Specialist Committee on Performance of Ships in Service

Final Report and Recommendations to the 27th ITTC

1. INTRODUCTION

1.1 Membership and Meetings

The members of the Specialist Committee on Performance of Ships in Service (PSS Committee) of the 27th International Towing Tank Conference are as follows:

- Dr. Anton Minchev (Chairman), Force Technology (FT), Denmark
- Dr. Uwe Hollenbach (Secretary), Hamburg Ship Model Basin (HSVA), Germany.
- Dr. Masaru Tsujimoto, NMRI, Japan
- Mr. Michio Takai, Sumitomo Heavy Industries Marine & Engineering, Japan
- Dr. Jinbao Wang, MARIC, China
- Mr. Heungwon Seo, Hyundai HI, Korea
- Mr. Angelo Olivieri, INSEAN, Italy
- Prof. G. Grigoropoulos, NTUA, Greece
- Mr. Henk van der Boom, MARIN, The Netherlands
- Dr. Sofia Werner, SSPA, Sweden
- Dr. W. Gorski, CTO, Poland

Five Committee meetings were held as follows:

- Force Technology, Denmark, 7-9 December 2011
- Vienna Model Basin, Austria, 8-9 March 2012
- MARIC, China, 10-12 October 2012,
- INSEAN, Italy, 6-7 June, 2013
- NTUA, Greece, 15-17 January 2014

The AC representative Prof. Gerhard Strasser attended all the meetings in order to follow closer the update of the speed/power trial procedure and provide feedback from IMO/MEPC meetings.

1.2 Terms of Reference (TOR) Assigned by the 26th ITTC

The 26th ITTC recommended the following work for the 27th ITTC Specialized Committee on Propulsion of Ships in Service:

1. Cooperate directly with the AC and ITTC representative in IMO with regard to EEDI (Energy Efficiency Design Index).

2. Liaise with the Resistance, Propulsion and Sea-keeping Committees as relevant, specifically with regard to estimating *fw*, in the EEDI.

3. Monitor and review the state of the art for EEDI and EEOI (Energy Efficiency Operational Index) prediction and determination methods, including CFD based ones.

4. Review the existing procedures for the ship model testing with regard to the requirements arising from the EEDI prediction process, including ITTC Recommended Procedure 7.5-02-07-02.2, Prediction of Power Increase in Irregular Waves from Model Tests, and liaise with the Seakeeping Committee to decide whether an update of the procedure is required.

5. Identify and describe the practical aspects of the EEDI prediction process involving ship model testing, and develop a guideline for EEDI prediction.

6. Take into account minimum power requirements for safe and effective manoeuvring with respect to the EEDI formula (sea margin)

7. Describe the type of data (and the quality of that data) that should be recorded during full scale monitoring trials, including the issues of surface roughness.

8. Review the existing ITTC trial test procedures in this context. Review the existing speed correction methods for Full Scale Trial Measurements including ISO 15016, and come up with recommendation if the problems are identified, taking into account the MARIN report as contained in document MEPC 62/5/5.

9. Review the technologies (hydrodynamic issues) for enhancement of the powering performance, such as speed reduction, energy saving devices, hull form and propeller design, etc.

10. Investigate the experimental and numerical possibilities to estimate the effect of steering and wind to the added resistance.

11. Look for full scale data that will allow improving powering estimation taking into account the surface roughness (hull, appendages and propeller).

12. Examine the possibilities for numerical methods in the prediction of the influence of surface roughness on the shaft power prediction in full.

1.3 General Remarks

One of the major objectives for establishing the present Specialist Committee on Performance of Ships in Service was to assist/cooperate with IMO/MEPC on the practical implementation of the EEDI calculation and verification process. Therefore, the focus of the Committee work was the major revision of the Speed/Power trial procedures:

7.5-04-01-01.1:Speed and Power Trials, Part I Preparation and Conduct

7.5-04-01-01.2: Speed and Power Trials, Part II Analysis of Speed/Power Trial Data

The process of their update, final version and a practical calculation example are presented in detail under Sections 8 and 9 of the present report.

2. COOPERATION WITH AC/IMO WITH REGARD TO EEDI

The Advisory Council (AC) to the 27^{th} ITTC nominated Prof. Gerhard Strasser (AC Chair) to act as an ITTC (AC) representative to IMO/MEPC. Following closely the work of IMO/MEPC, Prof. Strasser participated in MEPC63, 64, 65 and 66 sessions with subsequent attendance in I – V PSS Committee technical meetings. This close cooperation improved significantly the speed/power trial procedures update, with Prof. Strasser's valuable technical and editorial contributions.

The MEPC 63^{rd} session adopted four sets of guidelines intended to assist in the implementation of the mandatory Regulations on Energy Efficiency for Ships in MARPOL Annex VI, which are expected to enter into force on 1 January 2013:

- 2012 Guidelines on the method of calculation of the attained Energy Efficiency Design Index (EEDI) for new ships;
- 2012 Guidelines for the development of a Ship Energy Efficiency Management Plan (SEEMP);
- 2012 Guidelines on survey and certification of the Energy Efficiency Design Index (EEDI); and
- Guidelines for calculation of reference lines for use with the Energy Efficiency Design Index (EEDI).

The EEDI is a non-prescriptive, performance-based mechanism that leaves the choice of technologies to use in a specific ship design to the industry. As long as the required energy-efficiency level is attained, ship designers and builders would be free to use the most cost-efficient solutions for the ship to comply with the regulations.

The SEEMP establishes a mechanism for operators to improve the energy efficiency of ships.

The MEPC also agreed an updated work plan for the development of further guidelines and the development of energy efficiency frameworks for those ships not covered by the current EEDI regulations.

The MEPC 64^{th} session continued its work on further developing technical and operational measures relating to energy-efficiency measures for ships, based on a work plan agreed at the previous session. This follows the adoption of the new chapter 4 of MARPOL Annex VI, which entered into force on 1 January 2013 and included new requirements mandating the EEDI for new ships, and the Ship Energy Efficiency Management Plan.

The 65^{th} session adopted amendments to resolution MEPC.214(63) 2012 Guidelines on survey and certification of the energy efficiency design index, to add references to measuring sea conditions in accordance with ITTC Recommended Procedure 7.5-04-01-01.1 Speed and Power Trials Part 1; 2012 revision 1 or ISO 15016:2002.

More detailed presentation of the IMO documents related to EEDI and EEOI will be further elaborated in Section 4.

Following the IMO recommendation, ITTC started a closer cooperation with the ISO with the objectives of updating ISO 15016 standard based on the developed ITTC recommended procedures 7.5-04-01-01.1 and 7.5-04-01-01.2.

3. COOPERATION WITH RELEVANT ITTC COMMITTEES WITH REGARD TO ESTIMATING *FW* IN THE EEDI

The speed reduction coefficient *fw* was introduced in the 2012 Guidelines on the method of calculation of EEDI for new ships, adopted by MEPC.212(63). *fw* is a non-dimensional coefficient to compensate for the involuntary speed loss in a representative sea condition of wave height, wave frequency and wind speed.

In agreement with the AC as to the required action/deliverables on this task, it was decided that the Committee should not develop and deliver its version of *fw* prediction procedure, but rather just monitor and eventually cooperate with the Resistance, Propulsion and Sea-keeping committees on this issue.

In this respect the Committee needs to admit that despite numerous attempts, liaison and cooperation with the above committees was poor. It seemed that the Sea-keeping committee encountered difficulties in providing a sound basis for the pertinent calculations.

At its fifth meeting in Athens, the PSS Committee invited the Sea-keeping committee (SKC) chairman to present and discuss the latest work on the topic. The latter was summarized in SKC document "Process for the Estimation of Ship Speed Reduction Coefficient *fw* in Waves", 27th ITTC SKC, February 2014.

Based on the elaborate review of the above document, the PSS committee formulated the following comments:

- It should be clearly stated in the text that the added resistance in waves R_W is composed of two parts: the component due to ship motions; and the component due to wave reflection.
- For low and moderate wave frequencies R_w is calculated numerically by one of the acceptable methods. In the high wave frequency region, the ship is not excited in motions, and thus the component due to ship motions can be negligible. The wave reflection resistance component can be assumed as wave frequency independent, and can be derived experimentally, for example. In order to derive the complete added resistance RAO curve, the two curves are joined at the point where the low-medium frequency curve meets the high-frequency curve.
- In order to promote GHG reduction in actual operational conditions, the procedure should be able to accommodate the effect of the special bow shapes above waterline, which have been developed to reduce added resistance in waves.
- In the present draft the calculation method for added resistance in regular waves is not prepared. This is one of the most important part of the procedure, hence, the Committee will address this issue in the next ITTC term.

Finally the Committee would conclude, that the procedure for *fw* prediction prepared by SKC has not matured yet, and further work is needed for its finalization, which is presented in the recommendations for future work.

4. STATE OF THE ART FOR EEDI AND EEOI PREDICTION AND DETERMINATION METHODS

4.1 Regulatory Framework

The regulatory framework for GHG reduction from international shipping is based on amendment of Annex VI of MARPOL Convention at IMO/MEPC62 and it started from 1st of January, 2013 (Resolution MEPC.203(62)).

The new regulation aims at improving energy efficiency for ships engaged in international voyage and it comprises the technical regulation EEDI and operational regulation SEEMP.

Subsequently, at MEPC63, Feb. 2012, four guidelines required for amendment of Annex VI of MARPOL Convention have been adopted. These are Guidelines for EEDI calculation (Resolution MEPC.212(63)), Guidelines for SEEMP (Resolution MEPC.213(63)), Guidelines on EEDI survey and certification (Resolution MEPC.214(63)) and Guidelines for Reference Lines (Resolution MEPC.215(63)). ITTC has submitted an informative paper on existing recommended procedures and guidelines to support EEDI prediction and verification (MEPC63/INF.8).

At MEPC64, Oct. 2012, the Interim Guidelines for f_w, non-dimensional coefficient for decrease in ship speed in a representative sea condition, has been approved (MEPC.1/Circ.796). ITTC recommended procedure for speed/power trial analysis is approved as preferable standard (MEPC64/23).

Guidelines for determining Minimum Propulsion Power to maintain the manoeuvrability of ships in adverse conditions have been approved as interim guidelines at MSC91, Nov. 2012, on condition that it would be improved at next MEPC meeting (MSC-MEPC.2/Circ.11).

Through discussions at Corresponding Group 2013, Interim Guidelines for Minimum Propulsion Power, validity of phase 0 of EEDI regulation has been adopted at MEPC65, May 2013 (Resolution MEPC.232(65)). At MEPC65, 2013 Guidance on Treatment of Innovative Technology has been approved as well. For cruise passenger ships having non-conventional propulsion, Guidelines for reference lines has been adopted (Resolution MEPC.233(65)). Amendment to Guidelines on EEDI survey and certification has been adopted, where it prescribes ITTC recommended procedures for speed/ power trial part1 and part2 as preferable standard (Resolution MEPC.234 (65)).

4.2 EEDI

EEDI regulation is applied for new ships of 400GT and above. The number of ship types for calculating EEDI is eleven, which is listed in Table 1. Of these ship types, EEDI reduction is required from 1st of January, 2013: Bulk carrier, Gas carrier, Tanker, Container ship, General cargo ship, Refrigerated cargo carrier and Combination carrier.

Ship types requiring EEDI reduction will be extended to Passenger ships having non-conventional propulsion, Ro-ro cargo ships (vehicle carrier), Ro-ro cargo ships and Ro-ro passenger ships. At present, EEDI calculation and reduction rate for Passenger ships having conventional propulsion has not been proposed and not yet deliberated.

For each ship type, the reduction rate is determined by ship size and phase of application. The reduction rate is given in Table 2 where the base of the reduction rate is determined by Guidelines for reference lines.

Table 1 EEDI regulation

Ship types for EEDI calculation*	Reduction of EEDI	
	after 1st, Jan., 2013	after 1st, Sep. 2015
Bulk carrier	X	
Gas carrier	X	**
Tanker	X	
Container ship	X	
General cargo ship	X	
Refrigerated cargo carrier	X	
Combination carrier	X	
Passenger ship		X***
Ro-ro cargo ship (vehicle carrier)		X
Ro-ro cargo ship		X
Ro-ro passenger ship		X

* not apply to ships of diesel-electric propulsion, turbine propulsion and hybrid propulsion system
** separate to Gas carrier and LNG carrier
*** only regulated for Passenger ship having non-conventional propulsion

Attained EEDI formula is given in Eq. (1). The numerator represents the energy efficiency of the ship as CO_2 emissions in gram. The denominator in Eq. (2) is related to the transport work in tons times nautical miles.

$$Attained\ EEDI = \frac{EEDI_{Numerator}}{EEDI_{Denominator}} \tag{1}$$

$$EEDI_{Denominator} = f_i \cdot f_c \cdot f_l \cdot Capacity \cdot f_w \cdot V_{ref} \tag{2}$$

where

V_{ref} is ship speed in a calm sea condition on deep water,

Capacity is deadweight except that, for passenger ships and Ro-Ro passenger ships, *Capacity* is gross tonnage, and for container ships, *Capacity* is 70 per cent of the deadweight,

f_i, f_c, f_l and f_w are correction factors.

EEDI is an index of energy efficiency for transport work, so that the power which is not related to propulsion is deducted from the calculation. In addition, there are deduction or correction factors; energy saving due to innovative technologies in the numerator of attained EEDI, capacity corrections including ice class (f_i), cubic capacity corrections (f_c), correction for general cargo ships equipped with cranes and other cargo-related gears (f_l), and speed reduction at a representative sea condition (f_w) in the numerator of attained EEDI.

In the guidelines for EEDI survey and certification, EEDI calculation method based on CFD may be accepted as equivalent to propeller open water test or used to complement the tank tests conducted, such as evaluation of the effect of energy saving device with approval of verifier (Res. MEPC.214(63), 2012).

The CFD based methods for EEDI calculation will be reviewed when they are available.

Methods for survey and certification are prescribed at the respective Guidelines for EEDI. As a supplement to its interpretation, the industrial guidelines have been developed by IACS (MEPC64/INF.22, IACS PR No.38).

The ship speed in a calm water (Vref), is preliminarily verified on the basis of model tests. The final verification is carried out by speed/power trials of the ship. It should be noted that for ships which can undergo speed/power trials at the draught prescribed in EEDI Guidelines, such as tankers, the preliminary verification may be excluded.

Table 2 Reduction rate of EEDI.

Ship Type	Size	Phase 0 1, Jan., 2013- 31, Dec., 2014	Phase 1 1, Jan., 2015- 31, Dec., 2019	Phase 2 1, Jan., 2020- 31, Dec., 2024	Phase 3 1, Jan., 2025 and onwards
Bulk carrier	20,000DWT and above	0	10	20	30
	10,000-20,000DWT	n/a	0-10*	0-20*	0-30*
Gas carrier	10,000DWT and above	0	10	20	30
	2,000-10,000DWT	n/a	0-10*	0-20*	0-30*
Tanker	20,000DWT and above	0	10	20	30
	4,000-20,000DWT	n/a	0-10*	0-20*	0-30*
Container ship	15,000DWT and above	0	10	20	30
	10,000-15,000DWT	n/a	0-10*	0-20*	0-30*
General cargo ship	15,000DWT and above	0	10	15	30
	3,000-15,000DWT	n/a	0-10*	0-15*	0-30*
Refrigerated cargo carrier	5,000DWT and above	0	10	15	30
	3,000-5,000DWT	n/a	0-10*	0-15*	0-30*
Combination carrier	20,000DWT and above	0	10	20	30
	4,000-20,000DWT	n/a	0-10*	0-20*	0-30*
Ro-ro cargo ship (vehicle carrier)***	10,000DWT and above	n/a	5**	15	30
Ro-ro cargo ship***	2,000DWT and above	n/a	5**	20	30
	1,000-2,000DWT	n/a	0-5* **	0-20*	0-30*
Ro-ro passenger ship***	4,000GT and above	n/a	5**	20	30
	1,000-4,000GT	n/a	0-5* **	0-20*	0-30*
LNG carrier***	10,000DWT and above	n/a	10**	20	30
Cruise passenger ship*** having non-conventional propulsion	85,000GT and above	n/a	5**	20	30
	25,000-85,000GT	n/a	0-5* **	0-20*	0-30*

* Reduction factor to be linearly interpolated between the two values dependent upon vessel size. The lower value of the reduction factor is to be applied to the smaller ship size.

