented in ITTC procedure 7.5-04-01-01.1 "Preparation, Conduct and Analysis of Speed Power Trials".

The prediction accuracy of added resistance is determined by the Kochin function. In the EUT, the singularities are the strength of source distribution along x-axis in the outer solution (Kashiwagi, 2009). As a practical treatment, the strength of source is represented as the flux through the transverse section.

At least the following should be documented and included in the report:

- Numerical method: Motion analysis method, added resistance analysis method;
- Motion: Motion response and phase;
- V&V results: comparison with other results.

4.3.2 3D panel methods

Recently, the trend for predicting added resistance moved from slender-body theory to full 3D schemes. The 3D schemes are categorized according to the domain of calculations: (frequency or time domain) and the type of singularities (Green or Rankine sources), compare Table 2. A seakeeping analysis is required prior to the computation of added resistance. General procedures and guidelines for seakeeping computer codes are presented in ITTC procedure 7.5-02-07-02.5 "Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes".

As far as the computation of added resistance with 3D panel methods is concerned, two major approached can be distinguished: The far-field (control surface integration) method and the near-field method, see also Table 2. Far-field methods are based on momentum conservation theory while near-field methods calculate added resistance by integrating the second-order pressure on a body surface. The equations for added resistance due to waves using 3D panel methods are given into the Final Report of the Seakeeping committee of the 28th ITTC. (ITTC 2017).

The converged added resistance due to waves should be verified and validated as explained in ITTC procedure 7.5-03-01-01 "Uncertainty Analysis in CFD, Verification and Validation Methodology and Procedures" or 7.5-02-07-02.5 "Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes". At least following, but not restrictively, should be documented and included in the report:

- Input parameters: domain size, mass properties;
- Numerical method: Motion analysis method, added resistance analysis method;
- Example of panel, panel convergence test results;
- Motion: Motion response and phase;
- V&V results: comparison with other results.

4.3.3 Computational fluid dynamics (CFD)

In this method, resistance values for the ship in still water and in waves are calculated by solving the field equations, i.e. the continuity equation and the Navier-Stokes, or the Euler equations. The force acting on the ship can be calculated by direct pressure and shear stress integration. Below only the essential steps to calculate the added resistance due to waves are summarized. General procedures and guidelines of CFD application for naval hydrodynamic problems are presented in the ITTC procedure 7.5-03-02-03 "Practical Guidelines for Ship CFD Applications".

Figure 6 illustrates how to calculate added resistance using CFD methods. The CFD process can be divided into three steps: pre-processing, computation, and post-processing. The pre-processing is composed of defining geometry and domain, setting boundary and initial conditions, choosing an appropriate solver, and generating the grid. To predict the added resistance due to waves, an accurate generation of incident waves is important. Criteria of the number of grids within the wavelength (λ) or wave height (H) depends on the type of grid and solver. Thus, convergence tests for the incident wave generation should be conducted before calculating wave-ship interaction problems. It should be noted that not only the number of grid cells, but also the aspect ratio of grid cells is important to generate the incident wave correctly.

