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Uncertainty Analysis of Resistance Tests in Ata Nutku Ship Model Testing Laboratory of Istanbul Technical University

İstanbul Teknik Üniversitesi Ata Nutku Gemi Model Testi Laboratuvarında Direnç Testlerinin Belirsizlik Analizi

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ABSTRACT

In this study, some systematical resistance tests, where were performed in Ata Nutku Ship Model Testing Laboratory of Istanbul Technical University (ITU), have been included in order to determine the uncertainties. Experiments which are conducted in the framework of mathematical and physical rules for the solution of engineering problems, measurements, calculations include uncertainty. To question the reliability of the obtained values, the existing uncertainties should be expressed as quantities. The uncertainty of a measurement system is not known if the results do not carry a universal value. On the other hand, resistance is one of the most important parameters that should be considered in the process of ship design. Ship resistance during the design phase of a ship cannot be determined precisely and reliably due to the uncertainty resources in determining the resistance value that are taken into account. This case may cause negative effects to provide the required specifications in the latter design steps. The uncertainty arising from the resistance test has been estimated and compared for a displacement type ship and high speed marine vehicles according to ITTC 2002 and ITTC 2014 regulations which are related to the uncertainty analysis methods. Also, the advantages and disadvantages of both ITTC uncertainty analysis methods have been discussed.

Keywords: Measurement, bias & precision limit, displacement ship, Kriso Container Ship (KCS), high speed marine vehicle.

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ÖZET

Bu çalışmada, İstanbul Teknik Üniversitesi (İTÜ) Ata Nutu Gemi Model Laboratuvarında gerçekleştirilen model direnç deneylerinin belirsizliği incelenmiştir. Belirli fiziksel ve matematiksel yaklaşımlar ve varsayımlar altında gerçekleştirilen deneyler hem ölçüm sisteminin hem de çevresel şartların etkisi ile sonuçlar üzerinde belirsizlikler içermektedir. Deney sonucunda elde edilen değerin doğruluğu veya güvenilirliği mevcut belirsizliklerin incelenmesi ve sayısal olarak ifade edilmesiyle mümkündür. Eğer deney sonucunda elde edilen değerin belirsizliği tahmin edilmez ise bu değerin evrensel anlamda geçerliliği kısıtlıdır. Diğer taraftan, gemi direnci, gemi dizayn spirali içerisinde dikkat edilen en önemli parametrelerin başında gelmektedir. Eğer dizayn aşamasında gemi direnci değeri gerçeğe en yakın şekilde tahmin edilmez ise, bu durum sonraki dizayn aşamalarını da önemli ve olumsuz yönde etkileyebilecektir. Bu yüzden model testlerinde ve değerlerin analizi sırasında meydana gelebilecek muhtemel belirsizlik kaynakları incelenmelidir. Bu çalışmada, deplasman tipi gemi ve hızlı tekne modellerinin direnç testlerinde ortaya çıkan belirsizlikler ITTC 2002 ve ITTC 2014 belirsizlik analizi prosedürleri dikkate alınarak tahmin edilmiştir. Aynı zamanda, bu iki farklı yöntem karşılaştırılarak avantajlı ve dezavantajlı yönleri tartışılmıştır.

Anahtar Kelimeler:
Ölçme, eğilim & kesinlik limiti, deplasman gemisi, Kriso Konteynır Gemisi, hızlı tekne.

1. Introduction

Experimental studies are commonly used in the mathematical modeling solution using idealization and assumptions (Coleman and Steele, 2009). The reliability of the solution is directly related to the measurements. Therefore each step of the test system must be analyzed precisely. If any uncertainty that may occur in these steps, it will adversely affect the test results. Consequently, the measurement result may be far from the actual value. To prevent this, uncertainties in the system must be calculated how much they will affect the test results. Uncertainty analysis method is applied to the test system to get an answer to this question. Uncertainty analysis is a numerical expression of the measurement results that show how much close to the true result. If the uncertainty value is not known, results cannot be compared with the other tests and standards. So obtained results cannot be expressed as the global value (ASME, 2005).

Ship resistance is defined as the force acting on the hull with constant speed in calm water (Bal and Güner, 2011). Ship resistance is a very important parameter that is considered in the design stage. Errors made in estimating the resistance value will affect predominantly the other design features of the ship. Determining the closest resistance to the true value is very important both to reduce the cost of production and will lead to a noticeable improvements in the performance of the ship's propulsion (Bal, 2008a).

In design stage, resistance and power estimation can be done by numerical methods, computer programs as well as by model tests (Bal and Güner, 2011; Bal, 2008b). Of these methods, the resistance value calculated by the model tests are widely used for many years. However, there are sources of uncertainty occurring in the test system. Uncertainty sources should be analyzed in terms of the reliability of the test results. Particularly, the large components of uncertainty must be estimated as quantitatively. There are numerous predictable and unpredictable factors that influence the measurement results. One by one examination is not possible. However, limited sources of uncertainty can be examined through the existing academic knowledge (ASME, 2005). In this study, the uncertainties are examined occurred in resistance (towing) tests. For uncertainty analysis of ship resistance, the special procedure have been developed with standard uncertainty analysis method and data collected from the towing tanks by International Towing Tank Conference (ITTC). Procedures for uncertainty analysis of experimental resistance test were published by the ITTC (ITTC, 2002; ITTC, 2008; ITTC, 2014).

Tests have been carried out in Ata Nutku Ship Model Testing Laboratory in this study. The towing tank is 160 m long, 6 m wide and 3.5 m depth and the carriage maximum speed is 5.5 m/s. In this study, two common ship types, a displacement ship model (which is relatively slow) and a high speed marine vehicle (HSMV) model, have been selected. Also the uncertainties are estimated for both models. For displacement-type ship, the Kriso Container Ship (KCS) Hull Form is selected to determine the potential uncertainty sources in resistance tests. The scale ratio has been selected as a value that is different form the given in literature. The reason why this model has been selected is that there are a great number of results including model test results and computational fluid dynamics (CFD) applications. The model manufactured in the workshop of the laboratory. For HSMV model, which was previously manufactured in the laboratory, has been used in the present study. Both ITTC 2002 and ITTC 2014 methods were applied to the test results and uncertainty values estimated as quantitatively.