** Phase 1 commences for those ships when the amendments to MARPOL Annex VI come into effect

*** Reduction rate applies those ships constructed on or after [date of entry into force].

Note: n/a means that no required EEDI applies.

Ship speed in calm water (V_{ref}) can not be directly measured in speed/power trial runs. Therefore, corrections for wind effect, wave effect, current effect, displacement and shallow water are performed. At MEPC62 consideration for these corrections in order to reduce the vagueness and improve the robustness was requested from Norway (MEPC62/5/5).

The ITTC PSS Committee developed completely revised speed/power trials recommended procedures and these were proposed at MEPC64. ITTC contribution to IMO/MEPC has been acknowledged and the ITTC recommended procedures were denoted as preferable standard for analysis of speed/power trials (MEPC64/4/15, MEPC64/INF.6, MEPC65/INF.7).

IMO prompted ISO to update ISO15016:2002 taking into account ITTC recommended procedures 2012. Currently ITTC is cooperating with ISO to revise ISO15016 (MEPC66/4/4, MEPC66/INF.7).

4.3 EEOI/SEEMP

Each ship is obliged to keep on board a copy of SEEMP. SEEMP provides a possible approach for monitoring ship and fleet efficiency performance over time and some options to be considered when seeking to optimize the performance of the ship.

SEEMP is composed of a cycle of planning, implementation, monitoring, self-evaluation, and improvement.

In the planning stage goals are set. The goal can take any form, such as the annual fuel consumption or a specific target of EEOI.

5. PREDICTION OF POWER INCREASE IN WAVES

The existing model testing procedures, related to the EEDI prediction and verification process are reviewed in more detail in the next section of the report and will not be discussed here. The procedure for prediction of power increase in irregular waves from model tests is developed by the Sea-keeping committee, and has been a matter of discussion and revision during the recent ITTC conferences. ITTC/AC recommended that this procedure requires major update, in view of the latest EEDI developments.

Due to the very modest feedback from the SKC, as already noted in section 3, the PSS committee did not receive a recent update of the subject procedure; hence the committee was not in a position to comment.

6. PRACTICAL ASPECTS OF EEDI PREDICTION

This task is described in the Industrial Guidelines written by Joint Working Group (JWG), formed by the following international shipping associations and organizations: IACS, BIMCO, CANSI, CESA, CESS, ICS, INTERCARGO, INTERTANKO, KOSHIPA, OCIMF, SAJ, WSC and ITTC. The Industry Guidelines has been submitted to IMO MEPC 64 as MEPC 64/INF.22 “First version of industry guidelines on calculation and verification of the Energy Efficiency Design Index (EEDI)”.

ITTC, with AC chairman as its representative, and PSS committee contributed to Part III - Verification of EEDI of the Industry Guidelines. The following sub-sections present the outline of the Industry Guidelines, model-ship correlation process and recommendations for future work on this topic.

6.1 Verification Process

EEDI verification should be conducted on two stages:

(1) Preliminary verification at design stage
(2) Final verification at the sea trial

EEDI prediction is carried out at the design stage. In the Industry Guidelines, Part III shows the above process in detail. Here, the EEDI verifications are reviewed briefly.

6.2 Ship Model Testing

The model tests should be witnessed by a nominated verifier. Special attention should be given to the following items:

(1) Ship Model
(2) Propeller Model
(3) Model Tests
  a) Resistance Test
  b) Propulsion Test
  c) Propeller Open Water Test
(4) Speed Trial Prediction

Above model test should be performed according to ITTC Recommended Procedure 7.5-02-02-01, 7.5-02-03-01.1 and 7.5-02-03-02.1.

Numerical calculations may be submitted to justify derivation of speed power curves, where only one parent hull form have been verified with tank tests, in order to evaluate the effect of additional hull features such as bulb variations, fins and hydrodynamic energy saving devices.

These numerical simulations may include CFD calculation of propulsive efficiency at reference speed Vref as well as hull resistance variations and propeller open water efficiency.

In order to be accepted, these numerical simulations should be carried out in accordance with defined quality and technical standards (ITTC 7.5-03-01-04 at its latest revision or equivalent). The comparison of the CFD-computed values of the unmodified parent hull form with the results of the tank tests must be submitted for review.

6.3 Quality System

The verifier is to familiarize with the tank test organization test facilities, measuring equipment and quality system for consideration of complying with the requirements of section 6.2 prior to the test attendance when the verifier has none or no recent experience of the tank test facilities and the tank test organization quality control system is not certified according to a recognized scheme (ISO 9001 or equivalent).

In this case, the following additional information relative to the tank test organization is to be submitted to the verifier:

1. Descriptions of the tank test facility; this should include the name of the facility, the particulars of tanks and towing equipment, and the records of calibration of each monitoring equipment as described in Appendix 3 of Industry Guidelines.

2. Quality manual containing at least the information listed in the ITTC Sample quality manual (2002 issue) Records of measuring equipment calibration as described in Appendix 3 of Industry Guidelines.

3. Standard model-ship extrapolation and correlation method (applied method and tests description) .

6.4 Speed Trial Prediction

The principal steps of the Speed Trial prediction calculation, are given in ITTC Recommended Procedure 7.5-02-03-01.4 ITTC 1978 Performance Prediction Method (in its latest reviewed version of 2011). The main issue of a performance prediction is to get the loading of the propeller correct and also to assume the correct full scale wake. The right loading of the propeller can be achieved by increasing the friction deduction by the added resistance (e.g. wind resistance etc.) and run the self-propulsion test already at the right load or it can be achieved by calculation as given in Procedure 7.5-02-03-01.4.

A wake correction is always necessary for single screw ships. For twin screw ships it can be neglected unless the stern shape is of twin skeg hull type or other special shape.

The performance prediction should always be based on a resistance, propulsion, and a propeller open water test of the model propeller used during the tests and the propeller open water characteristics of the final propeller.

6.5 Model-Ship Correlation

Basic Principles. EEDI is defined at fully loaded condition. However for most of the ship types the speed/power trial cannot be carried out at full load condition.

It is recommended to use the graphical construction described in Figure 1 that can be described by the following general procedure, applied only to EEDI power reference point (75% of MCR):

Based on the final corrected measured power values, the ratios $P_{measured}$ / $P_{tanktestpredicted}$ are calculated foe each sea trial speed point. These ratios are put on the curve obtained from the model tests for EEDI condition to obtain the curve of the trial results for EEDI condition.

This means that the EEDI prediction for both laden and trial (ballast) conditions is very important. Only the speed at the trial(ballast) condition will be confirmed at the sea trial. The speed at the EEDI (laden) condition will be confirmed based on the EEDI prediction of the model test. Therefore the difference of the model-ship correlation between the fully loaded condition and trial condition is very important.

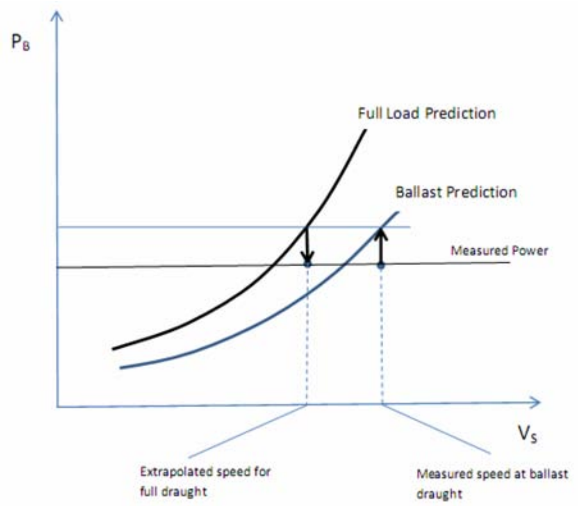


Figure 1 Extrapolation from measured values at sea trial condition to EEDI condition

Model-ship correlation method followed by the tank test organization or shipyard should be properly documented with reference to the 1978 ITTC Performance Prediction Method (PPM) given in ITTC Recommended Procedure 7.5-02-03-01.4 rev.02 of 2011 or subsequent revisions, mentioning the differences between the followed method and the 1978 ITTC PPM and their global equivalence.

The correlation method used should be based on thrust identity and the correlation factors should be according to method 1 ($C_P - C_N$) or method 2 ($\Delta C_{FC} - \Delta w_c$) of the 1978 ITTC PPM. If the standard method used by the tank test organization does not fulfil these conditions, an additional analysis based on thrust identity should be submitted to the verifier.

The verifier will check that the power-speed curves obtained for the EEDI condition and sea trial condition are obtained using the same calculation process and properly documented as requested in Appendix 4 of Industry Guidelines. In particular, the verifier will compare the differences between experience-based coefficients Cp and ΔC_{FC} between the EEDI condition (∇_{FULL}) and sea trial condition if different from EEDI condition (∇) with the indications given in Figures 2 and 3 extracted from a SAJ-ITTC study (see below presentation of the study) on a large number of oil tankers. If the difference is significantly higher than the values reported in the figures, a proper justification of the values should be submitted to the verifier.

Study for The Model-Ship Correlation Between Full and Ballast Condition. This study was carried out based on the data from SRC, Shipbuilding Research Centre of Japan. Number of data is 773 of all kind of ships.

- Design Full load condition	312
- The other condition	461

Figure 2 shows the method 1(ΔC_P) versus displacement ratio. The tendency indicates increasing ΔC_P values with decreasing displacement. These values, however, are provided by clients and most of them are not confirmed at sea trial or other.

Figure 3 shows the same data in method 2(ΔC_{FC}). The sea trial data of 59 series of tanker data also plotted in Figure 3. The variance of the data from sea trial is not small, but we can conclude that the scatter is distributed around the SRC data.

It seems that further study is necessary, because the scatter of the model-ship correlation is very large. All the model basins and ship yards should gather their own data. Figure 2 may be the only data which shows the model-ship correlation on different displacement. And the number of the data is not small. Before the study each model basin should decide the model-ship correlation carefully.

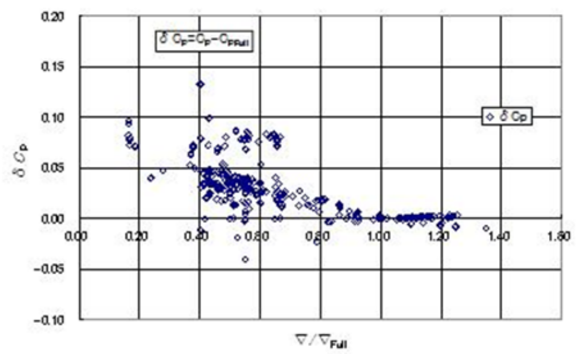


Figure 2 Variation of C_P-C_{PFULL} as a function of the displacement ratio.

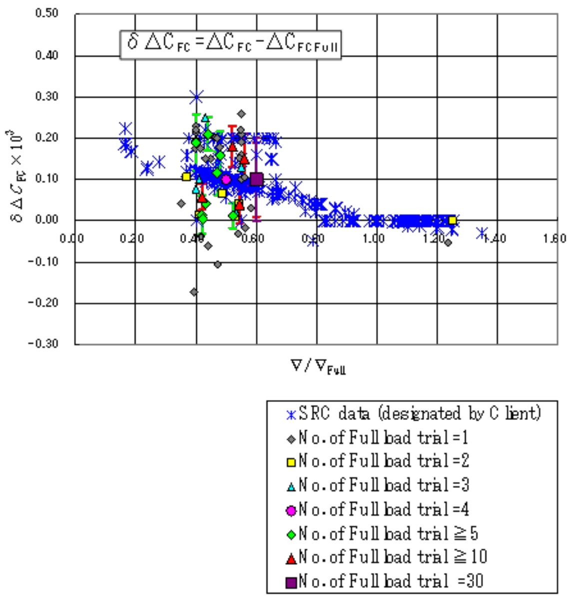


Figure 3 Variation of ΔC_{FC} as a function of the displacement ratio.

On the other hand, it is difficult to gather data of full load condition. Other methods should be invetigated, such as the feed back of the performance of the ship after delivery.

6.6 Conclusion

EEDI prediction process should follow the Industry guidelines. Model test and numerical calculations should be conducted according to ITTC Recommended Procedures.

In EEDI regulation, model basins are requested to build a quality control system, such as ISO9000 or equivalent. All the ITTC members should be accredited with such a QA system.

For EEDI verification or confirmation of the contract between ship owner and ship builder, the difference of model-ship correlation between full and trial condition is very important. Further studies in this respect are encouraged.

7. MINIMUM POWER REQUIREMENTS WITH RESPECT TO EEDI

7.1 General

The IMO MEPC at its 64th session and the Maritime Safety Committee (MSC), at its 91st session, approved the Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ship in adverse conditions. The Interim guidelines are presented in detail in document MSC-MEPC.2/Circ. 11. "Interim Guidelines for Determining Minimum Propulsion Power to Maintain Manoeuvrability of Ships in Adverse Conditions".

According to the above documents, the following definitions, applicability and assessment procedures apply:

Definition. “Adverse condition” mean sea conditions with the following parameters:

Significant wave height Hs = 6.0 m;
Peak wave period Tp = 8.0 to 15.0 sec;
Mean wind speed Vw = 19.0 m/sec

Applicability. The Guidelines should be applied in the case of all new ships in unrestricted navigation, required to comply with EEDI.

Assessment procedure. he assessment can be carried out at two different levels as listed below:

a) Assessment level 1 - Minimum power lines

If the ship under consideration has installed power not less than the power defined by the minimum power line for the specific ship type, the ship should be considered to have sufficient power to maintain the manoeuvrability in adverse conditions. The minimum power line values, in kW, should be calculated as follows:

Minimum power line value = a x $(DWT)+b$,

Where: DWT is the deadweight of the ship in metric tons; and a and b are the parameters given in Table 3

Table 3 Minimum power lines parameters

Ship type	*a*	*b*
Bulk carriers	0.0687	2924.4
Tankers	0.0689	3253.0
Combination carriers	See tankers above	

If the minimum power lines assessment is not fulfilled, then the simplified assessment may be applied.

a) Assessment level 2 – Simplified assessment

The simplified assessment is applicable only to ships whose rudder area is not less than 0.9% of the submerged lateral area corrected for breadth effect.

The simplified assessment procedure is based on the principle that, if the ship has sufficient installed power to move with a certain advance speed in head waves and wind, the ship will also be able to keep course in waves and wind from any other direction. The minimum advance speed in head waves and wind is thus selected depending on ship design in such a way, that the fulfilment of the advance speed requirements means fulfilment of course-keeping requirements.

If the ship under consideration fulfils the requirements as defined in the simplified assessment, the ship should be considered to have sufficient power to maintain the manoeuvrability in averse conditions.

