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General Guideline for Uncertainty Analysis in Resistance Tests

1. PURPOSE OF GUIDELINE

A general guide is provided for the practical implementation of the ISO-GUM (1995) and the ITTC Procedure 7.5-02-01-01 (2008) for uncertainty analysis of measurement of resistance tests in a towing tank that follow the ITTC Procedure 7.5-02-02-01 (2011), “Resistance Test”.

Analysis of the uncertainties related to extrapolation and full scale prediction of resistance is not included in this guideline.

2. MEASURANDS

The measurands that are measured directly in resistance tests include the total resistance (R_T) and the corresponding running sinkage and trim of a ship model at each towing speed. Water temperature during model testing should be recorded to determine the density and viscosity of water.

The measured resistance is usually non-dimensionalised as the total resistance coefficient, C_T, by the following equation,

$$C_\mathrm{T} = R_\mathrm{T} / (\frac{1}{2}\rho S V^2) \tag{1}$$

where, S is the wetted surface area of model ship, V the towing speed and ρ is the water density at the temperature during testing.

Usually, during the whole process of a typical set of resistance tests (e.g., within one daytime), the water temperature can be considered almost constant for a conventional indoor towing tank. If there is small but significant variation of temperature (say, much greater than 0.1 degrees) with different time and area of water in testing, all the temperature measurements (T_i) should be averaged to obtain the mean temperature $\bar{T}$ as the nominal temperature for the resistance tests. Each resistance measurements (at temperature T_i) should first be converted to the nominal temperature ($\bar{T}$) before any data analysis is performed.

When some tests are repeated or intra/inter-laboratory comparison is performed, if there is deviation in towing speed from each other, all the resistance measurement should also be corrected to the nominal speed that corresponds to the prescribed Froude number

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

where, L is the characteristic length of the model.

The uncertainties of the conversion and correction mentioned above are not included in this guideline.

Additionally, the blockage effect of the tank boundaries can be corrected with use of one of the formulae recommended in ITTC Procedure 7.5-02-02-01. These formulae are all based on mean-flow theory under some assumption and with some simplicity. Uncertainty of such correction is not included in this guideline. Typically, the blockage effect of a large deep towing tank is negligible and usually no correction is needed.

3. UNCERTAINTY SOURCES

The first step in implementing the ISO-GUM into the resistance tests is to identify all the significant sources of uncertainty, mainly on basis of the database or practical judgment by wellexperienced engineers in towing tank.

Along the whole flowchart of resistance test, the sources of uncertainty in measurement may be grouped under five blocks from No. ① to No. ⑤ as shown in Fig.1. Each group of uncertainty sources is outlined in the following sections.

