Journal of the Korean Society of Marine Environment & Safety
Vol. 26, No. 3, pp. 269-276, May 31, 2020, ISSN 1229-3431(Print) / ISSN 2287-3341(Online)

Research Paper
https://doi.org/10.7837/kosomes.2020.26.3.269

The Effect of Uncertainty in Sea Trial Measurement System on Speed-Power Performance

Dae-Won Seo* · Jackyou Noh**†

*, ** Professor, Department of Naval Architecture and Ocean Engineering, Kunsan National University, Gunsan 54150, Korea

Abstract : *Sea trial tests are necessary to verify speed-power performance, and are an import contract between ship owners and shipyards. The International Organization for Standardization (ISO) published ISO 15016:2015, which specifies the correlation method between model and full-scale ships. The results of sea trials have been questioned because of the uncertainty of speed and power measurements, especially when sea conditions differ from ideal calm water conditions. In this paper, such uncertainties were investigated by utilizing the standard speed-power trial analysis procedure defined in ISO 15016:2015 through Monte Carlo simulations. It was found that the expanded uncertainty of the delivered power (P_{Did}) at 95 % confidence interval (k = 2) was ±1.5 % under 75 % MCR conditions.*

Key Words : *Monte Carlo simulation, Uncertainty, Sea trials, Speed-power performance, Delivered power*

1. Introduction

The International Maritime Organization recently began enforcing the following as regulations to prevent marine pollution: the Energy Efficiency Design Index, an evaluation index in the design stage, and the Energy Efficiency Operational Indicator and Ship Energy Efficiency Management Plan, which are evaluation indices for operation. With the increasing importance of the speed-power performance of ships during sea trials for organizations, ship owners, and shipyards, the ISO established a standard method to analyze speed-power trials (ISO 15016, 2015).

Speed-power trials require a process for correcting the external force of actual sea conditions by replacing the ship's speed-power measured in actual seas with that obtained in calm waters. ISO 15016:2015 provides guidelines for this process for sea trial data analysis. Therefore, the uncertainty of speed-power corrected from actual sea conditions to that of calm waters may differ significantly depending on the reliability of measurements in actual sea conditions (Insel, 2008).

Ship speed-power trials require a significant number of measurements, the accuracy of which determines the uncertainty of speed-power performance. Although reducing measuring equipment errors and conducting trials under ideal conditions (calm waters) are recommended to minimize the uncertainty of speed-power performance, it is almost impossible to conduct trials under ideal conditions. Therefore, the results of every sea trial include uncertainties from both measuring equipment and environmental conditions.

The International Towing Tank Conference (ITTC) provides guidelines for uncertainty analysis in various hydrodynamic tests in laboratories, such as resistance tests and propeller-only performance tests (ITTC, 2002; 2005). However, there is no standard procedure for analyzing the uncertainty of speed-power trials at sea. Because of the absence of raw data from trials for uncertainty analysis, there is a lack of related studies.

This study examines the influence of measuring equipment uncertainty on the essential elements (wind, wave, water temperature) required for speed-power trial analysis. The speed-power uncertainty analysis was performed by considering only Type-B uncertainty owing to difficulties in obtaining Type-A uncertainty through repeated testing.

2. Uncertainty Analysis

This study performed a sea trial uncertainty analysis based on ISO JCGM (2008a). According to this procedure, the evaluation method includes Type-A and Type-B uncertainties, as listed in Table 1. The total uncertainty is the sum of the two uncertainties, as shown in Eq. (1).

$$u(y) = \sqrt{\sum_{i=1}^{N} u_i^2(\bar{q}) + \sum_{i=1}^{N} u_j^2} \tag{1}$$

---

* First Author : dwseo@kunsan.ac.kr, 063-469-1858
† Corresponding Author : snucurl@kunsan.ac.kr, 063-469-1855

where N is the number of variables, and u_i and u_j are the Type-A and Type-B uncertainties, respectively.

