Uncertainty Assessment in Ship Performance Evaluation by Monte Carlo Simulation Using Onboard Monitoring Data

by Naoto Sogihara*, Member

Summary

Onboard monitoring for ship performance evaluation in actual seas is widely conducted in the shipping sector. Onboard monitoring usually involves a large number of instruments for measuring ship performance and the sea conditions in which the ship navigates, and such instruments are subject to some amount of error, which means that the accuracy of the instruments influences the evaluation. In this study, an uncertainty assessment was carried out to investigate the influence of instrument accuracy on two subjects by Monte Carlo Simulation. One subject is ship performance in calm seas evaluated by correction of performance for the effects of waves and winds, and the other is voyage simulation. As a result, this study clarified the accuracy of the instruments used in onboard monitoring required for achieving a reliable evaluation of ship performance in actual seas.

Nomenclature

Abbreviations
BF Beaufort Scale
CV Coefficient of Variance
ISO International Organization for Standardization
ITTC International Towing Tank Conference
MCS Monte Carlo Simulation
PDF Probability Density Function
POC Propeller Open Characteristics

Greek symbols
α direction of elementary wave [deg.]
∆P power increase in winds and waves [kW]
∆R resistance increase in winds and waves [N]
Γ gamma function [-]
ηDid propulsive efficiency in calm seas [-]
ηDms propulsive efficiency in winds and waves [-]
ητ transmission efficiency [-]
ητsid propeller efficiency in calm seas [-]
ητms propeller efficiency in winds and waves [-]
ητ rotative efficiency [-]
µ mean in a normal distribution [-]
µP mean power in MCS [kW]
θ wave direction [deg.]
ρA density of air [kgm-3]
ρS density of sea water [kgm-3]
σ standard deviation in a normal distribution [-]
σP standard deviation of power in MCS [kW]
τDid load factor in calm seas [-]

Roman symbols
A37 projected transverse area above waterline [m2]
B ship breadth [m]
CAd wind resistance coefficient [-]
C1 coefficient in the numerical model [knots2]
C2 order of ship speed in the numerical model [-]
D angular distribution [-]
DP propeller diameter [m]
E directional spectrum of short crested irregular waves [-]
Ftms instantaneous measured fuel consumption [ton/day]
Fimms instantaneous simulated fuel consumption [ton/day]
Fz Froude number [-]
g gravitational acceleration [ms-2]
H significant wave height [m]
Jid advancing coefficient in calm seas [-]
Jms advancing coefficient in winds and waves [-]
KAR added resistance coefficient in short crested irregular waves [-]
KAms torque coefficient in winds and waves [-]
KTms thrust coefficient in winds and waves [-]
L ship length [m]
N data number in one voyage [-]
NF normalized cumulative fuel consumption [-]
ne corrected engine revolution [s-1]
nms measured engine revolution [s-1]
Pbrms corrected brake power [kW]
Pbrms measured brake power [kW]
Pdms corrected delivered power [kW]
Pdms measured delivered power [kW]
RAd added resistance in winds [N]

* National Maritime Research Institute, National Institute of Maritime, Port and Aviation Technology

Received 15 January 2021
\( R_{\text{AW}} \) \text{ added resistance in waves [N]}  
\( R_{\text{WIR}} \) \text{ added resistance in short crested irregular waves [N]}  
\( R_{\text{sd}} \) \text{ resistance in calm seas [N]}  
\( R_{\text{sw}} \) \text{ resistance in winds and waves [N]}  
\( S \) \text{ frequency spectrum [-]}  
\( T \) \text{ mean wave period [s]}  
\( T_{\text{ave}} \) \text{ average zero up – crossing wave period [s]}  
\( \theta - t \) \text{ thrust deduction coefficient [-]}  
\( V_{\text{G}} \) \text{ ship speed over ground [knot]}  
\( V_{\text{meas}} \) \text{ measured ship speed through water [knot]}  
\( V_{\text{sim}} \) \text{ simulated ship speed through water [knot]}  
\( V_{\text{S}} \) \text{ ship speed through water [knot]}  
\( V_{\text{BR}} \) \text{ relative wind speed [ms\(^{-1}\)]}  
\( V_{\text{WT}} \) \text{ true wind speed [ms\(^{-1}\)]}  
\( 1\text{-ws} \) \text{ effective wake coefficient in full-scale [-]}  

1. Introduction

Reduction of greenhouse gas (GHG) emissions from the shipping sector is an urgent issue. Ship builders are making many efforts to design eco-friendly ships or to develop energy saving devices. Similarly, ship operators have adopted slow steaming or weather routing to achieve low fuel consumption in operation, and onboard monitoring is conducted globally to validate the effectiveness of these activities. An adequate analysis of the data obtained by onboard monitoring is expected to clarify ship performance in actual seas. However, the analysis is influenced by the error of the measurement instruments since onboard monitoring usually involves a large number of instruments. Therefore, it is necessary to clarify the extent of the influence of the instrument error in order to ensure a reliable evaluation of ship performance.

