INTERNATIONAL MARITIME ORGANIZATION

IMO

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INTERSESSIONAL MEETING OF THE GREENHOUSE GAS WORKING GROUP
2nd session
Agenda item 2

GHG-WG 2/2/15
6 February 2009
ENGLISH ONLY

CONSIDERATION OF THE ENERGY EFFICIENCY DESIGN INDEX FOR NEW SHIPS

Progress Report on the work relating to f_W coefficient in the Energy Efficiency Design Index (EEDI)

Submitted by Japan

SUMMARY

Executive summary:	This document is the progress report on the work for refining the simulation guidelines for f_W as well as "standard f_W" curves, which are necessary for determining f_W in the EEDI calculation
Strategic direction:	7.3
High-level action:	7.3.1
Planned output:	7.3.1.3
Action to be taken:	Paragraph 12
Related documents:	MEPC 58/4, MEPC 58/4/27, MEPC 58/4/28, MEPC 58/4/29 and MEPC 58/23

Introduction

1 A non-dimensional coefficient, f_W, in the Energy Efficiency Design Index (EEDI) calculation formula shows a ship's performance in actual sea conditions, which the ship navigates throughout her long life, by indicating the decrease in speed in representative sea conditions of wave height, wave frequency and wind speed (e.g., Beaufort Scale 6). The f_W coefficient can be determined by conducting the ship-specific simulation based on the guidelines developed by the Organization or by taking a f_W value from the "standard f_W" table/curve, as explained in paragraphs 9.1 and 9.2 of the draft Interim Guidelines on the Method of Calculation of the EEDI for New Ships ("Interim Guidelines", hereafter, annex 11 to MEPC 58/23).

2 At MEPC 58, Japan submitted proposed draft guidelines for the ship-specific simulation of f_W (MEPC 58/4/27 and MEPC 58/4/28) and the draft "standard f_W" curve (MEPC 58/4/29). While the significance of f_W was recognized, it was felt that further work would be necessary. It was thus decided that f_W should be taken as 1.0 until the guidelines for the ship-specific simulation of f_W or "standard f_W" curves becomes available (paragraph 9.3 of annex 11 to MEPC 58/23).

For reasons of economy, this document is printed in a limited number. Delegates are kindly asked to bring their copies to meetings and not to request additional copies.

3 In order to enhance the reliability and robustness of f_W, MLIT (Ministry of Land, Infrastructure and Transport), in cooperation with NMRI (National Maritime Research Institute), has been endeavouring to refine the guidelines for the ship-specific simulation as well as "standard f_W" curves by involving as many stakeholders as possible from international maritime communities. This document is to report the progress of the work done to date.

Simulation guidelines for f_W

4 In order to test and refine the draft guidelines for the ship-specific simulation of f_W , it is necessary to involve many designers and shipbuilders in conducting trial calculations of f_W for their own ships and comparing the calculation results with their own estimates of ship performance at actual sea conditions based on their know-how and methodology including tank tests.

5 For this purpose, NMRI developed a sample programme for the ship-specific f_W simulation together with programme manuals. The draft guidelines for the ship-specific f_W simulation were revised based on MEPC 58/4/27 and MEPC 58/4/28, and the sample programme with manuals exactly follows the simulation procedures described in the revised guidelines.

6 A set of the programme, the manuals and the draft guidelines was offered firstly to five Japanese shipbuilders, all of which have their own test tanks and long experiences of estimating a ship's actual performance at sea. After their trial calculations for various ship types, it was confirmed that the draft guidelines provided a reasonable set of the simulation procedure and the approximation formulas, and that there was no problem in the function of the sample programme.

7 After the trial and verification in Japan, MLIT and NMRI have sent the programme, the manuals and the draft guidelines to research institutes and shipbuilding industries in major shipbuilding countries other than Japan, and requested their cooperation in conducting the trial calculation.

8 Cooperation with the wider shipbuilding community would be most desirable to ensure the robustness and transparency of the f_W simulation process. Japan would welcome such willing stakeholders to use the sample programme, to examine the draft guidelines and to give us their feedback. The latest versions of the draft guidelines is attached at annex 2 to this document, together with a cover note requesting the cooperation in f_W simulation trial as attached at annex 1. Any interested organization/company/associations are welcome to contact the focal points listed at the end of annex 1, and we will be happy to send the programme and manuals.

9 Following the trial project as described above, Japan intends to submit the revised version of the draft guidelines for the ship-specific simulation to MEPC 59. Japan considers that, once the robustness of the guidelines for the ship-specific simulation is proven, such guidelines should be attached as appendices to the Interim Guidelines, or be adopted as stand-alone guidelines referred to in the Interim Guidelines.

