Draft

Report of the

ITTC

Working group on parameters for full scale power predictions

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Rev. A

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1 Introduction

1.1 Working group

This is the report of the ITTC "*Working group on parameters for full scale power predictions*". ITTC appointed this new working group in 2020 to address the experienced based, draft dependent parameters in the ITTC extrapolation methods, in particular in relation to EEDI calculations. The action was a direct response to a discussion in IMO MEPC. In this discussion several delegations requested that the values of correlation factors used in speed–power-predictions should be kept the same for ballast and scantling draught. Although at that time there was no validation of this, the requirement is stated in IMO's description of the EEDI.

The working group consists of six organisations and one representative of ITTC Advisory Council. (One original member, Qinetiq from UK, withdrew and never participated in any meetings. SSSRI joined late as an observer.) Since the start in August 2020 until the end of September 2023, the group held 40 online meetings. The participation rate in the meetings was very high.

AC Chair Gerhard Strasser participated as observer and was present at almost all meetings. The group presented their plans at the virtual ITTC full conference in June 2021.

All the group member organisations except for one contributed with extensive data from previous model tests and sea trials (anonymised). The group also contacted ship owners and requested full scale data from ships in service. Several ship owners shared valuable data and expressed their support to the group.

Table 1. Members of the Working Group

Organisation	**Country**	**Representatives**
RISE (ex SSPA) (chair)	Sweden	Sofia Werner, Burak Korkmaz
MARIC	China	JinBao Wang
MARIN	Netherlands	Michiel Verhulst, Johan de Jong
HSVA	Germany	Jan Richter, Florian Kluwe
JMUC	Japan	Inukai Yasuhiko
KRISO	South Korea	Kwang Soo Kim
AC Chair	Austria	Gerhard Strasser (Observer)
SSSRI	China	WeiMin Chen (Observer)

1.2 Problem statement

This section describes the problem, which the working group was set to solve.

The EEDI speed and the contract speed of new built ships are verified at speed trials. For all common cargo vessels except oil tankers the speed trials are usually carried out at ballast draught.

The EEDI speed is for most ships defined at scantling draught and the contract speed in the builder's contract with the yard is most often defined at design draught. To verify the EEDI speed and the contract speed without sea trial at deeper draughts, the ballast draught sea trial result has to be converted. According to ITTC 7.5-04-01-01 and ISO 15016:2015 this is done using equation 1, as illustrated in Figure 1. It can be seen that the resulting EEDI speed or contract speed depends on two outcomes: the ballast speed trial, and the predicted relation between the power at full load and ballast from the model tests. This causes the *prediction of the power relation based on the model tests* to be very important.

$$\boldsymbol{Power}_{\boldsymbol{full\ load}} = Power_{speed\ trial\ ballast} \cdot \frac{P_{model\ test\ full\ load}}{P_{model\ test\ ballast}} \qquad (1)$$

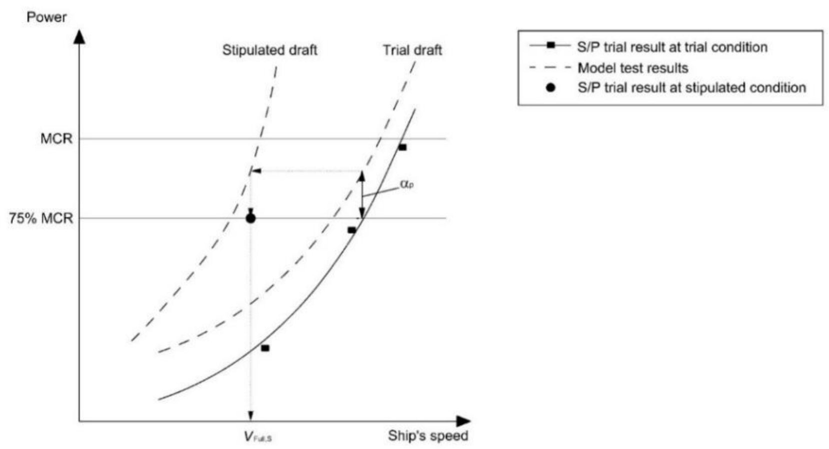


Figure 1. Conversion from speed trial at ballast to either scantling or contract draught.

The prediction of the full-scale power based on towing tank tests is done according to "ITTC 1978 Power Prediction methods" or equivalent. Each towing tank facility utilises variants of this procedure. In common for all tanks is that the analysis makes use of empirical correlation factors, either C_P and C_N , C_A or $\Delta C_{FC} - \Delta w_C$. According to ITTC 7.5-04-05-01, the correlation factors are derived by each towing tank organisation using a large number of speed trials. Since these speed trials are for most cases carried out at ballast draught, the correlation factors are set and validated primarily for ballast draught.

From ITTC inter-tank comparison campaigns it has been shown that the spread between measured *model scale* values for resistance is very small, in the magnitude of 1%. However, there are sometimes larger difference in *full scale* predictions between different towing tank facilities for the laden and scantling draughts. The reason is that the extrapolation methods are not the same and/or used differently and the ballast draught correlation factors are well correlated using speed trials but for the deeper draughts there is not enough evidence material for setting validated correlation factors.

The consequences of the current situation are:

- The predicted EEDI-speed or contract speed of a ship hull tested at two towing tanks can differ. Since the sea trials usually are conducted at ballast draught only, where the predictions are similar, it cannot easily be proved which of the predictions for higher draughts are correct.
- This leads to mistrust in the EEDI determination which risks undermining the whole EEDI system
- The actual fuel consumption once the ship is in operation might be not as expected, which affects operational costs, charter agreements and propeller margins.
- In the design phase, the best hull form might even be rejected in favour of a worse one, because the latter seems to be better “on paper”.

1.2.1 **CFD**

MEPC now allows that the power curves needed for EEXI (like EEDI but for existing ships) may be determined by CFD (IMO 2022). Full scale CFD for power prediction is now available as standard service from many organizations. It should be noted that the above problem is not only a problem related to towing tank test and cannot be solved by simply using CFD instead. Predictions from CFD will also need to be correlated, as for example described in the IACS guidelines for verifying EEXI (IACS, 2022). Either the CFD is correlated and conducted at model scale, in which case the same problem as described above is present. Or the CFD prediction is conducted at full scale directly and correlated to sea trials, in which case the same problem arises that correlation is only possible at ballast draft.

Ensuring accuracy of CFD predictions at all draughts is hence just as important, and just as difficult for CFD as for model test.

2 Approach to solution

This chapter outlines the solution that the working group recommends. The motivation and research behind are described in the subsequence chapters.

2.1 Rejected solutions

The following solutions were discussed but rejected:

1) Requiring that all towing tanks use exactly same evaluation procedure and coefficients

- No, ITTC members need for various reasons to keep their tank specific methods and coefficients

2) Requiring that each tank has correlation data from sea trials at full load drafts?

- Not feasible, very few available

3) Requiring that each tank has correlation data from operational data at different draughts?

- Scattered data –> each one can draw very flexible conclusions

4) Stipulate a fixed difference between correlation factor Cp at design draught and ballast draught

- No, it was shown by Specialist Committee for Performance of Ships in Service (PSS) 2014-2017 that a general correlation-factor-to-draught-relation is impossible to derive, due to the fact that all facilities use their own settings. (See Committee Report for more details)

2.2 Outline to selected solution

The overall strategy is to produce a Test that shows the acceptable limit for a reasonable power difference between two loading conditions, given that towing tank test results are available. The Test could be used by anyone to check extrapolated results from a towing tank test.

In addition, Benchmark cases should be published, open to public, which show reasonable power ratios. These could be used by organisations conducting predictions, by either model test or CFD, to check their procedures.

To produce the test and the Benchmark cases, the following steps were undertaken by the working group:

1. Assemble speed-power data at various draughts from real ships and extract the power relation between ballast and full-load.
2. Examine how accurate various extrapolation methods and correlation factors can predict the power relations compared to the set of full-scale data.
3. Derive one extrapolation method that is both accurate and simple enough to be used in the Test. This method is denoted the ITTC 2023 Power Ratio Guideline (in the following, “the Power Ratio Guideline” for short.
4. Demonstrating the accuracy of the method behind the Power Ratio Guideline by comparing with full scale data.
5. Decide reasonable thresholds for acceptance of the Test.
6. Demonstrate the Test using real data from the groups own towing tanks.
7. Derive power relations for a number of open Benchmark cases using the Power Ratio Guideline.

2.3 Proposed procedure for demonstration of acceptable power ratio of towing tank predictions

The following procedure can be used by towing tank facilities either within their own quality assurance work, or to demonstrate the accuracy of their methods to external verifiers.

The following procedure is proposed by the working group:

ITTC provides the Power Ratio Guideline as a locked software or website. The Power Ratio Guideline is an extrapolation method for scaling of towing tank measurements, and it is a simplified version of the 1978 Power Prediction method. The output is only to be used for checking power relations between draughts, NOT to be used for the predicting the absolute values of the speed-power curves. (The method is described in chapter 5. Absolut values will not be part of the output of the software/web service)

After the towing tank test for a new project, the facility provides extrapolated full-scale speed-power curves at trial and stipulated draught (EEDI draught and/or contract draught). The predicted power ratios are derived as

$$\Delta P_{PR} = P_{stipulated}/P_{trial} \quad (2)$$

An external verifier can check that the predicted power relations are reasonable by entering the model scale measurements and a few ship parameters (see listed required input in Appendix) into the software.

The output from the software is the Guideline power ratio:

$$\Delta P_{GL} = P_{stipulated}/P_{trial} \quad (3)$$

The fraction between the predicted and the guideline power ratios is derived:

$$D = \Delta P_{GL}/\ \Delta P_{PR} - 1 \quad (4)$$

D expressed in % is then the “error” in predicting the loaded draught curve, after that the trial model test curve is shifted to the sea trial results (as in Figure 1).

For EEDI verification, the working group suggest the following process. Note that this is a suggestion, which needs to be discussed with IACS, and other stakeholders.

The first time a tank is verified the verifier may request data for 10 past cases that has recently received EEDI verification from that verifier, plus the actual case. This collection is called Sample Collection. The actual case to be verified must be added to the Samples Collection. If the tank does not have 10 past cases with the particular verifier, then submitting only the statistics of D and main dimensions is acceptable.

Requirement for acceptance:

- 10-15 cases are submitted to the Sample Collection (no more, no less, in order not the skew the data set)
- The median D (design draught) (scantling draught) of the Sample Collection should be within ±3%
- The absolute value of D should be within 5% for 90% of the cases in the Sample Collection (the n^{th} point, where n=N*0.9 rounded to integer)
- The absolute value of D should be within 10% for 100% of the cases in the Sample Collection (otherwise a very good explanation is needed)

Figure 2 demonstrates the test for a Sample Collection of 15 cases.