Insel assessed uncertainty\(^1\) in the analysis of speed and powering trials using trial data from 12 sister ships and reported that the precision limit is governed by environmental condition such as winds, waves, and currents. He concluded that utilization of the Beaufort scale for winds and waves is a source of error, and encounter waves should be measured by means of radar or buoy.

Aldous et al. developed a method for assessing uncertainty\(^2\) in ship performance quantifications using different types of data: noon reports and continuous data. However, these two studies did not address the relationship between the accuracy of the measurement instruments and the result of an analysis of onboard monitoring data, which is indispensable for a reliable evaluation.

In this respect, Prpić-Oršić et al.\(^3\) raised uncertainties involved in the estimation of ship speed in actual seas and mentioned that it is essential to understand and quantify the impact of uncertainties in weather and operational conditions. Apart from ship propulsive performance, Papanikolaou et al.\(^4\) reviewed recent researches on the uncertainty assessment in predicting the wave induced loads on ships and introduces a practical application of uncertainty modelling to the assessment of risk-based decision support system for onboard guidance. Elzbieta et al. demonstrated some uncertainties associated with wind and wave description for engineering applications and suggested a better analysis of error in model tests. In the analysis, both the test results and the estimation by a theory are provided with error bands, which in consequence enables a validation of the theory.

With respect to ship propulsive performance, ISO 19030\(^6\) stipulates the procedure for measuring changes in hull and propeller performance and shows the required accuracy of the measurement instruments for onboard monitoring, but does not mention the treatment of measurements of waves, which should be taken into consideration for the accurate evaluation of ship performance. With respect to the accurate evaluation, the ship performance simulator VESTA\(^7\) was developed by Tsujimoto et al. as a tool for predicting fuel consumption in actual seas with high accuracy. They conducted voyage simulations using VESTA and compared results of the simulation with onboard monitoring data to validate the effectiveness of VESTA, which resulted in good agreement. However, their study did not discuss the deviation of voyage simulations derived from the accuracy of the measurement instruments, which is necessary to strengthen the effectiveness of VESTA in evaluating ship performance.

In this study, an assessment of uncertainties in ship performance evaluation was carried out by the Monte Carlo Simulation (MCS) method. In order to investigate how the accuracy of measurement instruments used in monitoring influences the ship performance obtained in evaluations, the uncertainty assessment addresses two different types of analyses; one is correction of engine revolution and power for the effects of winds and waves when evaluating ship performance in calm seas, and the other is voyage simulation for predicting fuel consumption in a voyage and comparing the results with the onboard monitoring data. This uncertainty assessment provides insights on the required accuracy for appropriate implementation of onboard monitoring and clarifies the influence of the accuracy of measurement instruments on simulated ship performance in actual seas.

2. Uncertainties in Ship Performance Evaluation

Both correction for winds and waves and voyage simulation are techniques for evaluating ship performance in actual seas. Performance evaluations utilize a theoretical model having a large number of model or physical parameters, and also involve the input variables for the evaluation based on the model. Further, a model itself usually contains uncertainty resulting from the difference between a model and a reality. Therefore, as illustrated in Fig. 1, the input variables, the parameters of the model, and the application of the model are all sources of uncertainty and lead to output having uncertainty.

![Fig. 1 Sources of uncertainty in modeling](image)

Ship performance evaluation involves the uncertainties listed in Table 1. Model uncertainty results from modeling of correction for winds and waves and voyage simulation. In this study, model...
parameter uncertainty includes the coefficients of added resistance in winds and waves and self-propulsion factors and propeller open characteristics. In this regard, the author has investigated the effect of uncertainty in the added resistance in waves estimated by model tests and reported the relationship between the uncertainty of the added resistance and a decrease of ship speed in actual seas\(^5\). Physical parameters include the ship principal particulars and physical constants. This study does not deal with these components, but rather, focuses on input variable uncertainty in order to assess its effect.

| Table 1 Uncertainties in ship performance evaluation |
|------------------------------------------|
| **Source**                             | **Representative uncertainty** |
| Model uncertainty                      | Modeling of correction for winds and waves |
|                                          | Modeling of voyage simulation |
| Model parameter uncertainty            | Added resistance in winds |
|                                          | Added resistance in waves |
|                                          | Self-propulsion factors |
|                                          | Propeller open characteristics |
| Physical parameter uncertainty        | Ship principal particulars |
|                                          | Density of sea water and air |
|                                          | Gravitational acceleration |
| Input variable uncertainty            | Ship speed |
|                                          | Engine revolution and brake power |
|                                          | Wind speed and direction |
|                                          | Wave height, period, and direction |

Input variable uncertainty is derived from the accuracy of measurement instruments and hindcast. In this study, input variable uncertainty is equivalent to the random errors around the mean (\(\mu\)) and follows a normal distribution with a standard deviation (\(\sigma\)) specified by the manufacturer’s certification or the nominal accuracy provided by a weather consulting company. This means that a sample for the measurands exists within the range \([\mu - 2\sigma, \mu + 2\sigma]\) with a 95\% confidence level.