Type-A uncertainty refers to uncertainty components resulting from the randomness of the experimental process, and is evaluated by repeated measurements, Type-B uncertainty is defined as the uncertainty of all components except Type-A uncertainty. Typical elements of Type-B uncertainty include previous measurements, experience, general knowledge, and equipment specifications.

Table 1. Type A and B standard uncertainty

	Type-A	Type-B
Expression	$u_i^2(\overline{q})$	u_j^2
Measurement	Repeated observation	Previous data, Manufacturer's spec., Certificates

When the input or test value is a function of different variables, it is defined as combined uncertainty. The combined uncertainty is expressed as $u_c(y)$ in Eq. (2).

$$u_c(y) = \sqrt{\sum_{i=1}^{N}\left(\frac{\partial f}{\partial x_i}\right)^2 u^2(x_i) + 2\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\frac{\partial f}{\partial x_i}\frac{\partial f}{\partial x_j}u(x_i,x_j)} \tag{2}$$

where $\frac{\partial f}{\partial x_i}$ is the sensitivity coefficient of x_i.

The expanded uncertainty used to indicate the confidence interval of the experimental value is defined as Eq. (3).

$$U = ku_c(y) \tag{3}$$

ISO JCGM (2008a) requires the provision of expanded uncertainty as the final result of uncertainty analysis as well as the k-value used in the process.

Monte Carlo simulations are used to predict results through repeated sampling based on the concept that increasing the number of samples provides more accurate results (ISO JCGM, 2008b). Increased computing power has systematized the Monte Carlo method, which is now used in various modeling methods to simulate actual situations (Kim, 2011). The implementation of the Monte Carlo process consists of four main steps (Fig. 1).

(1) Define the mathematical model
(2) Assign a probability distribution function to each input variable
(3) Calculate the output variable by entering the input variable in the model
(4) Analyze the results

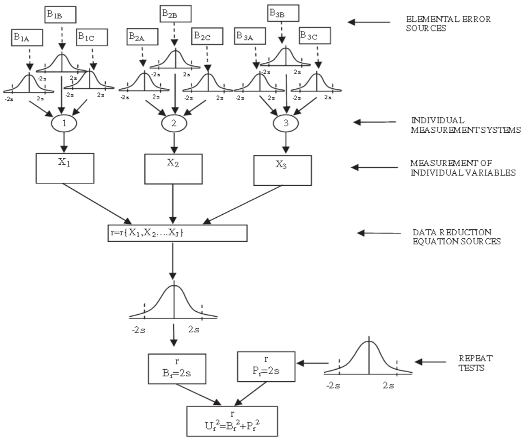

Fig. 1. Uncertainty assessment methodology by Monte Carlo method (Coleman and Steele, 2009).

The Monte Carlo simulation complies with the ISO JCGM (2008b) framework and propagates uncertainty using the system's mathematical model instead of the Law of Propagation of Uncertainty. This method can make reliable predictions regardless of the model's linearity, and investigate the effects of the uncertainty of each input variable on the measurement results. It also obtains the most reasonable results from test data in a short period of time.

This study applied the Monte Carlo method and repeated 200,000 calculations using Crystal Ball software to estimate the uncertainty of the correction for the sea trial analysis procedure. Type-B uncertainty was considered by assuming the probability distribution of the input data as normal and uniform distributions, while Type-A uncertainty was not considered owing to the lack of raw data and repeated test data.

3. Speed-Power Uncertainty

3.1 Sea trial results

A 300K DWT very large crude carrier (VLCC) was used for the trial, and round-trip tests were conducted under three conditions.