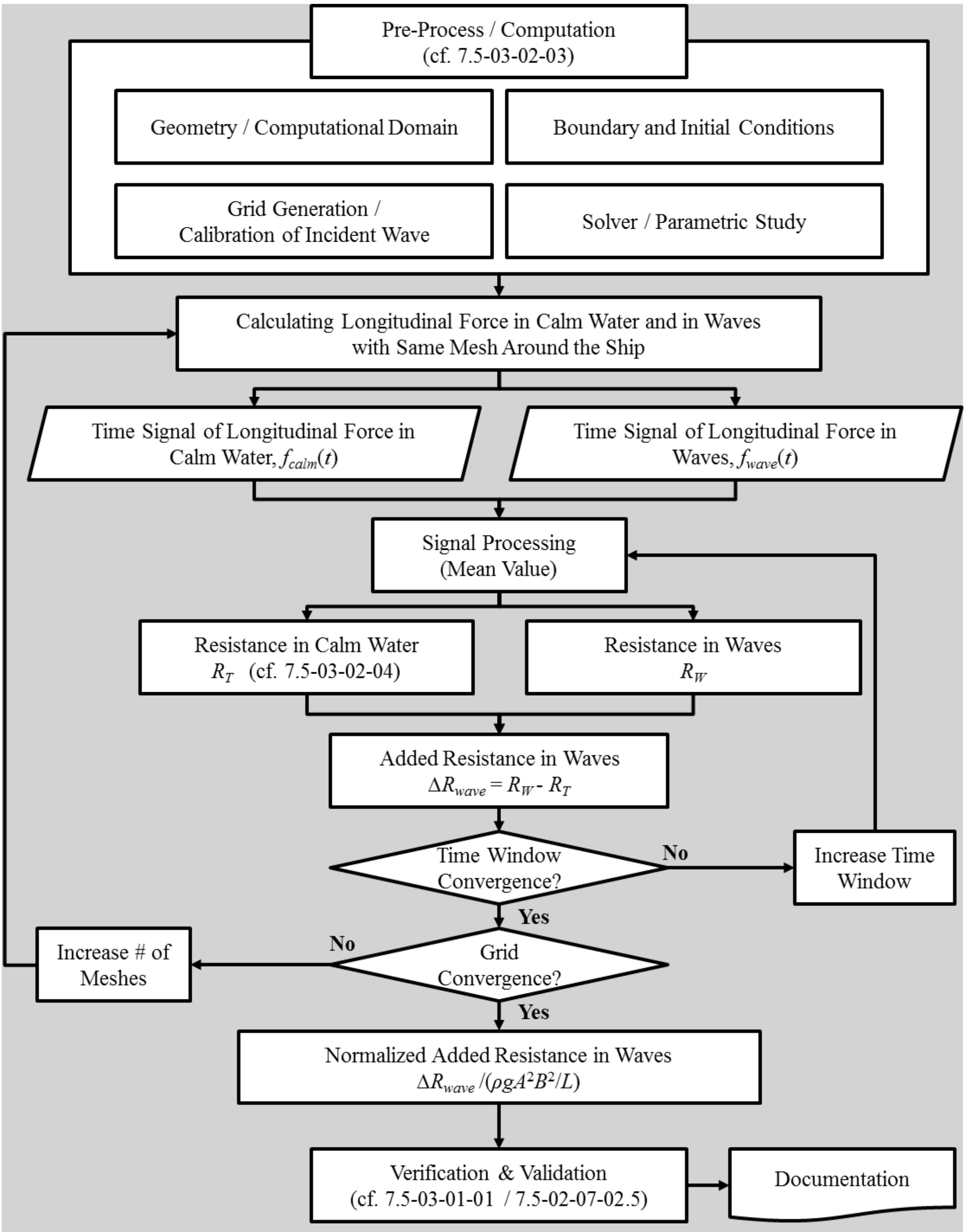

Figure 6: Flow chart of calculating added resistance due to waves based on CFD

To obtain the resistance in calm water and in waves, one needs to perform two different simulations. In both cases, the grid near the ship should be maintained as identical as possible. ITTC procedure 7.5-03-02-04 provides "Practical Guidelines for Ship Resistance CFD" and focuses on resistance in calm water. After obtaining longitudinal force signal in calm water and in waves, signal processing will be performed to calculate the resistance values. Subtracting resistance in calm water from that in waves provides added resistance in waves. However, it should be confirmed that a converged solution is obtained in terms of size of time window and grid. At least 10 encountered wave periods are recommended for CFD simulations in regular waves.

The converged added resistance due to waves should be verified and validated as explained in ITTC procedures 7.5-03-01-01 "Uncertainty Analysis in CFD, Verification and Validation Methodology and Procedures" or 7.5-02-07-02.5 "Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes". At least following, but not restrictively, should be documented and included in the report:

1. Formulation and input data:
    - Geometric parameters: scale, domain size;
    - Physical modelling: free surface capturing or tracking method, body motion tracking method, incident wave generation, radiation condition, and turbulence model;
    - Numerical method: temporal and spatial discretization method, grid system, time segment, and matrix solver.
2. Output:
    - V&V results: numerical uncertainty and comparison with other results;
    - Motion: time history of motions, RAOs as a function of wave frequency and wave amplitude, wave contour;
    - Added Resistance: time history of forces, magnitude of added resistance in waves, and pressure distribution on the ship, etc.

4.4 Verification and validation procedure for added resistance codes

The *verification* process of added resistance codes (regardless of method) should include:

- Wave-Induced motions: Check the motion response according to ITTC procedure 7.5-02-07-02.5 "Verification and Validation of Linear and Weakly Nonlinear Seakeeping Computer Codes";
- Systematic convergence test: Check the panel shape and size to get convergence results. Added resistance values are very sensitive to the panel shape and size;
- Asymptotic values: Check the transfer functions of the added resistance by comparing with asymptotic values for very long and very short waves;
- Check against computational result made with the same or similar theory.

The *validation* process of added resistance codes includes:

- Check of the transfer functions of the motion response against benchmark data of ships;
- Check of the transfer functions of the added resistance against benchmark data of ships at different speed and heading conditions.

5. RECOMMENDED PRACTICAL METHOD

Due to multiple available methods for each component, many combinations are possible for f_w computation. For practical purpose, the following methods as given in Table 3 are recommended.

Table 3: Recommended practical method for f_w prediction

Component	Recommended Method	Alternative Method
Calm-water resistance	Towing Tank Test (7.5-02–03–01.4 & 7.5-02-02-01) Calm water tank tests already mandatory for EEDI-compliance / pre-verification	CFD (7.5–03–02–03)
Added resistance due to wind	Blendermann (1993), Fujiwara (2005) (7.5-04-01-01.1)	Wind Tunnel Test
Added resistance due to waves (choose any method to the right)	Slender-body theory + Maruo's Formula + NMRI's formula for short waves (7.5-04-01-01.1)	
	3D panel method	+ NMRI's formula for short wave diffraction component (7.5-02-07-02.1 & 7.5-02-07-02.2)
	CFD	
	Seakeeping experiment (7.5-02-07-02.1 & 7.5-02-07-02.2)	
Power Increase due to wind and waves	Follow procedure 7.5-02-07-02.2, depending on method chosen: Open-water propeller tests (7.5-02-03-02.1) Propulsion tests (7.5-02–03–01.1)	CFD
f_w evaluation	Speed-power curve	By iteration

7. BENCHMARK TESTS

1. Comparative data for specific hull forms including experimental data:
    1. KVLCC2: Guo and Steen (2011), Sadat-Hosseini et al. (2013), Hwang, et al. (2013), Park, et al. (2015), Lee, et al. (2016);
    2. Series 60: Gerritsma and Beukelman (1972), Ström-Tejsen, et al. (1973);
    3. S-175: Fujii and Takahashi (1975), Nakamura and Naito (1977);
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