3. Correction for Winds and Waves

3.1 Methodology of correction

Ships navigating in waves and winds must increase engine revolution and power in comparison with those in calm seas. Therefore, in order to evaluate ship performance in calm seas, the measured engine revolution and power should be corrected for the effects of winds and waves. In this study, the correction is conducted in compliance with the Resistance-Thrust Identified Method\(^6\). Added resistance in winds is estimated using a regression formula based on wind tunnel tests\(^7\). Added resistance in waves is estimated using a theoretical method with simplified tank tests in short waves or an empirical formula\(^8\). These formulae have been discussed in the specialist committee in ITTC and adopted as more accurate methods than other methods.

Evaluating ship performance requires an estimation of the resistance increase due to winds and waves. Added resistance in winds \((R_{aw})\) and added resistance in waves \((R_{aw})\) are calculated by Eq. (1) and Eq. (2), respectively.

\[
R_{aw} = \frac{1}{2} \rho_w A_w \left( C_{Aw} \omega_w \right) V_w^2 - C_{Aw}(0) V_w^2 \right) \tag{1}
\]

Added resistance in winds and waves \((AR)\) is calculated as Eq. (3).

\[
AR = R_{aw} + R_{aw} \tag{3}
\]

The measured engine revolution and measured delivered power are corrected with the ship speed fixed. The measured delivered power is obtained from the engine transmission efficiency and the measured brake power as Eq. (4).

\[
P_{Dms} = P_{Bms} \cdot \eta_M \tag{4}
\]

The torque coefficient in winds and waves is calculated as Eq. (5).

\[
K_{\omega m} = \frac{P_{Bms} D^8}{2 \pi \rho \omega_{ms}^3 D^5} \tag{5}
\]

This study assumes that propeller rotative efficiency \((\eta_\theta)\) in winds and waves is equal to that in calm seas. The obtained torque coefficient and the propeller open characteristics in full-scale give the advancing coefficient and thrust coefficient corresponding to the torque coefficient. This study expresses thrust and torque coefficients as shown in Eq. (6) and Eq. (7), respectively.

\[
K_{\omega 0} = K_{\omega 0} + K_{\omega 0} \cdot J_{aw} + K_{\omega 0} J_{aw}^2 + K_{\omega 0} J_{aw}^3 \tag{6}
\]

\[
K_{\omega m} = K_{\omega m} + K_{\omega m} \cdot J_{aw} + K_{\omega m} J_{aw}^2 + K_{\omega m} J_{aw}^3 \tag{7}
\]

Therefore, the propeller efficiency, load factor, and effective wake coefficient in winds and waves are calculated by Eqs. (8) to (10).

\[
\eta_{Dms} = \frac{J_{aw} K_{\omega m}}{2 \pi K_{\omega m}} \tag{8}
\]

\[
\tau_{Dms} = \frac{K_{\omega m}}{J_{aw}^2} \tag{9}
\]

\[
1 - W_{aw} = \frac{J_{aw} \eta_{Dms} P}{V_S} \tag{10}
\]

Accordingly, propulsive efficiency and total resistance in winds and waves are calculated by Eq. (11) and Eq. (12) in the assumption that both the thrust deduction coefficient and the effective wake coefficient in winds and waves are equal to those in calm seas.

\[
\eta_{Dms} = \eta_{Dms} \eta_{aw} \frac{1 - t}{1 - W_S} \tag{11}
\]

\[
R_{aw} = \tau_{Dms} \left( 1 - t \right) (1 - W_S)^2 \rho w V_S^2 D^2 \tag{12}
\]
Resistance ($R_D$) and the load factor ($\tau_{pd}$) in calm seas are calculated by Eq. (13) and Eq. (14), respectively.

$$R_D = R_w - DR$$  \hspace{1cm} (13)

$$\tau_{pd} = \frac{R_D}{[1 - t] - w_s^2 D p^2}$$  \hspace{1cm} (14)

As the load factor in calm seas can be expressed in Eq. (15), the advancing coefficient in calm seas ($J_{id}$) is obtained in conjunction with Eq. (6). The thrust coefficient ($K_{Tid}$) and propeller efficiency ($\eta_{Oid}$) in calm seas are calculated in compliance with Eqs. (6) to (8).

$$\tau_{pd} = \frac{K_{Tid}}{J_{id}^2}$$  \hspace{1cm} (15)

The propulsive efficiency ($\eta_{Did}$) and engine revolution ($n_{id}$) in calm seas can be calculated by Eq. (16) and Eq. (17).

