ITTC Quality System Manual

ITTC – Recommended Procedures and Guidelines

Procedure

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Prepared	Approved
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Wave Profile Measurement and Wave Pattern Resistance Analysis

1. PURPOSE OF PROCEDURE

The purpose of the procedure is to provide guidance in the towing tank wave profile measurement by longitudinal wave cut method and in the wave pattern resistance analysis. The wave profile and wave pattern resistance are useful for validating the numerical method and evaluating hull form.

The procedure is mainly applicable for conventional displacement vessels which have relatively significant wave pattern resistance portion of the total calm water resistance at given measurement speeds. The water depth Froude number should not exceed 0.5 to avoid shallow water effect. Careful estimation for the blockage effect should be made.

The measurement for wave profile attached to ship model and breaking waves are not included in the procedure.

The wave profile measurement and wave pattern resistance analysis is recommended to be performed along with routine resistance test, to compare the difference with wave making resistance from the resistance test.

2. PARAMETERS

2.1 Data Reduction Equations

Wave number	$K_0 = \frac{g}{V^2}$
Longitudinal wave number	$\omega = \frac{1}{\cos\theta}$
Transverse wave number	$u = \omega\tan\theta$

2.2 Definition of Variables

b	Width of the towing tank (m)
$C(\theta)$	Cosinoidal function of far field wave amplitude
$F(\mathrm{u})$	Component of free wave spectrum
$G(\mathrm{u})$	Component of free wave spectrum
L_{PP}	Length between perpendiculars (m)
R_{WP}	Wave pattern resistance (N)
$S(\theta)$	Sinusoidal function of far field wave amplitude
V	Model speed (m/s)
x_c	Effective measured distance between first measured wave position and the encountered reflection wave position by tank wall (m)
y_c	Distance between measured wave cut and model longitudinal plane (m)
α	Kelvin angle (°)
θ	Wave direction (°)
ξ	Wave height (m)
ρ	Mass density of water (kg/m^3)

3. DESCRIPTION OF PROCEDURE

3.1 Model

The model should be made according to the ITTC Recommended Procedure 7.5-01-01-01, Ship Models. The weight and trim condition of the ballasted model should be kept the same as the condition for the resistance test.

The recognized turbulent simulation method is recommended to be kept as the condition during the resistance test, although it may not be necessary for the far field wave profile measurement.

3.2 Installation

3.2.1 Hull model

During the wave profile measurement, the model should be connected to the towing carriage as the same way for the resistance test.

For sufficient wave profile measurement length, the model is recommended to be placed a certain distance away from tank central longitudinal plane for some relatively big model and (or) narrow tank cases.

3.2.2 Wave measurement method

Three wave measurement methods are generally used for wave pattern resistance analysis.

For the longitudinal wave cut method which is shown in Figure 1, at least one wave gauge is fixed to the tank wall, and placed some distance away from the model. The wave height is recorded when the model is passing the gauge. This method is generally incorporated with routine resistance test, and is widely used in towing tanks. Wave reflection by the tank wall and additional truncation reduction should be paid attention carefully.

For the transversal wave cut method, the wave gauges are generally placed $1/2L_{PP}$ to L_{PP} after the model stern part. Wave height distribution in several transversal sections is measured. This method has few tank wall effects. However, this method is relatively complex and the measurement data is sensitive with the stern wake flow and relative deviation between the calm water and carriage rails.

Another typical wave profile measurement method is Hogben's matrix method. Four wave gauges are fixed to tank wall with certain distance between each other. Four wave profiles are measured synchronously and wave pattern resistance is calculated by the measured wave profiles.