Table 2. Measured data on speed-power performance and sea condition

Test condition		Wind		Wave			Ship		
MCR	run	Speed (*m/s*)	Direction (*deg*)	Height (*m*)	Period (*s*)	Direction (*deg*)	Vs (*knots*)	Shaft speed (*rpm*)	Power (*kW*)
50 %	1st -run	5.4	P30	1	3.5	30	13.835	53.9	11,581
	2nd -run	12.2	S 6	1	3.5	150	12.918	53.9	11,832
75 %	1st -run	3.3	P75	1.5	3.5	30	15.018	61.8	17,360
	2nd -run	17.1	S17	1.7	3.5	150	14.558	61.8	17,061
90 %	1st -run	3.1	P40	1.5	3.5	30	16.507	67.9	22,844
	2nd -run	18.2	S11	1.5	3.5	150	16.702	67.9	23,150

Table 2 lists the wind direction, wind speed, wave height, wave period, wave direction, speed, shaft speed, and power measured during the trial.

The wind speed measured under all conditions was 3.1 ~ 18.2 m/s. The wave height was 1 ~ 1.7 m, reflecting calm sea conditions during the trial. The ship was a 300K VLCC (LBP: 322 m, B: 60 m, T: 20.5 m). The measured data are the test results of 50 %, 75 %, and 90 % Maximum Continuous Rating (MCR). The data are the average values for each round trip test including the speed, ship direction, measured power, propeller rotation speed, relative wind speed, wind direction, wave, air temperature, and water temperature. As the specifications of each measuring equipment were not provided, they could be estimated through assumptions such as other research papers.

3.2 Speed-power uncertainty factor

The purpose of this study is to examine the influence of measuring equipment on the reliability of trial analysis results, and the factors related to the measuring equipment were examined through various assumptions.

As shown in Fig. 2, the uncertainties that can occur during sea trials are divided into factors related to shaft power measurements and trial analysis. The shaft power is obtained by measuring the torque using a strain gauge installed on the propeller shaft, and then measuring the rotational speed of the shaft using optical sensors. The measured shaft horsepower is also corrected by calculating various added resistances according to the ISO 15016 (2015) trial analysis method to correct the effects of disturbance. Therefore, the uncertainty of each element affects the final speed-power performance.

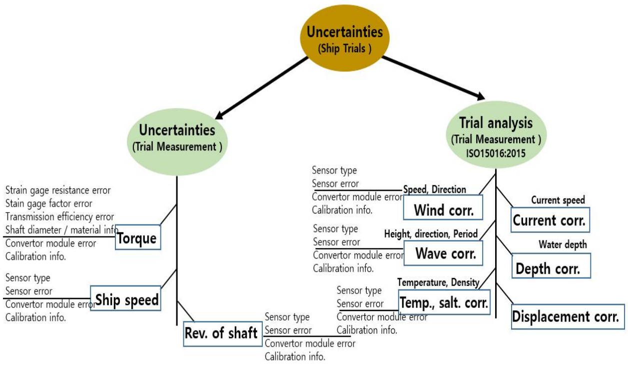

Fig. 2. Uncertainty sources in sea trial.

4. Shaft Power Uncertainty

The uncertainties that may occur while measuring shaft power are divided into Type-A and Type-B. Although there are various instruments for measuring shaft power, existing systems frequently use strain gauges to measure the torque, which is converted into power with respect to the relationship with the shaft speed. This study used the Kyma Shaft Power Meter (KPM). The accuracy of the equipment yields useful data when evaluating Type-B uncertainty.

The Type-B uncertainty ($u_c(Q_{ms})$) factors of the shaft power include the uncertainty of the strain gauge ($u(gauge)$), the calibration uncertainty ($u(\varepsilon)$), the uncertainty that occurs when installing sensors ($u(\alpha)$), and torque calculation uncertainty ($u(Q)$). Each of these can be subdivided as shown in Fig. 3, and the Type-B uncertainty ($u_c(Q_{ms})$) is calculated using Eq. (4).

$$u_c(Q_{ms}) = \sqrt{u^2(gague) + u^2(\epsilon) + u^2(\alpha) + u^2(Q)} \tag{4}$$

As a result of examining the specifications of the KPM shaft power measurement system, the total uncertainty including uncertainties that can occur when installing and calibrating the gauge and sensor is 0.29 %. After adding the combined uncertainty (1.2 %) from calculating the shaft torque (shear modulus standard uncertainty, shaft diameter standard uncertainty, relative displacement standard uncertainty), the total combined uncertainty of the shaft power measurement system $u_c(Q_{ms})$ becomes 1.24 %, as shown in Table 3.