7.2 Discussion

Greece accomplished a study to investigate the applicability of the guidelines and the assessment procedures for determining the minimum propulsion power to maintain the manoeuvrability under adverse conditions, as specified in the aforementioned circular. The results of this study were based on the interim guidelines on minimum propulsion power to maintain the manoeuvrability in adverse conditions, submitted in document MSC-MEPC.2/Circ.11, which relates to the procedures proposed for Phase 0 and Phase 1 and later of EEDI implementation.

Meanwhile, IMO/MEPC in Resolution MEPC 232(65) issued in Annex 16 of the Report of MEPC (65) on 24th May 2013, modified the weather and sea conditions for the evaluation of maneuverability to milder ones, especially for the smaller vessels. IMO/MEPC also modified slightly the minimum power lines for both tankers and bulk carriers to improve fitting with the available statistical data. Thus, a member of the PSS Specialist Committee, updated the original study for four typical bulk carriers of DWT 30000 (Handy), 57000 (Supra-Handy-Max), 79000 (Kamsar-Max) and 176000 T (Cape-Size) and a VLCC 306000 T to evaluate the most recent requirements. Lines plans and sea trial data were used to derive the performance of the aforementioned vessels in adverse weather conditions. Actual operation points were derived by matching the power requirements with the propeller characteristics and the main engine operational diagram. Long-crested head sea waves (worst case for added resistance) and the worst peak wave period T_P within the range specified by MEPC 232(65) were assumed.

Furthermore, calculations using the level 1 and 2 assessment methods, as described in MEPC 232(65), were carried out at two loading conditions: a fully laden and a heavy ballast one, both selected from the trim and stability booklet of each vessel.

To evaluate the Level 1 procedure, the characteristics of the investigated vessels are compared with the minimum line for bulk carriers (BCs) and tankers derived on basis of statistics.

To evaluate the Level 2 procedure the performance of each vessel in calm water and in waves was estimated numerically. On the basis of the sea trials and the propulsion characteristics the power required to propel the ship in calm water at various speeds was derived. Then, using a strip theory method the dynamic responses are derived and using an energy method the added resistance was calculated in the sea and wind conditions specified by MEPC 232(65), as well as the associated service speed under these circumstances. These operational points (main engine power and propeller revolutions) at the minimum speeds required for achieving sufficient manoeuvring capabilities of a ship in a seaway were specified assuming that the propeller characteristics and the hull - propeller interaction coefficients in waves don’t deviate from those in calm water.

On the basis of these results, useful conclusions with respect to the installed power margin that is necessary to ensure safe operation of the ships in the prescribed sea and weather conditions, are drawn, as follows:

- All five ships studied, very easily satisfy level 1 requirement, while some of them satisfy only marginally the requirements of level 2 – simplified assessment. This constitutes a major failure of rationalism, dictating that level 1 should be the strictest one. Since either level is sufficient to comply with the requirement, it follows that the simplest level 1 should not also be the easiest to fulfill.
- The submerged lateral area of the hull, corrected for breadth effect, estimated using the formulation proposed by IACS and incorporated in MSC-MEPC.2/Circ.11 and MEPC 232 (65) is 55-70% higher than the actual one, both at the full load and the heavy ballast conditions and in the case of the VLCC more than 80% higher.
- The differences between the estimated power requirements on the basis of MSC-MEPC.2 / Circ.11 and the calculated results are higher in the heavy ballast conditions than in the full load ones. This can be attributed to the fact that the approximate relations in the supporting document of IACS (IMO MEPC 64/INF.7, June, 2, 2012) to the document IMO MEPC 64/4/13 have been derived mainly on the basis of the full

load conditions. However, the heavy ballast condition was found to be more critical with respect to minimum power requirements than the full load one in three of the evaluated cases, basically due to the higher seakeeping vertical responses in head waves contributing to excessive added resistance in head waves. Furthermore, quite often the rudder is not fully submerged in the ballast condition.

- The minimum power requirements specified on the basis of IMO MEPC 232 (65), using Level 1 – Minimum Power Lines are exceeded by about 20% for all five cases investigated.
- The minimum power requirements specified on the basis of IMO MSC-MEPC.2/Circ.11 using Level 2 – Simplified Assessment are met only marginally in one of the two tested conditions for the four investigated BCs. Taking into account the fouling and the aging of ships, and the fact that the propulsive performance in waves is reduced compared to that in calm water, this criterion may be violated. On the contrary, they are well satisfied in the case of the VLCC in both loading conditions, where the required minimum speed is too low for the installed main engine – propeller configuration. Since all oceangoing ships regardless of their L_{OA} size encounter the same weather and sea conditions in the ocean, which affect more the smaller ones, the power margin must be increased in smaller ships. Instead, resolution MEPC. 232(65) - 2013 reduced the requirement for all ships and more so for ships below 250 m in length (i.e. the Panamax and Handy-supras workhorses of the seas) to levels equivalent to Beaufort 6-7.
- The minimum power requirement estimated on the basis of IMO MEPC 232 (65) ignores the increase of the calm water resistance due to hull and propeller fouling, as well as that due to ship aging. However, commercial ships are neither new-buildings nor just launched from the dry dock.
- The regression line for the minimum power requirements (Level 1) seems to be satisfied by the 90% of the plotted sample, while only 10% of the plotted sample are below the curve, implying that the required minimum installed power is substantially lower than actual typical current designs for bulk carriers. The same holds true for the tankers. Even before EEDI some vessels were built with much smaller engines than appropriate. These ships were underpowered. It is obvious that these ships constitute the bottom samples of the scattered data. It does not seem appropriate, nor conservative, to now provide an effective “IMO stamp of safety” to all ships as long as they are not within the worst 10% of the data as far as engine size is concerned.
- Thus, the Level 1, simplified method, which is included in the interim guidelines, adopted by resolution MEPC.232 (65) as the first level of a two or three-level assessment approach should be the most stringent and conservative, as a matter of principle.

Based on the results and conclusions of the above study it could be summarized that the Interim Guidelines seem to be premature and would need further refinement. Some recommnedations for future ITTC work on this topic are formulated in the Conclusions of this report.

8. SPEED/POWER TRIAL FUNDAMENTALS

8.1 Background

The speed/power characteristics of ships have always been at the core of ship design. To prove contractually agreed values, speed trials are conducted by the yard prior to delivery of the ship to the owner. In the past, operational schedule of the vessel was often the most important factor for the speed requirement. Today, owners and operators are keen to reduce fuel consumption to decrease operational costs.

The IMO brief asked that a transparent, unambiguous and practical method had to be delivered which would be acceptable for all stakeholders and that could be used for both contractual agreements between yard and owner as well as for the assessment of the IMO EEDI for any new-built ship worldwide. At the same time, the results of the speed/power trials should be completely documented and traceable for the EEDI Verifier representing the flag state of the vessel. This task was conducted by the ITTC Committee for the Performance of Ships in Service with the assistance of the STA-Group which has been working in this field since 2004.

8.2 History

Speed/power trials are conducted to establish the performance of the vessel at design draught and trim under stipulated weather conditions, usually deep water, no wind and no waves. As the conditions encountered during the trials often deviate from the contract conditions, corrections are applied during the analysis and reporting of the trial results. In the past, institutes such as BSRA, NSMB, SNAME and ITTC published methods for conducting and analysing speed/power trials. Shipyards "randomly" selected and developed their own "yard standard" from these methods. In 2002, the International Standard Organisation published ISO 15016, which included a cumbersome analysis method based on a wide choice of outdated correction methods and empirical data. The analysis method is based on the old manual Tanaguchi and Tamura method (11th ITTC, 1966).

In 2004, the STA-Joint Industry Project, supported by leading ship owners and major shipyards, investigated the current practice and developed significant improvements in the trial procedures, and in the analysis of the measured results, including new correction methods for waves and wind.

In December 2011, the PSS Committee invited STA-Group to co-operate on the new ITTC Guidelines for Speed/Power trials to be submitted to IMO MEPC for EEDI verification. STA-Group accepted the invitation and provided access for ITTC to STA-Group data and method.

8.3 Approach

The two basic parameters to be measured during the trials are ship speed and shaft power. By determining these parameters at different engine power settings and correcting them for non-ideal circumstances, the speed/power relation for the ship at trial draught and trim can be established.

As illustrated by Figure 4, the speed and shaft torque of a vessel in realistic weather conditions is varying constantly, both with wave frequency and with lower frequencies. It is obvious that reliable measurements and analysis methods are required and at the same time, strict limitations have to be taken into consideration during the speed/power trials such as the minimum water depth, maximum wave heights and maximum wind speed.

Although the speed log is one of the oldest sensors on board ships, it is still one of the most inaccurate instruments and it does not give the speed through water with an acceptable accuracy. The D-GPS, however, is capable of deriving the speed over ground. To eliminate the current from the speed over ground, the results of double runs (i.e. speed runs on reciprocal courses), can be averaged according to the "Mean of Means" method also referred to as "Pascal's triangle", which was already presented by Van Lammeren in 1939 and also recommended by the Principles of Naval Architecture (SNAME, 1988). To account for time varying currents such as tidal currents, two or more double runs are required for the same power setting.

Figure 4 Speed through water and over ground and shaft torque measured on an 1800 TEU container vessel in 4 m significant wave height (Courtesy; Vroon)

The "Mean of Means" is applied after correcting the measured speed/power points for wind, waves and other deviations from ideal conditions except the conversion from the (ballast) trial draught to the contract design draught. All corrections for non-ideal conditions are expressed in shaft power corrections (except for shallow water) and the propeller efficiency is corrected for non-ideal loads by use of the results of load-variation model tests.

The speed over ground is derived from the end-positions of the speed run over minimum measurement duration of 10 minutes. Each double run consists of a speed run in head waves and a counter run in following waves. The reason for this is that practical wave corrections are only available for those courses and rolling, steering and course deviations should be avoided.

Power corrections are applied for non ideal conditions such as wind, waves and small deviations in displacement. The propeller loading due to wind and waves and displacement deviations is accounted for by taking into account the deviations in propeller efficiency and rpm as obtained from the load variation model tests. The above approach is referred to as the Direct Power Method and is a transparent, reliable and practical method that can easily be understood by yards and owners. The method does not need curve fairing or fitting neither numerical solvers. The Direct Power Method was selected by ITTC PSS is the basis for the new Guidelines.

Number and length of speed runs. The minimum number and length of the speed runs has been discussed at length by the committee. The basis for the requirements is the accuracy in speed and in shaft power measurements in limiting current, wind and wave conditions as well as the analysis and correction methods which are all based on average figures. Not only current variations but also the low frequency components in the added resistance in irregular waves and the low frequency wind gusts have to be accounted for in the averaging procedures.

The required number of double runs at various power settings was specified:

- two double runs at contract power;
- two double runs at EEDI power (75% MCR);

- one double run at one other power setting between 65% and 100% of MCR.

For sister ships, the programme can be reduced to one double run at contract power, at EEDI power and at one other power setting between 65% and 100% of MCR. In adverse environmental conditions, additional double runs are required. The measurements and recording of all required signals during speed runs with a minimum duration of 10 minutes have been specified in detail in these Guidelines.

Wind correction. The wind drag on ships increases quadratically with the relative wind speed and therefore the actual encountered wind speed and direction should be measured as accurately as possible. Wind speed read from the anemometer on top of the wheelhouse should be treated with care as the wheelhouse normally generates over-speed at this location. For some wind directions the anemometer may be shielded by masts, funnels or cargo. To minimise these effects the wind vector is averaged over the results of the two counter runs in one double run set as illustrated by Figure 5.

As the ship navigates in the boundary layer of the wind over the sea, it is important to take the wind velocity profile into account. Wind speed is normally defined as the average velocity at a height of 10 meters above the surface. Wind drag coefficients are also normally derived in a wind profile defining the wind speed at 10 meter. For this reason the wind measured by the anemometer has to be corrected for the height of this sensor. When the anemometer is located 50 meter above water for example, this height correction results in a 21% reduction in wind speed and 46% in wind load. When the forward speed of the ship is included, the effect on the wind load can be even larger.

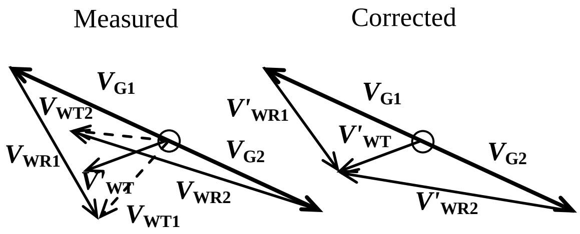


Figure 5 Averaging of measured wind vectors over two counter runs to derive the true wind vector

Wind drag coefficients for ships have been published by many authors in the past; however modern vessels are much larger and have a different geometry than ships used in well-known wind resistance publications. Therefore, it is important to use recent ship type and size specific data derived from proper wind tunnel measurements or validated computational tools such as LES-RANS CFD. For container ships, it is crucial to distinguish the wind drag in ballast condition without containers on deck but while taking into account the lashing bridges (which are exposed to wind during trials) and the design draught case where the vessel is loaded with containers. Remarkably the wind resistance coefficient of the loaded vessel is normally smaller as the full container pack provides a better flow shape than the wheelhouse and lashing bridges!

The STA-JIP collected systematic wind tunnel data sets for various ship types and loading conditions. Also, extensive CFD analyses have been conducted to correlate with wind tunnel data to arrive at a solid understanding of wind drag and to establish extensive empirical data sets for wind drag correction.

ITTC incorporated the wind correction approach from STA. Besides the STA-Wind data sets for the different ship types, PSS also included the regression method published by Fujiwara et al. in 2005.

In all cases, it is possible to use the drag coefficients derived by means of qualified wind tunnel tests or validated CFD analysis for the specific ship geometry.

More elaborate presentation of the recommended methods for wind drag correction follows in the next chapter.

Wave correction. Even within the trial limits for wave height, the added resistance due to waves can be a substantial part of the required shaft power. The added resistance in waves increases quadratically with wave height and thus even in low sea states the wave correction method should provide an accurate prediction of the added resistance for the specific ship and the actual encountered wind driven sea and swell conditions. At the same time, the method should be practical requiring limited input; today, many yards refuse to deliver the body plan to the shipowner and the encountered wave spectrum is not normally measured.

The added resistance in waves originates from two wave systems; firstly the reflection of short waves on the hull and secondly, the wave induced ship motions i.e. heave and pitch. The first component is dominant in short waves, the second component contributes if the wave lengths are similar to the ship length (Figure 6). STA used the "horses for courses" approach; STAwave-1 for reflecting irregular head waves and STAwave-2 for head waves in which the vessel is pitching and heaving. If desired, model test results for the specific ship geometry can be used.

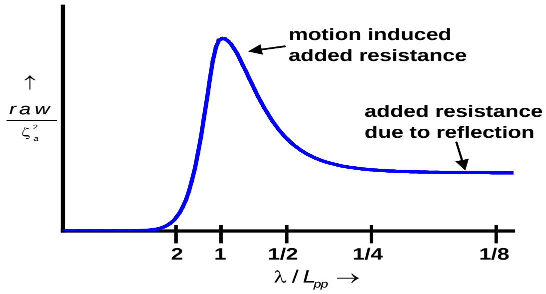


Figure 6 Added resistance in waves as function of wave length over ship length.