For simply and widely using purpose, and easily incorporating with routine resistance test, the longitudinal wave profile measurement

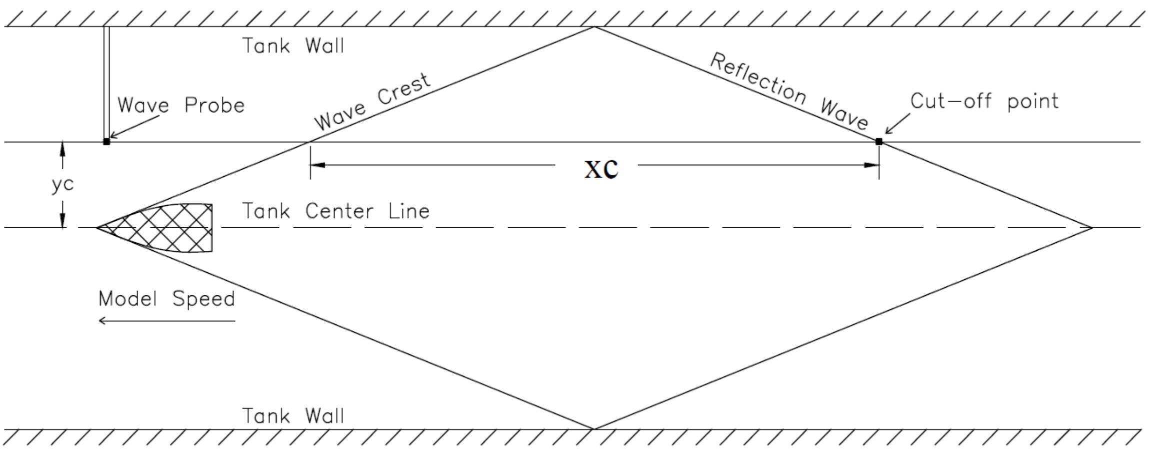

Figure 1 Wave profile measurement setup

method and wave pattern resistance analysis is demonstrated in the procedure.

3.2.3 Wave sensor

Many intrusive and non-intrusive wave measurement sensors are applicable for longitudinal wave profile measurement.

The resistive and capacitive type wave gauge are widely used as intrusive method in wave tanks and towing tanks.

The non-intrusive wave sensors include optical sensors, acoustic sensors, radars, imaging methods, and combined laser-scanner and video hybrid system, etc. More details are discussed in report by Sylvain Bourdier (2014).

The ultrasonic senor is another widely used non-intrusive wave gauge, as the resistive and capacitive intrusive wave gauge. All the three kind of wave sensors with stable measurement and easy use are recommended for the longitudinal wave profile measurement, after careful calibration with a calibrated rulers or other appropriately calibrated devices.

3.2.4 Wave sensor arrangement

The chosen wave sensor should be placed vertically and supported by a strut which is cantilevered from tank wall. The strut should be movable to adjust the appropriate position of the measured longitudinal plane of the model far field side wave. Figure 1 shows the typical wave profile measurement set up.

The longitudinal position of the wave sensor in the tank should provide enough time and distance for model acceleration and wave pattern stabilization.

The transverse distance (y_c) between wave sensor to the model central longitudinal plane is recommended to be varied from $0.21L_{PP}$ (1.0B when L_{PP}/B is smaller than 2.5) to $1.67L_{PP}$, to provide sufficient measured wave distance x_c and not to introduce more bow unsteady breaking wave into the wave sensor. Each towing tank may have their own y_c range according to their own experience for the specific ship model type and speed range.

The effective measured wave distance x_c is important for wave pattern resistance analysis and is affected by the transverse distance (y_c), the model size and tank width. Generally, the big model and narrow tank width reduce the effective measured wave distance x_c and affect the accurancy of the wave pattern resistance analysis. To minimize the effect, the model is recommended to be offset away from the wave sensor side and parrallel to the tank center line.

3.2.5 Trigger sensor

A trigger system is generally used for starting the wave measurement data recording when the model is approaching the wave probe, in order to determine the measured wave position relative to the model length. The trigger sensor location, trigger effectiveness and responsive sensitivity should be carefully checked with known carriage speed and known model position before the measurement.