2. Uncertainty Analysis

There are predictable factors which influence the results. On the other hand, there are factors which cannot be calculated even noticeable. Moreover, all sources of uncertainty in a test are related to each other. Thus an uncertainty may affect the other uncertainty in different step, finally total uncertainty can increase (Benedict, 1964). Even if the tests conduct in constant conditions, test results may be different from each other because of numerous uncertainty components.

2.1. Result Uncertainty

The results are generally not able to obtain from direct measurements. The result function is obtained from different factors, depending on several different measurements and some external parameters (e.g. temperature, pressure etc.). Each parameter creates uncertainty separately on result function (ASME, 2005). The uncertainty components, due to each independent variable in function, should be included in the result in order to estimate the uncertainty value (ASME, 2005).

The result function (R), is formed by combination of independent variables. Relationship between the result and input parameters are given below, eq. (2-1). The subscript I here represents the number of independent parameters in the result equation. The mean value $\bar{X}_i$ must be used in the result function.

$$R = f\ (\bar{X}_1, \bar{X}_2, \dots, \bar{X}_I) \qquad (2\text{-}1)$$

Sensitivity coefficient must be calculated for uncertainty of experimental studies. A change in a parameter is the instantaneous rate of change in the result. There are two approaches (analytically and numerically) for estimating the sensitivity coefficient (ASME, 2005). Analytically, if mathematical relationship between the result (R) and its parameters are known, the sensitivity coefficient of parameter can be obtained by partial differentiation (ASME, 2005). Absolute (dimensional) sensitivity coefficient can be computed by analytically as,

$$\theta_i = {}^{\partial R}/_{\partial \bar{X}_i} \tag{2-2}$$

Numerical sensitivity coefficient is determined from finite increments in parameter that change the result without the usage of function (ASME, 2005). Absolute (dimensional) sensitivity coefficient can be computed by numerically as,

$$\theta_i = {}^{\Delta R}/_{\Delta \bar{X}_i} \tag{2-3}$$

Although numerical calculation is practical, the reliability of this method is less affected by uncertainty. Because of this, the best approach to sensitivity would be obtained analytically (ASME, 2005). In this study, the analytical method is preferred in the calculations. There are some differences between the single test and multiple tests for uncertainty estimation.

2.1.1. Single test

The absolute random standard uncertainty of single (s_R) test result may be determined through Taylor series.

$$s_R = \left\{ \sum_{i=1}^{I} \left(\theta_i s_{\bar{X}_i} \right)^2 \right\}^{1/2} \tag{2-4}$$

The symbol θ_i is absolute sensitivity coefficient and $s_{\bar{X}_i}$ is the random standard uncertainty of measured parameter average ($\bar{X}_i$). It is determined according to the sample standard deviation (ASME, 2005).

The absolute systematic standard uncertainty of a result (b_R) may be determined from sensitivity coefficient and the systematic standard uncertainty of the measured parameter ($b_{\bar{X}_i}$) (ASME, 2005).

$$b_R = \left\{ \sum_{i=1}^{I} (\theta_i b_{\bar{X}_i})^2 \right\}^{1/2} \tag{2-5}$$

2.1.2. Multiple tests

When more than one test is conducted with the same test conditions and instrument package, the uncertainty of the average test results may be less than that of single test (ASME, 2005).

The random standard uncertainty of the result ($s_{\bar{R}}$) is estimated directly from sample deviation of the mean result (s_R) from multiple tests (2-6). M is the number of repeated experiments.

$$s_{\bar{R}} = {}^{s_R}/_{\sqrt{M}} \tag{2-6}$$

The systematic uncertainty is calculated as in the same manner as for single test (ASME, 2005). The general form of expression for determining the combined standard uncertainty of a result is the root-sum-square of both the systematic and the random standard uncertainties of the result (ASME, 2005).

$$u_R = [(b_R)^2 + (s_R)^2]^{1/2} \tag{2-7}$$

b_R is obtained from eq. (2-5) and s_R is obtained from either eq. (2-4) for a single result or from eq. (2-6) for a multiple test result. The expanded uncertainty of result with a confidence level is given below.

$$U_{R,\%t} = t.u_R \quad (2\text{-}8)$$

The Student's t value at a specified confidence coefficient is set by the user. However, a t value is usually taken 2 in the engineering problems, which defines an interval with a level of confidence of approximately 95%. Finally, the mean value and the expanded uncertainty with 95% confidence and large degrees of freedom is expressed as:

$$\bar{R} \pm U_{R,95} \quad (2\text{-}9)$$

3. Uncertainty of Resistance Tests

The main purpose of the model tests to determine the relationship between residual resistance coefficient (C_R) and Froude number (Fr) (Bal and Güner, 2011). On the other hand, the test system consists of several uncertainty sources. The uncertainty analysis must be applied to the results for classification of uncertainties and to estimate it as quantitative.

Otherwise, the total resistance value of the hull form must be determined accurately to reach the prescribed speed in design stage of a ship.

ITTC procedures examine only the uncertainty of the model. These procedures does not discuss either some specific details such as turbulence stimulation, drag of appendages, blockage and wall effect of tank, scaling effect on form factor (ITTC, 2002; ITTC, 2014).

Both methods have been described in general terms in present study. More details on two methods have been discussed in Delen (Delen, 2015; Delen ve Bal, 2015).

3.1. Uncertainty Analysis by ITTC 2002 Method

Examined sources of uncertainty in the ITTC 2002 method are given below (ITTC, 2002; ITTC, 2002a; ITTC, 2002b).

- Model length
- Wetted surface
- Temperature, density, viscosity,
- Model speed,
- Resistance,
- Frictional resistance coefficient,
- Form factor,
- Total resistance coefficient,
- Residual resistance coefficient.

In ITTC 2002 procedure, bias limit in model lengths are assumed ± 1 mm in all coordinates due to manufacturing error (ITTC, 2002). So the uncertainty in length between perpendiculars will be B_L=2 mm. Uncertainty of the main dimensions is also effective in uncertainty of wetted surface (B_S). The weights are added in order to satisfy the similarity for displacement between ship and model, and this produces also uncertainty on the B_S. Finally the uncertainty in wetted surface is obtained by taking the root-sum-square (RSS) of two bias components (ITTC, 2002).