The STAwave-1 method is based on the fact that for today's large ships the head waves encountered in trial conditions are normally short compared to ship length and speed. The added resistance due to the reflection of those short head waves is mainly dependent on the shape of the waterline in the bow region. Ship displacement, draught, trim and speed play a secondary role. Actually the dominating reflection part in added resistance is a component of the second order wave forces which can be analytically found from integration over the waterline geometry (Pinkster, 1980). For ship shapes in head waves this analytical expression was simplified for practicality to:

$$\bar{R}_{aw} = -\frac{1}{16}\rho g H_s^2 B\sqrt{\frac{B}{L_b}}$$

Where:

B = Beam of the vessel on the waterline[m]

L_b = Distance of the bow to 95% of maximum beam on the waterline [m]

H_s = Significant wave height [m]

The above expression is particularly practical for speed/power trials as only the ships beam, the length of the bow section and the significant wave height are required as input. No other ship particulars such as parametric coefficients or bluntness factors nor ship speed or wave spectrum are required. It is simply assumed that the asymptotic short wave value of the transfer function extends over the complete range of wave frequencies and thus that the vessel is not heaving and pitching, which can be easily checked during trials.

For small and medium sized vessels or in case long swells are encountered during the trials, the vessel actually will heave and pitch and those motions will contribute to the overall resistance. For this purpose STAwave-2 was developed. This is an empirical statistical method utilising seakeeping model test results from 200 ships. The transfer function of the added resistance in head waves is parameterised to a function of seven input quantities accounting for ship geometry and ship speed. A wave spectrum shape (Pierson-Moskowitz (PM) for seas and Jonswap for swells) is assumed in this method but both significant wave height and mean period have to be specified.

Both STAwave methods were validated with dedicated model tests for a Panamax containership and an Aframax tanker at scale 1:38 and 1:43 respectively in MARIN’s Seakeeping and Manoeuvring Basin. It should be noted that reliable added resistance measurements at model scale requires large models (typically 6 – 8 m.), a dedicated test setup and sufficient run length in the basin. Only the largest seakeeping basins in the world offer this capability. As illustrated by Figure 7 both STAwave-1 and STAwave-2 show an acceptable agreement with the model test results for both ship types.

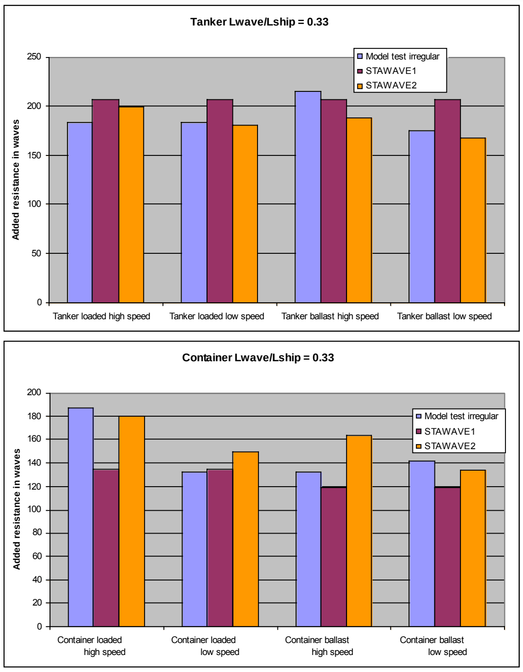


Figure 7 Added resistance in irregular head waves computed by STAwave 1 & 2 compared with results of large model tests for different speeds and loading conditions.

As reliable wave corrections can be made for head waves and if the added resistance in following waves is negligible for normal trial conditions, speed runs in head waves and following waves need to be carried out. For wave directions within the +/- 45 degrees bow sector STAwave for head waves is applied. However, if yard and owner want speed/power trials in other circumstances, they may conduct dedicated seakeeping model tests and measure the encountered wave spectrum during the speed/power tests. Measurement of the encountered wave spectrum is also required in case non-benign sea conditions are encountered during the speed/power trials.

Besides the STA-Wave methods ITTC PSS adopted also an approximation method utilising simplified model tests which was published by Tsujimoto et al in 2008. This method requires model tests in regular head waves for the specific ship geometry.

Prior to adopting the three wave correction methods, ITTC PSS subjected these methods to extensive correlation with model test results made available for this purpose by HSVA, MARIN, NMRI and SSPA. Some comparative results are presented in the next Chapter 9.

Alternative to the use of the above prediction methods, the transfer function of added resistance can also be derived from seakeeping model tests for the specific ship geometry and loading conditions. This transfer function can then be applied to the wave spectrum measured during the trials.

To ensure the reliability and accuracy of the wave correction methods, new wave height limits for speed/power trials have been developed by ITTC PSS. These new limits distinguish trials where the wave spectrum is measured and those where the wave height is derived from observations. In case use is made of transfer functions for added resistance derived from dedicated seakeeping model tests for the specific ship geometry, the wave spectrum has to be measured during the speed/power trials unless the waves are below the lower limit. The new wave height limits are presented in Figure 8.

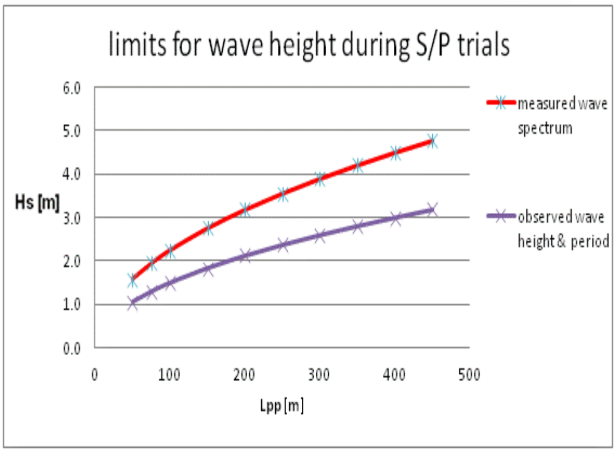


Figure 8 New limits for significant wave height

Corrections for propeller efficiency and rpm. With the power corrections for the encountered additional resistance due to wind, waves and possibly small displacement deviations (max. 2%), also the loading variation of the propeller and thus the propeller rpm and efficiency shall be accounted for. For this purpose the results of the load variation model tests shall be used. As not all model test facilities have experience with load variation tests, these test procedures and their analysis have been specified and documented in detail in Appendix A of ITTC recommended procedure 7.5-04-01-01.2. The load variation test analysis results in three coefficients which are subsequently used in the speed/power trial data analysis:

- The fraction of propulsion efficiency as function of the added resistance fraction.
- The fraction of the shaft rate as function of the fraction of power increase.
- The fraction of the shaft rate as function of the fraction of speed increase (shallow water).

The method has been validated by a comparison with model tests which were conducted by SSPA specifically for ITTC PSS.

The documented procedure has been included in the final version of the ITTC recommended procedure 7.5-04-01-01.2. The speed/power trial analysis thus requires the load variation tests as a standard procedure to be included in calm water ship power model tests.

Corrections for temperature & density. The usual corrections of power for temperature and deviations are incorporated in the new procedures.

Corrections for Water Depth. In the new ITTC speed/power trial procedure the speed corrections for shallow water according to the method published by Lackenby, 1963 has been implemented. With the use of CFD analysis it has been proven by Raven, 2013 that this method strongly overpredicts the effect of shallow water. The reason for this is that the method is based on systematic model tests in a shallow water basin. The resistance of the model is not only influenced by the water depth but also by the horizontal restrictions of the towing tank. Especially in shallow water the horizontal restriction of the basin has a large effect on the resistance. Work of the STA-Group is underway to develop and validate new method by means of speed-power trials at a range of water depths. This is considered to become one of the important improvements of the new procedures in the near future.

Effect of surface roughness. The added resistance due to (hull/propeller) surface roughness is not addressed in the procedure. It is required that the ship should go on sea trial with clean hull and propeller. In case some kind of surface fouling is documented, the hull needs to be cleaned and the propeller polished prior to trials.

Conversion from ballast draught to design draught. As several ship types such as containerships and dry cargo vessels, due to lack of cargo, cannot be subjected to speed trials at their design draught and trim during delivery trials, results of these trials have to be converted to the contractual design draught and trim conditions. This conversion is then based on the difference of calm water model test results for the trial condition and the design condition. This has proven to be one of the largest causes of deviations and discrepancies in the results of delivery speed trials.

Model test results are always extrapolated to full scale on the basis of scaling laws, as well as “correlation coefficients”. These statistical correlation coefficients relate the scaled-up model test power to the predicted power for the actual speed/power trials with that vessel. For a model basin with a sufficiently large trial database for the specific ship type and size, this practice has proven that it is able to deliver power predictions with acceptable accuracy over the years. Model test prediction accuracy is thus dependent on the experience of the model basin and, consequently, the availability of accurate speed/power trial data. For several ship types, however, design draught trial results are scarce. This is a particular problem for relatively new ship types, where data related to modern speed ranges and recent sizes is often missing.

Therefore, strict guidelines for this ballast draught-design draught conversion of speed/power trial results as well as for the extrapolation of model test results towards full scale have been incorporated in the new ITTC sea trial procedure. The wording in the Procedure is as follows:

"For all draughts and trims, the same methods, procedures and empirical coefficients shall be used to extrapolate the model scale values to full scale. In case different methods, procedures or empirical coefficients are used for the different draughts, these shall be documented in full detail and documentation must include justification by means of full scale S/P Trial data for the specific ship type, size, loading condition, model test facility and evaluation method."

This implicates that model basins can only deliver reliable speed power predictions for design draught when they derive their extrapolation coefficients from speed/power trials conducted at the design draught of that vessel type and size.

9. REVISION OF ITTC SPEED/POWER TRIAL PROCEDURES

9.1 Introduction

The background, history and the major principles of the work performed by the 27th ITTC Specialist Committee on Performance of Ships in Service for updating the speed/power trial procedure are presented in the previous chapter. In the current chapter, the different correction methods suggested will be reviewed in more detail with emphasis on the verification work done by the PSS committee.

9.2 Correction Methods

At speed/power trials, effects of wind, waves, current, water temperature, salt content, shallow water, displacement and trim should be analysed and corrected for from measured data. The studied data is summarized below. Verification of correction methods on respective elements are required in order to reduce the number of methods adopted in the updated speed/power trial procedure.

Wind effect. Using the wind tunnel database of NMRI for 54 ships, the following six methods are compared in view of practical use. The database contains contemporary ship shapes.

Selected methods are (1) Fujiwara 2005 (Fujiwara et al., 2005), (2) Fujiwara 1998 (Fujiwara et al., 1998), (3) Isherwood (Isherwood, 1973), (4) Yamano (Yamano and Saito, 1997), (5) Yoneta (Yoneta et al., 1992) and (6) STA DataSet (Sea Trial Analysis Joint Industry Project, 2006). The methods (1) to (5) are regression formulae and method (6) is dataset for coefficient of wind resistance.

To validate each method, the averaged standard error of wind resistance coefficient ($\overline{SE}_{EST}$) is calculated. $\overline{SE}_{EST}$ is defined in Eq. (3). The results of the comparison are shown in Figures 9 and 10 for each ship type.

$$\overline{SE}_{EST} = \sqrt{\frac{1}{n_S}\frac{1}{n_\psi}\sum_{j=1}^{n_S}\sum_{i=1}^{n_\psi}\left(C_{AAij} - \hat{C}_{AAij}\right)^2} \qquad (3)$$

Where n_S is number of ships, n_ψ is number of wind directions, C_{AAij} is the coefficient of wind resistance tested at wind tunnels and $\hat{C}_{AAij}$ is the coefficient of wind resistance estimated.

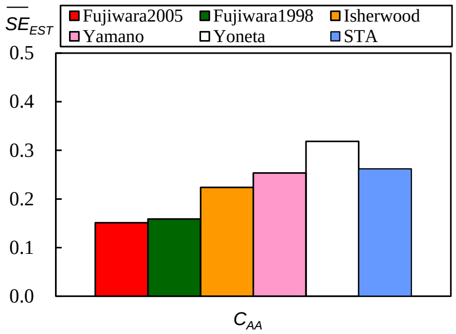
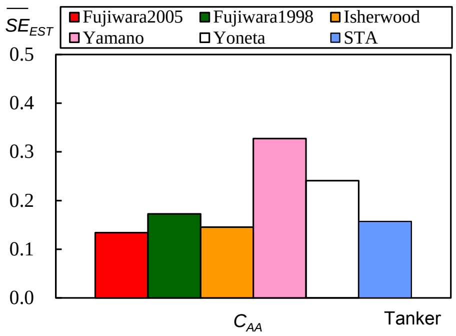
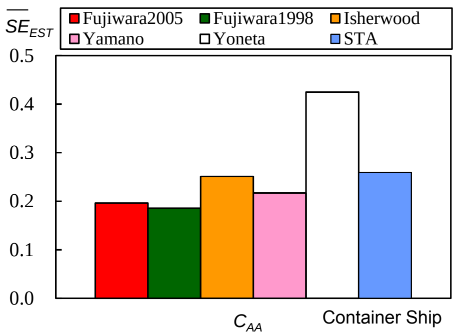


Figure 9 Averaged standard errors of longitudinal wind force coefficient (54 ships).

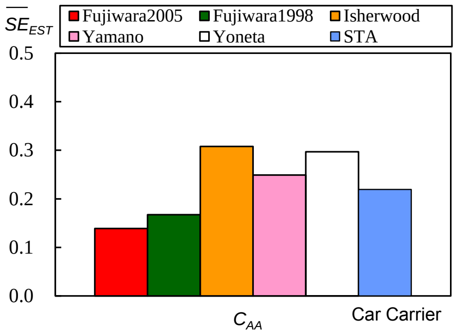
a) Tanker: 16 ships



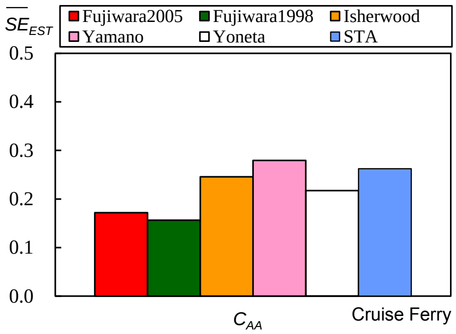
b) Container Ship: 9 ships



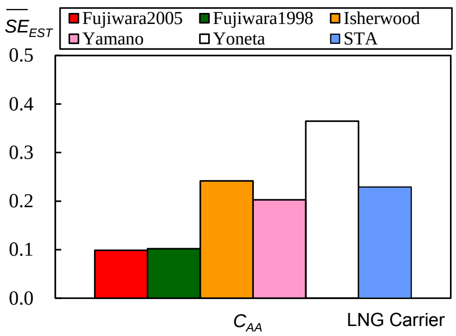
c) Car Carrier: 8 ships



d) Cruise Ferry: 7 ships



e) LNG Carrier: 4 ships



f) General Cargo Ship: 10 ships

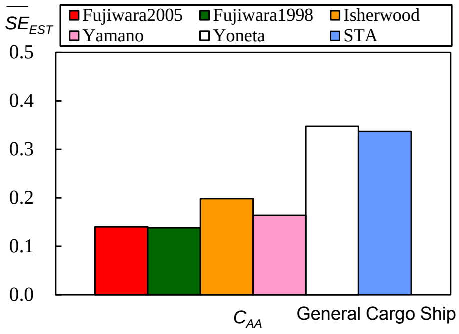


Figure 10 Averaged standard errors of longitudinal wind force coefficient for each ship type.

From the validation, it was found that Fujiwara 2005 method gives the best estimation.