Table 3. Uncertainty of the shaft power measurement system

$u_c(Q_{ms})$: 1.24	$u_c(Q)$: 1.211	$u_c(\varepsilon)$: 0.370
		$u(D)$: 0.029
		$u(G)$: 1.15
	$u_c(gauge)+u_c(\varepsilon)$ $+u_c(\varepsilon)$: 0.29	

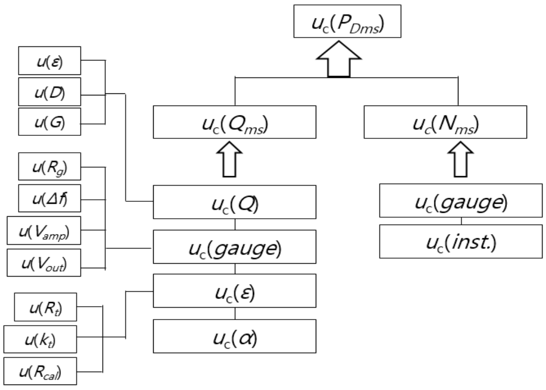

Fig. 3. Uncertainty sources in the measurement of shaft power (Seo et al., 2019).

$u_c(P_{Dms})$: Uncertainty of the power measurement system
$u_c(Q_{ms})$: Combined uncertainty of the total torque
$u_c(N_{ms})$: Combined uncertainty of the total shaft speed
$u_c(Q)$: Uncertainty due to recalculation of the torque
u_c(gauge) : Uncertainty due to the gauge of shaft speed
u_c(inst.) : Uncertainty due to installation on a shaft
$u_c(\alpha)$: Uncertainty due to strain gauge installation
$u(\varepsilon)$: Standard uncertainty of the relative strain of the gauge
$u(D)$: Standard uncertainty of the diameter
$u(G)$: Standard uncertainty of the shear module
$u(R_g)$:Standard uncertainty of the strain gauge bridge
$u(\Delta f)$: Standard uncertainty of the transmitter and receiver
$u(V_{amp})$: Standard uncertainty of the amplifier plug-in module
$u(V_{out})$: Standard uncertainty of the digital voltage meter
$u(R_t)$: Standard uncertainty of the strain gauge effective resistance
$u(k_t)$: Standard uncertainty of the gauge factor at 75°
$u(R_{cal})$: Standard uncertainty of the resistance of standard resistor

The total uncertainty of the rotational speed measurement system is ±0.1 %; the total combined uncertainty $(u_c(N_{ms}))$ is approximately 0.06 %. Therefore, the total combined uncertainty of the shaft power ($u_c(P_{Dms})$) calculated using Eq. (5) becomes 1.242 %.

$$u_c(P_{Dms}) = \sqrt{(u_c^2(Q_{ms}) + u_c^2(N_{ms}))} \tag{5}$$
$$= \sqrt{1.24^2 + 0.06^2} = 1.242\%$$

Although the shaft power measurement system may also have Type-A uncertainties, quantifying these requires raw data obtained through repeated testing. Therefore, this study excluded Type-A uncertainty because of the absence of such data.

5. Added Resistance Uncertainty Analysis

5.1 Uncertainty of added resistance due to wind

ISO 15016 (2015) provides three methods for analyzing added resistance due to wind. This study used the wind resistance coefficient of tankers provided by the ITTC. The added resistance model due to wind is shown in Eq. (6).

$$R_{AA} = 0.5\rho_A C_{AA}(\psi_{\mathrm{WRef}}) A_{XV} V_{\mathrm{WRef}}^2 - 0.5\rho_A C_{AA}(0) A_{XV} V_G^2 \tag{6}$$

Vane anemometers are currently the most widely used instruments to measure wind speed. The most common types of anemometers used in ships are reviewed, and the accuracy of vane anemometers is listed in Table 4.