Velocity uncertainty (B_V) is directly related to the carriage speed measurement system. It consists of individual measurement for pulse count (c), wheel diameter (D), 12 bit DA and AD card time base (Δt) (3-1) (ITTC, 2002).

$$V = \frac{c\pi D}{6000\Delta t} \quad (3\text{-}1)$$

There are four uncertainty sources due to uncertainty of pulse count (ITTC, 2002). The wheel diameter is considered accurate within B_D=0.000115 m. The bias limit in time base is considered as the reference range of the converter. The total bias limit can be calculated according to equation (3-2). All partial derivatives correspond to sensitivity coefficients.

$$B_V = \sqrt{\left(\frac{\partial V}{\partial c} B_C\right)^2 + \left(\frac{\partial V}{\partial D} B_D\right)^2 + \left(\frac{\partial V}{\partial \Delta t} B_{\Delta t}\right)^2} \quad (3\text{-}2)$$

Normally, in ITTC 2002 procedure, accuracy of thermometer should be ± 0.3 degrees (ITTC, 2002). However, since the accuracy of thermometer, which has been used in tank, is ±0.5 degrees, so the bias limit associated with the temperature measurement will be B_T=0.5 degrees.

There are three components to the density of uncertainty. The first component is obtained by multiplying the sensitivity coefficient of density function and uncertainty of thermometer (ITTC, 2002).

$$B_{\rho 1} = \frac{\partial \rho}{\partial t} * B_{t^\circ} \quad (3\text{-}3)$$

The second component introduced when converting the temperature to a density can be calculated as two times of Standard Error Estimation (SEE) of the curve fit to the density/temperature ratios for the whole temperature range (ITTC, 2002).

$$B_{\rho 2} = 2 * \mathrm{SEE} \quad (3\text{-}4)$$

The third component consists of the difference between the density value assumed by ITTC and actual density value (ITTC, 2002).

$$B_{\rho 3} = \rho_{ITTC} - \rho_{15^\circ} \quad (3\text{-}5)$$

The total bias for density can then be calculated as in eq. 3-6.

$$B_\rho = \sqrt{B_{\rho 1}^2 + B_{\rho 2}^2 + B_{\rho 3}^2} \quad (3\text{-}6)$$

The calculation of the viscosity uncertainty is similar to the calculation of density uncertainty.

The horizon x-force is to be measured for the model when towed through water (ITTC, 2002). There are five components of the total resistance bias limit. The first is related to tolerance of the calibration weights (B_{R1}). B_{R1} is calculated as the accuracy of the weights, times resistance measured (R) (3-7).

$$B_{R1} = (\text{accuracy of weights}) * R \quad (3\text{-}7)$$

The second bias limit is related to uncertainty due to the curve fit (ITTC, 2002). It can be calculated by two times of SEE (3-8).

$$B_{R2} = 2 * \mathrm{SEE} \quad (3\text{-}8)$$

The third bias limit consists of the load cell misalignment between calibration and test condition (ITTC, 2002). This bias limit is estimated to be ± 0.25 degrees and will affect the measured resistance (3-9).

$$B_{R3} = R - (R * (\cos(0.25))) \quad (3\text{-}9)$$

The forth bias limit consists of the Analog to Digital (AD) conversion. To calculate this uncertainty, the AD converter error (1 bit) is multiplied by AD voltage range (ΔV) divided by AD accuracy. Then this voltage can be translated into Newton by using the slope of calibration line (m) (3-10) (ITTC, 2002).

$$B_{R4} = \left(1.\Delta V / 2^{12}\right) * m_{calibration} \quad (3\text{-}10)$$

The fifth bias limit occurs from the angle (α) between model movement during the test and the measurement system as in the following eq. (ITTC, 2002):

$$B_{R5} = R_X - \left(R_X * cos(\alpha)\right) \quad (3\text{-}11)$$

The total bias limit in resistance is obtained RSS of the five bias components as in following eq. (ITTC, 2002):

$$B_R = \sqrt{(B_{R1})^2 + (B_{R2})^2 + (B_{R3})^2 + (B_{R4})^2 + (B_{R5})^2} \quad (3\text{-}12)$$

Total resistance coefficient (C_T) is a function of resistance of model (R_{TM}), wetted surface area (S_M), velocity (V_M) and density of water in the towing tank (ρ_M) (3-13) (ITTC, 2002).

$$C_{TM} = R_{TM} / (0.5\rho_M V_M^2 S_M) \quad (3\text{-}13)$$

Therefore systematic standard uncertainty could be calculated as RSS of the uncertainty of each independent variable. Systematic standard uncertainty of total resistance coefficient is then calculated as follows eq. (3-14) (ITTC, 2002).

$$B_{C_T} = \sqrt{\left(\frac{\partial C_T}{\partial S} B_S\right)^2 + \left(\frac{\partial C_T}{\partial V} B_V\right)^2 + \left(\frac{\partial C_T}{\partial R} B_R\right)^2 + \left(\frac{\partial C_T}{\partial \rho} B_\rho\right)^2} \quad (3\text{-}14)$$

The precision limit of the total resistance coefficient for M runs is calculated according to

$$P_{C_T} = t * Sdev_{C_T} / \sqrt{M} \quad (3\text{-}15)$$

where M=number of runs, Sdev is the standard deviation, t is the confidence level (usually taken as 2). For the single test, M=1.

The expanded uncertainty of total resistance coefficient is estimated by eq. (3-16) (ITTC, 2002).

$$U_{C_T} = \sqrt{(B_{C_T})^2 + (P_{C_T})^2} \quad (3\text{-}16)$$

Finally, the expanded uncertainty of the mean value of total resistance coefficient with 95% confidence and large degrees of freedom is expressed as (ITTC, 2002):

$$\bar{C}_T \pm U_{C_T,95} \quad (3\text{-}17)$$

3.2. Uncertainty Analysis by ITTC 2014 Method

For the uncertainty analysis, new method has been published a more simplified fashion than the ITTC 2002 and ITTC 2008 method in the last 27th ITTC Conference in Copenhagen (ITTC, 2014). This approach has taken into account by considering the particularly dominant uncertainty sources on results to find the total uncertainty. Also, in this procedure the uncertainty are not separated into two components as systematic and random ones. A general uncertainty term is used. For those reasons, the method is more practical.