This procedure verifies both the towing tank’s *prediction method*, and the actual case.

Each facility should strive for having a median error close to 0. Facilities that lay close to the limit for acceptance face a big risk to fail the test, since there is some variation between cases, and it is the statistics of the last 10-15 cases that counts.

It should be stressed that the test is meant to avoid large errors in the prediction of the *power ratio* between ballast draught and higher draughts. Each tank should use the most advanced and accurate method as possible for the absolute value of the power curves.

Table 2 Example of a successful verification of predicted power ratios.

	Number of cases	**Median D**	**|D| of 90% of samples**	**|D| of 100% of samples**
D_{design}	15	0.1%	3.0%	5.0%
$D_{scantling}$	13	0.3%	3.5%	5.6%

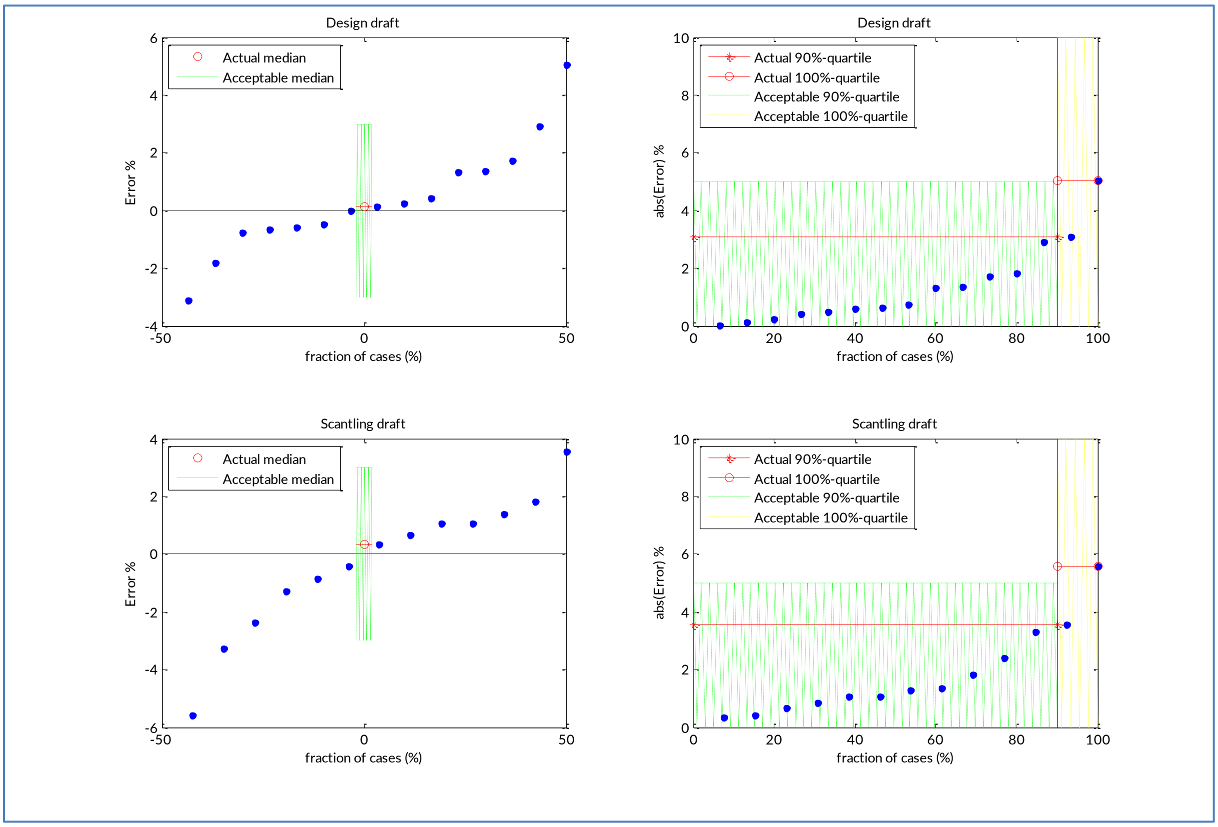


Figure 2. Example of a successful verification of predicted power ratios. Each blue dot represents a scaled model test at two drafughs. All 15 cases together make out the submitted Sample Collection for this facility.

2.4 Proposed procedure for demonstration of acceptable power ratio of CFD predictions

2.4.1 Model scale CFD

If power curves at various draughts are derived with model scale CFD:

According to ITTC Quality assurance for Ship CFD, the organisation should demonstrate its capability to conduct CFD predictions by demonstrating agreement with model test data for a large number of cases.

In addition, the full scale power ratios can be verified in the same way as for towing tank predictions as described above.

2.4.2 Full scale CFD

If power curves at various draughts are derived with full-scale CFD:

According to ITTC Quality assurance for Ship CFD, the organisation should demonstrate agreement with full-scale sea trial data for a large number of cases. This will mostly be ballast cases.

In addition, the following quality ranking is proposed:

Quality ranking 1. The organisation should demonstrate that their CFD process results in power ratios that agree on average with those from sea trials at various draughts for many cases.

Quality ranking 2 (lower). The organisation demonstrates using many cases (10) that have previously been model tested. The power ratios from CFD are compared with those from the model test when evaluated with the Power Ratio Guideline as above.

3 Speed-power data at various draughts from real ships

3.1 Collection of full-scale data

To develop and verify the Power Ratio Guideline, the working group needed trustworthy information on ships' propulsion power at various draughts. Unfortunately, this kind of data is very scarce since sea trials are almost always conducted at ballast draught only. Two sources of such data were identified:

- Data from the few occasions where sea trials have been conducted for the same vessel at various draughts.
- Ship monitoring data from ships in operation which are subject to a higher scatter than sea trials.

The group members worked intensely for more than two years to collect such data. A number of ship owners were contacted, and some did provide very valuable data sets, under the condition that the ships remain anonym. Some of the group members also received sea trial data from yards. Finally, some group members were able to provide data from sea trials that had earlier been provided by yards. After excluding some cases with uncertainties that have been judged poor, 19 cases remained, listed in Table 3.

Table 3. Full-scale cases used in the study

Provided by	Data type	Sisters	CB	Fn
HSVA	Sea trial (3 drafts)	6	0.80	0.17
MARIC	Sea trial (3 drafts)	2	0.80	0.16
MARIN	Sea trial (3 drafts)		0.79	
MARIN	Sea trial (2 drafts)		0.81	
MARIN	Sea trial (2 drafts)		0.78	
MARIC/SSSRI	Operational	1	0.85	0.18
SSPA	Operational	3	0.60	0.23

JMU	Operational	3	0.64	0.17
HSVA	Operational		0.66	
MARIN	Sea trial (2 drafts)		0.59	
MARIN	Sea trial (2 drafts)		0.69	
MARIN	Sea trial (3 drafts)		0.64	
HSVA	Sea trial (3 drafts)		0.65	
SSPA	Sea trial (3 drafts)	1	0.83	0.15
SSPA	Sea trial (3 drafts)	1	0.81	0.15
SSPA	Sea trial (2 drafts)	1	0.81	0.15
SSPA	Sea trial (2 drafts)	1	0.60	0.23
SSPA	Sea trial (3 drafts)	1	0.83	0.15
SSPA	Sea trial (3 drafts)	3	0.80	0.18

3.2 Full scale data processing

3.2.1 Sea trials

Only cases with speed trials available for more than one draught were selected. Even when the original speed trial report was available, the speed trials were analysed again according to the newest ITTC Recommended Procedure (7.5-04-01-01.1, Preparation, Conduct and Analysis of Speed/Power Trials). (Some trials were conducted prior to 2014 though).

A reference speed is selected, close to EEDI Vref and the power is extracted for that speed by interpolating the power curves at the different draughts. The power ratios are extracted as:

$$\Delta P_{STd}=P_{STdesign}/P_{STballast} \quad (5)$$

$$\Delta P_{STc}=P_{STscantling}/P_{STballast} \quad (6)$$

where

P_{ST} is the derived power from sea trial at the selected reference speed.

3.2.2 Operational data

The operational data were filtered according to the following:

- Shallow water – water depth smaller than: $h \leq 2.4Vs^2/g$ or h <=2.5T
- Wave height>1.5*sqrt(Lpp/100) (ITTC Recommended Procedures for Speed Trial)
- periods when the vessel is accelerating or slowing down
- non-sea-voyage parts of the vessel operation (for example, when a pilot is onboard, during canal transit, …)
- outliers (for example, ΔV/Δt >0.5knots, ΔSHP/Δt >5%)
- trimmed conditions

The data were corrected for wind, waves, temperature according to ISO 19030 or similar (providers standard).

Data points for ship’s speed around the selected reference speeds were selected. Power values for ballast, design and scantling is estimated by taking an average in a window for draughts close to ballast, design and scantling, and the power ratios computed applying equations (5)-(6). Two examples are shown below.

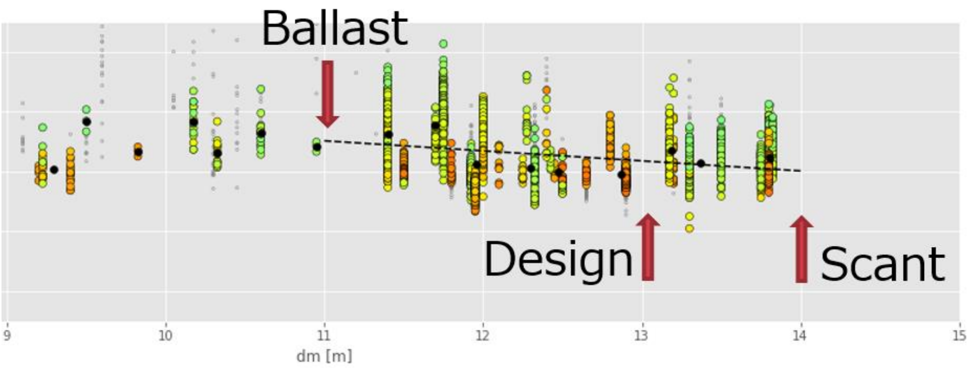


Figure 3 Example of extracting power relations from operational data in the study.