$$\eta_{Did} = \frac{\eta_{Oid} \eta_{R}}{1 - \frac{t}{1 - w_s}}$$  \hspace{1cm} (16)

$$n_{id} = \frac{V_s^2 (1 - w_s)}{J_{id} D p}$$  \hspace{1cm} (17)

Consequently, the power increase in winds and waves at constant ship speed and the corrected brake power are estimated as follows.

$$\Delta P = P_{Did} - P_{Did}$$  \hspace{1cm} (18)

$$\Delta P = \frac{\Delta R V_s^2}{\eta_{Did}} + P_{Did} \left[ 1 - \frac{\eta_{Did}}{\eta_{Oid}} \right]$$  \hspace{1cm} (19)

$$P_{Did} = \frac{P_{Did}}{\eta_{id}}$$  \hspace{1cm} (20)

The variables and constants in corrections for winds and waves are summarized in Table 2. The variables with uncertainty are measured parameters while those without uncertainty are pre-given parameters. The variables which are not shown in Table 2 are intermediate parameters and considered having uncertainty.

| Table 2 Variables and constants in the correction |
|-----------------------------------------------|
| with uncertainty | without uncertainty |
| $V_G$, $V_s$, $W_R$, $\Psi_R$, $\theta$, $T$, $H$, $P_{Bus}$, $n_{bus}$ | $\rho_s$, $p_s$, $g$, $L$, $B$, $Ax$, $Dr$, $C_{Adv}$, $K_{Adv}$, $\eta_{Did}$, $\eta_{Oid}$, $1-t$ |

### 3.2 Monte Carlo Simulation
#### 3.2.1 Comparison between accuracies of ISO 19030 and current instruments

Although the correction model requires model parameters and physical parameters, their uncertainties are not treated in this study. The uncertainty contained in the correction model itself is not considered. The MCS involves the uncertainty of the following input variables for ship performance and sea states.

- ship speed over ground
- ship speed through water
- engine revolution
- engine brake power
- relative wind speed and direction
- wave height direction and mean period

The accuracy of measurement instruments is provided by the requirement in ISO 19030 and the results of a survey on the accuracy of measurement instruments currently used in onboard monitoring, as listed in Table 3. Ship speed over ground, whose accuracy is not described in ISO 19030, is surveyed since it is necessary in the correction for winds expressed in Eq. (1). Similarly, the significant wave height and wave direction, which are treated as future technical issues in ISO 19030, are also surveyed.

The flowchart of the MCS of the correction is shown in Fig. 2. In this study, the number of iterations in the MCS is set at 10000. A random parameter is generated in accordance with a normal distribution, in which the mean and standard deviation are based on the measured value and the accuracy of measurement instruments, respectively. The bias error of the instruments is ignored. A random parameter in each iteration is determined by the accuracy of the instruments shown in Table 3.
The simulated performance by the simulator VESTA is used in the MCS. VESTA can estimate added resistance in winds and waves with high accuracy and can also predict ship speed and fuel consumption considering the engine characteristics of the ship.

The subject ships in this study and their added resistance in winds and waves are shown in Table 4, Fig. 3, and Fig. 4, respectively. The added resistance in short crested irregular waves is estimated using the directional spectrum expressed by Eqs. (21) to (25). While added resistance in winds for 33CT and DTC is estimated by the regression formula, that for JBC is examined by wind tunnel tests.

\[
E(\omega, \alpha; H, T, \theta) = S(\omega; H, T)D(\alpha; \theta)
\]

\[
S(\omega) = \frac{A}{\omega^4} e^{-\frac{\omega^2}{\omega_0^2}}
\]

\[
A = \frac{1}{4\pi} \left( \frac{2\pi}{T_{102}} \right)^4 H^2, B = \frac{1}{\pi} \left( \frac{2\pi}{T_{102}} \right)^4
\]

\[
T_{102} = \frac{\Gamma(3/4)}{\pi^{1/4}} T \approx 0.9204 T
\]

\[
D(\alpha) = \frac{2}{\pi} \cos^2(\alpha - \theta)
\]

The winds and waves data used to produce the simulated performance data are generated assuming that they are uniformly distributed under sea states milder than BF 5 described in Table 5.

The direction of winds and waves is assumed to be uniformly distributed in all directions. 600 simulated performance data are generated by VESTA and provided to the MCS as input data in addition to the data of winds and waves.

Simulated performance is corrected for winds and waves for all the data, which yields 600 corrected performances. The numerical model(13) expressed by Eq. (26) is applied to the discretized data of the corrected performances in order to estimate the brake power at service speed in calm seas.

\[
P_{\text{br}} = C_1 \cdot V_s^2 C_2
\]

The results of the MCS for the brake power of 33CT at service speed in calm seas are presented in Fig. 5, showing that variation around the mean of brake power seems to obey a normal distribution whichever accuracy shown in Table 3 is used. Such the variation is observed for JBC and DTC. The coefficient of variance (CV) as expressed in Eq. (27), is calculated for brake power as shown in Table 6.

\[
CV = \frac{\sigma_p}{\mu_p}
\]

where \( \mu_p \) and \( \sigma_p \) are mean and standard deviation of the brake power in MCS, respectively.