3.3 Measurement System

Figure 2 shows a typical measurement system combining with rountine resistance test. The following quantities are measured:

- • Resistance
- • Sinkage and trim
- • Model speed

- • Water temperature
- • Wave height

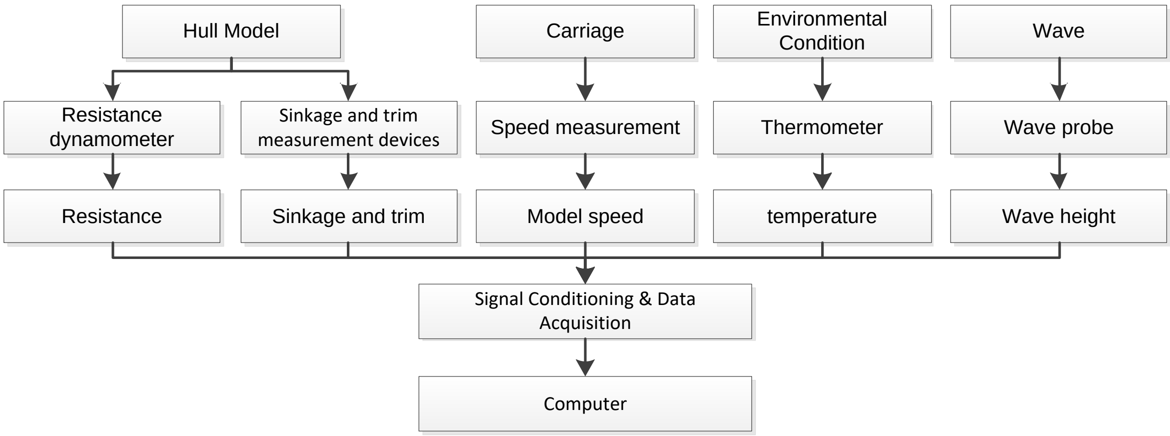

Figure 2 Wave profile and resistance measurement system

3.3.1 Resistance

The resistance is generally measured as complementary test of the wave profile measurement according to ITTC Recommended Procedure 7.5-02-02-01, Resistance Test, to make comparisons between measured wave making resistance by resistance test and wave pattern resistance derived from the wave profile measurement data.

3.3.2 Sinkage and trim

The sinkage and trim should be measured according to ITTC Recommended Procedure7.5-02-02-01, Resistance Test. For numerical method validation purpose, the model may be captive and restrained from free heave and pitch motion. Captive pre-setting sinkage and trim condition should be documented during the test.

3.3.3 Speed

The model speed should be measured according to ITTC Recommended Procedure 7.5-02-02-01, Resistance Test. The speed should be documented for each wave profile measurement run.

3.3.4 Temperature

The water temperature should be measured at a depth near half of the model draught using a calibrated thermometer.

3.3.5 Wave height

The resistive, capacitive or ultrasonic wave probe is generally used for measuring the wave height at certain longitudinal cut.

The wave probe should be calibrated regularly or before the test by a calibrated water level height. And the wave probe should be carefully checked before, during and after the wave measurement, to avoid the zero drifting, tank water level change or other unexpected uncertainty sources.

3.4 Discussion

- The side wave absorber along the wave sensor side of the tank should be lifted above the calm water surface for an enough distance or removed to minimize the wave disturbance and increase the measured wave distance x_c. However, absorber at the opposite can be used
- The wave probe signal should be monitored continuously to help deciding the next measurement run. The residual current underneath the water surface should be monitored by the current meter if available. The waiting time between consecutive runs should be longer than that during the resistance test if the side wave absorber is disabled.
- Repeat runs for specific test condition are recommended to check the data, and averaged value of the repeat runs may reduce the uncertainty of the wave height.
- The sampling frequency for the wave height is recommended to be appropriate for the wave profile changes according to tank's experience.

4. DATA REDUCTION AND ANALYSIS

4.1 Coordinate System

The coordinate system for the wave profile measurements is defined with the *x*-axis being parallel to model centreline, the *y*-axis pointing to starboard of ships and the *z*-axis being perpendicular to the calm water surface. The forward perpendicular is denoted at $x/L_{PP}=0$, and the aft perpendicular is denoted at $x/L_{PP}=1.0$.