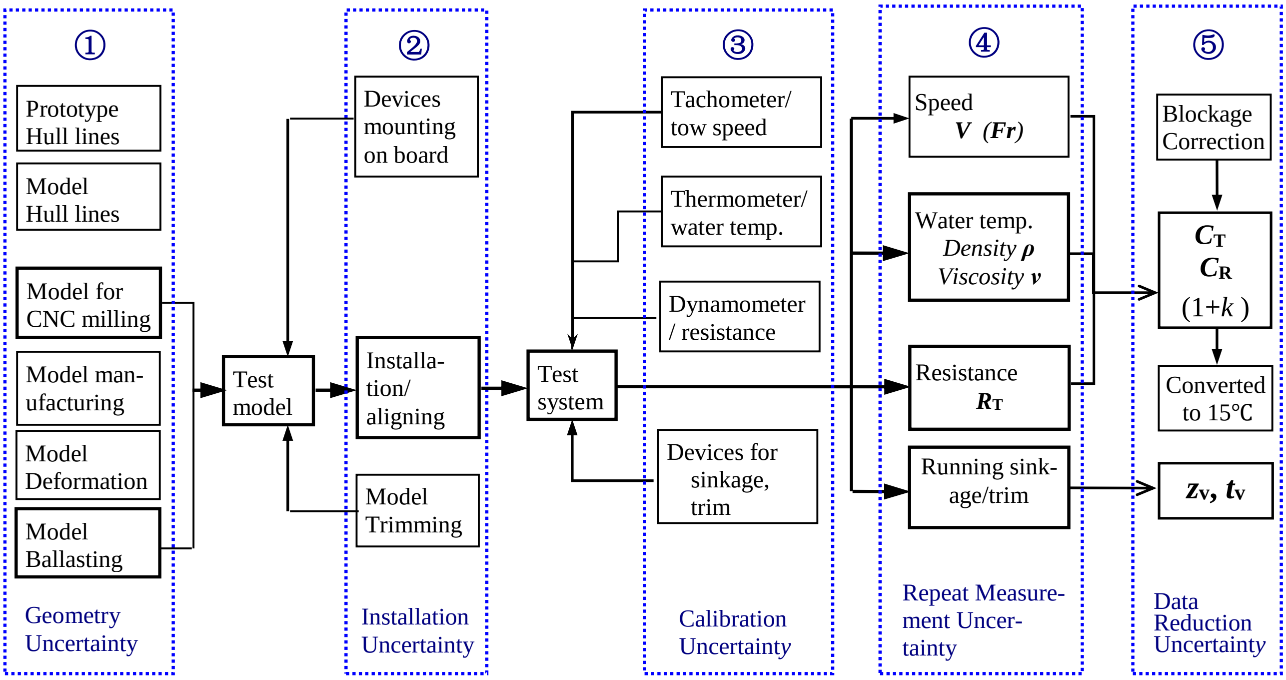

Figure 1. Schematic diagram for groups of uncertainty sources in resistance test

3.1 Model Geometry

No. ① block in Figure 1 lists the uncertainty sources related to model geometry. The geometry uncertainty mainly results from the tolerances in manufacturing and the deformation after manufacture and during model testing.

The wetted surface area is an important parameter in resistance data reduction. It is difficult to accurately determine the real wetted surface of a hull model under testing because of the effect of hull-making waves and running attitudes. Instead, a nominal area, i.e., the wetted surface area of a hull model at rest, is usually adopted and theoretically computed from the hull form lines.

As multi-axis computerized-numerical-control (CNC) milling machines are widely used for hull model manufacture, this nominal wetted area can be numerically computed by surface integral of the 3D numerical model for CNC milling. However, there will be a slight difference in the surface fairing of hull model between different workshops when the same hull form lines are used for manufacture. This difference is not an uncertainty in the hull geometry, but rather it is a definite bias between workshops.

On the other hand, the hull model is to be ballasted in accordance with its nominal displacement volume, which can be obtained by integrating the surface of 3D numerical model up to the nominal waterline/draught, that is,

$$\Delta_{\text{nominal}} = \rho_{\text{water}} \times \nabla_{\text{nominal}} \tag{3}$$

Therefore, the uncertainty in model ballasting will propagate into the real displacement volume of hull model. The relative standard uncertainty can be expressed as

$$u'(\Delta) \equiv \frac{u(\Delta)}{\Delta} = \frac{\rho_{\text{water}} u(\nabla)}{\rho_{\text{water}} \nabla} = \frac{u(\nabla)}{\nabla} \equiv u'(\nabla) \tag{4}$$

where, *u* stands for the standard uncertainty.

The displacement volume of a hull model represents a sort of "size" of the wetted part of hull model. The representative length (*L*) and area (*S*) used for non-dimensional coefficients can be assumed proportional to one-third and two-third power of the volume, respectively,

$$\begin{cases} L \propto (\nabla)^{1/3} \\ S \propto (\nabla)^{2/3} \end{cases} \tag{5}$$

Therefore, the uncertainty components of wetted surface area and representative length of the model can be estimated as,

$$\begin{cases} u'(S) = \dfrac{u(S)}{S} = \dfrac{2}{3}u'(\nabla) = \dfrac{2}{3}u'(\Delta) \\ u'(L) = \dfrac{u(L)}{L} = \dfrac{1}{3}u'(\nabla) = \dfrac{1}{3}u'(\Delta) \end{cases} \tag{6}$$

where, the length uncertainty will propagate into frictional resistance calculation through the Reynolds number,

$$Re = VL/\nu \tag{7}$$

The uncertainty in trimming the hull model is assumed to have no effects on the "size" of the underwater part of hull model.