The CV based on the accuracy of the current instruments is smaller than that based on ISO 19030 for all the subject ships, indicating that correction for waves is necessary in order to evaluate ship performance in calm seas. Table 6 also indicates that a smaller ship has a larger CV both for ISO 19030 and for the current instruments.
Fig. 6, where the contour means the CV of brake power. The largest CV appears in Case-1; specifically, a maximum CV of 10 % is obtained for 33CT and JBC. The result of Case-1 indicates that, even though the uncertainty of brake power is zero, a 3 % uncertainty of the ship speed leads to a CV of around 9 %, which is almost three times the CV given by 0 % uncertainty of speed and 3 % uncertainty of power. For example, uncertainty of ship speed 3 % and that of brake power 0% yields CV = 3.1% while uncertainty of ship speed 0% and that of brake power 3 % yields CV = 9.4% in the case of 33CT. The accuracies of the current measurements of ship speed and brake power are 1.0 % and 0.5 %, respectively, which is also required in ISO 19030, and provides CV = 3 %.

Either ship speed through water or engine brake power is important for evaluating ship performance. Especially, ship speed through water is used not only for estimating added resistance in winds and waves but also for correcting engine revolution and brake power. Therefore, careful attention is required when selecting the instruments for measuring ship speed through water.

The other cases are related to the measurements of winds and waves which ships encounter. The results of Case-2 to Case-5 show a common trend that the CV becomes smaller in the order of 33CT, JBC, DTC. This means that smaller ships are influenced more strongly by winds and waves, which therefore should be measured with high accuracy.

In Case-2, the comparison between 33CT and DTC shows that the effect on the CV of the relative wind speed and significant wave height for 33CT is three times larger than that for DTC. Uncertainty of significant wave height 0.5 m and that of relative wind speed 3.0 m/s yields CV = 3.5% for 33CT and CV = 1.2% for DTC.

In Case-3, no effect of uncertainty in the mean wave period on the CV is observed because the added resistance shown in Fig. 6 is constant irrespective of the mean wave period in sea states less than BF5.

Case-4 and Case-5 show a common trend that an increase in the uncertainties of significant wave height and relative wind speed results in an increase in the uncertainty of brake power which is not dependent on the uncertainty of wave and wind direction.

While a ship is usually equipped with an anemometer, ships do not always have instruments for measuring waves such as wave radar. Therefore, if neither wave radar nor hindcast data is available, there is no other means of measuring waves than visual observation. Since the accuracy of visual observation depends on the experience of the crew, visual observation can result in larger uncertainty than wave radar or hindcast. The parametric uncertainty assessment in this study clarifies the uncertainty of brake power resulting from the uncertainty of the significant wave height and wave direction, which can contribute to the assessment of the reliability of ship performance evaluations based on visually observed wave data.

**Table 6 Coefficient of variance for brake power at service speed in calm seas**

|                  | 33CT  | JBC   | DTC   |
|------------------|-------|-------|-------|
| ISO 19030        | 3.55 %| 3.35 %| 2.93 %|
| Current instruments | 3.43 %| 3.26 %| 2.93 %|

### 3.2.2 Parametric uncertainty assessment

It is important to clarify how the uncertainty derived from instrument accuracy affects the brake power resulting from correction. Therefore, a MCS is also conducted for a parametric uncertainty assessment in order to investigate the effect of the accuracy of the measurement instruments applied on onboard monitoring. A MCS with two variables is conducted, where the number of iterations is 10000. The following five cases of combinations of the two variables are addressed in the assessment, and the uncertainties of variables other than the two variables are assumed to be zero. It should be noted that, while values for the uncertainty of the variables can be provided in various ways, in this study, these values are given considering the evaluation of ship performance in calm seas.

- Case-1: ship speed through water and engine brake power
- Case-2: relative wind speed and significant wave height
- Case-3: significant wave height and mean wave height
- Case-4: significant wave height and wave direction
- Case-5: relative wind speed and direction

The parametric uncertainty assessment results are shown in Fig. 6, where the contour means the CV of brake power. The largest CV appears in Case-1; specifically, a maximum CV of
Fig. 6, where the contour means the CV of brake power. The largest CV appears in Case-1; specifically, a maximum CV of ship performance in calm seas. In this study, these values are given considering the evaluation of uncertainty of the variables can be provided in various ways, in assumed to be zero. It should be noted that, while values for the and the uncertainties of variables other than the two variables are combinations of the two variables are addressed in the assessment, monitoring. A MCS with two variables is conducted, where the accuracy of the measurement instruments applied in onboard uncertainty assessment in order to investigate the effect of the 3.2.2
correction. Therefore, a MCS is also conducted for a parametric Current instruments I

| Case          | Uncertainty of Significant Wave Height [m] | Uncertainty of Relative Wind Speed [m/s] | Uncertainty of Ship Speed [%] |
|---------------|-----------------------------------------|----------------------------------------|-----------------------------|
| Case-1        | 1.0%                                    | 3.0%                                   | 0%                          |
| Case-2        | 1.0%                                    | 3.0%                                   | 0%                          |
| Case-3        | 1.0%                                    | 3.0%                                   | 0%                          |
| Case-4        | 1.0%                                    | 3.0%                                   | 0%                          |
| Case-5        | 1.0%                                    | 3.0%                                   | 0%                          |

