ITTC Quality System Manual

Recommended Procedures and Guidelines

Guideline

Example for Uncertainty Analysis of Resistance Tests in Towing Tanks

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Example for Uncertainty Analysis of Resistance Tests in Towing Tank

1. PURPOSE OF PROCEDURE

The purpose of the procedure is to provide a real example in detail for performing uncertainty analysis in towing tank resistance tests that follow the ITTC Procedure 7.5-02-02-01, "Resistance Test", in which a model of DTMB 5415 combatant with 5.72m length is used.

This procedure can be regarded as a supplement to the ITTC guideline 7.5-02-02-02, "General Guidelines for Uncertainty Analysis in Resistance Tests" (2014) as well as provide quantitative results for extensive reference, since 41 institutions from 20 countries have participated in the Facility Bias World Wide Campaign, where two geosims of the DTMB 5415 model with 5.720m and 3.048m length, respectively, have been used.

Uncertainties related to extrapolation and full scale prediction are not included in this procedure. It should be noted that the unit of force is presented in *kgf* as it is in many laboratoies, however, in general the SI unit of *N* is preferred.

2. GENERAL DESCRIPTION OF THE EXAMPLE MODEL TEST

2.1 Test Model

A geosim hull model of DTMB 5415 surface ship, with 5.72m length, made of Wawa wood, was manufactured with 5-axis CNC milling machine at CSSRC in late 2012.

The geometric parameters of the model given in Table 1 are calculated up to design draught through the numerical model for CNC manufacturing and regarded as theoretical values of this model. The tolerances of model hull lines were measured with 3a D Terrestrial Laser Scanner and satisfy the requirements by the ITTC Procedure 7.5-01-01-01. A turbulence stimulation wire with diameter of 1.0mm is mounted at the 19# station (5%LPP aft of the FP).

Parameter		Model (1:24.824)
L_{PP}	Length between perp.	5.7203m
L_{WL}	Length on waterline	5.7258m
B	Breadth on waterline	0.7666m
D	Draught, even keel	0.2480m
C_M	Midship section coef.	0.8188
A_W	Waterplane area	3.3968m^2
S	Wetted surface area	4.8461m^2
∇	Displacement volume	0.5517m^3

Table 1. Particulars of Hull Model

2.2 Test Scheme

This model test were performed in the deep water towing tank at CSSRC in early summer of 2013. The tank is 474 meters long from the north to south end, 14 meters wide in the test section and 7 meters deep.

The measurands are the total resistance of model hull, running sinkage and trim at different Froude numbers. In each set of runs, Froude numbers increase successively from 0.1 to 0.45, which are set by towing speeds with the feedback control system of the towing carriage.

In this example, there were a total of nine (9) repeat sets of runs carried out, for sake of simplicity, continuously and with the same instruments and installation by the same experienced engineers in the same way as the routine practice in the tank.

The dynamometer of type R63 is used for measuring resistance. The measurement at each speed is obtained by averaging the time history of the signal from the DAS (Data Acquisition System) in an interval of time, $\Delta t = N/f_s$,

$$R_T = \frac{1}{N}\sum_{i=1}^{N} R_i \tag{1}$$

where, f_s is the sampling rate, N the number of sampling data points, R_i the i-th data in the time history. In this example, f_s is selected as 50Hz, Δt is at least 10 seconds and the low-pass cut-off frequency of filtering is 1.0Hz. The standard deviation of a filtered time history is usually less than 0.2% and then, the standard uncertainty of average of the sampling history will be less than $0.2\%/\sqrt{500}=0.009\%$. That is, the uncertainty of one “reading” (the average value of a time history) from the DAS is negligible.

A pair of resistive-type, linear motion potentiometers are vertically mounted at the 1# station (2mm aft of 1#) and 16# station (2mm fore of 16#), respectively and actually 4294mm apart, for measuring the running trim and sinkage at the mid-station (10#).

The temperature of tank water is measured with three thermometers that are located at near end, middle area and far end of the tank, or, at 50m, 200m and 300m away from the north end, respectively. The mass density and viscosity of water are determined according to the ITTC Procedure 7.5-02-01-03, “Density and Viscosity of Water”.

The mid-sectional area of model hull is about 0.16% of the tank sectional area. The blockage correction estimated by the Schuster formula is negligible.