Table 4. Standard uncertainty of the anemometer

Item	Type B
Wind speed	10 m/s or less : Within ±0.5 m/s
	10 m/s or more : Within ±5 %
Wind direction	±5°

With regard to the probability distribution of input data used to calculate the uncertainty of added resistance due to wind each MCR condition, the Monte Carlo simulation was performed by assuming the wind speed and wind direction as a normal distribution and uniform distribution, respectively.

Table 5 shows the results of analyzing the uncertainty of wind resistance. The analysis shows at the 95 % confidence interval and coverage factor (*k*) of 2, the uncertainty is approximately ±12 ~ 20 % at 50 % MCR, 15 % at 75% MCR, and 16 % at 90 % MCR.

Table 5. Uncertainty of wind resistance

	R_{AA} (*kN*)	U (95 %, *k* = 2) (*kN*)	U (95 %, *k* = 2) (%)
50 % 1st -run	-24.95	±2.78	±12
50 % 2nd -run	37.7	±7.44	±20
75 % 1st -run	-39.59	±1.64	±4
75 % 2nd -run	-94.9	±13.64	±15
90 % 1st -run	-46.2	±2.26	±5
90 % 2nd -run	107.7	±15.5	±16

Fig. 4 shows the uncertainty of wind resistance (50 % 1st -run) and the frequency distribution and variance contribution graph as a result of the Monte Carlo simulation analysis. The average wind resistance is －24.95 kN. The deviation of wind resistance at 95 % confidence interval is ±2.78 kN, which is approximately 12 % of the average added resistance.

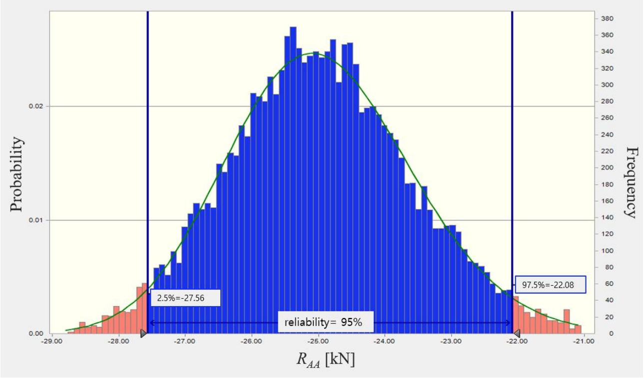

Fig. 4. Uncertainty of wind resistance (50 % 1st -run).

Fig. 5 shows the contribution to a variance chart to examine the magnitude of the factors affecting the uncertainty of added resistance. The contribution to the variance chart is a graph that shows the order correlation coefficients between the data and input elements obtained by Monte Carlo simulation. The values were squared and adjusted to achieve a total of 100 %. As shown in the figure, the largest factor contributing to the variation in wind resistance under the condition of 50 % 1st-run was relative wind speed (V_WR_1), which accounts for approximately 57 % of the total. The second factor was relative wind direction (Pis_WR_1) at 36 %; ship direction (Psi_1) accounted for －8 %. This shows that relative wind speed has a greater influence on the calculation of wind resistance than relative wind direction under this condition.

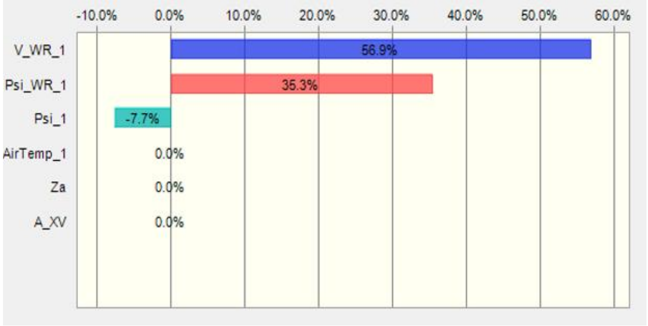

Fig. 5. Sensitivity of wind resistance (MCR: 90 % 1st -run).