Table 6 Coefficient of variance for brake power

| Variable  | ISO 19030 | Current Instruments |
|-----------|------------|---------------------|
| P.D.F.    | -10        | -10                 |
| P.D.F.    | -9         | -9                  |
| P.D.F.    | -8         | -8                  |
| P.D.F.    | -7         | -7                  |
| P.D.F.    | -6         | -6                  |
| P.D.F.    | -5         | -5                  |
| P.D.F.    | -4         | -4                  |
| P.D.F.    | -3         | -3                  |
| P.D.F.    | -2         | -2                  |
| P.D.F.    | -1         | -1                  |
| P.D.F.    | 0          | 0                   |
| P.D.F.    | 1          | 1                   |
| P.D.F.    | 2          | 2                   |
| P.D.F.    | 3          | 3                   |

provides CV = 3%. and 0.5%, respectively, which is also required in ISO 19030, and current measurements of ship speed and brake power are 1.0% yields CV = 9.4% in the case of 33CT. The accuracies of the uncertainty of ship speed 0% and that of brake power 3% yields CV = 3.1% while uncertainty of ship speed 3% and that of brake power 0% yields CV = 1.2% for DTC.

The other cases are related to the measurements of winds and significant wave height and wave direction, which can contribute to the assessment uncertainty than wave radar or hindcast. The parametric uncertainty assessment in this study clarifies the uncertainty of visually observed wave data.

while a ship is usually equipped with an anemometer, ships indicate that, even though the uncertainty of brake power is zero, 10% is obtained for 33CT and JBC. The result of Case-1 a 3% uncertainty of the ship speed leads to a CV of around 9%, which is almost three times the CV given by 0% uncertainty of ship speed through water is used not only for estimating added resistance in the CV is observed because the added resistance shown in Fig. 6.5 is constant irrespective of the mean wave period in sea states less than BF5. As for significant wave height for 33CT is three times larger than that measured with high accuracy.

Uncertainty Assessment in Ship Performance Evaluation by Monte Carlo Simulation Using Onboard Monitoring Data
4. Voyage Simulation

In order to reduce GHG emissions from the shipping sector, both energy saving operation and the design and construction of eco-friendly ships are strongly required. To ensure the reliability of voyage simulations, the output uncertainty derived from input variable uncertainty should be clarified in such simulation. Therefore, a MCS was conducted for voyage simulation, and the results for the uncertainty in the navigated distance and fuel consumption were compared with those of the onboard monitoring data.

Table 7 Particulars of subject ships for voyage simulation

| Ship ID | PCS | MRT | Unit |
|---------|-----|-----|------|
| Length between perpendiculars | 270.0 | 185.0 | m |
| Breadth | 35.0 | 32.2 | m |
| Draft in design full condition | 12.0 | 13.0 | m |

This study deals with the two ships indicated in Table 7, which are equipped with auto data-logging systems. The main sea area of PCS and MRT is North Pacific Ocean. Performance in calm seas\(^{14}\) obtained by the authors is used based on onboard monitoring. Self-propulsion factors and propeller open characteristics are estimated using ship principal particulars\(^{15}\). The added resistance in winds and that in waves of the ships for the operation draft condition are calculated as shown in Fig. 7 and Fig. 8, respectively. In the calculation of the added resistance in waves, Eqs. (21) to (25) are applied.

![Fig. 7 Added resistance in winds. (left: PCS, right: MRT)](image1)

![Fig. 8 Added resistance in waves. (left: PCS, right: MRT)](image2)

![Fig. 9 Wind, wave, and performance data measured by onboard monitoring. (left: PCS ship, right: MRT)](image3)
Fig. 9 shows the data used for the simulation, where the inputs are wave and wind data and engine revolution, and the output data include the ship speed and fuel consumption. Fig. 9 also includes the comparison of the ship speed and fuel consumption in the measurement and the simulation by MCS. While the hindcast wave data are provided by the Japan Weather Association\(^a\), the simulation input variables for winds and ship performance are measured onboard. Fig. 9 indicates that the voyage simulation results are in good agreement with the onboard monitoring data.

The flowchart of the MCS for the voyage simulation is shown in Fig. 10. The number for iterations of the simulation was 1000. Similar to the MCS on the correction for winds and waves, this MCS treats only the uncertainty of the input variables and does not consider the uncertainty of other factors. The uncertainty of the input variables other than the engine brake power follows the values listed in the column “Survey results” in Table 2. The uncertainty of the engine brake power is given as 1.0 % and 3.0 % based on the results of the parametric simulation of Case-1 described in section 3.2.2.