4.2 Truncation Treatment

The measured wave profile signal is truncated before the reflected waves by tank wall reaching to the cut-off point as shown in Figure 1. The wave profile after the cut-off point is extrapolated by introducing an analytical asymptotic expression.

$$\xi(x, y_c) = \frac{c_1 \cos x - c_2 \sin x}{\sqrt{c_3 + x}} \tag{1}$$

where the coefficients c_1, c_2 and c_3 can be determined based on a regression on the signal before truncation. Hence, sufficient effective wave length is recommended for the accuracy of truncation correction.

4.3 Wave Pattern Resistance Analysis

Newman- Sharma Method is recommended for the wave pattern resistance analysis.

The far field wave elevations generated by a body travelling at constant speed with no confinement are given by.

$$\xi(x,y) = \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} C(\theta)\cos[K_0 sec^2\theta(xcos\theta + ysin\theta)]d\theta + \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} S(\theta)\sin[K_0 sec^2\theta(xcos\theta + ysin\theta)]d\theta \tag{2}$$

where K_0 is the wave number. θ is the angle between *x*-axis and the direction of propagation of a given wave component, $C(\theta)$ and $S(\theta)$ are cosinusoidal function and sinusoidal function of the far field wave amplitude respectively.

The wave pattern resistance then can be integrated from the following equation:

$$R_{WP} = \frac{\pi}{2}\rho V^2 \int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} [C^2(\theta) + S^2(\theta)]\cos^3\theta d\theta \tag{3}$$

The cosinusoidal and sinusoidal wave amplitude function can be obtained by a Fourier transform of the wave height measurements along a longitudinal cut.

$$C(\omega, y_c) + iS(\omega, y_c) = \int_{-\infty}^{+\infty} \sqrt{\omega^2 - 1}\,\xi(x, y_c) exp(i\omega x) dx \quad (4)$$

The far field wave amplitude spectrum coefficients $F(\mathrm{u})$ and $G(\mathrm{u})$ can be expressed as

$$F(\mathrm{u}) = \frac{4}{2\omega^2-1}[C(\omega, y_c)\sin(uy_c) + S(\omega, y_c)\cos(uy_c)] \quad (5)$$

$$G(\mathrm{u}) = \frac{4}{2\omega^2-1}[C(\omega, y_c)\cos(uy_c) + S(\omega, y_c)\sin(uy_c)] \quad (6)$$

The wave pattern resistance then can be integrated from the following equation:

$$R_{\mathrm{WP}} = \frac{1}{16\pi}\int_{-\infty}^{+\infty}[F^2(u) + G^2(u)]\frac{\sqrt{1+4u^2}}{1+\sqrt{1+4u^2}}du \quad (7)$$

where ω is the longitudinal wave number, u is the transverse wave number.

5. DOCUMENTATION

The wave profile measurement report should contain at least the following information.

- Model information
  - Model ID
  - Draught
  - Turbulence stimulation method, if any
  - Scale ratio
  - Main dimensions and hydrostatics data
- Tank dimensions including length, width and water depth
- Wave sensor location relative to model and tank
- Tank water temperature, water density and kinematic viscosity
- The following data should be recorded for each speed and each wave probe location:
  - Model speed V_{M}
  - Resistance R_{TM}
  - Heave and trim by $H_{\mathrm{F}}/H_{\mathrm{A}}$ or direct angular measuring device with the measurement of the sinkage at one point.
  - Wave height ξ along the longitudinal wave profile

6. VALIDATION

6.1 Uncertainty Analysis

Uncertainty analysis should be performed in accordance with the ITTC Recommended Procedure 7.5-02-01-01, Guide to the Expression of Uncertainty Analysis in Experimental Hydrodynamics.

The following ITTC Recommended Procedures related to uncertainty analysis for resistance test can be used as the references for wave profile measurement uncertainty analysis.

- 7.5-02-02-02, General Guidelines for Uncertainty Analysis in Resistance Tests
- 7.5-02-02-02.1, Example for Uncertainty Analysis of Resistance Tests in Towing Tanks
- 7.5-02-02-02.2, Practical Guide for Uncertainty Analysis of Resistance Measurements in Routine Tests

6.2 Benchmark Tests

Benchmark data are described and collected in ‘Benchmark Database for CFD, Validation for Resistance and Propulsion’, ITTC 7.5-03-02-02.