2.3 Data Reduction

There will be a slight deviation of towing speed from the nominal value as prescribed, e.g., V=0.749m/s for Fr=0.1 according to the Froude number calculation,

$$Fr = V/\sqrt{gL} \tag{2}$$

where, L is the waterline length and g the local acceleration of gravity in this example. The resistance measured at an actual towing speed, e.g., V=0.748m/s for Fr=0.1, should be corrected to the nominal speed V=0.749m/s. Using the total resistance coefficient formula,

$$C_T = 2R_T/(\rho S V^2) \tag{3}$$

the correction can be made by

$$\hat{R}_T = R_T - \delta R_T = R_T(1 - 2\cdot \delta V/V) \tag{4}$$

In this example, no correction is performed as the value of speed displayed on screen is the same as the nominal speed.

There may also be a little variation in temperature of water with time and location along the tank during the period of testing. All the measured resistance should be converted to the same nominal temperature, i.e., the mean of temperature during the whole tests. Such a conversion can be made as the following steps,

STEP 1: Calculate the mean of temperature measured during the whole tests,

$$\bar{t} = \sum_i t_i \tag{5}$$

STEP 2: Calculate the frictional resistance coefficient of a specific run at temperatures t_i and $\bar{t}$ by ITTC-1957 model-ship correlation line,

$$C_F = 0.075/(\log_{10}\mathrm{Re}-2)^2 \qquad (6)$$

The effect of temperature is included in the Reynolds number,

$$\mathrm{Re} = VL/\nu \qquad (7)$$

where, L is selected as the waterline length in this example and ν the water kinematic viscosity. The effect of a little temperature variation on the model geometry is considered negligible.

STEP 3: Calculate the total resistance coefficient of the same run by Eq.3, and

STEP 4: Modify the resistance measured at the temperature t_i to the mean temperature $\overline{t}$ by

$$\begin{cases} \hat{R}_T = R_T + \Delta R_T \\ \dfrac{\hat{R}_T}{R_T} = \dfrac{\rho(\overline{t})}{\rho(t_i)}\left[1+\dfrac{C_F(\overline{t})-C_F(t_i)}{C_T(t_i)}\right] \end{cases} \qquad (8)$$

In this example, the water temperatures measured during nine repeat sets of tests are shown in Figure 1. The mean temperature is 16.5°C.

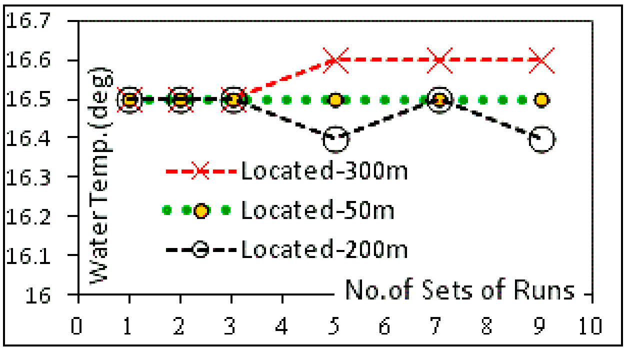

Figure 1. Water temperature measured in tank

It should be noted that, when necessary, the resistance should first be corrected and modified by the following equation before uncertainty analysis is performed,

$$\hat{R}_T = R_T - \delta R_T + \Delta R_T \qquad (9)$$

However, the uncertainties related to the above correction and modification themselves may be assumed negligible.

2.4 Data of Resistance Measurement

The data of resistance measurements of 9 repeat tests, as examples, for Fr=0.1, 0.28 and 0.41, are given in Table 2, corresponding to the nominal temperature 16.5 °C.

Total Resistance (16.5 degrees)_April_30_2013			
R_T *(kgf)*	Fr=0.10	Fr=0.28	Fr=0.41
Run #1	0.541	4.558	15.119
Run #2	0.540	4.514	15.116
Run #3	0.554	4.558	15.074
Run #4	0.550	4.558	15.135
Run #5	0.553	4.562	14.989
Run #6	0.544	4.558	15.006
Run #7	0.546	4.585	15.008
Run #8	0.544	4.540	14.990
Run #9	0.538	4.577	15.063
g=9.7946 m/s^2			

Table 2. Data of resistance measurement

3. UNCERTAINTY EVALUATION

1.1 Model Ballasting

The model hull with the instruments mounted onboard is ballasted to its displacement mass that is determined by its nominal displacement volume and the mass density of towing tank water at the temperature (16.5 °C) measured the day before test,

$$\Delta_{\mathrm{nominal}} = \rho_{\mathrm{water}} \times \nabla_{\mathrm{nominal}} = 551.032\ kg \qquad (10)$$

As a result, the model was measured 551.0kg by a digital scale with limit bias of ±0.5kg, for which uniform distribution can be assumed. Then, the standard uncertainty of the displacement mass is u(Δ)= 0.5kg/ √3=0.29kg, or

$$u'(\Delta)=0.29/551.0=0.052\% \tag{11}$$

Therefore, the relative standard uncertainties of the resistance is estimated as,

$$u_1'(R_T) \approx \frac{2}{3}u'(\Delta) = 0.035\% \tag{12}$$

Temperature variation of the tank water with time and location is within ±0.1℃ during the model tests, which will lead to the variation of water density less than 0.0017% and its effect is negligible.