5.2 Uncertainty of added resistance due to waves

ISO 15016 (2015) provides three methods (STAWAVE-1, STAWAVE-2, NMRI) to correct added resistance due to waves, and STAWAVE-2 (Eq. 7) is the most widely used.

$$R_{AW} = 2\int_0^{2\pi}\int_0^{\infty}\frac{R_{wave}(\omega,\alpha,V_s)}{\zeta_A^2}E(\omega,\alpha)\,d\omega\,d\alpha \qquad (7)$$

$$R_{wave} = R_{AWML} + R_{AWRL}$$

$$R_{AWML} = 4\rho s g\zeta_A^2\frac{B^2}{L_{PP}}\overline{r_{aw}}(\omega)$$

$$R_{AWRL} = \frac{1}{2}\rho s g\zeta_A^2 B\alpha_1(\omega)$$

RAW is the total amount of added resistance due to waves, which is obtained by the sum of the increased resistance due to ship motion (R_{AWML}) and the increased resistance due to reflected waves (R_{AWRL}). $E(\omega,\ \alpha)$ is the direction spectrum per unit area.

Wave height, wave direction, and wave period are essential to obtain the added resistance due to waves. When a swell occurs in the sea trial conditions, the swell height, swell direction, and swell period are also required.

General sea trials should be performed in calm waters to reduce correction uncertainty due to waves. However, if the sea trial cannot be performed in calm waters, the wave characteristics must be measured accurately. The wave characteristics are usually measured by observation or using buoys, radars, and satellites; third-party observation and radars are the most widely used methods. This study assumed the use of radar equipment, and the accuracy of general radar equipment is listed in Table 6.

Table 6. Uncertainty of the wave measurement system

Item	Uncertainty of Type B
Wave height	±10 % m or ±0.5 m
Period	± 0.5s

When assigning the probability distribution of the wave measurement system mentioned above, the wave height and period were assumed and applied as normal and uniform distributions to the model in Eq. (7) to perform the Monte Carlo simulation.

Table 7 shows the results of analyzing the uncertainty of added resistance due to waves using input variables to determine the accuracy of the wave measurement system.

The uncertainty analysis of the added resistance due to waves under all MCR conditions shows that the 95 % confidence interval is approximately ±40 %. The reason is because the standard uncertainty of the instrument (±0.5 m) was significantly greater than the measured wave height (approximately 1 – 1.7 m).

Table 7. Uncertainty results of added resistance due to waves

	R_{AW} (kN)	U (95 %, $k=2$) (kN)	U (95 %, $k=2$) (%)
50 %	29.2	±11.6	±40
75 %	88.0	±35.0	±40
90 %	71.9	±28.6	±40

5.3 Uncertainty of water temperature & density

ISO 15016 (2015) uses Eq. (8) based on 15℃ and 1,026 kg/m^3 to correct the viscosity effect of the sea to the viscosity of the reference temperature to consider the density change caused by water temperature or the effect on viscosity.

$$R_{AS}=R_{T0}\left(\frac{\rho_s}{\rho_{s0}}-1\right)-R_F\left(\frac{C_{F0}}{C_F}-1\right) \tag{8}$$

During sea trials, the water temperature is not measured in real time but before the trial starts. The accuracy of the measurement system was assumed to be ±0.1℃, as shown in Table 8.

Table 8. Uncertainty of measurement system for water temperature

Item	Uncertainty of Type B
Precision	±0.1℃

Although the total resistance (R_F) uncertainty of the model ship is necessary for calculating uncertainty when applying the Monte Carlo simulation, this value was considered insignificant and negligible.

Table 9 and Fig. 6 show the results of the uncertainty analysis of the added resistance due to water temperature and density. The expanded uncertainty is approximately 5 % at 95 % confidence interval ($k=2$) in all cases.