As a result of the validation, the following three possible approaches were recommended in the updated procedure:

(1) Statistical regression formula for various ship types developed by Fujiwara et al.

(2) STA Dataset – see previous chapter

(3) Use of wind tunnel measurements for the specific ship

Wave Effect. Many calculation methods for added resistance due to waves have been developed and these are categorized into empirical method, slender body theory, panel method, and CFD. For the application to wave correction at speed/power trial, the methods should be robust, practical and validated in full scale. Based on these considerations, the following three methods were selected and compared.

The three methods are: (1) STAWAVE1, (2) STAWAVE2, and (3) NMRI (Tsujimoto, 2008).

STAWAVE1 and STAWAVE2 methods are presented in the previous chapter.

The NMRI method is a theoretical method with practical correction, which calculates frequency response function. Two options are provided to apply the NMRI method to wave correction. One is a theoretical method combined with simplified tank tests in short waves. The other is a theoretical method combined with empirical functions for the required parameters estimation.

The PSS committee initiated comparison study for added resistance in regular and long crested irregular waves to understand which of the three methods: STAWAVE1, STAWAVE2, and the NMRI method combined with simplified tank tests in short waves is the best suited for the estimation of added resistance in waves for speed/power trial.

The added resistance response function is compared for six ships with the results of tank tests in regular head waves. For reference, the estimated functions by Maruo (Maruo, 1963) with Fujii-Takahashi (in the figures F-T) (Fujii and Takahashi, 1975) and Faltinsen (Faltinsen et al., 1980) are drawn. These results are presented in Figures 11-16.

From these results, it is clear that the NMRI method combined with simplified tank tests in short waves gives the best estimation, while Fujii-Takahashi method and Faltinsen method underpredict added resistance in short waves. Application of STAWAVE2 in ballast conditions should be carefully checked in short waves.

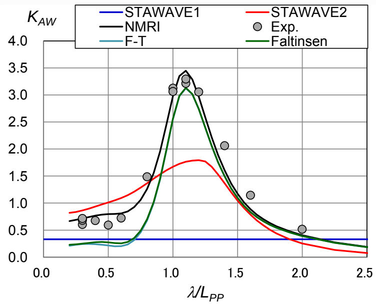


Figure 11 Container ship (L=300m, F_r=0.247; Full)

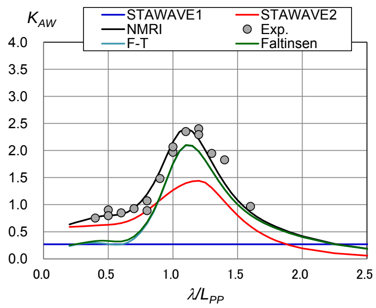


Figure 12 Car carrier (L=190m, F_r=0.249;Full)

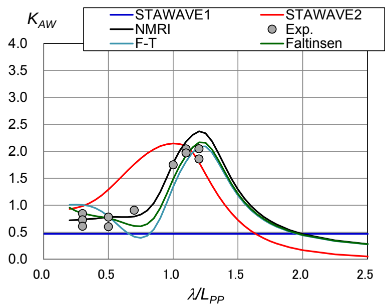


Figure 13 Bulk carrier (L=217m, F_r=0.167; full)

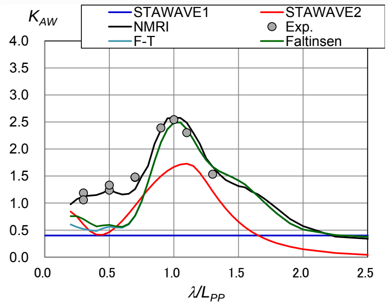


Figure 14 Bulk carrier (L=217m, F_r=0.188; Ballast)

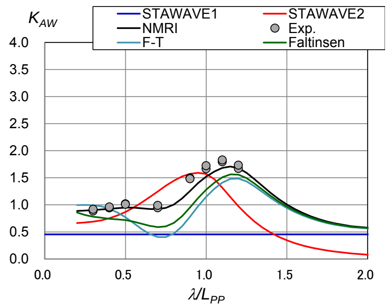


Figure 15 VLCC (L=324m F_r=0.121; Full)

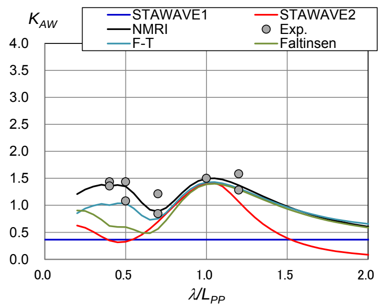


Figure 16 VLCC (L=317m F_r=0.141; Bal last)

Validation in long crested irregular waves has been performed by the contribution of MARIN, HSVA, SSPA and NMRI. Correlation diagrams are shown in Figures 17 and 18.

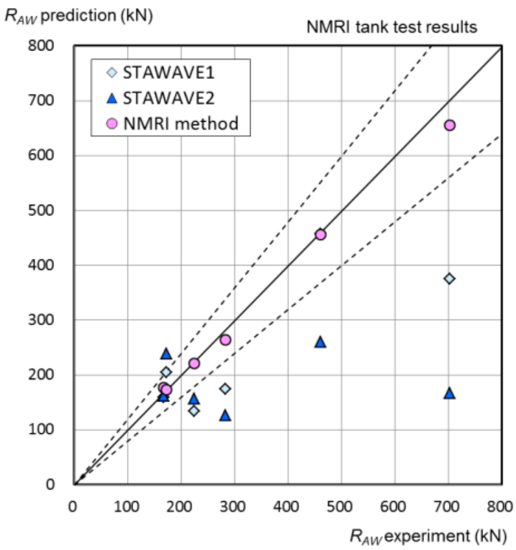


Figure 17 Wave correction methods compared with NMRI model test data; note NMRI model test results were used for the NMRI prediction method.

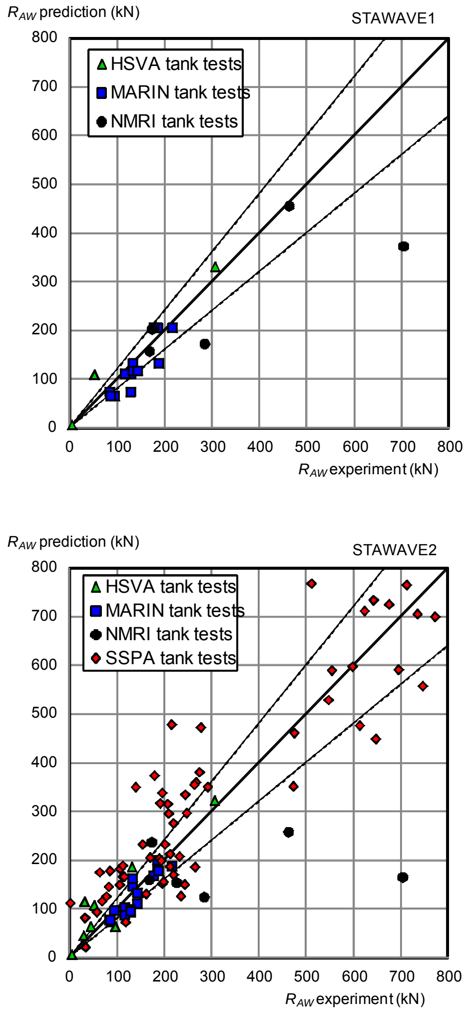


Figure 18 STAwave-1 and STAwave-2 correlated with model test results for various ship types, loading conditions and speeds in irregular head waves

Comparison results for the NMRI method combined with empirical relation for the parameter estimation applied to oblique/beam waves has been provided by NMRI. Correlation diagram is shown in Figure 19.

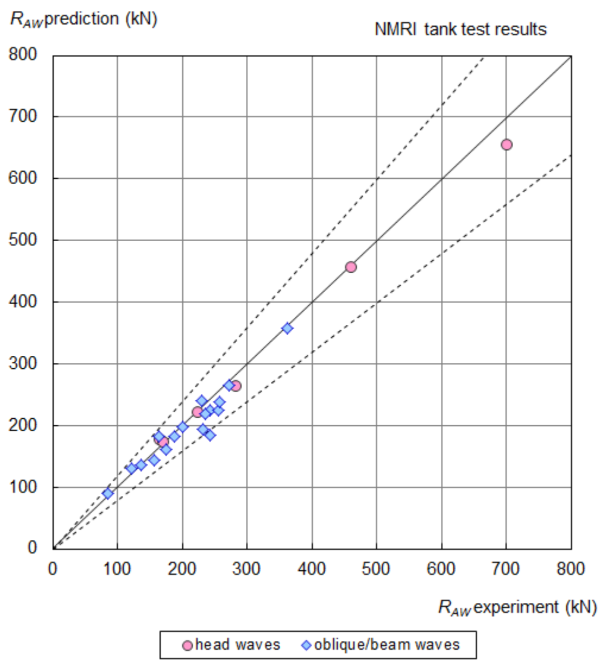


Figure 19 Comparison results for the NMRI method combined with empirical relation for the parameter estimation applied to oblique/beam waves.

From the validation, it is found that the NMRI method combined with simplified tank tests in short waves gives the best estimation.

Based on the above validation results, the treatment of the wave correction method is summarized as:

(1) STAWAVE1
Under the condition that the pitching and heaving are small/missing and head waves, the simplified estimation method can be used.

(2) STAWAVE2
In case only ship dimensions are available and head waves, empirical correction method with frequency response function can be used.

(3) NMRI method

In case C_P (longitudinal prismatic coefficient) and C_{WP} (water plane area coefficient) curves are available, the NMRI method having two options can be used.

(4) Use of sea-keeping tests to obtain frequency response function for the specific ship

Current Effect. Current correction by current curves has uncertainty due to the fairing process of the curve.

To solve the problem, current elimination by Mean of means method has been proposed. Since the method requires two or more double runs (DR) and relates with the requirements for speed/power trial conduct, extensive discussions on this topic were carried our during the PSS committee technical meetings. During the deliberations, it was pointed out that cost increases in proportion to the number of runs. Therefore, as a compromise, in the final recommended procedures, it was allowed to apply a combination of two double runs (2DR) and one double run (1DR).

In case of 2DR, current change is assumed as a quadratic function of time, while in case of 1DR the current is assumed time independent.

It was also pointed out that for large low speed ships as VLCC, one run needs a time duration of approximately two hours. On the other hand, current direction changes with a period of six hours. For such case, 2DR may be insufficient to keep accuracy since quadratic function is hard to express the tidal changes, as illustrated in Figure 20.

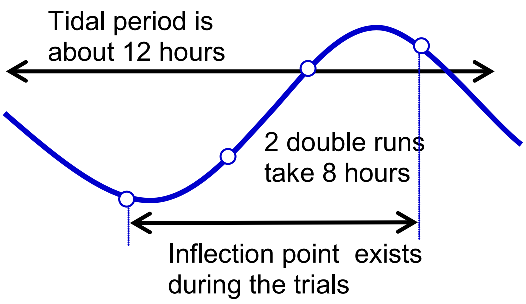


Figure 20 Relation on tidal velocity and trials for large low speed ship as VLCC.

Load Correction. The load variation model test has been selected to account for the influence of propeller loading on the propulsive efficiency. This method is also more transparent and straight forward comparing to the previous method (K_T/J^2 approach).

The example of load variation tests is shown in Figure 21.

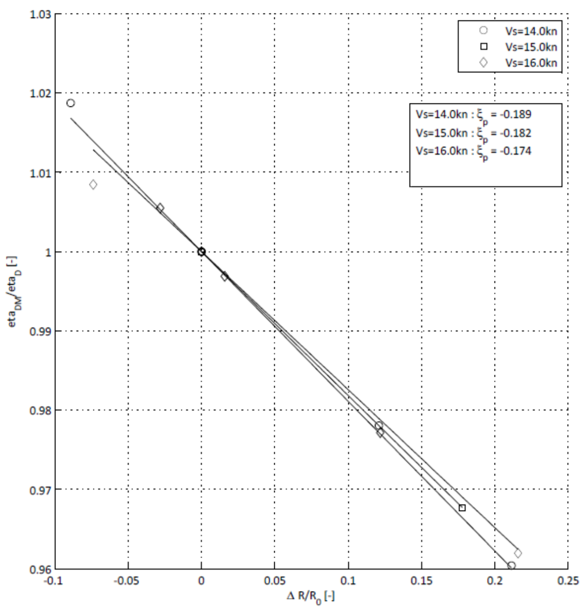


Figure 21 Example of load variation tests – relation between propulsion efficiency change and resistance increase.

Effect of Water Temperature and Salt Content. The effects of water temperature and salt content are corrected considering difference of water density and frictional resistance.

Effect of Shallow Water. In the absence of a more reliable method, the effect of shallow water is corrected according to the ship speed by Lackenby formula (Lackenby, 1963).

Displacement and Trim. Displacement and trim are, in general, factors that can be adjusted to stipulated values at the time of the trials, but there may be substantial reasons for discrepancies. Thus the limit for trim and displacement to allow speed/power trial is documented. Correction of displacement is carried out under the concept that Admiralty coefficient is constant.

9.3 New Recommended Procedure Issued

In June 2012 the ITTC/PSSC submitted its completely revised speed/power trial procedures:

7.5-04-01-01.1:Speed and Power Trials, Part I Preparation and Conduct

7.5-04-01-01.2: Speed and Power Trials, Part II Analysis of Speed/Power Trial Data

to IMO MEPC 64. Part I concerns the preparation and conduct of speed/power trials and was accepted as an informative paper. Part II concerns the analysis of measured speed/power trial data and was accepted by IMO MEPC 64 in September for EEDI use. The final wording of Part I was accepted by IMO MEPC 65 in March 2013. MEPC 65 stated that the ITTC 2012 (a simplified reference for the combined two procedures) is the preferred method for deriving the speed/power performance of ships for EEDI.

With the acceptance of these new procedures, the ITTC and IMO have established a transparent, straightforward **best practice** and a **level playing field** for the delivery of new ships for all stakeholders.

Impact on model tests and speed trials. It should be noted that these Speed/Power Trials procedures have three direct impacts on the procedures for model testing, extrapolating the model scale results to full scale and number of speed runs:

1. Load variation tests should be part of the calm water propulsion model test program and the analysis of these tests should be according to the described procedure.

2. For extrapolation to full scale the same procedure and empirical coefficients should be used for all draughts unless these procedures and coefficients are justified and documented with results of full scale trials for the specific ship type, size and loading condition.

3. Speed trial shall consist of 5 double runs with minimum 10 minutes for the first ship, though for sister ships the programme can be reduced to 3 double runs.

10. CONTEMPORARY TRENDS IN OPTIMIZING SHIP PROPULSIVE PERFORMANCE

10.1 Speed Optimization

Speed reduction is an effective way to reduce consumption and emission. However, the lowest speed is not necessarily the speed where the amount of fuel consumed per tonne-mile is the minimum. Further, it should be considered that slow speed operation may lead to increased vibration and other problems which should be taken into account.

Jan et al (2010) studied the total operational cost change curves for the 13,500 TEU Container vessel, see Figure 22. For the 13,500 TEU, the optimum speed is found to be 21.5 kn rather than the design speed of 25 kn. The cost reduction at that speed is about 7%, the fuel consumption reduction 43 %. Up to a speed of 16.7 kn the ship could operate without monetary loss. However, the very low loading of the engine would likely cause some additional mechanical problems.