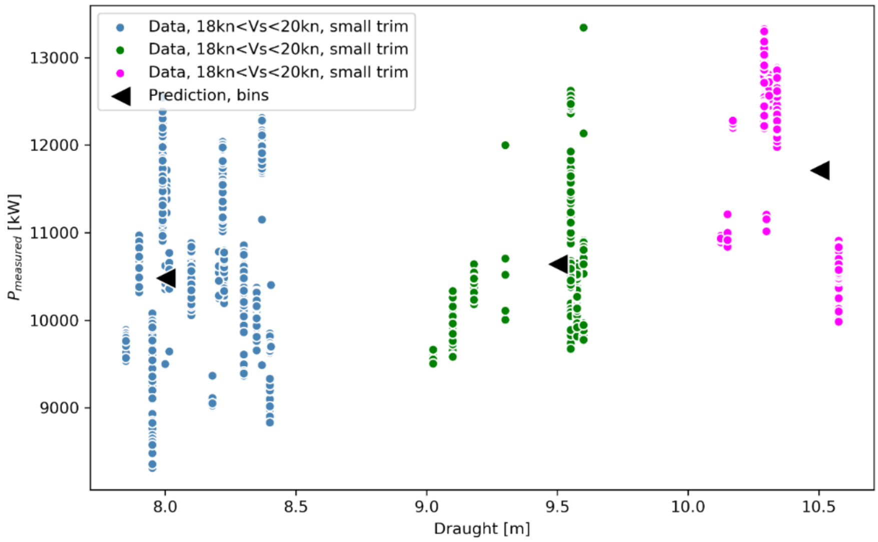


Figure 4 Example of extracting power relations from operational data in the study. Power over draught.

4 Derivation of the method behind the Power Ratio Guideline

4.1 Examine various methods

To derive the Power Ratio Guideline, the group first investigated the capability of various existing extrapolation methods to accurately predict the power ratios. The methods under investigations were the methods currently used by the group members organisations, and variants of these. Several features were investigated:

- 2D or 3D method
- Form factors from
  - Prohaska
  - Hughes-Plot
  - CFD-based form factor at model-scale (Korkmaz, 2021)
  - CFD-based form factors with fairing piece aft of transom

  - CFD-based form factor at model-scale without friction line, (Wang, 2016&2019)
  - CFD-based form factor at model and full-scale (Korkmaz, 2022)
  - Polynomial (Shirase, 1982)
- Friction line
  - ITTC-57
  - Schoenherr
  - Grigson
- Correlation factors
  - Draught dependent *C*a
  - Draught independent *Ca*
  - Draught independent *C*p
- Transom correction
  - Sintef

To judge which methods were capable, the power ratios over draughts derived from the full-scale data were compared to the power ratios predicted with the various methods.

The conclusions from this part of the study were that:

a) Not one method or variant could be pointed out as superior
b) The determination of form factor is crucial for accurate prediction of the power ratio. The Prohaska method currently recommended in the ITTC 1978 Power Prediction Method is in a lot of cases not usable, there are better alternatives nowadays.
c) The group identified that scale effects of deeply submerged transoms are not specifically accounted for in the current ITTC 1978 Power Prediction Method.

4.2 The Power Ratio Guideline

To create the Test explained in section 2.3, the group needed to develop a new extrapolation method for the higher draughts based on the result for the ballast draught, called the Power Ratio Guideline. This method needed to be:

- Simple to program and use without human interpretation
- Accurate enough to predict power differences between draughts (but not absolute power)

After intense work with various options, the group agreed on the definition of the Power Ratio Guideline. It is based on the standard ITTC 1978 Power Prediction Method, as currently used by SSPA/RISE, with a few modifications:

a) **Form factor** is defined by calculating the difference in form factor between various draughts (Δk) using a regression formula that was developed within the working group, see below Section 4.2.1. (Remember that the purpose of the extrapolation method is only to predict the power ratio between different draughts, not absolute power).

b) **Transom**. A new method for scaling the transom resistance is introduced.
c) **Correlation factors**. No *C*a or *C*p are used.

4.2.1 Regression formula for Δ*k*

CFD has shown to be superior to determine form factors for a variety of vessels (Korkmaz, 2021, Wang, 2016&2019, Raven et al., 2008). The working group therefore decided to use form factors from CFD to generate an empirical expression for the difference in form factor between different draughts, Δ*k*. 170 sample points of form factor *k* from CFD double model, viscous simulations were collected from three members of the working group, RISE/SSPA, MARIN and MARIC, on the basis of the best practices of each institute. These points include the different draughts of different ship types such as oil tankers, bulk carriers, containers, and gas carriers. The ship parameter ranges of sample points are shown in Table 4

Table 4 Ship Parameter range of CFD sample points for derivation of Regression formula for Δk

	Fn	**Rn(*10^6)**	C_B	X_{CB} (%Lpp)	***L/B***	B/T_m	B/T_a	**trim(°)**	t_r
MIN	0.13	6.6	0.52	-6.03	5.1	2.2	2.2	-1.3	0%
MAX	0.28	23.9	0.85	5.11	7.1	7.9	7.4	1.1	18%

T_m and T_a are mid and aft draft respectively, and t_r is the transom ratio, i.e., transom area over maximum cross-section area.

The final regression formula was derived by Jinbao Wang, referring to Michiel's work, with the joint effort from this group.

The number of points for Δ*k* regression was reduced to 139, because *k* at design draft of each ship is used as a reference point. When the formula was developed, the main factors affecting Δ*k* are focused, while the parameters with less influence are ignored. This is for engineering considerations. The formula needs to meet the engineering accuracy requirements, and it should be convenient to use and not too complicated.

After multiple rounds of gradual approximation of multivariate regression analysis, the following empirical formula for Δ*k* is established:

$$\Delta k = [7.35\left(\frac{B}{L}\right)^{1.94}\left(\frac{T_a}{B}\right)^{0.384}(C_B)^{0.782}+0.058](1+t_r)^{20tr} - [7.35\left(\frac{B}{L}\right)^{1.94}\left(\frac{T_{a\_D}}{B}\right)^{0.384}\left(C_{B\_D}\right)^{0.782}+0.058](1+t_{r\_D})^{20t_{r\_D}} \quad (7)$$

The subscript *D* indicates the design draft.

The relationship between regression-based *Δk* and CFD-based Δ*k* is shown in Figure 5.

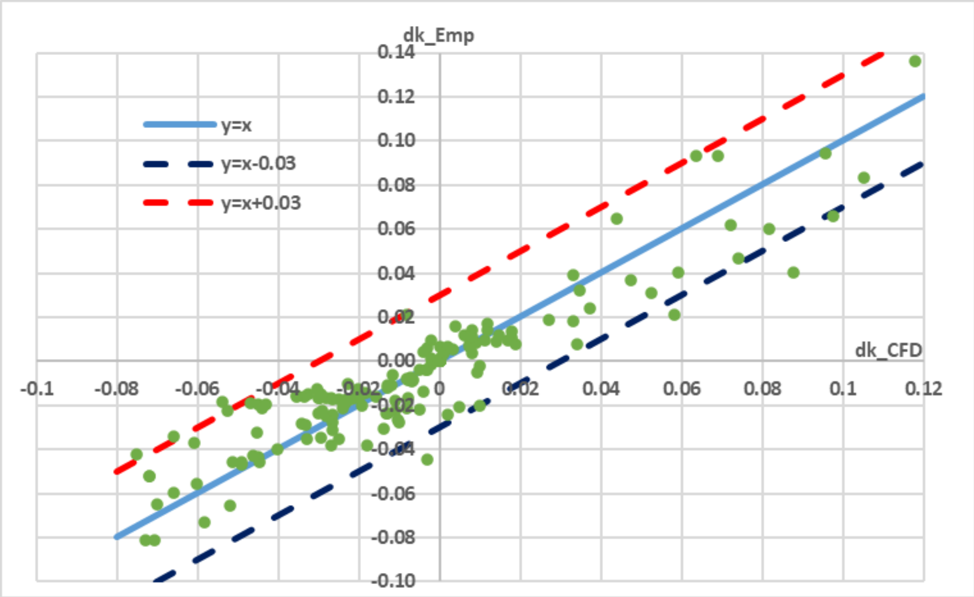


Figure 5. The relation between Δk from regression and CFD

The number of points where the Δ*k* difference exceeded the 0.03 boundary was 9 (accounting for 6.5%), and the remaining points are within the boundary. Statistical analysis shows that the Pearson correlation coefficient of the two variables has reached 0.926.

The deviation distribution of Δ*k* from regression and CFD is shown in figure 6.

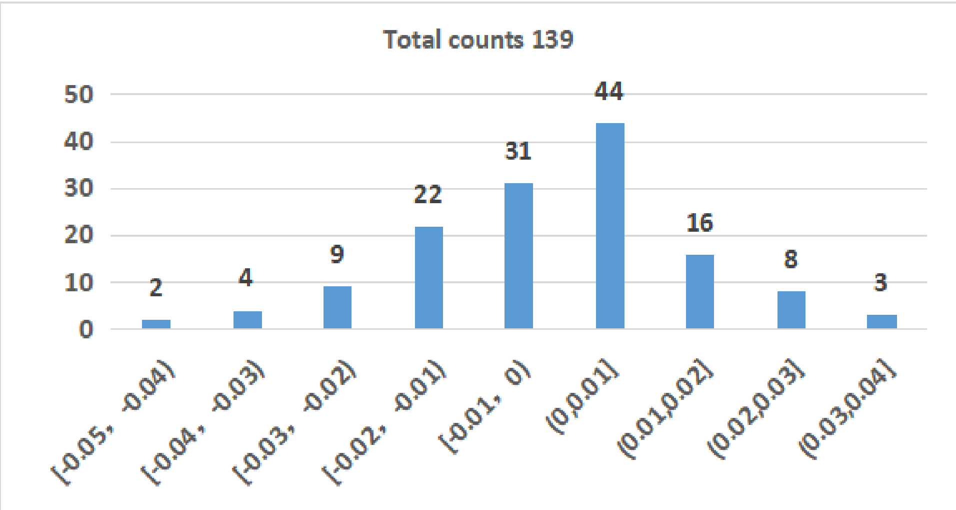


Figure 6. Distribution of difference between Δk from CFD and regression

The mean error of deviation is -0.0004, and mean absolute error is 0.0114. It can be seen that, Δ*k* obtained from the regression is in good agreement with the Δ*k* obtained from CFD.

In addition, in order to conveniently obtain a relatively reasonable k value as necessary input at design draft for power ratio prediction, when CFD or model test was not performed, or k at design draft is not available for interesting parties, the regression formula for k has been further developed by Jinbao Wang, on the basis of 125 points at even draught from the above 170 sample points, with limits in Table 5.

.

$$k = [4.59\left(\frac{L}{B}\right)^{-1.43}\left(\frac{B}{T}\right)^{-0.61}(C_B)^{0.66} + 0.044]\,(1+tr)^{15tr}(1+Xcb)^{0.5} + 0.0045\frac{B}{T} - 0.015 \quad (8)$$

Table 5 Ship Parameter range of CFD sample points for derivation of Regression formula k at even draught

Case	Fn	Rn(*106)	C_B	X_{CB} (%Lpp)	L/B	B/Tm	t_r
MIN	0.13	6.6	0.59	-3.57	5.09	2.20	0.00
MAX	0.26	22.3	0.85	5.11	7.14	5.80	17.7%

The relationship between regression-based k and CFD-based k is as Figure 6.