In ITTC 2014 Method, uncertainties was examined under a total of 5 main subject. These titles are Model Geometry, Test Setup, Calibration and Data Reduction. Examine sources of uncertainty in the ITTC 2014 method is given below (ITTC, 2014; ITTC, 2014a; ITTC, 2014b).

- Form,
- Dynamometer,
- Water temperature,
- Speed,
- Repeated tests.

The total resistance of a hull model at a specific Froude number is a function of the wetted area of hull and the Reynolds number (ITTC, 2014).

The relative standard uncertainty components (wetted surface area and representative length of hull model) of resistance related to the hull geometry can be estimated approximately by the following equations, respectively (ITTC, 2014):

$$u'_{11}(R_T) = u'(S) \approx \frac{2}{3} u'(\Delta) \quad (3\text{-}18)$$

$$u'_{12}(R_T) = \frac{C_F}{C_T} \frac{0.87}{\log_{10} Re - 2} u'(L) \approx \frac{C_F}{C_T} \frac{0.29}{\log_{10} Re - 2} u'(\Delta) \quad (3\text{-}19)$$

Since the Reynolds number in typical resistance test is on the order of 10^7, u'_{12} is relatively negligible to u'_{11}. The combined standard uncertainty of resistance resulted from hull geometry can be estimated by the eq. (3-20) (ITTC, 2014).

$$u_1'(R) = \sqrt{\left(u'_{11}(R)\right)^2 + \left(u'_{12}(R)\right)^2} \approx {}^2/_3\, u'\,(\Delta) \quad (3\text{-}20)$$

The uncertainty component of resistance resulted from calibration of dynamometer is estimated by standard error estimation (SEE) (ITTC, 2014).

$$u_2\,(R_T) \equiv u\,(R_T) \equiv SEE \quad (3\text{-}21)$$

The deviation of water temperature has a minor effect on water density. Therefore, uncertainty of water density is negligible. On the other hand, water viscosity is affected substantially with the deviation of water temperature. The relative uncertainty of water viscosity resulted from temperature can be estimated by eq. (3-22) (ITTC, 2014).

$$u'_3\,(R_T) = \frac{C_F}{C_T}\frac{0.87}{\log_{10} Re - 2}u'\,(\gamma) \quad (3\text{-}22)$$

The uncertainty of carrier speed propagates into the resistance measurement as both dynamic pressure and Reynolds number (ITTC, 2014). These uncertainties are obtained as quantitatively by the following equations, respectively:

$$u'_{41}(R_T) = 2u'\,(V) \quad (3\text{-}23)$$

$$u'_{42}(R_T) = \frac{C_F}{C_T}\frac{0.87}{\log_{10} Re - 2}\frac{\delta V}{V}u'\,(V) \quad (3\text{-}24)$$

u'_{42} is usually much less then u'_{41}. Therefore it is negligible (ITTC, 2014). Then, the combined standard uncertainty of resistance resulted from towing speed can be estimated by eq. (3-25) (ITTC, 2014).

$$u_4'(R_T) = \sqrt{\left(u'_{41}(R_T)\right)^2 + \left(u'_{42}(R_T)\right)^2} \approx 2u'\,(V) \quad (3\text{-}25)$$

The standard uncertainty component from single test and repeat tests can be estimated by the following equations, respectively:

$$u'_A(R_T) = \frac{Sdev}{\hat{R}_T} \quad (3\text{-}26)$$

$$u'_A(R_T) = \frac{Sdev/R_T}{\sqrt{N}} \quad (3\text{-}27)$$

Analysis of all significant uncertainty components related to the total resistance are combined to obtain the overall standard uncertainty by RSS method (ITTC, 2014).

$$u_C'(R_T) = \sqrt{(u_1')^2 + (u_2')^2 + (u_3')^2 + (u_4')^2 + (u_A')^2} \quad (3\text{-}28)$$

The expanded standard uncertainty of the resistance with confidence level (t) is estimated by eq. (3-26) (ASME, 2005; ITTC, 2014).

$$U_{R,\%t} = t.u_R \quad (3\text{-}29)$$

The Student's t value at a specified confidence coefficient is set by the user (usually taken as 2 for 95% confidence) (ASME, 2005). Finally, the expanded uncertainty for 95% confidence and large degrees of freedom is expressed as:

$$\bar{R} \pm U_{R,95} \quad (3\text{-}30)$$

4. Experimental Results and Uncertainty Analysis

4.1. Displacement Ship (KCS Hull)

Kriso Container Ship (KCS), designed by Korea Research Institute of Ships and Ocean Engineering, has been selected with the scale ratio 60.75 (URL-1, 2015). The main parameters of KCS, in the model scale, are shown in Table 1. Model views are shown Figure 1. KCS model is named "ITU M392" in laboratory records.

Uncertainties are estimated on low, middle and high Froude Numbers of KCS. Froude numbers are 0.16, 0.21, and 0.26 and then the corresponding model velocities are 0.975 m/s, 1.279 m/s and 1.584 m/s, respectively. Tests have been repeated 12 times in July 2014.

Table 1. The main parameters of KCS hull model.

Model characteristics		Value
Scale	λ	60.75
Length between perpendiculars	L_{BP}	3.786 (m)
Length on waterline	L_{WL}	3.826 (m)
Breadth	B	0.53 (m)
Draft	T	0.178 (m)
Wetted surface area (including rudder)	S	2.585 (m^2)
Waterline area	A_{WP}	1.667 (m^2)
Displacement volume	∇	0.232 (m^3)
Block coefficient	C_B	0.643
Waterline area coefficient	C_{WP}	0.822
Wetted area coefficient	C_S	2.758
Service speed	V_M	1.584 (m/s)

Figure 1. The general views of KCS hull model.

4.1.1. Uncertainty Analysis (ITTC 2002) of Resistance Tests for KCS Hull Model

The average resistance values and its standard deviation (S_{dev}) are given in Table 2. The combined standard uncertainty value is estimated on Table 3. The expanded standard uncertainty value is estimated within confidence level (95 %) on Table 4.