The thermal deformation of the hull model due to the change of ambient temperature between the model workshop and tank water is usually assumed negligible, as the coefficient of thermal expansion (CTE) of wood is small (on the order of 5×10^{-5}/℃) and variation of temperature can keep within several degrees at indoor laboratory from model manufacturing to model testing.

There is no analytic relationship between the non-uniform deformation of hull geometry and the hull resistance (especially the form drag), let alone the effect of the waviness of hull surface on the resistance.

Finally, as is known from Eq.3, there is also propagation of the uncertainty of water density into the real displacement volume of hull model in tank water, i.e.

$$u'(\nabla) = \frac{u(\nabla)}{\nabla} = \frac{u(\rho_{\text{water}})}{\rho_{\text{water}}} = u'(\rho_{\text{water}}) \tag{8}$$

Usually, the temperature of tank water during a set of routine tests varies very little, say, much less than ±0.5℃, which corresponds to a change of about ±0.01% in the water density and the uncertainty component resulted in geometry is considered negligible. However, when the same model is tested at different dates and there is change of several degrees in water temperature, the model hull should be ballasted to the water temperature corresponding to the specific date.

3.2 Test Installation

No.② block in Fig.1 includes the uncertainty sources related to the hull model trimming, the alignment of the center-lines of hull model and dynamometer and the motion direction of the towing carriage, the alignment of tow force to the line of propeller shaft, and so forth.

Usually, the installation process in commercial tanks can be controlled so well that the uncertainty from installation into the hull model resistance is assumed to be negligible, when there is no reliable database available to estimate such uncertainty in resistance measurements.

There is directno way to analytically evaluate the effect of non-zero drift angle of the hull model resulted from the uncertainty of alignment on the hull resistance, so that this effect is usually assumed negligible. With dynamometer systems that measure sideforce it is possible for symmetrical models to carry out a series of runs at different angles of drift to assess possible misalignment. Overall it is noted that this is an area where good practice is essential.

3.3 Instrument Calibration

The devices for measuring the tow speed of carriage, the running sinkage and trim and the temperature of tank water are all calibrated regularly. The uncertainties given in the update calibration reports or certificates can be directly quoted for the resistance tests. However, those uncertainty values should be firstly converted into the corresponding standard uncertainties according to the ISO GUM.

The resistance dynamometer is usually calibrated before test and checked immediately after a test. All the calibration results should be traceable to a National Metrology Institute.

The dynamometer calibration should be performed according to the ITTC Procedure 7.5-01-03-01. Usually, ten equal increments of loads or forces over the range are adopted for End-to-End calibration process, in which the signal conditioner and data acquisition system (DAS) are all included. It is no need to analyze the details of uncertainty components from inside DAS unless it is desired to make some improvement in the measuring system.

Linear curve fitting is always used for dynamometer calibration,

$$m_{\mathrm{i}}(1-\rho_{\mathrm{air}}/\rho_{\mathrm{weight}}) = K_{\mathrm{g}}\cdot V_{\mathrm{i}} + O(\varepsilon), \quad i=1,N \quad (9)$$

where, m_{i} is the i-th mass of weight for loading, V_{i} the corresponding output of voltage, g the local acceleration of gravity, K_{g} the so-called coefficient of calibration. The experimental standard deviation for the linear regression analysis is usually adopted as the standard uncertainty of calibration, e.g., (in Newton)

$$u(R_{\mathrm{T}}) \equiv SEE = g\cdot\sqrt{\frac{\left(m_i - K_g\cdot V_i\right)^2}{N-1}} \quad (10)$$

The accuracy of weights is always so high that its uncertainty is negligible.