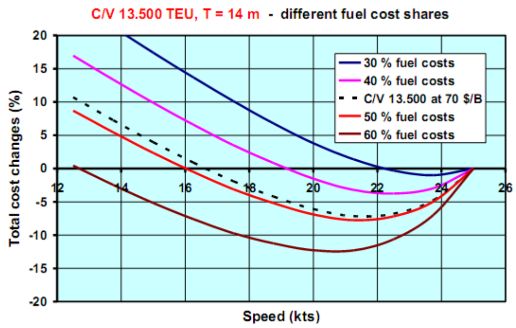


Figure 22 Total cost changes by speed reduction

10.2 Hull Form Design and Optimization

Hull form design and optimisation usually starts with the selection of optimum main dimensions. Depending on the ship type and the ship size, the difference between "optimum" main dimensions from hydrodynamic point of view and "optimum" main dimensions from the manufacturer's point of view (lowest building costs) can easily reach 20-30%.

Contemparary hull form design and optimisation is heavily supported by CFD (computational fluid dynamics) tools. Although the potential flow methods neglect all viscous effects and cannot predict steep, breaking waves these simple methods are still the working horses in the optimisation process. Combined with parametric hull form modelling tools several hundred up to some ten-thousand hull form variants can be investigated during the optimisation process in a reasonable time.

More and more RANS codes are used during the hull form design process giving much more insight in local flow phenomena, boundary layer details or the complex wave formations emerging from partly submerged bulbous bows in “off-design” conditions.

Van et al (2010) used a RANS code, coupled with a parametric hull form optimization tool to develop hull forms that both minimize resistance and improve the wake quality into the propeller. In a sample case that examines the afterbody of a tanker, the significant reduction in resistance was achieved with good agreement with experimental data. However, it is insufficient to judge the performance of afterbody on the basis of wake and resistance only. Self-propulsion simulation and validation are further needed.

Developments and applications of SBD (Simulation-based Design） to ship design was also reported. Kim et al(2010) investigate on the flexibility of use of some choices of design variables including local and global ones in the optimization of the KCS containership.

Li (2012) developed a method to optimize the ship line automatically considering real-geometry propeller. These efforts should be a positive step to promote hull form design.

Actually, hull form designers focus no longer on the optimisation for one draught and one speed, but they are optimising the hull shape for a range of speeds and draughts with remarkable influence of bulbous bow and fore body designs, especially for container vessels.

10.3 Propeller Design

There are several high efficiency propeller types, such as ducted propeller, podded propeller, hybrid contra-rotating pod, tip-plate propeller and composite propeller.

Ducted propeller. The latest research is from Long Yu et al(2013), who published an optimization design method for ducted propeller analysis. It combines geometry generation, auto-meshing, optimization algorithm and CFD analysis techniques and make the process automatically operated which helps extend the CFD analysis to the design process. A ducted propeller case study is validated and optimized, which is a propeller substitution and upgrading for higher thrust force and efficiency. The optimum result can provide better thrust force than original ducted propeller installed on the vessel. However, the automatic optimization process is also time-consuming and very sensitive to the geometry twisting.

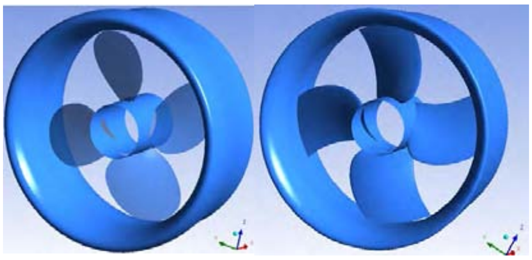


Figure 23 ducted propeller (left: original, right, optimized)

Podded propeller. Raimo（2013）studied the energy saving possibilities in twin or triple propeller cruise liners. The good solutions for improved ship designs are podded propulsion, Dual-End CRP, ECO efficient conventional propulsion concept and hybrid propulsion concept. With careful appendage and propulsion design, large fuel saving is possible to achieve. With the aid of CFD tools, new hull form concepts can be developed prior to the model-testing phase of a project. Yet, podded propeller has the disadvantage of shorter docking interval comparing with normal propeller which should be taken into account.

Figure 24 Ship model of a Hybrid Cruise Ferry

Hybrid contra-rotating pod (CRP). CRP concept makes use of Pods in combination with the existing single screw shafting arrangement, which gains in efficiency caused by the lighter propeller loading and the contra-rotating effect of the propellers. Also, the dimensions of the conventional shafting arrangement can be reduced, and the rudders, headboxes and stern tunnel thruster can be removed which will lead to reduced appendage resistance. CRP is expected to have 15% benefit with suitable design.

Figure25 Hybrid CRP

Tip-plate Prop. The Contracted Loaded Tip propellers (CLT) are screw propellers with highly loaded blade tips. The fitted end plates at the blade tips act as a barrier avoiding the communication of water between both sides of the blades. The end plates are positioned so as to cause a minimum viscous resistance and therefore are parallel to the incoming flow and shaped to the relative motion of the water. The end plate is located at the pressure side of the blade with the aim to obtain a higher overpressure downstream. All research findings are included in the book "*Detailled Design of Ship Propellers*". Possible gain in the range of 6-12% in full scale is claimed. However, reliability and ship owner's acceptance may be the main difficulties to wide use of CLT.

Figure 26 Tip-plate Prop

Kappel propeller. The Kappel propeller concept was initially proposed by Jens J. Kappel and Poul Andersen, Poul Andersen et al (2005). The principle of non-planar lifting surfaces is applied to the design of modern aircraft wings to obtain better lift to drag ratios. The application of a pronounced fin or winglet at the tip of the propeller blade has led to the Kappel propeller with blades curved towards the suction side integrating the winglet into the propeller blade. The combined theoretical, experimental and practical approach to develop and design marine propellers with non-planar lifting surfaces has resulted in propellers with higher efficiency and lower levels of noise and vibration excitation compared to conventional state-of-the-art propellers designed for the same task. The authors claim efficiency gain in the order of 4% based on sea trial results.

For both CLT and Kappel propellers, however, a standard procedure for the open water hydrodynamic characteristics scaling is still missing. Therefore, a recommendation to the full Conference could be addressed to look into this issue.

Composite propeller. A. Sánchez–Caja (2013) explored combination of Pod, CLT and CRP propulsion for improving ship efficiency: EU Project TRIPOD. The main objective of the TRIPOD project is to develop and validate a new propulsion concept for improved energy efficiency of ships which is based on the combination of three existing propulsion technologies. In particular, TRIPOD explores the feasibility of integrating podded propulsors and tip loaded endplate propellers into energy recovery systems based on counter rotating propeller (CRP) principle. A non-rotatable pod unit called Rudderpod is installed behind the ship main propeller. CRP units consisting of different combinations of CLT and conventional propellers are being analyzed in ballast and load conditions for a retrofit and a new building scenario. CFD tools and model tests are combined to facilitate the design process. A method for the extrapolation of model tests to full scale and another for the accurate estimation of effective wakes by CFD tools have been developed.

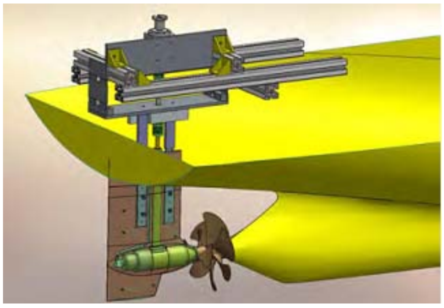


Figure 27 Composite propeller

10.4 Energy-Saving Devices

Energy-saving devices are widely used to improve the propulsive performance. There are many kinds of devices. Y.B Choi(2008) summarized the energy-saving devices and their rates and some are listed below.

John Carlton(2007) classified all hydrodynamics energy-saving devices into 3 categories. The first category located upstream of the propeller. One solution tries to improve the axial flow of water reaching certain areas of the propeller, especially the upper region of the disk (such as the flow equalizer duct). The second category contains all those devices located downstream the propeller to recover rotation energy, including boss cap fin, the fins on the Costa bulb type and the "Additional thrust fins", etc. The third category contains all those devices located near waterline, relatively far from the propeller, to reduce wave resistance. These devices include Spray deflector ,Wave suppression plate etc.

Figure 28 Different Energy-saving devices and gain rates

With the rapid increase of fuel oil price and EEDI pressure, more and more interested parties start to investigate the mechanism of energy-saving device both experimentally and numerically .

Jie (2011) introduced a new Joint Industry Project (JIP) initiated by MARIN, which aims to look into the working principles and scale effects on Energy Saving Devices (ESDs). Three ESDs have been chosen for the investigations in the first phase. They were a pre-duct with a supporting stator in the duct, a pre-swirl stator with asymmetric blade design and Propeller Boss Cap Fins (PBCF). Measurements of forces and moments on all components of the ESDs have been carried out in self-propulsion model tests with dedicated sensors. Particle Image Velocimetry (PIV) technique has been used in the investigation of the detailed flow around the ESDs. In order to investigate the scale effects in model tests, a full-scale wake field was approximated by a 'smart ship model'. Computational Fluid Dynamics (CFD) calculations were carried out both for designing the smart ship model and also for the detailed flow around the ESDs.

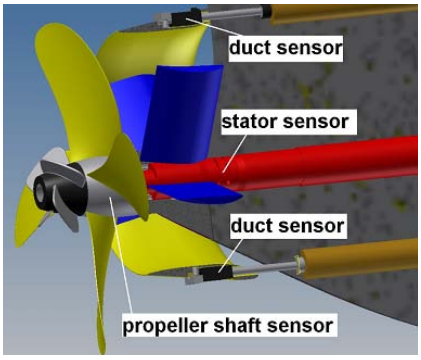


Figure 29 The sensors used to measure forces and moments.

Yuhai etal(2013) performed numerical self-propulsion simulation of a VLCC with real-geometry propeller.

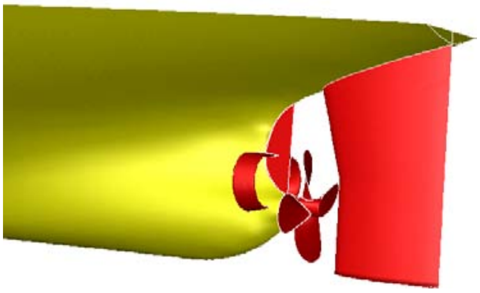


Figure 30 Configuration of Duct on VLCC

The mechanism of the duct's influence on the wake field, ship's resistance, and propulsive performance was studied and analyzed in detail. From analysis, the author concluded that the ship's resistance variation induced by the duct is very limited, the duct produces a beneficial tangential velocity field for propulsive performance. Also, the duct reduces the transverse pressure difference between two sides of the ship which is helpful to course-keeping. This is an additional benefit.

Some more energy-saving devices are briefly introduced below.

Rudder bulb. This energy-saving device is installed on rudder. It's used to reduce the hub vortex, increase wake fraction, reduce contraction of the propeller slipstream, reduce pressure pulse induced by propeller. HSVA model test shows that rudder bulb can have up to 2% benefit, and other tanks such as SSPA gives the same conclusion.

Figure 31 Rudder with bulb

Propeller boss cap fins (PBCF). CAI et al (2013) introduced an integrative design method of propeller and PBCF. PBCF and propeller are considered as a whole system and the design is an integrative process, in which the concept of uploading in blade root is merged. The load distribution of blade becomes well-proportioned due to the uploading in blade root, and it is advantageous to the depression of vibratory force and blade tip vortex. The blade root area has larger thickness and strength, which is beneficial to noise reducing. The disadvantage of uploading in blade root is the generation of hub vortex behind boss cap, but the hub vortex can be absorbed by PBCF. Therefore, the integrative design method can provide higher efficiency propellers for the same design conditions. Yet, whether and how to perform open-water test with PBCF needs to be further investigated.

Figure 32 PBCF

Combined devices. In 2012, an energy - saving model test on a VLCC was carried out in MARIC towing tank. The energy-saving devices consist of Simplified Compensative Nozzle(SCN), Rudder Bulb(RB) and Thrust Fin(TF).

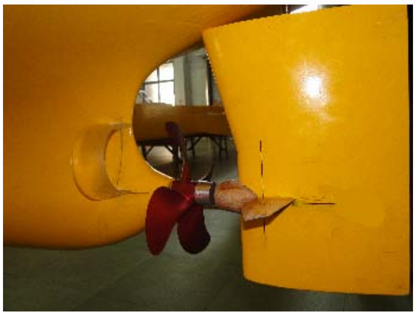


Figure 33 Combined energy-saving devices

10.5 New Idea of Energy Saving

Sasaki (2013) introduced ZEUS(Zero Emission Ultimate Ship) challenging project of NMRI . The objective of ZEUS project is to obtain the maximum energy efficiency. Some innovative ideas are developed. Reaction pod is quite a new idea for podded propulsion system and it means the optimum pod arrangement for the twin skeg hull form.

Weather Adapted Duct(WAD) The system is composed of a propeller with special pitch distributions and a front duct placed very close to the propeller. The size of diameter of the duct is less than 45% of propeller diameter and the size is so small that harmful cavitation hardly occurs.

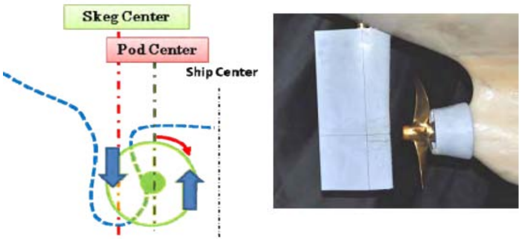


Figure 34 Concept of Reaction Pod (left) and Weather Adapted Duct (right)

Spray Tearing Plate (STEP) is a device to reduce added resistance in waves to change a direction of wave dynamic pressure from longitudinal direction to lateral direction. Therefore STEP is very effective if the vessel has sharp stem and high speed enough to grow bow waves. The effectiveness is confirmed by on-board measurements and STEP has been installed in some RoRo cargo ships (Kuroda et al. 2012, Kuroda et al. 2013).

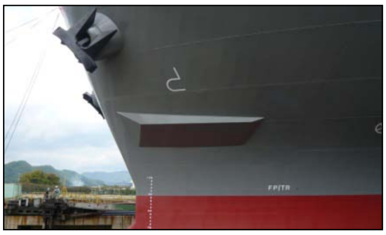


Figure 35 STEP installed in a RoRo vehicle carrier

10.6 Resistance Reduction by Air Injection

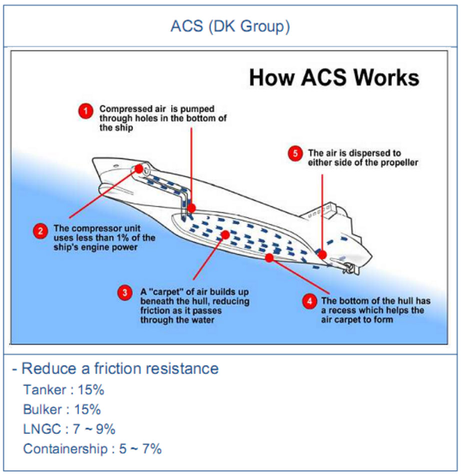


Figure 36 Resistance reduction by air

Since frictional resistance reduction is the only function of air carpet, slow-full ship will be more likely to get benefit. Below figure shows the best Fn range is from 0.05-0.15.

The resistance reduction effect of air tends to decrease in waves, hence inland navigation vessels are better suited for this approach. Here, one important aspect is to lead escaping air properly to avoid propeller cavitation.