Table 2. Total resistance coefficient of KCS hull model.

KCS (15 °C)	Fr=0.16	Fr=0.21	Fr=0.26
C_T	4.27E-03	4.05E-03	4.43E-03
Standard deviation	2.20E-04	1.41E-04	8.38E-05

Table 3. Bias uncertainty sources.

	Fr=0.16			Fr=0.21			Fr=0.26		
	Value	% of Value		Value	% of Value		Value	% of Value	
L (m)	3.786			3.786			3.786		
B_L (m)	0.002	0.05	% of L_{PP}	0.002	0.05	% of L_{PP}	0.002	0.05	% of L_{PP}
S (m^2)	2.585			2.585			2.585		
B_S (m^2)	3.69E-03	0.14	% of S	3.69E-03	0.14	% of S	3.69E-03	0.14	% of S
V (m/s)	0.975			1.279			1.584		
B_V (m/s)	3.57E-03	0.37	% of V	3.57E-03	0.28	% of V	3.57E-03	0.23	% of V
R_T (N)	5.9			8.29			13.9		
B_R (N)	0.12	2.42	% of R	0.12	1.48	% of R	0.12	0.88	% of R
ρ (kg/m^3)	996.905			996.905			996.905		
T (ºC)	22.5			22.5			22.5		
B_T (ºC)	0.5	2.22	% of T	0.5	2.22	% of T	0.5	2.22	% of T
B_ρ (kg/m^3)	0.12	0.01	% of ρ	0.12	0.01	% of ρ	0.12	0.01	% of ρ
γ (m/s^2)	9.46E-07			9.46E-07			9.46E-07		
B_γ ($m/s^{2)}$	1.07E-08	1.13	% of γ	1.07E-08	1.13	% of γ	1.07E-08	1.13	% of γ
C_T	4.14E-03			3.93E-03			4.30E-03		
B_{CT}	**1.05E-04**	**2.52**	**% of C_T**	**6.24E-05**	**1.59**	**% of C_T**	**4.31E-05**	**1.00**	**% of C_T**

Table 4. The expanded standard uncertainty.

	Fr=0.16		Fr=0.21		Fr=0.26	
	Value	% of C_T	Value	% of C_T	Value	% of C_T
C_T	4.27E-03		4.05E-03		4.43E-03	
B_{CT}	1.05E-04	2.45	6.24E-05	1.54	4.31E-05	0.97
P_{CT} (S)	4.41E-04	10.32	2.82E-04	6.96	1.68E-04	3.78
P_{CT} (M)	1.27E-04	2.98	8.14E-05	2.01	4.84E-05	1.09
U_{CT} (S)	4.53E-04	10.61	2.89E-04	7.13	1.73E-04	3.90
U_{CT} (M)	**1.65E-04**	**3.86**	**1.03E-04**	**2.53**	**6.47E-05**	**1.46**

Index S and M in the Table 7 represent that the experiment has been carried out single test and multiple tests, respectively.

According to the Table 2, sensitivity of thermometer (B_T) has minor effect on density (ρ). On the other hand it is quite dominant on the viscosity (γ). Therefore,

viscosity uncertainty (B_γ) is calculated to be higher than density uncertainty. Viscosity uncertainty will be particularly dominant in calculating the frictional coefficient (C_F).
Resistance uncertainty is higher than expected one. The most important reason for this is the calculation of the AD conversion uncertainty (B_{R4}).Square of it constitutes approximately 85% square of the total bias resistance uncertainty (B_R). Another significant uncertainty is caused by calibration of the dynamometer (B_{R2}). Square of it constitutes 14.62% square of the total bias resistance uncertainty (B_R). B_{R1} and B_{R3} components of resistance uncertainty are negligible level compared with other components of resistance uncertainty. Uncertainty of B_{R1} and B_{R3} is constant over whole tests. Although the absolute values of these uncertainties are the same for three Froude numbers, the relative values are different each other. Therefore they are effective in different rates on the resistance values.
The precision limit value is related to the number of experiments. If multiple experiments carried out, the random standard uncertainty value will reduce (ASME, 2005). However, the bias standard uncertainties are assumed constant throughout the experimental set (ASME, 2005).
Uncertainties are quite dominant at low velocities or Froude numbers. Because of the measurement system and environmental conditions etc., at low Froude number (or velocities), the expanded uncertainty is relatively higher than that of upper Froude numbers. Therefore the error range in the tests is higher at low Froude numbers. A significant portion of the expanded uncertainty constitute the precision limit. Therefore, the measuring system can be mentioned to be less suitable for low Froude numbers. The expanded standard uncertainty value could be reduced by revising bias uncertainty components from large values to small values.
The total resistance coefficient of KCS and the error bars (according to ITTC 2002) are given in Figure 2.

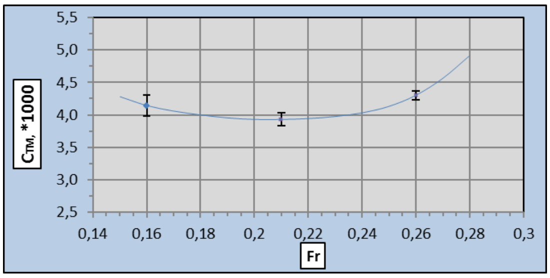

Figure 2. The total resistance coefficient of KCS and the error bars (ITTC 2002).

4.1.2. Uncertainty Analysis (ITTC 2014) of Resistance Tests for KCS Hull Model

The average resistance values and its standard deviation (Sdev) are given in Table 5. The combined standard uncertainty value is estimated on Table 6. The expanded standard uncertainty value is estimated within confidence level (95%) on Table 7.
The predominant sources of uncertainty were investigated in ITTC 2014 method. In this procedure, if the dominant component (U_o) is greater 3 times than the lower component (U_1), lower component is negligible (4-1) (ITTC, 2014).

$$U_1 < {}^1/_3\, U_0 \qquad (4\text{-}1)$$

Table 5. Resistance value of KCS hull model.

KCS (22.5 °C)	Fr=0.16	Fr=0.21	Fr=0.26
R_{mean} (N)	5.073	8.286	13.904
Sdev (% of R_{mean})	5.16 %	3.48 %	1.89 %

Table 6. The combined standard uncertainty.