3.4 Direct Measurement

3.4.1 Resistance

No.④ block in Fig.1 indicates the uncertainty sources related to the measuring data that are directly output from DAS of measurement system. On one hand, the effect of DAS on uncertainty of resistance measurement is preferably included in the calibration by end-to-end calibration. On the other hand, some special consideration should be given in the time history of sampling data.

Usually, the time history in an interval of time, $\Delta t=n/f_{\mathrm{s}}$, is obtained after low-pass filtering, where f_{s} is the sampling rate and n the number of the sampling data points. Thereafter, the filtered time history is averaged to obtain one “reading” of the measurement,

$$\hat{R}_\mathrm{T} = \frac{1}{n}\sum_{i=1}^{n}\tilde{R}_{\mathrm{T}i} \tag{11}$$

and the standard deviation of the filtered time history is calculated as

$$\hat{s} = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\hat{R}_\mathrm{T}-\tilde{R}_{\mathrm{T}i}\right)^2}, \quad \hat{s}' = \frac{\hat{s}}{\hat{R}_\mathrm{T}} \tag{12}$$

where $R_{\mathrm{T}i}$ is the *i*-th data point within the filtered time history. Then, the standard uncertainty of the "reading" (average) can be obtained,

$$u(\hat{R}_\mathrm{T}) = \frac{\hat{s}}{\sqrt{n}}, \quad u'(\hat{R}_\mathrm{T}) = \frac{\hat{s}'}{\sqrt{n}} \tag{13}$$

It is recommended that the sampling rate and interval of time and the cut-off frequency of low filtering should be properly chosen so that the standard uncertainty of the "reading" can be assumed negligible.

Furthermore, if repeat tests are performed, it is customary to adopt the mean of multiple "readings" from repeat tests rather than the "reading" of single run as the "best" estimate of measurand,

$$\bar{R}_\mathrm{T} = \frac{1}{N}\sum_{j=1}^{N}\left(\hat{R}_\mathrm{T}\right)_j \tag{14}$$

where N is the number of repeat tests. The experimental standard deviation of these N "readings" can be estimated by the following Eq.15 if N is large enough,

$$s = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(\bar{R}_\mathrm{T}-\hat{R}_{\mathrm{T}\cdot j}\right)^2} \equiv u\left(\hat{R}_{\mathrm{T}\cdot j}\right) \tag{15}$$

Thereafter, the standard uncertainty of repeat tests can be obtained,

- For single measurement

$$u(\hat{R}_\mathrm{T}) \equiv s, \quad u'(\hat{R}_\mathrm{T}) = \frac{s}{\hat{R}_\mathrm{T}} \tag{16a}$$

- For a mean of repeat measurements

$$u(\bar{R}_\mathrm{T}) \equiv \bar{s} = \frac{s}{\sqrt{N}}, \quad u'(\bar{R}_\mathrm{T}) = \frac{s/\bar{R}_\mathrm{T}}{\sqrt{N}} \tag{16b}$$

3.4.2 Running Sinkage and Trim

The uncertainty in direct measurement of running sinkage and trim can be analyzed similarly as the above.

3.4.3 Water Temperature

The density and viscosity of water in towing tank are determined by water temperature and calculated according to the ITTC Procedure 7.5-02-01-03.

The water temperature is usually measured with an accuracy of ±0.1℃. The corresponding uncertainty of water density will be about 0.002% and negligible. However, the uncertainty of water viscosity will be about 0.2%. The deviation of water temperature has a relatively large effect on water viscosity and thereafter on the Reynolds number and frictional drag of the hull model.