The static trim and heel angles of the hull are trimmed to be within ±0.05 degrees and ±0.15 degrees, respectively. These uncertainties are assumed negligible to the wetted surface area and resistance of the hull model.

1.2 Model Installation

Uncertainties from installation related to the hull resistance are mainly attributed to the alignment between the longitudinal centrelines of hull, resistance dynamometer, towing guide and towing tank/towing carriage rails.

In this example, the misalignment between the centreline of hull and the towing force of dynamometer is estimated to be within ±0.1 degrees, which results in a negligible uncertainty in the model hull resistance measurement. In general it is not practical to evaluate the uncertainty of the model hull resistance due to the misalignment of the hull and tank except if a suitable sideforce measurement dynamometer is installed.

1.3 Instrument Calibration

3.1.1 Tachometer for Towing Speed

The tachometer for towing carriage speed is mainly composed of a trailing wheel and encoder and the towing carriage is calibrated regularly. The bias limit of towing speed for the range 0.75~3.5m/s can be quoted as 0.1%, although the bias limit is less than 0.1% for speeds greater than 1m/s. Then the relative standard uncertainty under assumption of normal distribution is

$$u_V' = \frac{u_V}{V} = \frac{1}{3} \times 0.1\% = 0.033\% \tag{13}$$

from which results the relative standard uncertainty of resistance as

$$u_4'(R_T) \approx 2u_V' = 0.067\% \tag{14}$$

3.1.2 Dynamometer for Resistance

The dynamometer was calibrated before model tests according to the ITTC Procedure 7.5-01-03-01. The calibration range is chosen as not less than 1.5 times the maximum of hull drag that is estimated beforehand. In this example, the maximum load is selected as 32kgf. Eleven loads are implemented by weights and randomly applied three times for each load as shown in Fig.2.

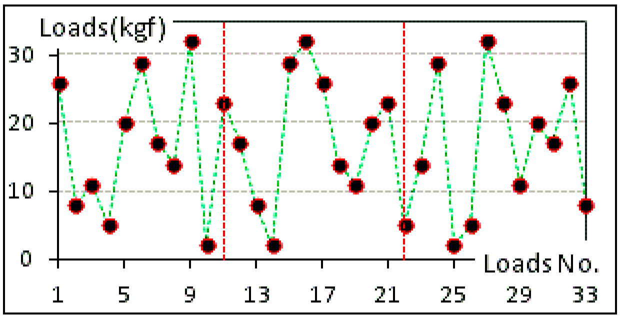

Figure 2. Calibration loadings for dynamometer

The fitting curve for predicting force is obtained by linear regression,

$$\text{Force}(kgf) = \text{Voltage}(V) \times 8.3528 \qquad (15a)$$

with a standard deviation of

$$SEE = 0.0087kgf \qquad (15b)$$

which will result in a standard uncertainty of resistance measurement,

$$u_2(R_T) = 0.0087kgf \qquad (16)$$

The resistances measured, in this example, at Fr=0.1, 0.28 and 0.41 are 0.541kgf, 4.557kgf and 15.056kgf, respectively. The relative standard uncertainties corresponding to the calibration component are about 1.59%, 0.19% and 0.058%, respectively.

Additionally, the weights for loading are rated the OIML Class M2, which have a limit bias of 0.015%. This will result into a standard uncertainty of 0.015%/3=0.005% (normal distribution) in resistance measured by the above calibration. Such uncertainty component related to weights is negligible.

The dynamometer is checked after tests by successively loading and unloading weights of 5kgf, 10kgf, 15kgf, 20kgf, 25kgf and 30kgf. The deviation of checking result from Eq.15a is 0.014% and negligible, which confirms the dynamometer is in good condition during tests.