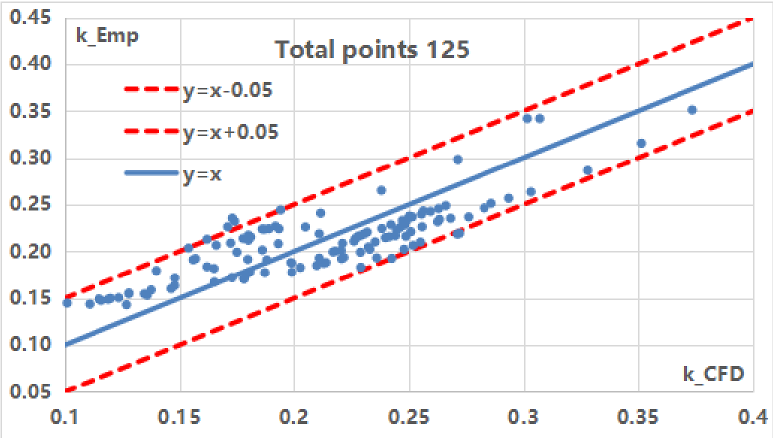


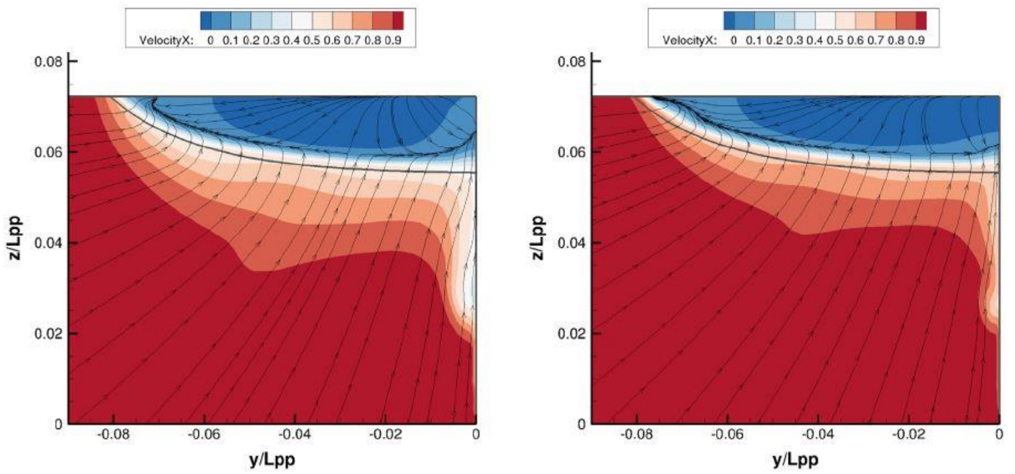
Figure 7 Relation between k from CFD and regression

5 points are out of the scope of 0.05(accounting for 4%), and Pearson Correlation Coefficient is 0.833. Accordingly, formula (8) can be used as an approximation of k *for the test as the input at design draught for power ratio prediction*, when CFD or model test is not performed.

Note that formula (8) is not necessarily required if k at design draught is known, and can be replaced by k obtained in more advanced way, such as CFD or model test.

4.2.2 **Empirical correction for transom submergence**

The existence of flow separation in model or full-scale causes the form factor approach of the current recommended procedures for the scaling of the towing tank tests ITTC 7.5-02-03-01.4 to be invalid, as noted in ITTC 7.5-02-02-01. An example of the commonly observed flow separation is the recirculation flow region behind a substantially submerged transom, i.e. wetted-transom flow which was investigated by RISE/SSPA in Korkmaz (2022). The qualitative investigation on the local flow field and quantitative investigations on the viscous resistance in model and full scale confirmed that the current recommended procedures of the form factor approach for any vessel with a substantial transom stern for which the transom runs wet is not valid. It is demonstrated that the form factor is not independent of the Reynolds number when there is flow separation in the boundary layer. When the same model and full-scale form factors are used to extrapolate the resistance, the full-scale viscous resistance is under-predicted in the case of a wetted-transom flow. An illustration of this can be observed in Figure Caption A where the wake behind the transom (indicated with black solid line) remains nearly unchanged from model scale to full scale, while the rest of the wake is thinner with the increasing Reynolds number as expected. Assuming the same form factors in the model and full scale implies that the wake behind the transom should be thinner and the viscous pressure resistance caused by transom reduces proportional to the frictional resistance coefficient. However, qualitative investigations on form factors based on numerical frictional lines (Korkmaz, 2019) pointed out that the contribution of the flow separation behind the transom is not proportional to the frictional resistance coefficient.



(a) Model scale u/U contours with limiting streamlines at $x/L_{PP} = -0.03$

(b) Full scale u/U contours with limiting streamlines at $x/L_{PP} = -0.03$

Figure 8 Local flow behind the transom of a test case at scantling draught at model and full scale using EASM turbulence model Korkmaz (2022)

As a result of the investigations on scaling of wetted-transom resistance two alternative methods were suggested in Korkmaz (2022); the two-form-factor method (2-*k* method) and an empirical transom correction. The latter is obtained from a regression analysis on the transom form factor, which is the measure of the viscous pressure resistance deficit when the form factor concept of recommended ITTC 7.5-02-03-01.4 procedure is used. The transom form factor, k_{tr}, is calculated as

$$k_{tr} = [-0.025 + tr_{ratio}(1.5 - 2.3tr_{ratio} - 0.07LCB)] \times \left[-5.45 + \log_{10}\left(\overline{Re_M}\right)(1.415 + 4.32\, tr_{ratio}) - \log_{10}\left(\overline{Re_M}\right)^2 (0.081 + 0.55\, tr_{ratio})\right] \quad (9)$$

where

tr_{ratio} is the ratio between the submerged transom area and the maximum cross section area for the given draught at rest,

$\overline{Re_M}$ is the average of Reynolds numbers in the model tests and LCB is relative to $L_{PP}/2$ in percent of L_{PP}.

The extrapolation procedure with the suggested empirical correction method is as follows

I. Total resistance coefficient, C_{TM}, is obtained from the towing tank tests,

II. The model scale form factor, k_M, is determined either by the Prohaska method or by CFD based form factors as described in ITTC 7.5–03–02–04,

III. The residual resistance is calculated as $C_R = C_{TM} - (1 + k_M)C_{FM}$

IV. The full-scale form factor, k_S, is calculated as $k_S = k_M + k_{tr}$ where

- If $tr_{ratio} \leq 0.025,\ k_{tr} = 0$
- $tr_{ratio} > 0.025,\ k_{tr}$ is calculated from the empirical correction equation
  - If the calculated $k_{tr} \leq 0$ then $k_{tr} = 0$
  - If the calculated $k_{tr} > 0$ then k_{tr} value from the empirical correction can be used

V. The full scale total resistance coefficient is calculated as

$$C_{TS} = (1 + k_S)C_{FS} + \Delta C_F + C_A + C_R + C_{AAS} \tag{10}$$

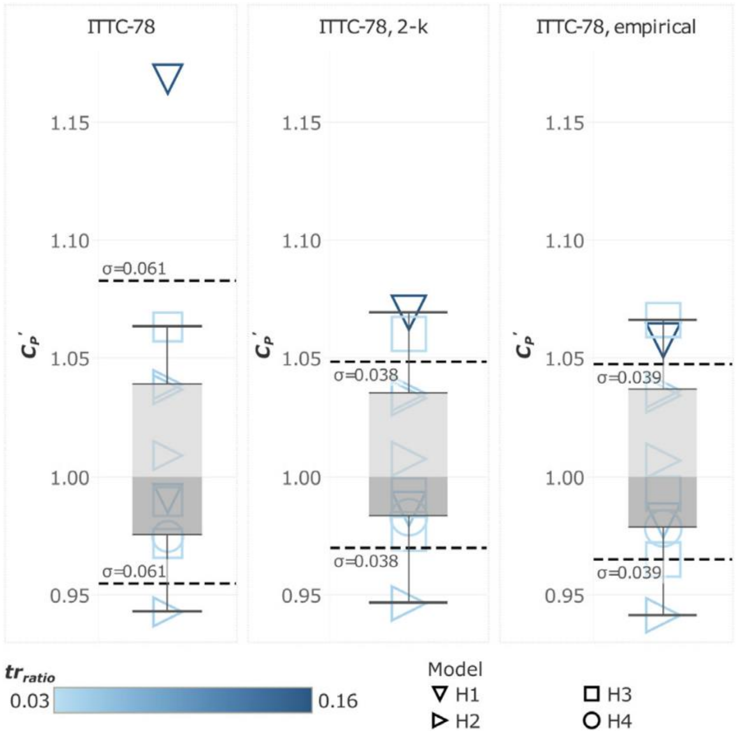


Figure 9 Normalised correlation factors from the standard ITTC-78 method (left), CFD based 2−k form factor method (middle), and the empirical correction procedure (right) Korkmaz (2022)

The power predictions from the two proposed procedures were compared to the predictions from the standard ITTC-78 method (with form factors from Prohaska plot of resistance test with separated transom) and the speed trials. The comparison between the speed trial measurements and the model test power predictions were performed through the correlation factors which is the division between the speed trial measurement and the prediction from the extrapolation method in Figure 9. As indicated by the standard deviation of the correlation factors, the scatter between the measured and predicted power reduced significantly by the 2-*k* method and the empirical correction method. The empirical correction method, which requires no CFD, can be incorporated into the current ITTC-78 method. It can accurately restore the deficit of the extrapolated full-scale viscous resistance from Prohaska plot method in the event of a wetted-transom flow. The suggested alternative method is expected to be instrumental in improving the accuracy and reliability of the EEDI predictions performed at the scantling draught, where the transoms of many vessels are submerged.

5 Demonstration of the solutions credibility

5.1 Demonstrating confidence in the extrapolation

To be able to recommend the Test to the public, the group needed to demonstrate that the Power Ratio Guideline is capable of predicting the power ratios. For this purpose, we used the following error indicator:

$$E=\Delta P_{ST}/\ \Delta P_{GL}\ -1 \qquad (11)$$

Note that E corresponds to the *error in predicting power at design or at scantling draught by the Power Ratio Guideline*, after that the ballast model test curve is shifted to the sea trial results (as in Figure 1).

Figure 10 and Table 6 shows the distribution of the errors. The following can be noted:

a) The median error is very small. Hence, the method is accurate on average.

b) Two standard deviation is around 10%. This is well aligned with the total uncertainty of sea trials reported in literature. The combination of the precision and bias limits of single speed trial result is approximately 10% as indicated by Werner and Gustafsson (2020) and Insel (2008). Hence, the spread we see is likely to be due to sea trial uncertainty, rather than prediction error.

Based on these observations, it is reasonable to claim that this is as well proven as a prediction method can ever be.