3.5 Data Reduction

In this guideline, only the uncertainties related to the resistance measurement are analyzed and those uncertainties in extrapolation are not considered, therefore, the uncertainties related to the form factor and residuary resistance coefficient determined by the resistance test are not covered and no data reduction is involved in the uncertainty analysis.

4. UNCERTAINTY PROPAGATION

4.1 Hull Geometry

The total resistance of a hull model at a specific Froude number is a function of the hull's wetted surface area and Reynolds number when it is assumed that the geometry uncertainty of ship model hull usually has no effect on the residuary resistance coefficient (C_R), i.e.,

$$\begin{aligned} R_T &= f\left(S, Re, Fr\right) = C_T \cdot \left(0.5\rho V^2 \cdot S\right) \\ &= \left[(1+k)\cdot C_F(Re) + C_R(Fr)\right]\cdot\left(0.5\rho V^2 \cdot S\right) \end{aligned} \tag{17}$$

where the frictional resistance coefficient (C_F) is calculated using the ITTC-1957 ship friction correlation line,

$$C_F = 0.075/\left(\log_{10}\mathrm{Re}-2\right)^2 \tag{18}$$

The changes of resistance with the wetted surface area and representative length of hull model can be estimated approximately by the following equations, respectively,

- Wetted surface area

$$\frac{\delta R_T(S)}{R_T} \approx \frac{\partial R_T}{\partial S}\cdot\frac{\delta S}{R_T} = \frac{\delta S}{S} \tag{19}$$

- Length (Reynolds number)

$$\begin{aligned} \frac{\delta R_T(L)}{R_T} &\approx \frac{\partial R_T}{\partial C_F}\cdot\frac{\partial C_F}{\partial Re}\cdot\frac{\partial Re}{\partial L}\cdot\frac{\delta L}{R_T} \\ &= \frac{C_F}{C_T}\cdot\frac{2/ln10}{log_{10}Re-2}\cdot\frac{\delta L}{L} \\ &= \frac{C_F}{C_T}\cdot\frac{0.87}{log_{10}Re-2}\cdot\frac{\delta L}{L} \end{aligned} \tag{20}$$

Combining Eq.7 with Eq.19 and Eq.20, we can obtain the relative standard uncertainty components of resistance related to the hull geometry, respectively,

$$u'_{11}(R_T) = u'(S) \approx \frac{2}{3}u'(\Delta) \tag{21}$$

$$\begin{aligned} u'_{12}(R_T) &= \frac{C_F}{C_T}\cdot\frac{0.87}{log_{10}Re-2}\cdot u'(L) \\ &\approx \frac{C_F}{C_T}\cdot\frac{0.29}{log_{10}Re-2}\cdot u'(\Delta) \end{aligned} \tag{22}$$

Reynolds number in a typical resistance test is on the order of 10^7 and generally,

$$u'_{12}(R_T) \sim 0.05\cdot u'(\Delta) \tag{23}$$

Therefore, u'_{12} is relatively negligible to u'_{11} and the combined standard uncertainty of resistance resulted from hull geometry can be estimated as,

$$u'_1(R_T) = \sqrt{\left(u'_{11}(R_T)\right)^2 + \left(u'_{12}(R_T)\right)^2} \approx \frac{2}{3}u'(\Delta) \tag{24}$$

The accuracy of displacement mass of hull model is on the order of 0.1%, its standard uncertainty will be on the order of (0.1%/ √3) ≈ 0.05% , which will result into a standard uncertainty of order of 0.05% in resistance. Such an uncertainty component is usually considered negligible for resistance measurement.

4.2 Dynamometer Calibration

The uncertainty component of resistance resulted from calibration of dynamometer is estimated by Eq.10 and propagated directly into the uncertainty of resistant measurement. This component can be designated as $u_2(R_T)$.