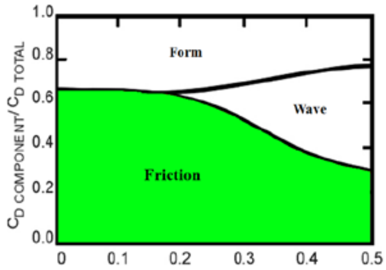


Figure 37 Resistance component – Fn

The research of resistance reduction by air injection method have been actively carried out. Using a 1m-wide-50m-long flat plate model ship, the effectiveness of the resistance reduction by air injection is shown in a series of experiments in a 400 m long towing tank of NMRI (Hinatsu et al. 2008). With these results, full-scale ship experiments using air injection were performed for a large cement carrier (Kodama et al. 2008).

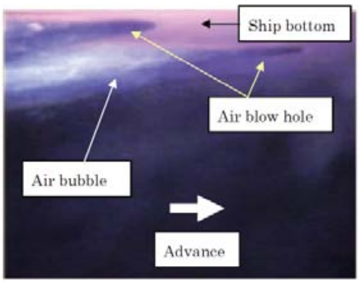


Figure 38 Air injection for full-scale ship

Figure 39 Wake flow without air injection (left) and with air injection (right)

Some shipyards developed and engaged into operation air lubrication systems.

The first system was installed on two sister ships of flat bottomed module carrier (Mizokami et al. 2010). Following applications were on ordinary type of ocean going ships, like a 28,000DWT bulk carrier (Mizojiri et al. 2012) and a ROPAX (Mizokami 2013).

Recently, a new air lubrication system has been developed. For a large ship having a deep draft, the air supply to the ship bottom is one of critical problems to get net energy saving. In order to overcome the problem, a new concept to use bypassed scavenging gas for the air lubrication has been applied to 90,000DWT bulk carrier (Kaiji Press 2013).

Figure 40 Air lubrication system used in service (90,000DWT bulk carrier).

10.7 Other Measures to Improve Ship's Performance From Resolution MEPC.213 (63)

Improved voyage planning. The optimum route and improved efficiency can be achieved through the careful planning and execution of the voyages. IMO resolution A.893(21) (25 November 1999) on "Guidelines for voyage planning" provides essential guidance for the ship's crew and voyage planners. Better course control by means of less frequent and smaller corrections will minimize losses due to rudder resistance.

Optimum trim. Most ships are designed to carry a designated amount of cargo at a certain speed for a certain fuel consumption. This implies the specification of set trim conditions. Loaded or unloaded, trim has a significant influence on the resistance of the ship through the water and optimizing trim can get significant fuel savings. For any given draft there is a trim condition that gives minimum resistance. In some ships, it is possible to assess optimum trim conditions for fuel efficiency continuously throughout the voyage.

10.8 Conclusion and Suggestions

To enhance the powering performance, such measures as speed reduction, energy saving devices, hull form and propeller optimization can be used. However, some challenges/problems still exist, which need further study.

(1) How to coordinate multi-draft and multi-speed optimization
(2) How to correlate energy-saving rate from model scale to full scale.
(3) Reliability of high efficiency propeller
(4) Wide application of Air-carpet resistance reduction technology.

11. EFFECT OF STEERING AND WIND TO THE ADDED RESIS-TANCE

Experimental methods to determine the effect of wind (wind force measurements in the wind tunnel) and the effect of drift in side wind conditions (force measurements using computerised planar motion techniques for a range of specified drift angles, rudder angles and heeling angles, if necessary) are state of the art and will not be described in this context.

11.1 Wind resistance

Wei Jin-fang, et al. (2010) investigated the coefficient *fw* for the decrease of ship speed of EEDI, and introduced a calculation method for *fw* taking into account of added resistance of wind by empirical formula.

Zhu H., et al. (2009) measured the mean wind pressure distribution and shape factors of local members of the platform with the steady gradient wind through wind tunnel tests under different wind directions.

A. Mohseni, et al. (2012) presents the effects of waves, wind speed and direction, current speed and direction, and depth of water in vessel voyage planning which is based on meteorology and satellite data and computer program based in the ISO/DIS 15016. The interpolation between satellite data, historical chart data and observed data can optimize voyage route and cause reduction in sea passage time and fuel oil consumption. Various analysis methods for resistance increase due to ship motion, wave diffraction, wind, steering, drifting, water temperature, salt content, deviation of displacement, hull and propeller surface roughness and shallow water effects are considered and could be contained in computer program.

With the rapid progress of CFD technique, numerical simulation has played more and more important role in predicting wind resistance.

Zhu H., et al. (2009) performed the simulation of mean wind pressure distribution, form factors and the wind loads of the platform based on N-S equation.

Hou L., et al. (2009) calculated the wind moment of a container ship by N-S equation based on commercial software.

Yue X-R, et al.(2011) calculated wind loads on a VLCC, and the calculation results were compared with the experimental results.

Ma Y. (2009) studied and analyzed the aerodynamic performance of the sail in the Olympic Games by use of the numerical simulation and experimental method in a wind tunnel.

11.2 Steering effect on resistance

An experimental approach investigating ship drift and steering in winds and waves free-running tests at a towing tank is performed using a container ship model of 6.3m length (Fujiwara et al. 2008). Figures 41 and 42 show the setting of the experiment. For the evaluation of full-scale ship, the load variation on the propeller and rudder, and difference of wake pattern are to be considered.

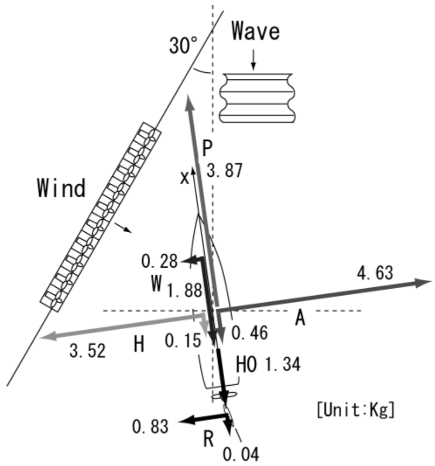


Figure 41 Force balances acting on the ship for external forces (wind speed: 4m/s and wave height: 0.12m, with wave length ship length ratio: 0.9).

Figure 42 Photo of free-running model experiment of a container ship (from behind the ship).

Chuang (2013) performed a series of experiments on a model of 8000 DWT tanker in a large towing tank and ocean basin. The model was self-propelled and mainly running in moderate long wave conditions. Numerical simulation work was carried out in order to make comparisons with experimental results. It was concluded that time domain simulation is the preferable method for the steering effect evelauation.

For the empirical formula, longitudinal force due to ship drift (X_H') is conventionally considered as the difference of ship resistance (X_{0U}'). To improve the accuracy in the small range of drift angle, a method has been developed assuming the static motion (Sogihara et al. 2010). This method integrated lift-induced drag for small aspect ratio into the formula. Comparison between experimental and calculated results are shown in Figures 43 and 44. These figures also show the improvement of the estimation in the small range of drift angle.

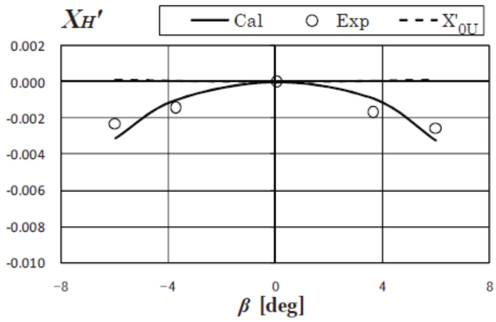


Figure 43 Longitudinal force due to ship drift (bulk carrier, F_r=0.15

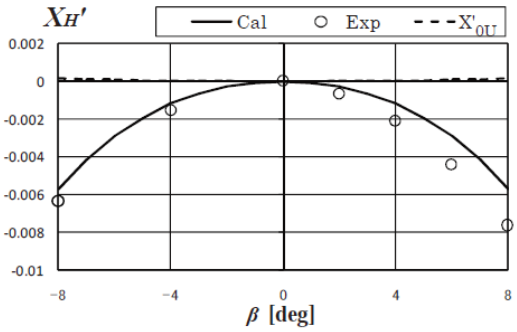


Figure 44 Longitudinal force due to ship drift (container ship, F_r=0.25)

There have been large improvements in automated heading and steering control systems technology from Resolution MEPC.213(63). An integrated Navigation and Command System can achieve significant fuel savings by simply reducing the distance sailed "off track". The principle is simple; better course control through less frequent and smaller corrections will minimize losses due to rudder resistance. Retrofitting of a more efficient autopilot to existing ships could be considered.

12. SURFACE ROUGHNESS ISSUES (HULL, APPENDAGES AND PROPELLER)

In order to systematize the search through the researchers works, reference was made to the following aspects:

- effects of novel coatings application on the ship hull surface
- ship performance data recording and monitoring
- impact on the power prediction methods based on model test

12.1 Effects of Novel Coating Application on the Ship Hull Surface

Comprehensive review of the research works within the area of hull surface coatings can be found in ITTC (2011). It consists of market based review of available surface treatment methods, discusses the impact of coating systems on ship performance in terms of hull resistance, propeller characteristics, cavitation and noise. Furthermore it provides the review of the measurement methods used for determination of surface roughness as may be applicable to ship hull and those used for skin friction measurement both in model and full scale.

It must be stated that although relatively large database exists within the field some publications are influenced by ship coating systems producers and may reflect their commercial interest. Although significant reduction (up to 10%) of frictional resistance is claimed it is hardly supported by verifiable data or reliable measurement provided by industry (ITTC, 2011). Furthermore, it should be noted that majority of discussed measurements were carried out at Re below the full scale ship conditions and require some sort of extrapolation.

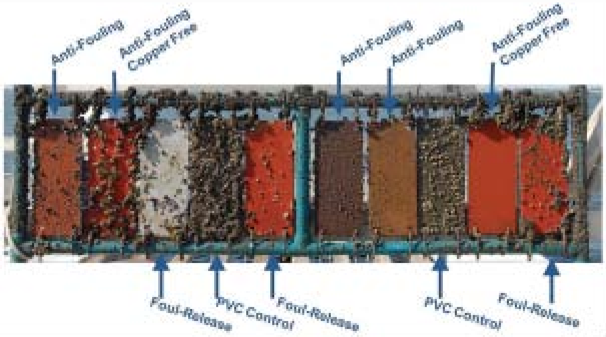


Figure 45 Fouling of several commercial formulations after 180 days static immersion (Swain, 2011).

Many researchers deal with the problem of comparison of different surface coating systems in terms of frictional resistance. Comparative studies of Tin-free biocide-containing (TF) Self-polishing copolymer (SPC) and foul release (FR) coatings is provided by Corbett et al. (2011) where the fuel consumption data gathered in operation of bulk carrier and tanker pre and post FR coating application as well as data recorded on newly build sisterships coated with FR (two ships) and Tributylin (TBT)-free SPC (three vessels) were analysed. Significant fuel savings (10% for the tanker, 22% for bulk carrier) were reported due to application of FR coating. The fuel saving effect was not observed for the case of container vessel however it was noted that FR coated vessels carried out approximately 10k metric tons more cargo comparing to their SPC coated sisters. The paper contains also the fleet-wide extrapolation of FR coating usage revealing huge potential of GHG limitation. Although such superior performance was not confirmed by other sources it was noted by Anderson et al. (2004) and Candries et al. (2003) that 2%-23% drag reduction may be accounted for FR based on quality of application and test type (flat plates of different size and cylinders). In case of similar application procedure the differences in friction are much smaller and amount to ~2% which is to some extent confirmed by rotating cylinder tests presented by Abdul Ghani et al. (2010) where drag benefit of FR coating over SPC reduces with increased speed (Re number).

The drag/fuel consumption increase in time is discussed by Taylan (2010) for a number of different coating systems including FR and SPC confirming previous conclusions regarding the performance of FR systems. A rate of roughness increase over time was reported to be between 20 to 40 microns per year depending on the coating type. Some additional information on time dependent surface deterioration due to fouling may be found in Willsher (2007) where also the effect of slime growth is indicated. This phenomen reached significant focus in Candries et al. (2003) where it is indicated that operational experiences shows little difference between FR and SPC coatings after a period of time. Although significant increases of drag (reaching 10% after 10 days of immersion in still water) in flat plate towing tests was reported it was finally stated that eventual ship drag increase would be within few percents of clean surface drag. This discrepancy results from the fact that part of slime layer detaches from the surface when the ship is in motion, what explains why FR coating rapidly losses its initial drag benefit but does not exhibit more drag than SPCs over longer period of time (after reaching slime growth/detachment equilibrium). These findings were supported by the measurement of power increase carried out for two sister ship fleet oilers each painted with different coating system (FR and SPC) in a period of over 1 year of operation (Logan, 2011). Similar conclusions of FR and SPC coatings performance comparison based on static and dynamic immersion tests were presented by Swain (2011). Author stressed also the importance of the hull condition control and its proper maintenance by use of the novel technique of grooming (i.e. gentle, habitual and frequent mechanical conditioning of hull surface).

Economic impact of the hull fouling was considered by Schultz et al. (2011) on example of DDG-51 destroyer class. The special consideration was taken with respect to the hull condition maintenance strategy in comparison to current US-Navy practice. Introduction of the effective proactive hull cleaning strategy offers substantial savings in total cumulative costs per ship in long term horizon.

Effects of the application of FR coating on marine propeller was presented by Anderson et al. (2004) by recalculation of propulsive performance of slow speed tanker. Calculations were done with use of corrected drag and lift coefficient of the propeller blade according to the results laboratory analyses of number of coated surfaces. The 6% efficiency gain over the uncoated propeller being in service without cleaning for one or two years was reported. Similar range of propeller efficiency enhancement was theoretically determined due to application of the coating generating a hydrophobic (i.e. water repellent) surface as reported by Schwanecke (2010).

Fouling prevention re-gained the research focus since mid-1990 due to the restrictions on use of TBT-based paints. It was however observed that majority of the studies used the barnacles as a model for biofouling. This approach was criticised by Holm (2012) due to the fact that fouling community of organisms is extremely diverse and may not be properly described by single specie. Furthermore it was pointed out that current research made use of relatively simple assays while more advanced tools including molecular genetic and atomic force microscopy could be utilised. Author requested the holistic approach to the biofouling problem. He concluded that although the studies on barnacles continue to advance the state of the art, the successful resolution may be only reached by similar depth of knowledge for other fouling organisms.

12.2 Ship Performance Data Recording and Monitoring

An ability to build the ship performance model and therefore predict her performance under specific operational conditions allows for efficient ship operation. Whenever the crew or owner officers attempt the task of ship routing, selection of fuel efficient combination of speed, draft and trim or deciding the hull surface conditioning, the adequate ship performance model allows for making technically justifiable choices.

The need and benefits of ship performance monitoring has been well recognized in marine practice (Carlton, 2007) although relatively simple methods were used. Latest works of IMO GHG Committee, in particular those connected to mandatory determination of ship's Energy Efficiency Operational Index (EEOI) and Ship Energy Efficiency Management Plan (SEEMP), directly point out the need of application of onboard performance optimisation systems as tools for reduction of environmental footprint.

The success of performance monitoring largely depends on incorporating the versatile ship performance models which allow for benchmarking the performance data against reference performance and for selection of operational variables (e.g. speed or trim) in order to perform the transport task of the ship at minimum costs and/or environmental impact. In general, such performance models fall into three main categories:

- white-box models,
- black-box models and
- grey-box models.