7. REFERENCES

Bourdier, S., Dampney, K., Fernandez, H., Lopez, G., Richon, J., Non-intrusive wave field measurement, MARINET WP4 Report, 2014

Newman, J. N., The determination of wave resistance from wave measurements along a parallel cut, Proceedings of the international seminar on theoretical wave resistance, University of Michigan, 1963

Appendix A. EXAMPLE OF WAVE PATTERN RESISTANCE CALCULATION FROM WAVE PROFILE MEASUREMENT DATA

An example of the wave pattern resistance analysis process based on wave profile measurement data of a benchmark scaled ship model at given towing speed is descripted.

The model hull is a single propeller multi-purpose cargo ship type, which has a block coefficient of 0.721 at its test condition. One longitudinal wave cut measurement data at one towing speed of 1.987m/s for the 7.052m long ship model is analyzed. The measurement was carried out in deep water towing tank of CSSRC.

A.1. Wave Profile Measurement Data

The wave profile measurement setup is shown in Figure 3 for the example test case.

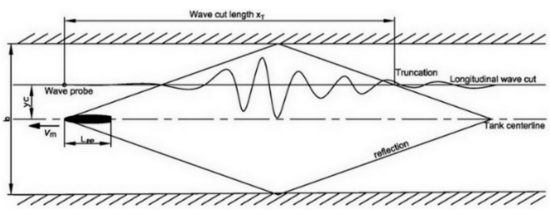

Figure 3 Wave profile measurement setup

The towing tank is 474m long, 14m wide and 7m deep. One capacitive wave probe is placed 1.5 times ship model width (1.56m) away from the tank centerline. The ideal wave cut length (35.2m) is calculated based on the Kelvin wave angle. The actual wave cut length (32m) was selected to avoid the influence of wave reflected by the tank wall.

$$x_T = (b - y_c)/\tan 19^{\circ}28' = 35.2\text{m} \quad (8)$$

The measured wave height data is shown in Figure 4.

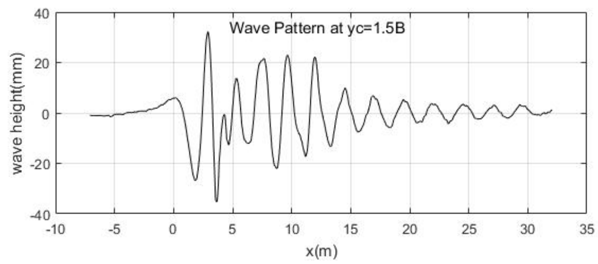

Figure 4 Measured wave height curve at $y_C = 1.5B$

A.2. Wave pattern resistance analysis

A.2.1. Wave pattern extrapolation after cut-off point

Parameters used in the analysis are nondimensionalized by multiplying wave number K_0.

Wave pattern after cut-off point should be extrapolated according to equation (9). Coefficient c_1, c_2 and c_3 can be derived by regression on the signal before truncation, where c_3 can be generally set zero when the sampling wave signal is long enough. The coefficients c_1, c_2 and c_3 in this example case are -0.013, 0.039 and 0 respectively.

$$\xi(x, y_c) = \frac{c_1 \cos x - c_2 \sin x}{\sqrt{c_3 + x}} \quad (9)$$

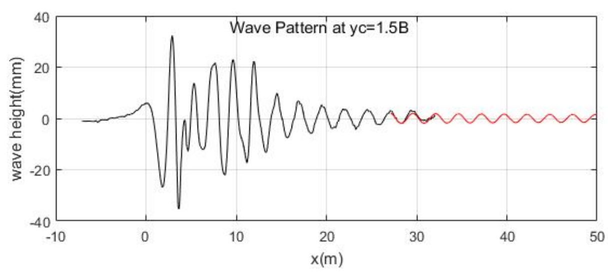

Figure 5 Extrapolated wave pattern

The extrapolated wave pattern after the cut-off point is highlighted in red colour in Figure 5.