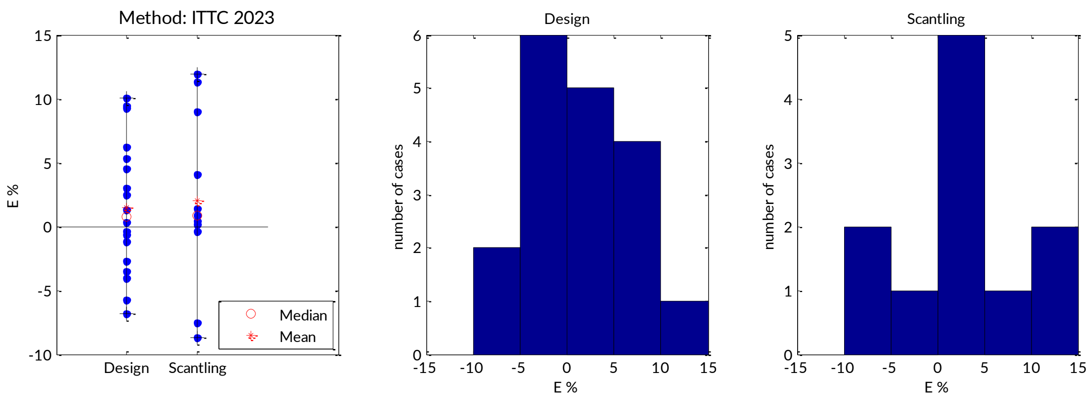


Figure 10. Error in predicting design-to-ballast power ratio and scantling-to-ballast power ratio using the new Power Ratio Guideline, compared to sea trials and operational data.

Table 6 Error in predicting design-to-ballast power ratio and scantling-to-ballast power ratio using the new Power Ratio Guideline, compared to sea trials.

	Number of cases	**Median D**	**2*std**
E_{design}	18	0.8%	10.3%
$E_{scantling}$	12	0.6%	12.9%

As explained in section 4.2.1, the Power Ratio Guideline uses a regression formula for the form factor determination. The Power Ratio Guideline is a simplified method that should only be used for the power ratio Test. It is therefore interesting to compare the prediction with this method against more advanced case specific methods. Figure 11 shows the error compared to the sea trials when the group members most advanced extrapolation methods are used.

- Tank 1 uses CFD based form factor and transom correction
- Tank 2 uses 2D scaling, transom correction and draft dependent *C*a
- Tank 3 uses CFD based form factor and transom correction
- Tank 4 uses polynomial form factor derivation and draft dependent Ca
- Tank 5 uses CFD based form factor and transom correction

Unfortunately, the case specific methods could not be applied to all cases, due to confidentiality. With reservation for the limited statistics, it can be noted that the performance of the simplified method is similar to the more advanced. (That is, in predicting power ratios. It should be stressed that the simplified method is not capable of predicting absolute power curve).

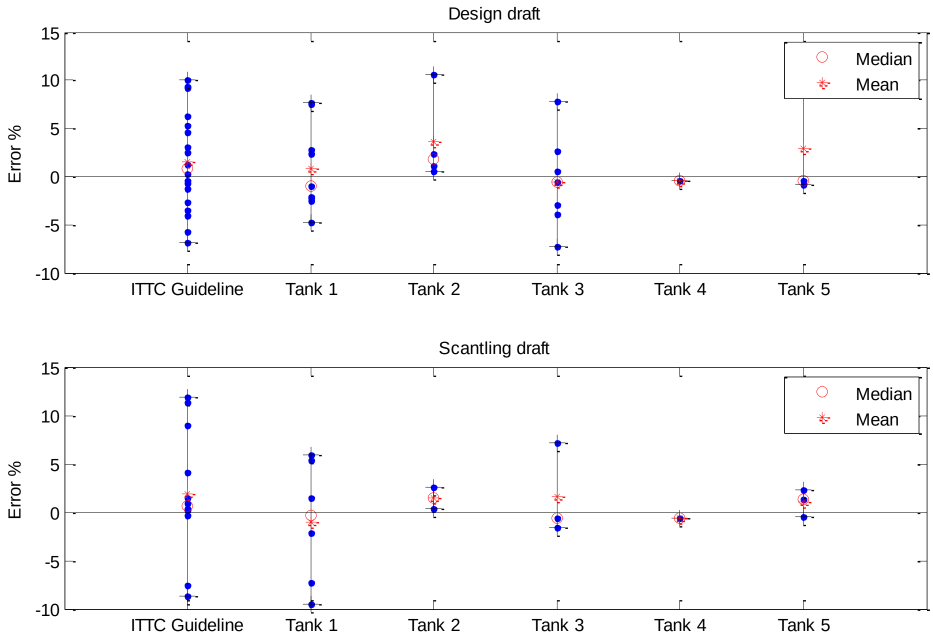


Figure 11. Error in predicting design-to-ballast power ratio and scantling-to-ballast power ratio using different methods, compared to sea trials and operational data.

5.2 Block coefficient dependency

As shown in Figure 12, the error of the new Power Ratio Guideline tends to be higher for slender vessels than for full block. That would mean that the power at design draft is underpredicted for slender ships, when using the Power Ratio Guideline.

The working group notes this tendency has been observed before with other prediction methods.

There are several possible explanations:

- A scale effect on wave resistance, which is not accounted for in the ITTC extrapolation. This would affect the slender ships more, since they are also faster. Raven (2008) discusses this issue.
- A scale effect on braking waves in ballast for full block ships. Holtrop studied sea trials statistics and found that for full block vessels with low *T*f, the *C*p should be higher.

However, this tendency is not obvious at scantling. The working group recommends the R&P committee to study this further.

Perhaps it is possible to get access to the IMO database of EEDI/EEXI ships, to get more data.

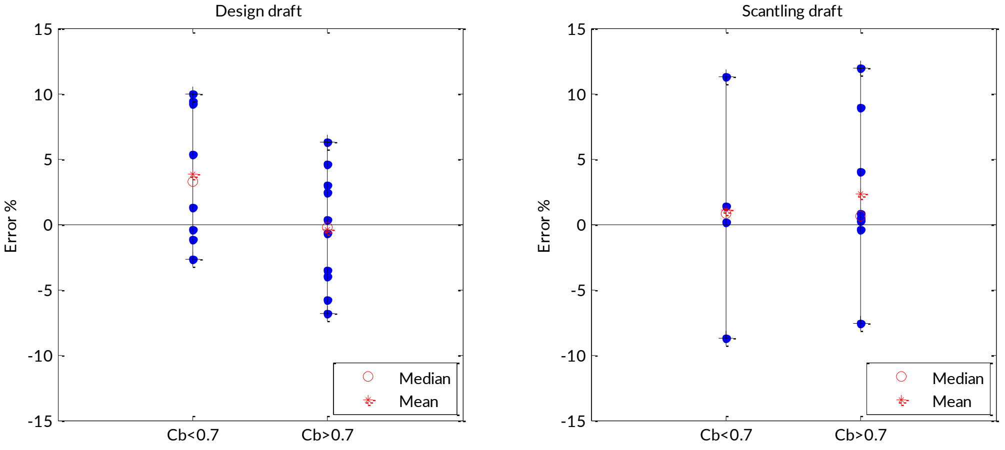


Figure 12. Error in predicting design-to-ballast power ratio and scantling-to-ballast power ratio using the new Power Ratio Guideline, compared to sea trials and operational data.

6 Example of usage

6.1 Application of the Test

To illustrate how the test is used for real cases, it has been applied to past cases from the towing tanks of the working group. Five towing tanks used their current most accurate extrapolation method, applied to recent towing tank test of conventional cargo vessels. Different cases are used for each tank. Table 7 and

Table 8 list the results. Plots are shown in Appendix 2. As seen in Figure 13, there is no clear trend over block coefficient for over or under predicting relative to the Test.

All tanks except for one pass the test.

Table 7 Application of the Test for real towing tank data of past cases. Indicator D (%) for Design draught.

Method	Number of cases	Median D	|D| of 90% of the cases	|D| of 100% of the cases
'Tank 1'	15	0.1	3.1	5.0
'Tank 2'	13	1.5	4.9	8.1
'Tank 3'	13	-0.3	3.0	3.3
'Tank 4'	11	0.9	6.1	6.2
'Tank 5'	16	0.3	2.7	3.8
'All'	68	0.3	4.9	8.1

Table 8 Application of the Test for real towing tank data of past cases. Indicator D (%) for Scantling draft.

Method	Number of cases	Median D	|D| of 90% of the cases	|D| of 100% of the cases
'Tank 1'	13	0.3	3.5	5.6
'Tank 2'	12	0.9	4.8	6.7
'Tank 3'	10	-2.3	3.3	4.8
'Tank 4'	2	-2.8		
'Tank 5'	15	0.7	2.5	2.8
'All'	52	0.2	4.3	7.1

Table 9. Limits for passing the Test

	Number of cases	Median D	|D| of 90% of the cases	|D| of 100% of the cases
Accept limit	10	< 3%	< 5%	< 10%

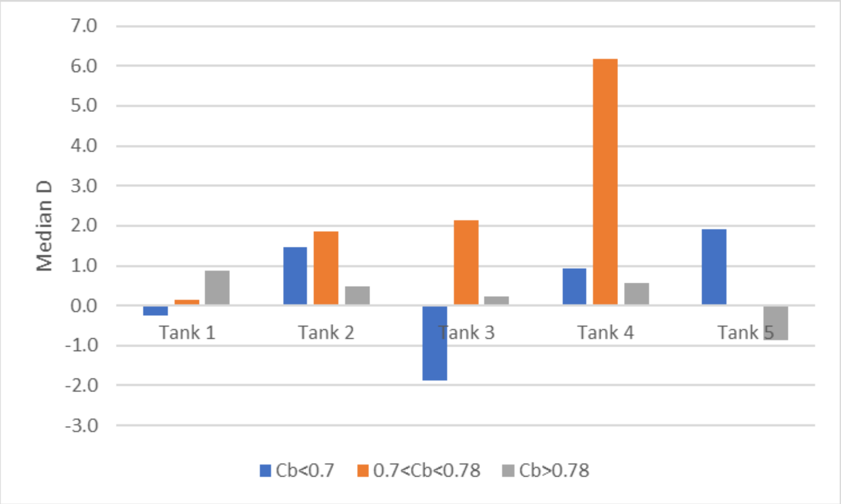


Figure 13 Median D% at design draft

6.2 Benchmark cases

As a service to the community, the group provides the result with the Power Ratio Guideline for three open ship cases: JBC, KVLCC2 and KCS. These are well known cases that have been used in various benchmark studies and which hull forms are openly available.

The purpose of publishing these results is to give all organisations the opportunity to test their prediction methods (CFD or EFD).