![Flowchart of Monte Carlo Simulation of voyage simulation](image)

This study focuses on the cumulative value of fuel consumption and the navigated distance in the subject voyage. In each iteration, the normalized cumulative fuel consumption and navigated distance are calculated by Eq. (28) and Eq. (29).

The results of the MCS for the voyage simulation are summarized in Table 8. Regardless of whether the input uncertainty of brake power is 1 % or 3 %, the dimensionless mean of the navigated distance and fuel consumption is substantially equal to 1 for PCS and MRT. While the dimensionless standard deviation of the navigated distance is around 0.01 and is not affected by the uncertainty of brake power, the dimensionless standard deviation of the fuel consumption depends on the uncertainty of brake power. The reason for this is that the variables other than the brake power are given one uncertainty while the uncertainty of the brake engine is provided with 1.0 % and 3.0 %.

| Item | Ship   | Input uncertainty of brake power | Dimensionless mean | Dimensionless standard dev. |
|------|--------|---------------------------------|--------------------|----------------------------|
| \(nF\) | PCS    | 1%                              | 0.998              | 0.010                      |
|       |        | 3%                              | 0.998              | 0.010                      |
|       | MRT    | 1%                              | 1.005              | 0.011                      |
|       |        | 3%                              | 1.005              | 0.011                      |
| \(nL\) | PCS    | 1%                              | 1.010              | 0.009                      |
|       |        | 3%                              | 1.010              | 0.027                      |
|       | MRT    | 1%                              | 0.996              | 0.007                      |
|       |        | 3%                              | 0.998              | 0.017                      |

Fig. 11 shows a probability density function (PDF) for the normalized cumulative fuel consumption resulting from the MCS and the measured cumulative fuel consumption under the assumption that the accuracy of fuel consumption measurement is 1 % for a simplified assessment. Although there is a small gap between the peaks, the two PDFs show good agreement. It is also found that the PDF simulated with 3 % uncertainty of brake power has a lower peak and much wider spread, since the dimensionless standard deviation is larger than in the case of 1 % uncertainty.

For the comparison of the PDFs, it is convenient to apply the validity\(^7\) quantified by determination of the overlapping area of the two PDFs. Although the validity itself does not provide any information on the accuracy of the simulation, users of the simulation can make decisions on the adequacy of the simulation results on this basis. The validity \(\psi\) with variable \(x\) can be calculated by Eq. (30).

\[
\psi = \int_{-\infty}^{\infty} \min\{PDF_{\text{meas}}, PDF_{\text{sim}}\} dx
\]
where the subscript meas denotes onboard monitoring, and sim denotes voyage simulation. As shown in Eq. (30), perfect agreement of the PDFs gives $\psi = 1$ and no overlapping area gives $\psi = 0$. Applying Eq. (30) to the PDFs in Fig. 11 resulted in Fig. 12 and indicates that the validity of MRT does not depend on the uncertainty of brake power, while that of PCS is slightly influenced by this uncertainty. This is caused by the larger standard deviation of PCS than that of MRT.

Since $\psi$ itself does not provide any information on the accuracy of the simulation, users should make their own decisions. Criteria for $\psi$ is helpful for the decisions and should be determined by users taking a required accuracy into account. In this study, the author sets $\psi = 0.5$ as the criteria. According to the criteria, the comparison of the PDFs leads to the conclusion that the accuracy of the current instruments is sufficient for validation of the model of the voyage simulation.

Validation of the simulation results based on onboard monitoring is useful with respect to validity. At the same time, a comparison of the PDFs of the simulation and onboard monitoring enables a highly-robust validation of theoretical models in accordance with users’ decisions. In the cases of this study, the voyage simulation has enough accuracy in accordance with the criteria determined by the author. On the other hand, stricter validation can be conducted with higher $\psi$, which suggests that more accurate instruments should be incorporated to onboard monitoring for measuring ship performance and the ambient condition. The higher $\psi$ is determined as the criteria, the stricter validation of the simulation of ship performance in actual seas can be conducted.

5. Conclusions

In this study, uncertainty assessments of ship performance evaluations are conducted based on the Monte Carlo Simulation method in order to clarify how the accuracy of the measurement instruments used in onboard monitoring affects the results of those evaluations. Uncertainty assessments by MCS are applied to two subjects, correction of engine revolution and power for the effects of winds and waves and voyage simulation of fuel consumption. The accuracy of the measurement instruments currently applied in onboard monitoring is surveyed prior to the uncertainty assessment.