Table 9. Uncertainty of the corrected resistance due to the effects of water temperature and density

MCR	R_{AS} (kN)	U (95 %, $k=2$) (kN)	U (95 %, $k=2$) (%)
50 %	3.35	±0.17	±5.0
75 %	3.83	±0.20	±5.0
90 %	4.8	±0.24	±5.0

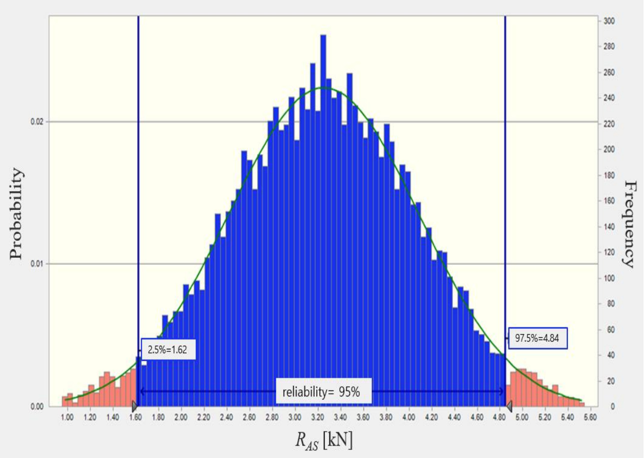

Fig. 6. Uncertainty of the corrected resistance due to the effects of water temperature and density (50 % 1st -run).

6. Uncertainty of the Delivered Power

The P_{Did} is calculated by Eq. (9).

$$\begin{aligned} P_{Did} &= P_{Dms} - \triangle P \\ &= P_{Dms} - \left(\frac{\triangle R V_s}{\eta_{Did}} + P_{Dms}\left(1 - \frac{\eta_{Dms}}{\eta_{Did}}\right) \right) \end{aligned} \tag{9}$$

where $\triangle R$ is the sum of the added resistance to correct the sea trial conditions to that of calm waters, such as the added resistance due to wind and waves. As previously mentioned, this study only considered Type-B uncertainties for each factor. An additional study that considers Type-A uncertainties will be conducted in the future after acquiring raw data.

Based on the shaft power uncertainty calculated in Section 4 and the uncertainty in added resistance (5.1 – 5.3), the uncertainty of power (P_{Did}) was analyzed under ideal environmental conditions corrected by sea trial measurements. The results show uncertainties up to 1.5 % at 95 % confidence interval under each MCR condition (Table 10). As shown in Fig. 7, the P_{Did} was 11,381 kW when using the ISO 15016 (2015) sea trial analysis method based on the trial data of 50 % MCR. The uncertainty analysis show a range of ±130 kW (approximately ±1.2 %) at 95 % confidence interval. At 75 % MCR and 90 % MCR, the expanded uncertainty was approximately ±1.5 % and ±1.3 %, respectively, at 95 % confidence interval.

Table 10. Uncertainty for corrected ideal power

MCR	P_{Did} (kW)	U (95 %, $k=2$) (kW)	U (95 %, $k=2$) (%)
50 %	11,381	±130	±1.2
75 %	16,693	±246	±1.5
90 %	22,027	±288	±1.3

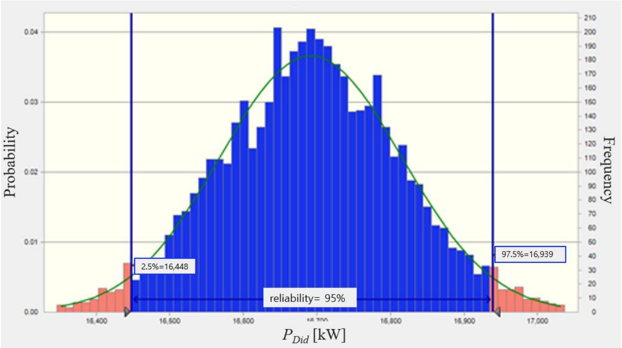

Fig. 7. Uncertainty for corrected power (75 % MCR).