Model tests for these cases have been published previously, but only at design draught. Therefore, additional towing tank tests were conducted within the working groups:

- RISE-SSPA conducted test for additional draughts for KVLCC2
- KRISO conducted test for additional draughts for KCS
- JMUC provided additional draught for JBC with the cooperation with NMRI (Now, open on the website of NMRI)

The power ratios derived with the Power Ratio Guideline for the three cases are provided in Table 10. The model scale values will be published as a separate report. The group members also applied their methods to the Benchmark cases. The difference $D = \Delta P_{GL}/\ \Delta P_{PR}$-1 are shown in Table 11. It can be seen that those who passed the test (Section 6.1) have D<6% for the Benchmark cases. This can be used as an indication to organisations who have no access to real data, and which want to perform a quality check. However, it should be stressed that this is not enough for a valid qualification, due to the limited number of cases. It would be good if ITTC could published a larger number of Benchmark cases.

Table 10. Power ratios of open benchmark cases, derived with the Power Ratio Guideline

	Speed (knots)	$\Delta P_{GLd}=P_{design}/P_{ballast}$	$\Delta P_{GLs}=P_{scantling}/P_{ballast}$
KCS	20	1.256	1.40
JBC	12.05	1.459	
KVLCC2	14.5	1.412	1.505

Table 11. Difference between the tanks' methods and the Power Ratio Guideline

Ship	**Tank**	D_d	D_s
JBC	Tank 1	1%	
KCS	Tank 1	-3%	-6%
KVLCC2	Tank 1	1%	4%
JBC	Tank 2	-1%	
KCS	Tank 2	0%	-1%
KVLCC2	Tank 2	-2%	-3%
JBC	Tank 3	2%	
KCS	Tank 3	-3%	-5%
KVLCC2	Tank 3	0%	-1%
JBC	Tank 4	6%	
KCS	Tank 4	-4%	-7%
KVLCC2	Tank 4	1%	1%
JBC	Tank 5	4%	
KCS	Tank 5	-1%	-1%
KVLCC2	Tank 5	1%	2%

7 Motivation for the Test formulation

The motivation for requiring a collection of cases rather than verifying each case is the following:

The Power Ratio Guideline behind the test is proven to be accurate against sea trials and operational data on average, but with a large precision uncertainty (scatter). Individual cases may deviate from the average error. This could be compensated with a large threshold for acceptance. However, this could be misused in such a way that all cases end up in one end of the acceptable threshold. By requiring both a certain median *and* precision, we prevent misuse and at the same time acknowledge that there is a spread between cases.

Median acceptance

The Power Ratio Guideline is shown to be accurate on average, with median error less than 1%. Hence, it could be argued that the required limit for acceptable Test should be 1%. However, with reference to the unclear dependency of block coefficients, it is agreed that the Limit for acceptable median should be 3%.

90 percentile

The limit for 90 percentile is set after reviewing the result of applying the test to over 65 real cases. It is acknowledged that there will be cases that fall outside for various reasons. The limit should not be set so that ALL existing methods pass. It should be set so that the best available methods pass. There should be a motivation for improving the prediction methods.

100percentile

In the same manner the 100 percentile limit is set based on common sense and the experience from the 65 cases in the study.

8 Other corrections of model scale data

(eg blockage, what is reasonable between different drafts)

TO BE ADDED

9 Technical and commercial consequences of a modified correlation procedure

If ITTC publish and recommend the Test to be used by any stakeholder in the shipping industry, it will have some consequences.

Technical consequences for the towing tank facilities

Each towing tanks facility should already today derive their own correlation factors (ITTC 7.5-04-05-01) in order to deliver credible power predictions. The new Test will apply to cargo vessels that go on speed trials at a different draught than contract or EEDI draught. Facilities that wish to deliver credible power predictions for such vessels, need to make sure that their extrapolation process meets the requirement. In practice, the facilities need to check their current process for a number of past cases of various types. (More than 10). If the collection of results fails the Test, the facility needs to modify the extrapolation procedure or correlation factor. Introducing the new transom correction, CFD-based form factors or the new Δk-formula is recommended by the work group to improve the results.

If a towing tank’s extrapolation method or correlation factors must be changed, it can be difficult to compare the performance of new projects with past projects. This can be worked around by re-evaluating the past projects with the new method.

Commercial consequences for the towing tanks facilities

There will be some initial work required by the towing tank facilities to demonstrate that they comply with the Test the first time. After that, it is not expected to increase the workload much for the towing tanks. However, if a towing tank facility needs to modify its extrapolation method or correlation factors, it will require some effort.

If the method needs to be changed and the past projects deviate much from the new standard, it may be seen as a negative impact for the facilities credibility. ITTC should therefore prepare a common set of information material that minimise this consequence (see Section 10.4).

Those tanks which have accurate extrapolation methods and are able to demonstrate this based on many cases will benefit from the new Test. On the contrary, it could be negative to new tanks or tanks with few cargo vessel projects. However, this is the case already today, since we require correlation work is carried out by each facility (ITTC 7.5-04-05-01).

Consequences for EEDI rules

It would be a good idea for MEPC to include the Test in the EEDI regulation, as a requirement for achieving an EEDI value. Today, the rules require that model test are conducted at trial and scantling draughts. Furthermore, the EEDI verifier (usually a class society) requires witnessing the model test and inspecting for example test protocol and extrapolation procedures. Introducing the new Test would be in line with the already existing rules. The consequences would be that the EEDI-value is verified with higher fidelity.

It could happen that an existing vessel has an EEDI-value based on past towing tank predictions that would heavily fail with the new rules. A new, similar vessel would then achieve a different EEDI-value. This would be experienced as confusing to the shipping industry. This can only be counteracted by clear information on the changed rules.

Consequences for yards

The Test will have a beneficial effect on the fair competition between the yards, since the performance predictions will be less dependent on which towing tank facility they use. If a towing tank that a yard regularly uses needs to change the extrapolation method or correlation factors drastically, it can be difficult for the yard to compare the performance of new and past projects. It can then be difficult to show that a new design is improved compared to the previous. This problem can be worked around by re-evaluating the past projects with the new method and referring to ITTC information package (see Section 10.4).

Because a yard needs to guarantee the contract speed on a speed sea trial, scatter in speed trial results is often taken into account in a speed-power curve at trial draught. The Guildeline power ratio doesn’t account for such scatter, accordingly a yard might adjust a margin for the contract speed.

Consequences for ship owners

The new Test is expected to give more accurate power predictions at all drafts, which is overall beneficial for ship owners. Power predictions are important input to various processes such as charter party agreements, investment business case, weather routing, and fleet management. Accurate power predictions are also important for dimensioning the propulsion machinery and propeller. Underestimated power requirement may lead to failure to keep the speed in adverse weather, which may have both commercial and safety consequences.

Negative consequences to the ship owner may be if a new ship performs worse according to tank test compared to existing ships of similar type. This may affect e,g, the charter rate.

Commercial consequences for the ITTC community

By raising awareness of the Test, we also put the spotlight on the problem. This in itself may have negative consequences for the trust in towing tank testing in general. It is *very* important that the information about the new Test for towing tank test is accompanied with the recommendation to put same requirement on CFD predictions. People not aware of the actual uncertainties in the prediction chain may be negatively surprised by them now that we put the spotlight on. So important as well for us to stress it will be no better with CFD instead.

Consequences for NOT acting, for the ITTC community

MEPC has identified the problem with uncertain correlation factors at different drafts since many years and requested ITTC to act.

Ship owners get increasingly aware of the problem.

Providers of pure CFD-based power predictions claim that CFD is the solution to the problem. (Which is not true, CFD is less accurate and requires correlation factors as well.)

If we fail to solve the issue now, we risk losing the high credibility that the towing tanks enjoy.

10 Conclusion and Recommendation

Model tests are the most reliable method for the prediction of ship performance. A working group within ITTC has presented an addition, which increase the accuracy further.

The contract speed and the EEDI speed of new ships are verified by speed trials. For all common cargo vessels, except oil tankers, speed trials are performed at ballast draught. Model tests at two draughts are used to transform the speed trial results to other drafts, to fulfil contract guarantee or EEDI verification.

Due to the small number of speed trial data on full load draught, it has been difficult for towing tank facilities to correlate the performance prediction methods for the deeper draughts. This has led to an unfortunate situation where the power prediction at deeper draught can differ depending on which towing tank facility has conducted the test.

Although this challenge is not new and is known to most stakeholders, we think that now is the time for the industry as a whole to take responsibility, improve predictions and create a more level playing field.

The ITTC "*Working group on parameters for full scale power predictions*" has worked intensely for 3 years to find a solution. The group gives the following recommendations to AC:

10.1 Recommended Procedures for assuring high accuracy in towing tank power predictions at all draughts

The group recommends introducing a new procedure for demonstration of acceptable power ratio of towing tank predictions (described in detail in Section 2.3). It is based on a Test where model and full-scale values of several projects are entered, and with prescribed margins for acceptable median and spread of the Test error.

We recommend all towing tanks to check and if needed adjust their methods, in the waiting for a possible introduction to IMO. Each facility should strive for having a median error as close to 0 as possible. Facilities that lay close to the limit for acceptance face a big risk to fail the test, since there is some variation between cases, and it is the statistics of the last 10-15 cases that counts.

It should be stressed that the test is meant to avoid large errors in prediction of the *power ratio* between ballast draught and higher draughts. Each tank should use the most advanced and accurate method as they can for the absolute value of the power curves.

<u>A new procedure or adding to an existing?</u>

The existing ITTC 7.5-04-05-01 *Guideline on the determination of model-ship correlation factors* describes how towing tank facilities should use full-scale speed trials to continuously assure highest possible accuracy of power predictions. Since this is in practice mainly applicable to ballast draught, we recommend introducing the new procedure as a compliment.

It would be somewhat misleading to add the new procedure to the existing 7.5-04-05-01, since it is a procedure for checking and possibly improving the *complete extrapolation method*, and whereas 7.5-04-05-01 only deals with determining the correlation factors.

Since the new proposed procedure rely on a correct prediction of the absolute value of the Trial draught power curve, it is fundamental that the correlation factors for Trial draught is correctly derived. However, an important step is missing in the ITTC 7.5-04-05-01 *Guideline on the determination of model-ship correlation factors*. It does not state that the correlation factors should represent the **median** of all trials in the statistics, such that 50% of the cases are below and 50% above. Some towing tanks derive instead the correlation based on other percentiles, making their predictions to be optimistic and larger risk to fail the trial. For EEDI verification it should be required to base the correlation on the median, and for the contract draught it should be mandatory to clearly state which percentile is used for the correlation.

It should also be mandatory to state in the test report if the correlation factors or prediction assumes low friction hulls.