The simulated performance data generated by the simulator VESTA are used in the uncertainty assessments in the corrections for three benchmark ships. This assessment refers to the accuracy required in ISO 19030 as well as the results of the aforementioned survey. These two accuracies are applied in the uncertainty assessment, which provides equivalent results for the coefficient of variance for engine brake power at service speed in calm seas. The assessment also indicates that a smaller ship has a larger CV for brake power.

In addition to the above assessment, a parametric uncertainty assessment is conducted with two parameters with respect to ship performance and sea state. This assessment indicates that the accuracy of the instruments for measuring ship speed through water should be ensured at a high level, and that a smaller ship is subject to greater effects of winds and waves. Considering that a performance evaluation by onboard monitoring should provide accurate information on waves, the effect of the uncertainty in waves on the evaluation results should be clarified. The parametric uncertainty assessment contributes to this aim.

The uncertainty assessment for the voyage simulation is carried out using the data measured by onboard monitoring for two ships in service. The comparison of the probability density functions of normalized cumulative fuel consumption in the voyage simulation and onboard monitoring shows good agreement, which can strengthen the validation of the voyage simulation. This can realize highly accurate evaluations of ship performance in actual seas since their reliability is ensured by the uncertainty assessment based on Monte Carlo Simulation.
Acknowledgments

This study was carried out as part of the Initiative on Evaluation of Ship Performance in Actual Seas, the “OCTARVIA Project,” a Japan Maritime Cluster Collaborative Research project. The author is grateful to all the parties concerned who discussed the content of this study in the working groups.

References

1) Insel, M.: Uncertainty in the analysis of speed and powering trials, Ocean Engineering, Vol. 35, pp.1183-1193, 2008.
2) Aldous, L., Smith, T., Bucknall, R., and Thompson, P.: Uncertainty analysis in ship performance monitoring, Ocean Engineering, Vol. 110, pp.29-38, 2015.
3) Pripić-Oršić, J., Sasa, K., Valčić, M., and Faltinsen, O. M.: Uncertainties of Ship Speed Loss Evaluation under Real Weather Conditions, Journal of Offshore Mechanics and Arctic Engineering, Vol. 142, 2020.
4) Papanikolaou, A., Mohammned, E. A., and Hirdaris, S. E.: Stochastic Uncertainty Modelling for Ship Design Loads and Operational Guidance, Ocean Engineering, Vol. 86, pp.47-57, 2014.
5) Biter-Gregersen, E. M., Ewans, K. C., and Johnson M. C.: Some Uncertainties Associated with Wind and Wave Description and Their Importance for Engineering Applications, Ocean Engineering., Vol. 86, pp.11-25, 2014.
6) International Organization for Standardization: Ship and marine technology -Measurement of changes in hull and propeller performance, 2016
7) Tsujimoto, M., Sogihara, N., Kuroda, M., and Sakurada, A.: Development of a ship performance simulator in actual seas, Proceedings of the ASME 2015 34th International Conference in Ocean, Offshore and Arctic Engineering, OMAE2015-41708, 2015.
8) Schulten, P., and Stapersma, D.: A study of the validity of a complex simulation model, Journal of Marine Engineering and Technology, Vol. 10, pp.67-77, 2009.
9) Sogihara, N., Tsujimoto, M., Fukasawa, R., and Hamada, T.: Uncertainty Analysis for Measurement of Added Resistance in Short Regular Waves: Its Application and Evaluation, Ocean Engineering, Vol. 216, 2020.
10) International Towing Tank Conference: Recommended Procedures and Guidelines, Prediction of Power Increase in Irregular Waves from Model Test, 7.5.-02-07-02.2, 2011.
11) Fujiwara, T., Ueno, M., and Ikeda, Y.: Cruising performance of a large passenger ship in heavy sea, Proceedings of Sixteenth International Offshore and Polar Engineering Conference, Vol. III, pp. 304-311, 2006.
12) Tsujimoto, M., Kuroda, M., Shibata, K., and Takagi, K.: A Practical Correction Method for Added Resistance in Waves, Journal of Japan Society of Naval Architects and Ocean Engineers, Vol. 8, pp. 177-184, 2008.
13) Sakurada, A., Sogihara, N., and Tsujimoto, M.: Development of a Filtering Method for Evaluation of Performance in a Calm Sea Based on Onboard Monitoring Data, Journal of the Japan Society of Naval Architects and Ocean Engineers, Vol. 33, 2021.
14) Sogihara, N., Kuroda, M., Sakurada, A., Yokota, S., and Tsujimoto, M: UNITAS: Tool for supporting evaluation of ship performance in actual seas, Papers of National Maritime Research Institute, Vol. 19, No. 1, pp. 101-122, 2019.
15) Sato, Y., and Matsuura, K.: Forecasting and hindcasting, The Naval Architect, November, pp.31-34, 2019.
16) Vrijdag, A., Stapersma, D., and van Terwisga, T.: Systematic modelling, verification, calibration and validation of a ship propulsion simulation model, Journal of Marine Engineering and Technology, Vol. 8, Issue 3, pp.3-20, 2009.