A.2.2. Wave amplitude spectrum calculation

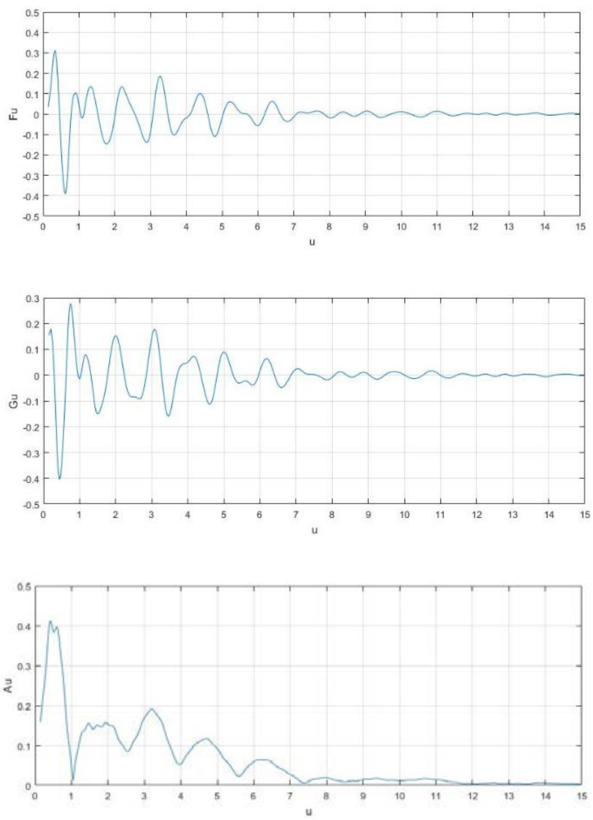

Figure 6 Far field wave amplitude spectrum coefficients

The cosinusoidal and sinusoidal wave amplitude function and coefficients can be obtained by the following equations.

$$C(\omega,y_c)+iS(\omega,y_c)=\int_{x_0}^{x_e}\sqrt{\omega^2-1}\,\xi(x,y_c)exp(i\omega x)dx \qquad (10)$$

$$\Delta C(\omega,y_c)+i\Delta S(\omega,y_c)=\int_{x_e}^{+\infty}\sqrt{\omega^2-1}\,\frac{c_1\cos x-c_2\sin x}{\sqrt{c_3+x}}exp(i\omega x)dx \qquad (11)$$

$$C*(\omega,y_c)=C(\omega,y_c)+\Delta C*(\omega,y_c) \qquad (12)$$

$$S*(\omega,y_c)=S(\omega,y_c)+\Delta S*(\omega,y_c) \qquad (13)$$

$$G(\mathrm{u})=\frac{4}{2\omega^2-1}[C*(\omega,y_c)\cos(uy_c)+S*(\omega,y_c)\sin(uy_c)] \qquad (14)$$

$$F(\mathrm{u})=\frac{4}{2\omega^2-1}[C*(\omega,y_c)\sin(uy_c)+S*(\omega,y_c)\cos(uy_c)] \qquad (15)$$

$$A(\mathrm{u})=\sqrt{G(u)^2+F(u)^2} \qquad (16)$$

The example far field wave amplitude spectrum coefficients $F(\mathrm{u})$, $G(\mathrm{u})$ and $A(\mathrm{u})$ in this case are given in Figure 6.

A.2.3. Wave pattern resistance calculation

The wave pattern resistance coefficient can be integrated by the following equations.

$$R_{WP}=\frac{1}{16\pi}\int_{-\infty}^{+\infty}[F^2(u)+G^2(u)]\frac{\sqrt{1+4u^2}}{1+\sqrt{1+4u^2}}du \qquad (17)$$

$$C_{WP}=\frac{K_0}{\rho V^2}\mathrm{R_{WP}} \qquad (18)$$

For this example, the wave pattern resistance coefficients at the given speed of 1.987m/s are listed in Table 1.

Table 1 Wave pattern resistance coefficients calculation results

Fr	**V_M(m/s)**	**1000C_{WP}**	
		w/o truncation correction	**w/ truncation correction**
0.237	1.987	0.473	0.476