10.2 Timeline for the introduction of the modified procedures.

<u>ITTC internally</u>

The group does not expect that a lot of more high-quality data will be found, considering that hard efforts for more than 2 years were spent on achieving the current data set. Considering the urgency of the problem, unless valid technical arguments against the proposed method are put forward, we recommend the new procedures to be implemented as soon as possible as an internal quality assurance process.

The introduction of the new procedure should preferably be introduced in the ITTC community simultaneously. This will make it easier for all stakeholders, and to be able to refer to a Before and an After.

The new procedure could be introduced as information without binding rules for EEDI in a interim period, to let the industry to adapt.

Gradually, if more knowledge and data is achieved, the threshold can be decreased.

<u>IMO</u>

Before a possible introduction to IMO, the following actions are proposed:

- Discuss with IACS and get their feedback on the proposed new test and the possible consequences of its introduction.
- Discuss with a reference group of ship owners and yards?

After possible feed-back and updates, and if AC agrees, a short version of the current report should be submitted to MEPC.

10.3 Recommended procedure for demonstration of acceptable power ratio of CFD predictions

Full scale CFD for power prediction is now available as standard service from many organizations. MEPC now allows that the EEXI (EEDI for existing ships) may be determined by CFD (IMO 2022). It should be noted that the challenge of correlation at loaded draught is not only related to towing tank tests. Predictions from CFD also need to be correlated, as for example described in the IACS guidelines for verifying EEXI (IACS, 2022). In addition to ITTC 7.5-03-01-02 *Quality assurance for Ship CFD* we propose a guideline for demonstrating acceptable power at all drafts, as outline in Section 2.4.

We recommend that ITTC put this forward to IACS and MEPC.

10.4 Information campaign

Since the proposed procedure for limiting power ratio may have commercial consequences for towing tank facilities, yards, designers, and ship owners, it is important that ITTC provides clear and open information about the change. This should include:

- An explanation of the cause being the collective lack of knowledge on loaded draught correlation, which all facilities have suffered from. If a facility needs to change their methods, it should not be pointed out as having poor methods. We all go into this new level shift together.
- Stressing that CFD-prediction should face same quality assurance.

Information should be spread using for example:

- A scientific journal article
- An industrial magazine article
- Information on ITTC webpage

10.5 To Resistance and Propulsion committee

During the investigations, several new findings were made, which can improve the accuracy of the existing procedure 7.5-02-03-01.4 *1978 ITTC Performance Prediction Method*. We recommend the Resistance and Propulsion Committee to consider the following:

- Introducing the new transom correction formula (see Section 4.2.2)

- For determining the form factor use the methods the following order of preference:
  1. CFD (Korkmaz, 2021, Wang, 2016& 2019, Raven et al., 2008)
  2. Polynomial (if very low speed possible) complemented by Empirical formular described in Section 4.2.1 for the difficult drafts
  3. Prohaska for the drafts the assumptions are valid, complemented by Empirical formular described in Section 4.2.1 for the difficult drafts
- Further investigation for scale effect on wave resistance and breaking waves and differences in effect of energy saving devices between different draughts which were not considered in the Power Ratio Guideline.
- Further investigate the effect of the Power Ratio Guideline on ships with low friction (with corresponding changed correlation factors)

10.6 The continuation of the working group

The main goals of the working group have now been achieved. We recommend that, if AC agrees on our proposal, the group completes the following tasks:

- prepare the information material
- discuss with IACS and other stakeholders
- hand over to relevant committees to introduce the findings in new or existing procedures
  - Specifically, the block coefficient dependency (which may be speed dependent) mentioned in Section 5.2 should be studied further by the Resistance and Propulsion committee.
- if relevant, some working group members could preferable be included as members in relevant committees in the coming term

11 References

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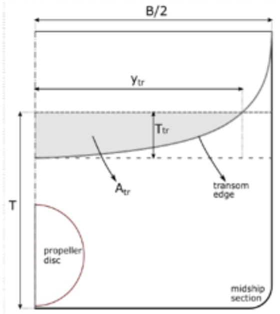
Appendix 1

Required input to the proposed Test

Beam waterline [m]	
Scale factor α [-]	
Number of propellers	
Number of blades Z	
Propeller Diameter D [m]	

Model propulsor open water characteristics		
Advance ratio J [-]	Thrust coeff. KTm [-]	Torque coeff. KQm [-]



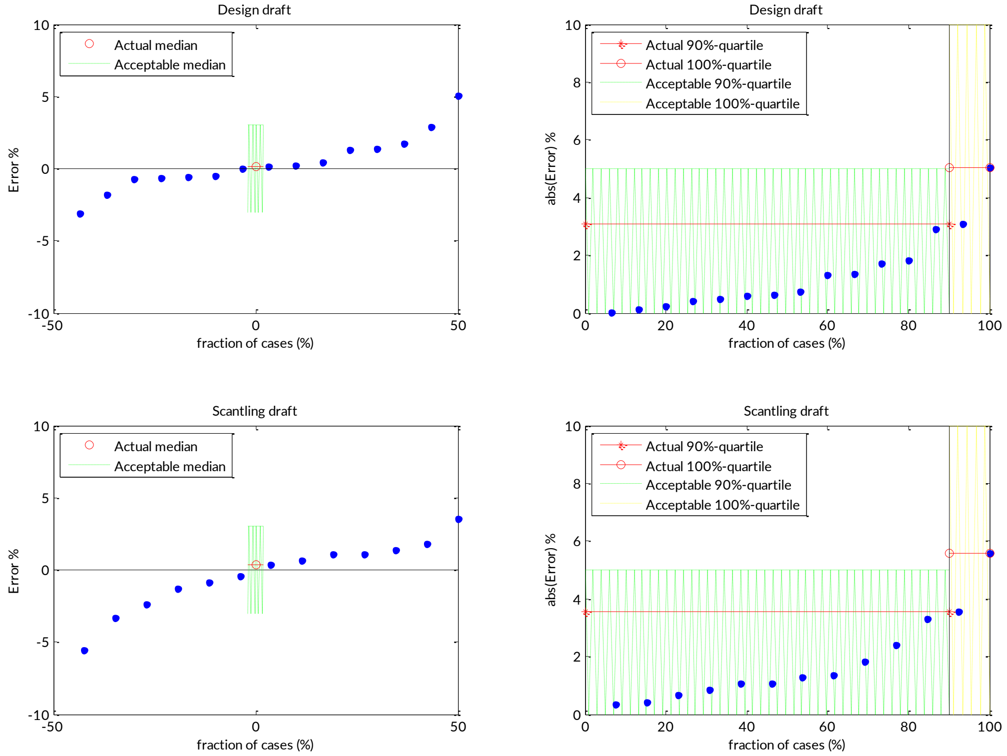
$$tr_{ratio} = A_{tr}/A_{max} \cdot$$

	Length LWL [m]	Wetted surface Shull+rudder [m2]	Proj. area above water line AT [m2]	LCB position rel. to LPP/2 [% of LPP]	tr_ratio	Draft aft Ta [m]	Cb [-]	Mean draft [m]
ballast								
design								
scantling								

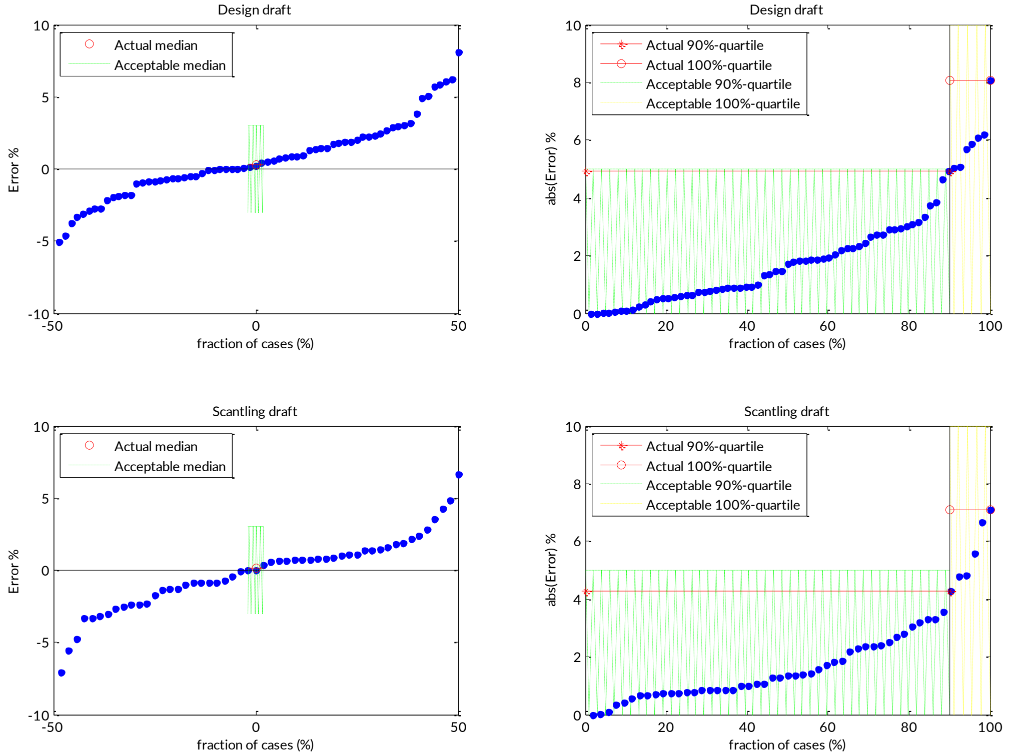
	Model test results									
	Ship Speed Vs [kn]	Resistance RTm [N]	Frict. corr. FD [N]	Thrust Tm [N]	Torque Qm [Ncm]	Rate of revs. [1/s]	Water density (resistance test) ρm [kg/m3]	Water density (self. prop. test) ρm [kg/m3]	Water temperature (resistance test) T [°C]	Water temperature (self. prop. test) T [°C]
ballast										
design										
scantling										