Uncertainty components	Fr=0.16		Fr=0.21		Fr=0.26	
	% of Value	Remark	% of Value	Remark	% of Value	Remark
Form	0.009%	Negligible	0.009%	Negligible	0.009%	Negligible
Speed	0.067%	Negligible	0.067%	Negligible	0.067%	Negligible
Water Temp.	0.081%	Negligible	0.079%	Negligible	0.068%	Negligible
Dynamometer	0.462%	Minor	0.283%	Minor	0.169%	Minor
Sdev (S)	5.16%	Dominant	3.48%	Dominant	1.89%	Dominant
u' (S)	5.18%		3.49%		1.90%	
Sdev (M)	1.49%		1.00%		0.55%	
u' (M)	**1.56%**		**1.05%**		**0.57%**	**0.57%**

Table 7. The expanded standard uncertainty.

KCS	U' (t=2)	T=22.5 °C		T=15 °C	
Fr		R	C_T	R	C_T
0.16	3.13%	5.073 ±3.13%	4.14E-03±3.13%	5.234±3.13%	4.27E-03±3.13%
0.21	2.10%	8.286±2.10%	3.93E-03±2.10%	8.551±2.10%	4.05E-03±2.10%
0.26	1.16%	13.904±1.16%	4.30E-03±1.16%	14.347±1.16%	4.43E-03±1.16%

The results analyzed by ITTC 2014 similarly, are seemed to cause a decrease in the total uncertainty. The uncertainties in the form, speed and water temperature are negligible since they are not a significant effect on the results. The uncertainty value from the dynamometer was included in the calculations despite it has a minor effect. The largest contribution to the uncertainty is coming from standard deviation of resistance. So in repeated tests, the test conditions must be kept constant and an appropriate measurement system must be used in order to get lower the standard deviation value.

The total resistance coefficient of KCS and the error bars (according to ITTC 2014) are given in Figure 3.

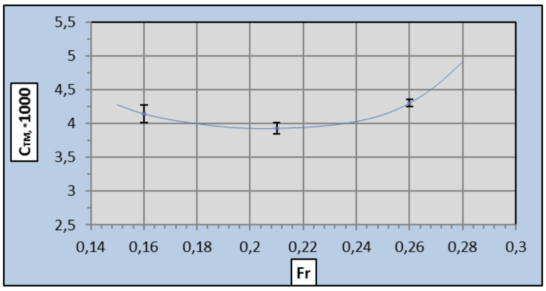

Figure 3. The total resistance coefficient of KCS and the error bars (ITTC 2014).

4.2. High Speed Marine Vehicle Hull Model

HSMV model has been previously used for some model tests in Ata Nutku Ship Model Testing Laboratory. The main parameters of HSMV model in the model scale are shown in Table 8. The general views of model are shown Figure 4.

Uncertainties are estimated for the peak resistance and planning hull regime (design draft) Froude number. So, they are 0.50 and 0.90, and the corresponding model velocities are 2.19 m/s and 3.94 m/s, respectively. Tests have been repeated five times in November 2014.

Table 8. The main parameters of HSMV model.

Model characteristics		Value
Scale	λ	8.5
Length between perpendiculars	L_{BP}	1.958 (m)
Length on waterline	L_{WL}	1.958 (m)
Wetted length	L_{WS}	1.958 (m)
Breadth	B	0.588 (m)
Draft	T	0.108 (m)
Wetted surface area	S	0.975 (m^2)
Displacement volume	∇	0.052 (m^3)
Block coefficient	C_B	0.447
Waterline area coefficient	C_{WP}	0.77
Service speed	V_M	3.94 (m/s)

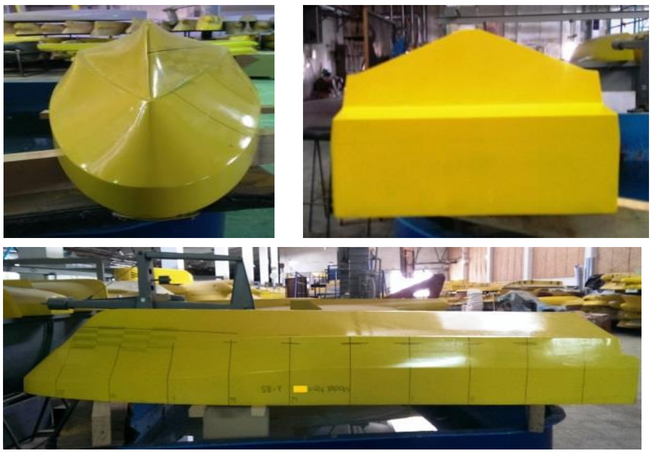

Figure 4. The different views of HMSV model.

4.2.1. Uncertainty Analysis (ITTC 2002) of Resistance Tests for HSMV Model

The mean resistance and its standard deviation values are given in Table 9. The systematic (bias) and expanded standard uncertainty values are given in Table 10-11, respectively.

Table 9. Resistance value of HMSV hull model.

HSMV (15	Fr=0.50	Fr=0.90
R_{mean} (N)	48.57	77.10
Sdev (N)	0.725	0.364

Table 10. Bias uncertainty sources.

	Fr=0.50			Fr=0.90		
	Value	% of Value		Value	% Value	
L (m)	1,958			1,958		
B_L (m)	0,002	0,10	% of L	0,002	0,10	% of L
S (m^2)	0,975			0,975		
B_S (m^2)	1,92E-02	1,97	% of S	1,92E-02	1,97	% of S
V (m/s)	2,19			3,94		
B_V (m/s)	3,57E-03	0,16	% of V	3,57E-03	0,09	% of V
R_T (N)	48,33			76,63		
B_R (N)	0,12	0,25	% of R	0,12	0,16	% of R
ρ (kg/m^3)	998,032			998,032		
T (ºC)	17			17		
B_T (ºC)	0,5	2,94	% of T	0,5	2,94	% of T
$B_ρ$(kg/m^3)	0,09	0,01	% of ρ	0,09	0,01	% of ρ
γ (m/s^2)	1,08E-06			1,08E-06		
$B_γ$ (m/s^2)	1,39E-08	1,28	% of γ	1,39E-08	1,28	% of γ
C_T	2,08E-02			1,02E-02		
B_{CT}	**4,17E-04**	**2,01**	**% of C_T**	**2,13E-04**	**2,10**	**% of C_T**

Table 11. The expanded standard uncertainty.