4.3 Water Temperature

The uncertainty of water viscosity resulted from temperature can be easily estimated on basis of the ITTC Procedure 7.5-02-01-03, “Density and Viscosity of Water”. Then, similarly as Eq.20, we can obtain,

$$\begin{aligned}\frac{\delta R_{\mathrm{T}}(\nu)}{R_{\mathrm{T}}} &\approx \frac{\partial R_{\mathrm{T}}}{\partial C_{\mathrm{F}}}\cdot\frac{\partial C_{\mathrm{F}}}{\partial Re}\cdot\frac{\partial Re}{\partial \nu}\cdot\frac{\delta \nu}{R_{\mathrm{T}}}\\ &=\frac{C_{\mathrm{F}}}{C_{\mathrm{T}}}\cdot\frac{0.87}{log_{10}Re-2}\cdot\frac{\delta\nu}{\nu}\end{aligned}\tag{25}$$

and , the corresponding relative standard uncertainty of resistance is estimated as,

$$u'_3(R_{\mathrm{T}})=\frac{C_{\mathrm{F}}}{C_{\mathrm{T}}}\cdot\frac{0.87}{log_{10}Re-2}\cdot u'(\nu)\tag{26}$$

The accuracy of water temperature measurement is usually within ±0.1℃. The standard uncertainty of kinematic viscosity, $u'(\nu)$, may be on the order of (0.2%/√3) ≈ 0.1%, and lead to a standard uncertainty of order of 0.02% in resistance. Such an uncertainty component can be assumed negligible in resistance test.

As stated in Section 3.4.3, the uncertainty of water density resulted from temperature measurement is negligible.

4.4 Towing Speed

The uncertainty of towing speed propagates into the resistance measurement in two ways. One is the dynamic pressure and the other the Reynolds number.

- Dynamic pressure

$$\frac{\delta R_{\mathrm{T}}(V)}{R_{\mathrm{T}}}\approx\frac{\partial R_{\mathrm{T}}}{\partial(\rho V^2)}\cdot\frac{\partial(\rho V^2)}{\partial V}\cdot\frac{\delta V}{R_{\mathrm{T}}}=2\frac{\delta V}{V}\tag{27}$$

- Reynolds number

$$\begin{aligned}\frac{\delta R_{\mathrm{T}}(V)}{R_{\mathrm{T}}} &\approx \frac{\partial R_{\mathrm{T}}}{\partial C_{\mathrm{F}}}\cdot\frac{\partial C_{\mathrm{F}}}{\partial Re}\cdot\frac{\partial Re}{\partial V}\cdot\frac{\delta V}{R_{\mathrm{T}}}\\ &\approx\frac{C_{\mathrm{F}}}{C_{\mathrm{T}}}\cdot\frac{0.87}{log_{10}Re-2}\cdot\frac{\delta V}{V}\end{aligned}\tag{28}$$

We can obtain the corresponding uncertainty components in resistance by the following equations, respectively,

$$u'_{41}(R_{\mathrm{T}})=2\cdot u'(V)\tag{29}$$

$$u'_{42}(R_{\mathrm{T}})=\frac{C_{\mathrm{F}}}{C_{\mathrm{T}}}\cdot\frac{0.87}{log_{10}Re-2}\cdot u'(V)\tag{30}$$

where, u'_{42} is usually much less than u'_{41} and negligible. Then, the combined standard uncertainty of resistance resulted from towing speed can be estimated as,

$$\begin{aligned}u'_4(R_{\mathrm{T}}) &=\sqrt{\left(u'_{41}(R_{\mathrm{T}})\right)^2+\left(u'_{42}(R_{\mathrm{T}})\right)^2}\\ &\approx 2u'(V)\end{aligned}\tag{31}$$

4.5 Repeat tests

When the average of repeat tests is adopted as the final measurement, the standard uncertainty component from repeat tests can be estimated by Eq.16b. If any single test is adopted as the final measurement, the standard uncertainty should be estimated by Eq.16a.

When no repeat test has been performed for a specific case concerned, a database of the same kind of model tests can be quoted as an estimate.