3.1.3 Devices for Sinkage and Trim

On basis of the potentiometer specification, the bias limit of calibration is 0.1%×400mm =0.40mm and then, the corresponding standard uncertainty is estimated 0.13mm, which will result in a standard uncertainty of running sinkage measurement by a pair of potentiometers as the following,

$$u_\varsigma = \sqrt{(0.13)^2 + (0.13)^2} = 0.19mm \qquad (17)$$

Similarly, the resulting standard uncertainty of trim measured with a pair of potentiometers 4294mm apart is obtained as,

$$u_\theta = \sqrt{2}arctg\left(\frac{0.19}{4294}\right) = 0.0036\deg \qquad (18)$$

The deviation (within ±2mm) of distance (4294mm) between potentiometers and the verticality (within ±0.1 degrees) of their installation will have a negligible contribution to the uncertainties of sinkage and trim measurement.

There is no analytic relationship between the ship model resistance and running trim and sinkage. Besides they are among the parameters for validating CFD, running trim and sinkage can also provide indispensable information for analyzing repeat tests and performing inter-laboratory comparison of resistance tests.

3.1.4 Thermometer for Water Temperature

The digital thermometer has a display resolution of 0.1 $^\circ$C (uniform distribution). From its technical specification, the bias limit of the thermometer is quoted as 0.2 $^\circ$C (normal distribution). The readings of thermometer for water temperature will have a standard uncertainty as follows,

$$u(T) = \sqrt{\left(\frac{0.1/2}{\sqrt{3}}\right)^2 + \left(\frac{0.2}{3}\right)^2} = 0.073^\circ\text{C} \qquad (19)$$

For water at 16.5 $^\circ$C, temperature deviation of 0.073 $^\circ$C will lead to a change of 0.18% in the water kinematic viscosity,

$$u'_\nu = \frac{u_\nu}{\nu} = 0.18\% \qquad (20)$$

The corresponding component of uncertainty in resistance for each tow speed will be estimated by,

$$u'_3(R_\mathrm{T}) = \frac{C_\mathrm{F}}{C_\mathrm{T}} \cdot \frac{0.87}{log_{10}Re - 2} \cdot u'(v) \qquad (21)$$

In this example, the values of C_F/C_T at Fr=0.1, 0.28 and 0.41 are 0.91, 0.70 and 0.43, respectively, while the values of Re are 3.9×10^6, 1.1×10^7 and 1.6×10^7, respectively. Then, the values of $u'_3(R_T)$ are 0.031%, 0.024% and 0.014% for Fr=0.1, 0.28 and 0.41, respectively.

1.4 Repeat Tests

3.1.5 Resistance

The means, standard deviations *(StDev)*, minimums and maximums of measured resistance at water temperature 16.5℃ in 9 repeat tests are given Table 4 for all three *Fr*. No outliers are observed.

The mean of repeat measurements is usually adopted as the best estimate for a measurand. The standard uncertainty component of the mean from *N* repeat tests is estimated by

$$u_A(\mathrm{mean}) = StDev / \sqrt{N} \qquad (22)$$

Fr	R_T (*kgf*)_(16.5 ºC)			
	Mean	*StDev*	Min	Max
0.10	0.545	1.04%	0.538	0.554
0.28	4.557	0.45%	4.540	4.585
0.41	15.056	0.39%	14.989	15.135

Table 4. Statistical analysis of repeat measurement for resistance

However, it should be noted that the standard uncertainty of any single tests can be estimated by *StDev*, or

$$u_A(\mathrm{single}) = u_A(\mathrm{mean}) \cdot \sqrt{N} \qquad (23)$$

Fr	R_T (*kgf*)_(16.5℃)			
	Mean	u'_A(mean	u'_A(single	$2 \cdot u'_A$(single
0.10	0.545	0.35%	1.04%	2.08%
0.28	4.557	0.15%	0.45%	0.90%
0.41	15.056	0.13%	0.39%	0.78%

Table 5. Uncertainty of repeat measurements for resistance

It is shown from Table 5 that, in a customary sense, the precision of measurement in resistance tests for this hull model is estimated at around ±2% for *Fr*=0.1, ±1.0% for *Fr*=0.28 and *Fr*=0.41, respectively, at 95% confidence level (k_p≈2).

3.1.6 Running Sinkage

No outlier is observed among all the running sinkages measured in nine repeat sets of runs. The uncertainty analysis for direct measurement of sinkage is given in Table6. It is shown that, in a customary sense, the precision of measurement is estimated at around ±1.0mm.

No further detail is provided for the running sinkage measurement in this procedure.