	Fr=0.50		Fr=0.90	
	Value	% C_T	Value	% C_T
C_T	2.08E-02		1.02E-02	
B_{CT}	4.17E-04	2.01	2.13E-04	2.09
P_{CT} (S)	6.21E-04	2.99	9.61E-05	0.94
P_{CT} (M)	2.78E-04	1.33	4.30E-05	0.42
U_{CT} (S)	7.48E-04	3.60	0.02%	2.30
U_{CT} (M)	**5.01E-04**	**2.41**	**0.02%**	**2.14**

Since there are assumptions as absolute value in the ITTC 2002 procedure, inconsistent and dominant uncertainty values are estimated on especially uncertainty of wetted surface area. Then B_S could create directly a dominant uncertainty on C_T.

Because the thermometer sensitivity is low, uncertainties associated with the temperature (density and viscosity etc.) are higher.

According to the precision limit value, the effects of uncertainties are thoroughly reduced in high speeds. The measuring system is more suitable for these velocities. The total resistance coefficient of KCS and the error bars (according to ITTC 2002) are given in Figure 5.

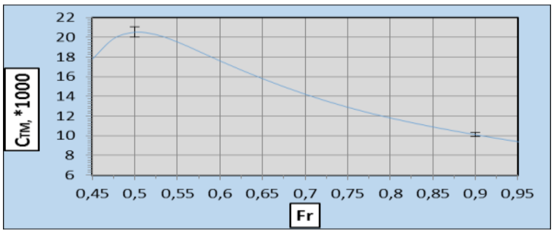

Figure 5. The total resistance coefficient of HSMV and the error bars (ITTC 2002).

4.2.2. Uncertainty Analysis (ITTC 2014) of Resistance Tests for HSMV Model

For the average resistance values, the standard deviation (S_{dev}) is given in Table 12. The combined standard uncertainty value is estimated on Table 13. The expanded standard uncertainty value is estimated within confidence level (95%) on Table 14.

The total resistance coefficient of KCS and the error bars (according to ITTC 2014) are given in Figure 6.

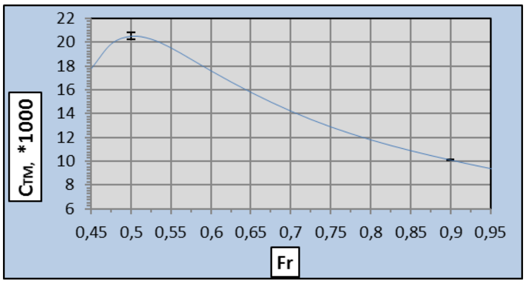

Figure 6. The total resistance coefficient of KCS and the error bars (ITTC 2014).

Table 12. Resistance value of HMSV hull model.

HMSV (15 °C)	Fr=0.50	Fr=0.90
R_{mean} (N)	48.33	76.63
Sdev (% of R_{mean})	1.49 %	0.47 %

Table 13. The combined standard uncertainty.

	Fr:0.50		Fr:0.90	
	% Value	Remark	% Value	Remark
Form	0.039%	Negligible	0.039%	Negligible
Speed	0.067%	Negligible	0.067%	Negligible
Water temperature	0.018%	Negligible	0.032%	Negligible
Dynamometer	0.048%	Negligible	0.031%	Negligible
Sdev (S)	1.49%	Dominant	0.47%	Dominant
u’ (S)	1.49%		0.47%	
Sdev (M)	0.67%		0.21%	
u’ (M)	**0.67%**		**0.21%**	

Table 14. The expanded standard uncertainty.

Fr	U' (t=2)	T=17 °C		T=15 °C	
		R	C_T	R	C_T
0.50	1.33%	48.33 ± 1.33%	0.02076 ± 1.33%	48.57 ± 1.33%	0.02079 ± 1.33%
0.90	0.42%	76.63 ± 0.42%	0.01016 ± 0.42%	77.11 ± 0.42%	0.01019 ± 0.42%

4.3. Results of Uncertainty Analysis

For multiple tests of KCS hull, ITTC 2002 method gives higher uncertainty values than those of ITTC 2014 method. Based on the results of both methods, the systematic uncertainty components from larger values to smaller values are resistance, speed, wetted surface area and temperature, respectively.

As expected, Froude number increased while uncertainties lost their impact on the results. Due to this effect, error or uncertainty range of results is decreased.

The uncertainty values of KCS hull model on C_T are given below for both methods.

Because uncertainty is predominant at low speeds, the uncertainty of KCS range at low speeds is found to be higher. So the measurement system should be revised starting from the dominant uncertainties to minor uncertainties.

Table 15. Expanded uncertainties of KCS.

Fr	ITTC 2002	ITTC 2014
0.16	3.86 %	3.13 %
0.21	2.53 %	2.10 %
0.26	1.46 %	1.16 %

For multiple tests of HSMV, since the difference between results of both methods is quite high, the uncertainty ranges are inconsistent with each other. In small models, the uncertainty of wetted surface area is estimated as high by ITTC 2002 because of absolute assumptions. Especially for small models, if the assumptions are taken as absolute, there will be a dominant uncertainty over the wetted area. On the other hand, according to ITTC 2014, uncertainty of wetted surface has a negligible level because the relative assumptions are applied in the calculations. Consequently, ITTC 2002 procedure should not be used for calculating the uncertainty of the wetted surface area in small models.

The uncertainty values of HSMV on C_T are given below for both methods.

Table 16. Expanded uncertainties of HSMV.

Fr	ITTC 2002	ITTC 2014
0.50	2.41%	1.33%
0.90	2.14%	0.42%

The main reason for the difference between ITTC 2002 and 2014 methods, different approaches applied to the estimated value of uncertainty.