White-box models are based on physical principles resulting from model and full scale experiments and observations. Application of white-box model for the purpose of ship routeing with respect to minimisation of emissions was presented by Prpić-Orŝić & Faltinsen (2012). Another example was published in (Leifsson et al, 2008) where linear and non-linear regression methods were implemented in order to tune the general model to fit the characteristics of specific ship. It must be noted that such models were developed for the purpose of conceptual design. Therefore, use of white-box models with their limitations and underlying assumptions and uncertainties implicitly affects their accuracies. These limitations were briefly discussed by Petersen et al. (2012) revealing that even large changes of ship performance due to hull surface deterioration over one year would not be detected. Similar conclusions were found by Dinham-Peren & Dand (2010) Some additional information with respect to accuracy of white-box models were provided by Leifsson et al. (2008).

By contradiction, the black-box models do not require any prior knowledge or consideration about the modelled system. Black-box model describes the relations between input and output variables e.g. between ship operational variables and ocean environmental conditions and ship fuel consumption. The application of black-box model for performance monitoring of domestic ferry operating between Danish islands along with comprehensive set of full scale data collected onboard for the period of almost two months is presented by Petersen et al. (2012). Similar approach was used for monitoring of 110k DWT tanker performance (Pedersen & Larsen, 2009). Both cases made use of Artificial Neural Network (ANN) for the purpose of building the model. It was reported that promising results were obtained indicating the ability of predicting the fuel consumption within accuracy of ~2% after proper training of the system. The resulting accuracy is close to standard deviation of shaft power determination onboard the vessel therefore further improvement of the prediction may be only achieved by more accurate registration of performance data used for feeding the model. Despite these results the limitations of the proposed approach were noted. It was found that although the method copes relatively well with system identification inside the range of measured parameters the extrapolation beyond the identified boundary fails. Large variation of the parameters which may be a case of determination of ship performance in ballast and design conditions could not be covered by homogenous model.

Use of so called grey-box models i.e. combination of semi-empirical (white) models and black-box models were proposed in order to overcome the limitations of pure black-box models with reference to extrapolation. Both parallel and serial combination of white and black box models were tested by (Leifsson et al, 2008) revealing similar performance. Similarly to Petersen et al. (2012) and Pedersen & Larsen (2009) the ANN was used as the black-box model. The white-box model was based on Holtrop (calm water) and Isherwood (rough water) methods. The developed model was used for performance approximation of the 10k DWT container ship sailing at design speed of 20 knots. The model was trained on the data set registered during the quasi-static part of the voyage (port approach and manoeuvres were filtered) with use of MAREN energy management system installed onboard. Application of grey-box model performed much better than white-box model in terms of fuel consumption prediction. However, it was noted that such result may be achieved due to largely simplified white-box model used in comparison. Furthermore, it was stated that the same grey-box model did not reveal satisfactory performance in predicting the ship speed. Surprisingly, the achieved results were only slightly better comparing to performance of pure white-box model. Such results were difficult to explain. However, as the possible cause of the underperformance, the small range of speed change in training data was suggested.

Some authors e.g. Pedersen & Larsen (2009) and Logan (2011) discussed the influence of data quality on the accuracy of ship performance prediction model. It was generally noted that daily log data did not allow for building the accurate prediction model since they contain both reliable data (such as GPS speed or engine rpm) and data which are subject to interpretation (e.g. wave conditions). Furthermore, ship log data mix instantaneous data (e.g. wind speed) with time averaged data (e.g ship speed calculated based on distance travelled) which may be another source of inaccuracies. Therefore, it was pointed out that use of automatic data recording systems allows for improvement of performance prediction. Further, significant improvement of prediction quality may be achieved by incorporation of reliable weather data available on systems such as NOAA (Pedersen & Larsen, 2009).

12.3 Impact on the power prediction methods based on model test

Hull surface roughness can have a significant impact on the vessel propulsive performance thus causing increased fuel consumption and harmful emissions. As indicated by Swain (2011) in case of the 280m cruise ship operating at 20kn, an increase of the average hull roughness (AHR) results in 1% penalty in fuel consumption for every 15μm.

Surface roughness influences a ship power prediction through the impact on the hull resistance and propeller performance. The standard method (ITTC-78) of ship model tests extrapolation includes the roughness corrections for bare hull resistance (roughness allowance ΔC_F) and open water propeller characteristics (difference in propeller profile's drag coefficient ΔC_D). The appendages resistance is not affected by the roughness in general (except the bilge keels which area is included in total wetted hull surface and thus influenced by roughness allowance). The recommended methods for appendages resistance scaling are approximate and therefore implementing the roughness effects can be considered as unnecessary complication without the visible effect on prediction accuracy.

Surface roughness is represented by a single parameter referred to as average surface roughness k_S (for ship hull) and k_P (for propeller). The average roughness is obtained by numerous measurements performed along the surface in question with use of roughness analyser. Default values recommended for use in case the direct roughness measurements are missing are 150µm for hull and 30µm for propeller.

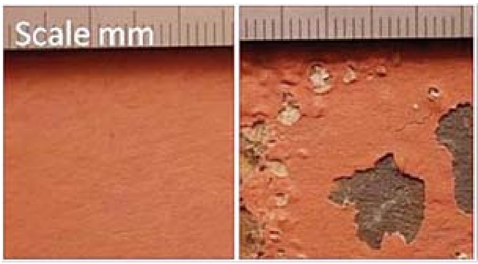


Figure 46 Ship hull coating condition. Left: 3 year self-polishing copper 70 µm AHR. Right: 11 year hybrid copper 264 µm AHR plus damage (Swain, 2011).

It was, however, suggested by Candries et al. (2003) that single parameter roughness characteristics adopted in ITTC extrapolation procedure may not be sufficient to describe surface characteristics. This finding complies with works of Mejia-Alvarez and Christensen (2010) where effects of rough surface simplifications on the flow quality were presented. The study consisted of the PIV flow measurement over the original, damaged turbine blade surface and its physical replicas built up with use of rapid-prototyping based on two low-order models (retaining 95% and 71% of the original surface roughness). In order to trace the similarities and differences of the replica surfaces, they were scanned and the streamwise profiles of the roughness amplitude were analysed with use of probability density functions (PDFs). Both low-order representations preserved relatively well flow characteristics outside roughness sublayer. In case of the flow inside the boundary layer, the differences are substantial. Only low-order model, retaining 95% of the roughness details, allowed to maintain the flow characteristics close to the wall. It should be noted that in the study of Mejia-Alvarez and Christensen (2010), the roughness height was not the only scale used to describe the surface. Beside the roughness height, the root-mean-square roughness, skewness, flatness, streamwise and spanwise surface gradients were presented. The need of research within the field of correlation between friction drag characteristics and surface texture parameters was indicated by Flack and Schultz (2010). They studied roughness parameters presented in literature and the common surface statistical parameters in order to identify hydraulically relevant roughness scales. Results indicated that root-mean-square roughness height (krms) and skewness of the surface elevation PDFs (sk) were the most effective parameters in terms of hydraulic performance of the surface. A correlation between mentioned parameters and commonly used sandgrain roughness height (kS) was also provided:

$$k_S = f(k_{rms}, s_k) \approx 4.43 k_{rms}(1+s_k)^{1.37} \qquad (4)$$

It should, however, be applied with caution since the data used for setting up the correlation contained only few examples of the negative skewness (i.e. describing pitted surfaces due to corrosion, surface wear etc.). Furthermore, it should be noted that the correlation was done for the fully rough flow and may not work in transitionally rough regime.

Current propeller open water characteristics scaling procedure was re-evaluated in the recently completed research project PREFUL. Joint research conducted by HSVA Hamburg and CTO Gdansk was aimed on development of the alternative methods of recalculating the model propeller performance to the full scale. Two alternative procedures were presented by Streckwall et al. (2013) and Bugalski et al. (2013). Both proposals, however, do not incorporate the effect of propeller surface roughness.

13. SURFACE ROUGHNESS SIMULATION BY NUMERICAL METHODS

13.1 Methods

The task to numerically simulate the effect of surface roughness can be divided into two parts: first the translation of a real roughness condition as it appears in reality into simplified parameters, like the "equivalent sand roughness"; and second to introduce the simplified parameters into the numerical equations describing the near wall flow.

Modelling Real Roughness. Modelling the real roughness in detail with CFD can be done for some cases in a small scale, for example the flow around individual barnacles, whereas slime and similar biological growth cannot be properly modelled. Realistically, this step has to rely on experiments that link certain roughness properties to velocity shifts and skin friction.

Measuring real roughness and translating to one or more parameters is a difficult matter:

- Roughness can consist of several types of surfaces such as different coatings, aged or damaged coating, bio film and bio fouling, and the severity can vary locally on the hull surface.
- Measuring the roughness on the immense surface of a ship is demanding at best, and require different techniques (e.g. a roughness analyser for coatings, wet film measurement for bio film and roughness analyser plus density measurement on, for example, barnacles)
- Quite a decent number of skin friction measurements on rough surfaces are available and reported in literature but they are difficult to compare and compile into a larger context since they are based on very different test techniques.
- Most measurements reported in literature have been translated into a single parameter function such as the equivalent sand roughness, when a two parameter function including also for example density would be appropriate.

Sand-Grain Roughness in The Flow Equations. Thin boundary layer methods used together with a potential flow solver was until recently commonly used for ship flow simulations and is still relevant for many applications. Surface roughness can be included in thin boundary layer methods by introducing a velocity shift function. This applies a decrease in the log-arithmetic layers mean velocity corresponding to the effect of roughness, see Leer-Andersen & Larsson, 2003.

RANS methods used for ship application simulate the flow near a no-slip surface either by wall functions or by resolving the flow all the way to the wall – near wall resolution. Roughness, at least in terms of an equivalent sand roughness, can be introduced in either of these methods. For example, Eca & Hoekstra (2011) demonstrated that sand-grain roughness effects can be well simulated with these methods for a flat plate at Reynolds numbers corresponding to full scale ship applications. They used the turbulence model SST k-ω which is relevant and commonly applied in ship hydrodynamics.

13.2 Applications

Trial Speed-Power Prediction. The hull surface of a newly built ship can be assumed to be homogenous and well defined in terms of size, texture and distribution (if we neglect the fact that bio film growth can occur within a few weeks in some locations). The step to translate this kind of roughness to a single or dual parameter to be fed into the flow equations should be possible, even though no examples thereof have been found in the open literature. Castro et al, (2011) demonstrate however how the surface roughness k_S appearing in the roughness allowance ΔC_F in the ITTC scaling procedure can be translated to the surface roughness used in wall functions and applied to the KRISO container ship test case with good results.

Operational Conditions. Numerical simulations of a ship in operation with extensive bio fouling could be relevant not only for the resistance increase, but also for the effect of hull roughness on the inflow to the propeller, the propeller efficiency and the rudder forces. The ITTC scaling procedures do connect relatively small skin friction increase with an increase of the wake. However, if the effect is very large this method might not be adequate (which can actually lead to an underestimation of the propulsive efficiency).

The hull surface during operational condition is characterised by inhomogeneous roughness; barnacles, slime and corrosion that are unevenly distributed over the hull and with large variation in height, texture and density.

The study by Leer-Andersen (2003) show the possibility to link the coefficients required in the flow equations to test samples with roughness of various type and extent via photos and roughness measurements. This combined experimental/computational approach could make it possible to simulate the effect of roughness with greater accuracy than using empirical methods. However, the lack of suitable experimental data is troublesome, as described above.

13.3 Conclusions

Surface roughness is likely to affect not only the skin friction on hull and propeller but also the wake flow into the propeller.

Introducing homogeneous sand-grain roughness into numerical methods for speed/ power prediction in trial condition seems to be possible and several well documented methods exist.

The possibility to study the effect of non-homogenous roughness such as bio fouling in operational condition is still limited. Progress in this area would be helped by experiments with consistent test techniques of a large number of realistic surface conditions (preferably from the same laboratory). This could be used to formulate models that bridge between real roughness conditions and the simplified coefficients used in the numerical equations.

14. CONCLUSIONS

14.1 Recommendations to the Full Conference

The 27th ITTC PSS Committee recommends to the Full Conference to:

- Adopt the revised procedure 7.5-04-01-01.1 Speed and Power Trials, Part I Preparation and Conduct

- Adpot the revised procedure 7.5-04-01-01.2 Speed and Power Trials, Part II Analysis of Speed/Power Trial Data

14.2 Recommendations for the next PSS Committee work

1. Refinement of the recommended procedures:

   a. Temperature and density correction to take into account temp/density gradient
   b. Investigate ISO proposed ‘iterative method’ as an alternative for load variation method and current elimination
   c. Investigate statistical results from load variation tests
   d. Investigate new shallow water method to replace Lackenby
   e. Investigate wave limits for the wave correction methods
   f. Investigate application of CFD methods for wind loads
   g. Expand the wind coefficient database for more ship types
   h. More extensive validation of the wave correction methods (STA1, STA2, NMRI)
   i. Investigate feedback of speed/power data for correlation purpose especially for the design and EEDI draft

2. Explore “Ship in Service” issues

   a. f_w application of tools investigated by the sea-keeping committee
   b. Investigate feedback of speed/power da ta for f_w
   c. Investigate the monitoring and analysis of speed/power performance of ships in service
   d. Investigate EEOI issues originating from IMO requirements
   e. Investigate the influence of ship hull surface degradation due to fouling and aging on the speed/power performance

3. Develop new roughness correction methods for both hull and propeller; this suggestion could be more applicable for the Resistance/Propulsion committees

4. Develop procedures how model tests with Energy Saving Devices such as ducts, pre-swirl fins, hub vanes, hull vanes, rudder fins and unconventional propellers should be conducted and how the measured results should be extrapolated to full scale; this suggestion is more applicable for the Propulsion committee

ITTC to develop guidelines for the model testing community how to deal with the EEDI verifiers: what are they allowed to see; what documents to deliver to them; how to secure data confidentiality of our direct customers, etc.

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Nomenclature

ANN – Artificial Neural Network

BIMCO – Baltic and International Maritime Council

CANSI – China Association of thr National Shipbuilding Industry

CESA – Community of European Shipyards’ Associations

CESS – Committee for Expertise of Shipbuilding Specifics

CFD – Computational Fluid Dynamics

CTO – Ship Design and Research Centre (abbreviation from Polish)

DR – Double run(s)

EEDI – Energy Efficiency Design Index

EEOI – Energy Efficiency Operational Index

GHG – Greenhouse gas

HSVA – Hamburgische Schiffbau Versuchsanstalt

IACS –International Association of Classification Societies

ICS – International Camber of Shipping

IMO – International Maritime Organization

INTERCARGO – International Association of Dry Cargo Shipowners

INTERTANKO – International Association of Independent Tanker Owners

ISO – International Organization for Standardization

JASNAOE –Japan Society of Naval Architects and Ocean Engineers

JIN – Japan Institute of Navigation

KOSHIPA – Korea Offshore & Shipbuilding Association

KSNAJ – Kansai Society of Naval Architects

MARIC – Marine Design and Research Institute of China

MARIN – Maritime Research Institute Netherlands

MARPOL – The International Convention for the Prevention of Pollution from Ships

MEPC – Marine Environment Protection Committee

NMRI – National Maritime Research Institute

NOAA – National Oceanic and Atmospheric Administration

OCIMF – Oil Companies International Marine Forum

PDF – Probability Density Function

RINA – Royal Institution of Naval Architects

SNAME – Society of Naval Architects and Marine Engineers

SAJ – The Shipbuilders' Association of Japan

SNAJ – Society of Naval Architects of Japan

SSPA – Statens Skepps Provnings Anstalt

SEEMP – Ship Energy Efficiency Management Plan

VLCC – Very large crude oil carrier

WSC – World Shipping Council