Fr	Sinkage *(mm)*_(16.5 °C)			
	Mean	u_A (mean)	u_A (single)	$2 \cdot u_A$ (single)
0.10	-1.08	0.11	0.33	0.66
0.28	-9.83	0.13	0.40	0.80
0.41	-24.86	0.10	0.31	0.62

Table 6. Uncertainty of repeat measurement for running sinkage

3.1.7 Running Trim

No outlier is observed among all the running trims measured in nine repeat sets of runs. The uncertainty analysis for direct measurement of trim is given in Table7. All the running trims are less than one degree and the uncertainty of repeat measurement is much less than 0.05 degrees. Considering the accuracy of static trim is estimated within ±0.05 degrees, the repeat uncertainty of running trim is not significant.

Fr	Trim *(degrees)*_(16.5℃)			
	Mean	u_A (mean)	u_A (single)	$2 \cdot u_A$ (single)
0.10	-0.004	0.005	0.015	0.029
0.28	-0.099	0.003	0.008	0.016
0.41	0.392	0.004	0.013	0.027

Table 7. Uncertainty of repeat measurement for running trim

No further detail is provided for the running trim measurement in this procedure.

1.5 Combination of Uncertainty Components of Resistance Measurement

Based on the above analysis, all the significant components of uncertainty in resistance measurement are summarized and combined through RSS (Root-Sum-Square) as listed in the following Table 8~10.

R_T (*Fr*=0.10, 16.5 ℃)	Type	Uncertainty	Remark
Wetted area	B	0.035%	negligible
Speed	B	0.067%	negligible
Water temp.	B	0.031%	negligible
Dynamometer	A (*v*=32)	1.59%	dominant
Repeat test, Deviation	A (*N*=9)	1.04%	minor
Combined for single test		1.89%	u'_C (single)
Repeat test, Deviation of mean	A (*N*=9)	0.35%	
Combined for repeat mean		1.62%	u'_C (mean)

Table 8. Combination of uncertainty in measurement for resistance (*Fr*=0.1)

R_T (*Fr*=0.28, 16.5 ℃)	Type	Uncertainty	Remark
Wetted area	B	0.035%	negligible
Speed	B	<0.067%	negligible
Water temp.	B	0.024%	negligible
Dynamometer	A (*v*=32)	0.19%	minor
Repeat test, Deviation	A (*N*=9)	0.45%	dominant
Combined for single test		0.49%	u'_C (single)
Repeat test, Deviation of mean	A (*N*=9)	0.15%	

Combined for repeat mean		0.25%	u_C'(mean)

Table 9. Combination of uncertainty in measurement for resistance (*Fr*=0.28)

R_T (*Fr*=0.41, 16.5 ℃)	Type	Uncer-tainty	Remark
Wetted area	B	0.035%	negligible
Speed	B	<0.067%	negligible
Water temp.	B	0.014%	negligible
Dynamometer	A (*v*=32)	0.058%	negligible
Repeat test, Deviation	A (*N*=9)	0.39%	dominant
Combined for single test		0.40%	u_C'(single)
Repeat test, Deviation of mean	A (*N*=9)	0.13%	
Combined for repeat mean		0.16%	u_C'(mean)

Table 10. Combination of uncertainty in measurement for resistance (*Fr*=0.41)

1.6 Combination of Uncertainty Components of Measurement of Running Sinkage

Based on the above analysis, all the significant components of uncertainty in measurement of running sinkage and trim are summarized and combined through RSS as listed in the following Table 11~13.

Sinkage (*Fr*=0.10)	Type	Uncer-tainty	Remark
Potentiometer	B	0.19*mm*	minor
Repeat test, Deviation	A (*N*=9)	0.33*mm*	dominant
Combined for single test		0.38*mm*	u_C(single)
Repeat test, Deviation of mean	A (*N*=9)	0.11*mm*	
Combined for repeat mean		0.22*mm*	u_C(mean)

Table 11. Combination of uncertainty in measurement for running sinkage (*Fr*=0.10)

Sinkage (*Fr*=0.28)	Type	Uncer-tainty	Remark
Potentiometer	B	0.19*mm*	minor
Repeat test, Deviation	A (*N*=9)	0.40*mm*	dominant
Combined for single test		0.44*mm*	u_C(single)
Repeat test, Deviation of mean	A (*N*=9)	0.13*mm*	
Combined for repeat mean		0.23*mm*	u_C(mean)

Table 12. Combination of uncertainty in measurement for running sinkage (*Fr*=0.28)