Analog to Digital (AD) conversion bias uncertainty has large effects on the results in the method of ITTC 2002. This is closely related to the characteristics of AD converter and dynamometer. To calculate this uncertainty, the AD converter error is multiplied by the slope of calibration line. But if the operating voltage range of measurement device is low, the slope of calibration line can be higher. This will cause an increase in uncertainty. For instance, in ITTC 2002 procedure, the slope of dynamometer calibration line (voltage range is between -10V and +10 V) is obtained as 12.562 (ITTC, 2002a).

However, the slope of dynamometer calibration line (voltage range is between -2V and +2V in the present test), is obtained as 115. 983.
Therefore, the error value is higher in this study. In ITTC 2014 however it is not considered this type of calculation of conversion bias uncertainty.
Another difference is related to the assumptions (ITTC, 2002; ITTC, 2014; ITTC, 2014; ITTC, 2014a). The assumptions process is taken as the absolute value in ITTC 2002 method, which is taken relative in ITTC 2014 method (ITTC, 2002a; ITTC, 2008).
A further difference between the two methods is used in the calculation of confidence level (t). In ITTC 2002, the bias uncertainties were considered to affect measurements in a certain direction. Therefore, the uncertainty is considered no effect on repeated experiments. So the confidence level is only multiplied by the precision limit value. On the other hand, in ITTC 2014 method, the bias uncertainty is considered to be affected by environmental conditions etc., so the combined standard uncertainty value is obtained after that it multiplied by the confidence level (t).
In 2002, the uncertainty analysis of resistance experiments was performed in Ata Nutku Ship Model Testing Laboratory (Goren ve Danisman, 2002). The Manuel Atwood measurement system was used in this study. The precision limit (random uncertainty) was only examined. Precision limit was calculated to 0.49 % of the total resistance coefficient for Fr=0.277 and VM=1.265 m/s. The precision limit of KCS was calculated as 1.09 % of the total resistance coefficient on Fr=0.26. The major reason for this difference is due to different measurement systems. R35 electronic dynamometer has less accuracy low velocities, especially below 2 m/s. Therefore, R35 dynamometer generally preferred in high speed marine vehicles due to precise and reliable results for the velocities above 2 m/s. Since Atwood dynamometer is controlled manually, it is difficult to satisfy their uncertainties. So it has not been used in this study.
The residual resistance coefficients have been compared with those of “The Force Technology” and “The National Maritime Research Institute (NMRI)” experiments values and the differences have been found to be 0.38 % and 6.6 %, respectively (Delen, 2015; Simonsen ve ark., 2013; Hino, 2005; Bugalski & Hoffman, 2011). The residual resistance coefficients are shown in the Table 17. Even though the scale ratios and Reynolds numbers are different each other, the residual resistance coefficients are close to each other satisfactorily, especially with the results of Force Technology.
Wave profiles on hull are shown on Figures 7-10.

Table 17. The comparison of different laboratory results.

KCS	ITU (Re=6.3E+06)	FORCE (Re=6.52E+06)	NMRI (Re=1.4E+07)
Scale (λ)	60,75	52,667	31,60
C_R	1,060E-03	1,064E-03	1,130E-03
Difference (% of ITU’s C_R)		0,38%	6,60%

Figure 7. Wave profile on hull (Fr=0.16).

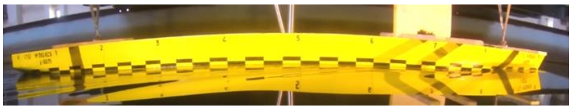

Figure 8. Wave profile on hull (Fr=0.21).

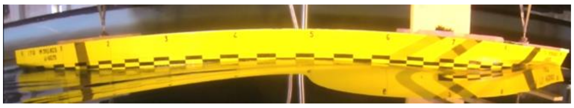

Figure 9. Wave profile on hull (Fr=0.26).

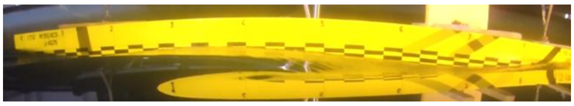

Figure 10. Wave profile on hull (Fr=0.31).

5. Conclusions and Recommendations

The uncertainty (or errors) occurring during the measurements must be determined accurately and reliably as quantitatively. There are many ways to estimate the uncertainty of a test system. Two of them are ITTC 2002 and ITTC 2014. The main purpose is to reach the most accurate results in uncertainty analysis by combining current academic knowledge and engineering review. These are just two different approaches to the estimation uncertainty on result. Therefore, they do not contradict with each other.

ITTC 2002 method is used to estimate the impact of the great number of examinable uncertainty sources on the results. However, the revised method in 2014 investigates the dominant components that are important on the results. Thus, the applicability of the ITTC 2014 method has been increased.

In this study, uncertainty of resistance test was investigated for a displacement type of ship and a high speed marine vehicle by two different methods. The uncertainty values are not the same for similar ship types and ship models in different model scales. So uncertainty analysis should be applied for each ship model. The results presented here give only an idea about uncertainty for similar ship models and the experiments conducted in this laboratory. Otherwise the measuring systems are used in the laboratories can be different from each other since uncertainty sources of each laboratory will be different than each other. For this reason, the comparison of the uncertainty value is not a very convenient way and the generalization of uncertainty values is not very possible at now (Delen ve Bal, 2015).

Finally, the uncertainty of ship resistance has been studied through the KCS hull model and HSMV hull model. For KCS hull model uncertainty values are suitable according to two methods. For HSMV model, uncertainty results of ITTC 2014 are much satisfactory. However, uncertainty value should be reduced by improvements in the test system and towing tank conditions. It should also be noted that uncertainty cannot be reset since uncertainty itself is uncertain. So each test system has already uncertainties.

Based on results, some recommendations on the test system can also be summarized as:

- Towing carriage and tank features should be developed for high tonnage displacement ship and high speed marine vehicles.
- The sensitivity of the thermometer, used in tank, should be increased. Multiple thermometers should be situated towing tank.

• Manual inclinometer should be replaced with digital inclinometer.
• Mechanical components of towing carriage and their rails should be repaired regularly.
• Tachometer should be controlled with the same data acquisition system as used in resistance test.
• A new computer controlled measurement system should be designed for low speeds.
Finally, it is advisable to compare these test results with CFD applications or mathematical methods.

5. Acknowledgements

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