Appendix 2 – The Test applied to real cases

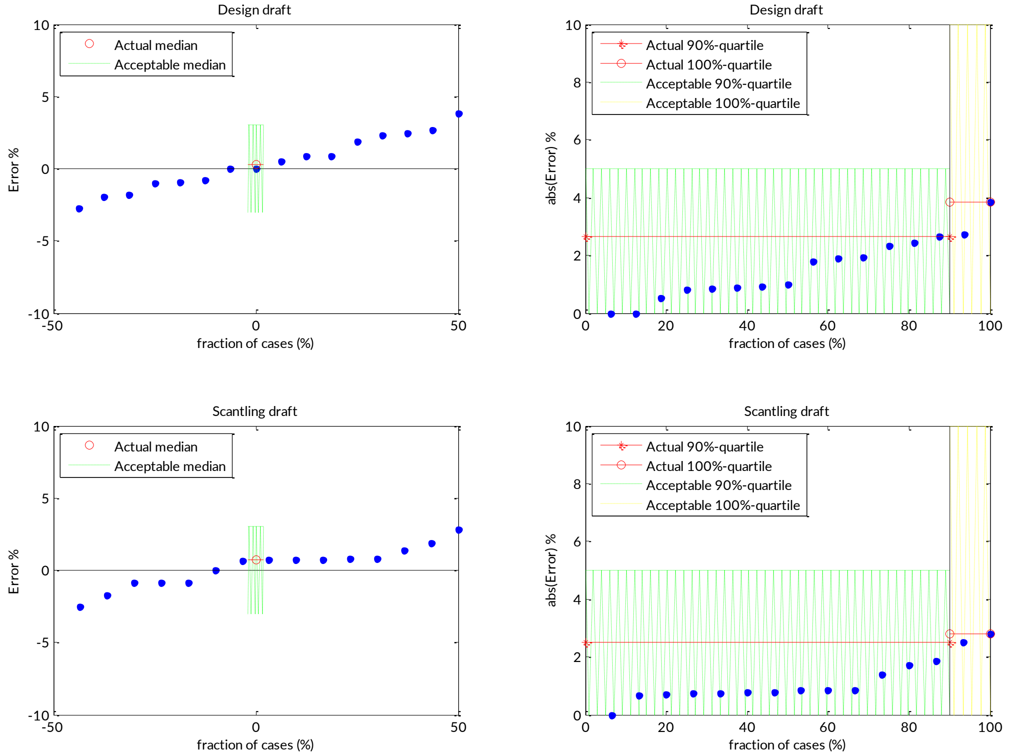
Method: Tank 1



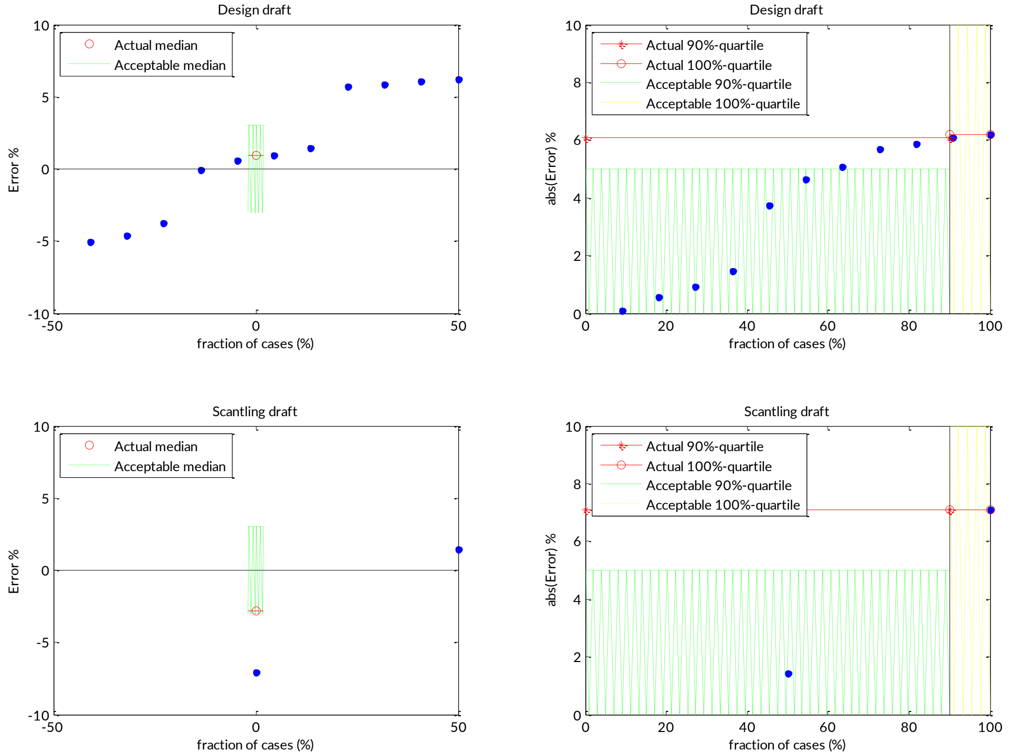
Method: All



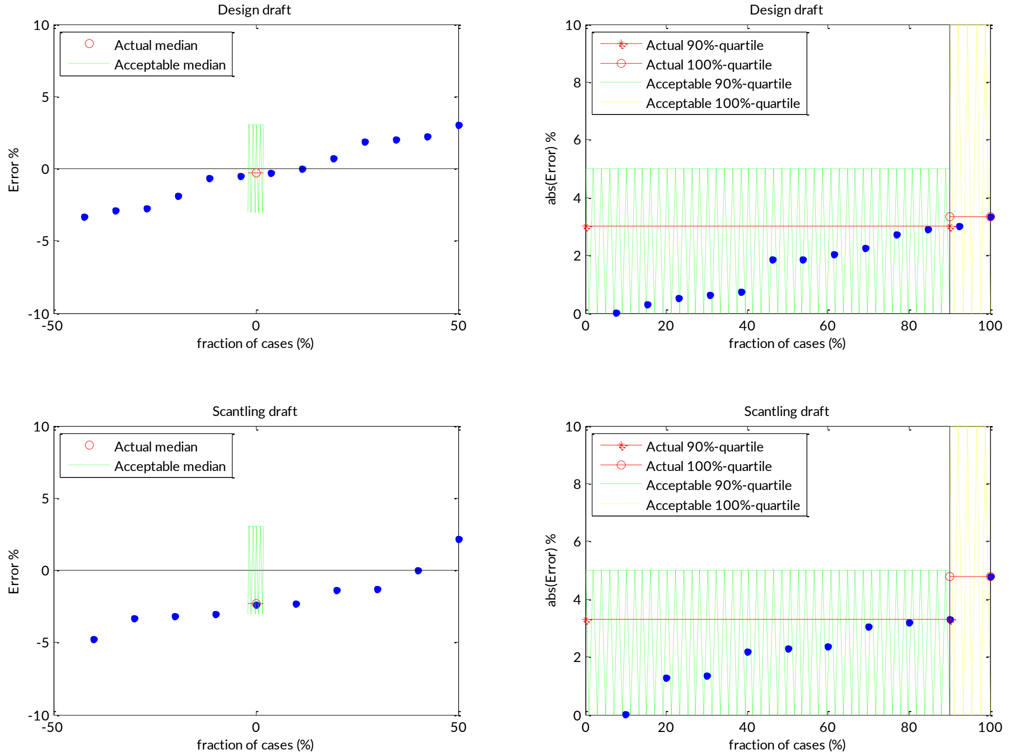
Method: Tank 5



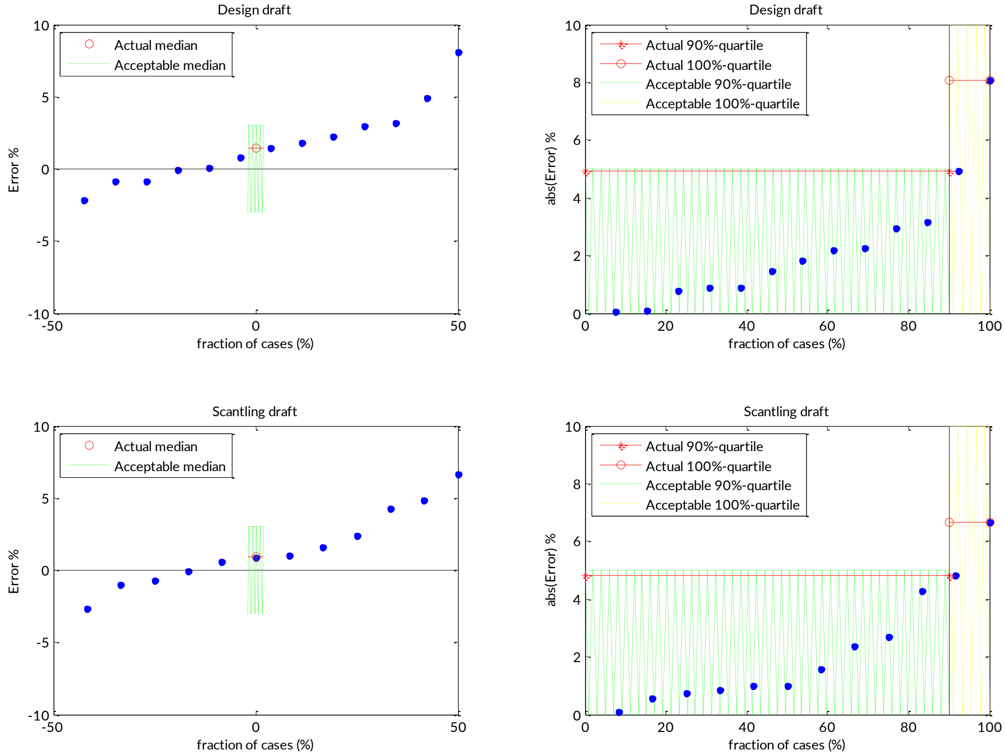
Method: Tank 4



Method: Tank 3



Method: Tank 2



Appendix 3

The evaluation methods that have been considered for (part of) the cases

Method	Short description
ITTC'78	Revision 4 of the ITTC 1978 performance prediction method using a form factor obtained from model tests by means of a Prohaska-Plot.
ITTC'57	2D performance prediction as described in "a procedure for resistance and propulsion experiments with ship models", Moor and Silverleaf (1959)
CFD k ITTC'57 line	ITTC 1978 performance prediction using numerical form factor based on the ITTC 1957 friction line
CFD 2k with NFL	ITTC 1978 performance prediction using different form factors for model scale and full scale, both based on the numerical friction line
CDF 2k ITTC'57 line	ITTC 1978 performance prediction using numerical form factor based on the ITTC 1957 friction line
HSVA (standard)	2D performance prediction based on the current HSVA standard procedure with draught-independent correlation allowance
SINTEF	ITTC 1978 performance prediction using empiric form factor and additional immersed transom stern resistance correction based on the SINTEF standard procedure
MARIN 3D Grigson	3D performance prediction based on the MARIN standard procedure using a numerical form factor following Grigson
ITTC'78 with SSPA transom correction	ITTC 1978 performance prediction method with the form factor from Prohaska-Plot and an additional immersed transom stern correction
ITTC'78 with MARIC form factor	ITTC 1978 performance prediction method with a form factor k=Cp/Cf and both Cp and Cf based on numerical computations (w/o friction line)
k: JMU ITTC'57	JMU performance prediction method based on the ITTC'57 friction line
k: JMU Schoenherr	JMU performance prediction method based on the Schönherr (ATTC) friction line
ITTC'78 k-Hughes	Revision 4 of the ITTC 1978 performance prediction method using a form factor obtained from model tests by means of a Hughes-Plot.
HSVA (legacy)	2D performance prediction based on the legacy HSVA standard procedure with draught-dependent correlation allowance