Fig. 8 shows the contribution to variance of the estimated power (P_{Did}) according to the results of round-trip sea trials at 75 % MCR. The analysis results show that the added resistance due to waves at 75 % MCR condition of the 2nd-run had a significant influence on the uncertainty. This is because the wave height was measured to be 1.7 m higher than that of other conditions, which increased the uncertainty. The uncertainty of the shaft power measurement system was approximately 25 %, while the uncertainty of the added resistance due to wind was relatively small. This is because the added resistance due to wind under this condition did not have a significant influence as the average value of the round-trip trial was small.

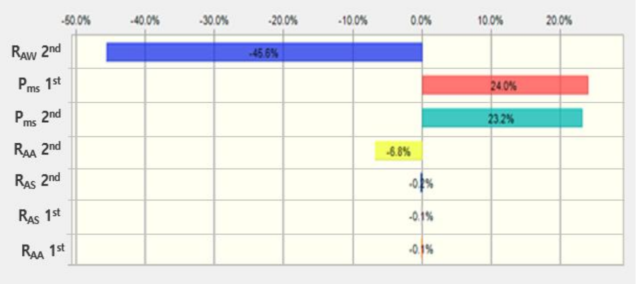

Fig. 8. Sensitivity of corrected power (75 % MCR).

7. Conclusion

Based on actual sea trial data, this study applied the ISO 15016:2015 analysis method to analyze the uncertainty in ideal power using the Monte Carlo simulation method. The findings are as follows:

1. The delivered power was analyzed by considering the Type-B uncertainty of each measuring equipment during sea trials. Under 50 %, 75 %, and 90 % MCR conditions, the expanded uncertainty of delivered power (P_{Did}) at 95 % confidence interval ($k=2$) was ±1.2 %, ±1.5 %, and ±1.3 %, respectively.

2. The speed-power uncertainty due to each measuring equipment was ±1.5 % at 95 % confidence interval, and approximately ±0.13 kts when converted to speed. This means the ship speed may vary by ±0.13 knots owing to the uncertainty of various measuring equipment.

3. The added resistance due to waves under 75 % MCR condition of the 2nd-run had the greatest influence on the uncertainty of ideal power, and the contribution to variance was approximately 46 %.

As previously mentioned, this study considered only Type-B uncertainties for each factor. An additional study that considers Type-A uncertainties will be conducted in the future after acquiring raw data.

Acknowledgements

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No.20183010025200).

References

[1] Coleman, H. W. and W. G Steele(2009), Experimentation, validation, and uncertainty analysis for engineers, 3rd Ed., John Wiley & Sons, Inc.

[2] Insel, M.(2008), Uncertainty in the analysis of speed and powering trials, Ocean Engineering, 35, 1183-1193.

[3] ISO JCGM 100(2008a), Evaluation of measurement data - Guide to the Expression of Uncertainty in Measurements.

[4] ISO JCGM 101(2008b), Evaluation of measurement data – Guide to the Expression of Uncertainty in Measurements – Propagation of distributions using Monte Carlo method.

[5] ISO 15016(2015), Ships and marine technology - Guidelines for the assessment of speed and power performance by analysis of speed trial data.

[6] ITTC(2002), International Towing Tank Conference, Final report and recommendations to the 23rd ITTC - The Specialist Committe on Speed and Powering Trials.

[7] ITTC(2005), International Towing Tank Conference, Recommended procedures and guidelines - Testing and extrapolation methods loads and responses, seakeeping experiments (7.5-02-07-02.1).

[8] Seo, D. W., M. S. Kim and S. Y. Kim(2019), Uncertainty Analysis for Speed and Power Performance in Sea Trial using Monte Carlo Simulation, Journal of the Society of Naval Architects of Korea. Vol. 56, No.3, pp. 242-250.

Received : 2020. 03. 24.
Revised : 2020. 05. 01.
Accepted : 2020. 05. 28.