5. UNCERTAINTY SUMMARY

Analysis of all the significant uncertainty components related to the total resistance as illustrated above can be summarized as in the following Table 1. These standard uncertainty components will be multiplied by their sensitivity coefficients respectively and then combined to obtain the overall standard uncertainty by RSS (root-sum-squares) method,

$$u'_c(R_T)=\sqrt{(u'_1)^2+(u'_2)^2+(u'_3)^2+(u'_4)^2+(u'_A)^2} \tag{32}$$

Source & Component		Sensitivity Coef.	*Type*
Hull ballasting	Displacement $u'(\Delta)$-Eq.24	2/3	B (u'_1)
Dynamometer	Calibration $u'(R_T)$-Eq.10	1	A (u'_2)
Water temp.	Viscosity $u'(v)$-Eq.26	$\frac{C_F}{C_T}\,\frac{0.87}{log_{10}Re-2}$	B (u'_3)
Towing speed	Dynamic Pressure $u'(V)$-Eq.31	2	B (u'_4)
Repeat tests	Repeatability $u'(R_T)$-Eq.16	1	A (u'_A)
Combined	$u'_c(R_T)=\sqrt{(u'_1)^2+(u'_2)^2+(u'_3)^2+(u'_4)^2}+(u$		
Expanded	$U_P=k_P\times u_c$ (k_P=2 for 95% confidence level)		

Table 1. Summary of significant uncertainty components in resistance measurement

Table 2 shows an example of uncertainty analysis in the resistance tests for a geosim of DTMB 5415 surface vessel at *Fr=0.28* in fresh water of 16.5℃ (Wu, et al, 2013), where 9 repeat tests are performed. It can be concluded that the total uncertainty of resistance from single measurement in this example is about 1.0% at the level of confidence 95%. If the mean of repeat tests is adopted as the final result, then the measurement can be reported by the following,

$$\begin{aligned} R_T(\text{mean})&\times\left[1\pm k_P\cdot u'_C(\text{mean})\right]\\ &=44.631N\times(1\pm0.51\%)\\ &=44.63N\pm0.23N \qquad (k_P=2)\end{aligned} \tag{33}$$

where, only two significant figures are usually remained in the uncertainty value.

Total resistance mean: R_T=44.631N (16.5℃) < Running sinkage: (-9.8±0.3)*mm*; trim: -0.1° >			
Uncertainty Components	Type	Uncertainty, relative	Remark
Hull ballasting	B	0.035%	negligible
Towing speed	B	0.067%	negligible
Water temperature	B	0.024%	negligible
Dynamometer	A (v=32)	0.19%	minor
Repeat test, for single	A (N=9)	0.45%	dominant
Combined for single		0.49%	u'_C(single)
Expanded for single		0.99%	(k_P=2)
Repeat test, for mean	A (N=9)	0.15%	(0.45%/√3)
Combined for mean		0.25%	u'_C(mean)
Expanded for mean		0.51%	(k_P=2)

Table 2. Analysis of uncertainty for resistance measurement of DTMB 5415 model (*Fr*=0.28)

When the resistance measured in the water of 16.5℃ (in this example) is converted to the nominal temperature 15℃, we can obtain the resistance expression

$$\begin{aligned} R_{\mathrm{T}} &= 44.856N \pm 0.23N \qquad (k_{\mathrm{P}} = 2) \\ &= 44.86N \times (1 \pm 0.51\%) \end{aligned} \tag{34}$$

And then by the non-dimensional equation (1), the corresponding total resistance coefficient is obtained as

$$\begin{aligned} C_{\mathrm{T}} &= 4.213 \times 10^{-3} \times (1 \pm 0.51\%) \qquad (k_{\mathrm{P}} = 2) \\ &= 4.213 \times 10^{-3} \pm 0.021 \times 10^{-3} \end{aligned} \tag{35}$$

where, in this example, the wetted surface area of model hull is 4.846m^2 and the displacement 0.5517m^3 at the ratio of scale 1:24.82.

6. REFERENCES

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