Sinkage (*Fr*=0.41)	Type	Uncer-tainty	Remark
Potentiometer	B	0.19*mm*	minor
Repeat test, Deviation	A (*N*=9)	0.31*mm*	dominant
Combined for single test		0.37*mm*	u_C(single)
Repeat test, Deviation of mean	A (*N*=9)	0.10*mm*	
Combined for repeat mean		0.22*mm*	u_C(mean)

Table 13. Combination of uncertainty in measurement for running sinkage (*Fr*=0.41)

4. REPORT OF UNCERTAINTY OF RESISTANCE MEASUREMENT

The total resistances of the model ship measured in water temperature of 16.5 °C can be expressed as the following,

- Measurement of Single Test:

$$\hat{R}_{\mathrm{T}} = R_{\mathrm{T}}(\text{single}) \times \left[1 \pm k_{\mathrm{P}} \cdot u'_C(\text{single})\right] \qquad (24a)$$

- Measurement of Mean of Repeat Tests:

$$\begin{cases} \hat{R}_{\mathrm{T}} = R_{\mathrm{T}}(\text{mean}) \times \left[1 \pm k_{\mathrm{P}} \cdot u'_C(\text{mean})\right] \\ u'_C(\text{mean}) = u'_C(\text{single}) / \sqrt{N} \end{cases} \qquad (24b)$$

where, the coverage $k_{\mathrm{P}}=2$ corresponds to the confidentce level of 95% and N the number of repeat tests. Usually, only two significant figures are remained in the expression of uncertainty values.

The measurement results (mean values of repeat tests) of this example are given in Table 14 and the corresponding non-dimensional values, i.e., the total resistance coefficients given in Table 15.

Total Resistance at 16.5℃ (g=9.7946m^2/s)			
Froude number	Resistance (*kgf*)	Sinkage (*mm*)	Trim (*degrees*)
Fr=0.10	0.545±3.2% (0.545±0.018)	-1.1	-0.004
Fr=0.28	4.557±0.51% (4.557±0.023)	-9.8	-0.099
Fr=0.41	15.056±0.32% (15.056±0.049)	-24.9	0.39

Table 14. Resistance with expanded uncertainty (k_{P}=2) measured in fresh water of 16.5 °C

Total Resistance Coefficient at 16.5℃			
Froude number	C_{T} (10^{-3})	Sinkage (*mm*)	Trim (*degrees*)
Fr=0.10	3.93 ±0.13 (3.933±3.2%)	-1.1	-0.004
Fr=0.28	4.193±0.021 (4.213±0.50%)	-9.8	-0.099
Fr=0.41	6.460±0.021 (6.478±0.32%)	-24.9	0.39

Table 15. Resistance Coefficient with expanded uncertainty (k_{P}=2) in fresh water of 16.5 °C

Total Resistance at 15℃ (g=9.7946m^2/s)			
Froude number	Resistance (*kgf*)	Sinkage (*mm*)	Trim (*degrees*)
Fr=0.10	0.549±0.018	-1.1	-0.004
Fr=0.28	4.580±0.023	-9.8	-0.099
Fr=0.41	15.100±0.049	-24.9	0.39

Table 16. Resistance with expanded uncertainty (k_{P}=2) in fresh water of 15 °C

Using the Eq.8, the resistance at temperature of 16.5 °C can be converted to the nominal temperature 15 °C of fresh water, as given in Table 16, while the non-dimensional coefficients, C_{T} by Eq.3, are listed in Table 17. The uncertainty in such conversion is not included in this example.

Total Resistance Coefficient at 15℃			
Fr=0.10	3.96 ±0.13 (3.960±3.2%)	-1.1	-0.004
Fr=0.28	4.213±0.021 (4.213±0.50%)	-9.8	-0.099
Fr=0.41	6.478±0.021 (6.478±0.32%)	-24.9	0.39

Table 17. Resistance Coefficient with expanded uncertainty (k_{P}=2) in fresh water of 15 °C

It should be noted that the running sinkage and trim will provide important information for intra- and inter-laboratory comparison although, as shown in this example, their uncertainties of measurement are not significant.

Additionally, with reference to this example, engineers who are planning to perform routine resistance tests can focus on the dominant sources of uncertainties, paying little attention to those "negligible" sources of uncertainty, if the tests are performed according to the ITTC recommended procedures.

It is also shown in this example that the accuracy of resistance measurement depends highly on the accuracy of dynamometer and the number of repeat tests. Uncertainty analysis will help engineers to choose the proper type of dynamometer and adequate number of repeat tests to meet with a desired accuracy of measurement.

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