“Standard f_W” curves

10 “Standard f_W” curves, which are used to determine f_W value in cases where the simulation is not conducted, are to be determined by a conservative approach, i.e. based on data of actual speed reduction of as many existing ships as possible under representative sea conditions (paragraph 9.2 of annex 11 to MEPC 58/23). Before MEPC 58, Japan collected the operational data of as many as 170 existing ships of Japanese shipping companies, and submitted the draft “Standard f_W” curves based on the analyses of those operational data (MEPC 58/4/29). In order to get a wider spectrum of operational data for improving the reliability of “standard f_W” curves, Japan had requested international shipping associations and shipping companies to provide operational data.

11 Some overseas shipping companies have kindly provided their operational data to date and those data are now being processed and analysed. Taking into account the result of analysing additional operational data, Japan will examine “standard f_W” curves further and intends to submit a revised version of “standard f_W” curves.

Action requested of the Intersessional Meeting

12 The Intersessional Meeting is invited to take note of the information provided above, in view of the consideration of the guidelines for the ship-specific simulation of f_W as well as “standard f_W” curves at and take action as appropriate.

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ANNEX 1

国土交通省
Ministry of Land, Infrastructure, Transport and Tourism

22 January 2009

REQUEST FOR THE TRIAL USE OF THE GUIDELINES FOR THE CALCULATION OF THE COEFFICIENT (fw) FOR THE DECREASE OF SHIP SPEED IN REPRESENTATIVE SEA CONDITION

As a task relating to the Energy Efficiency Design Index under development at IMO-MEPC, the MLIT (Ministry of Land, Infrastructure, Transport and Tourism, Japan) would like to solicit the cooperation from world-wide shipbuilding industry in the development of the Guidelines for the Calculation of the Coefficient (fw) for the Decrease of Ship Speed in the Representative Sea Condition ("fw Simulation Guidelines"). The attached files are the current version of the fw Simulation Guidelines, the sample programme to calculate fw in accordance with the fw Simulation Guidelines, and the programme outline/manual. We believe that it is indispensable for transparency and robustness that major shipbuilding countries are involved in the development of the fw Guidelines through the trial use of the Guidelines and the sample programme. The MLIT is making this request in view of the potential benefits to the maritime industries through the assessment of ship performance in actual sea conditions.

Background

1 MEPC 58 approved the trial use of the draft Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships (paragraph 4.54.1 of MEPC 58/23 and annex 11 thereto, "the draft EEDI Guidelines", hereafter).

2 The Interim Guidelines contains the provision of "*fw*" factor which would serve to reflect the ship performance in actual sea in the calculation of the EEDI. *Fw* coefficient was developed in an attempt to express quantitatively the speed reduction in actual sea; the speed reduction means the increase of fuel consumption and CO_2 emission under the same voyage distance.

<Paragraph 9 of annex 11 to MEPC 58/23>

9 <u>*fw* is a non-dimensional coefficient indicating the decrease of speed in representative sea conditions</u> of wave height, wave frequency and wind speed (e.g., Beaufort Scale 6), and should be determined as follows:

.1 it can be determined by conducting the ship-specific simulation of its performance at representative sea conditions. The simulation methodology should be prescribed in the Guidelines developed by the Organization and the method and outcome for an individual ship shall be verified by the Administration or an organization recognized by the Administration;

.2 in case that the simulation is not conducted, *fw* value should be taken from the "standard *fw*" table/curve. A "standard *fw*" table/curve, which is to be contained in the Guidelines, is given by ship type (the same ship as the "baseline" below), and expressed in a function of the parameter of Capacity (e.g., DWT). The "standard *fw*" table/curve is to be determined by conservative approach, i.e. based on the data of actual speed reduction of as many existing ships as possible under the representative sea conditions; and

.3 *fw* should be taken as 1.0 until the Guidelines for the ship-specific simulation (paragraph .1) or *fw* table/curve (paragraph .2) becomes available.

3 At MEPC 58, GHG working group, although Japan submitted the draft Guidelines for the ship-specific simulation (paragraph 9.1 of annex 11 to MEPC 58/23) and the draft "standard *fw"* table/curve (paragraph 9.2 of annex 11 to MEPC 58/23), it was then argued that the establishment of the calculation and verification procedure of *fw* coefficient should be done at a later stage, in view of the necessity of the earliest development of the draft EEDI Guidelines and the concerns expressed for the verification of *fw* coefficient. As a result, a new paragraph 9.3 was inserted to state that *fw* should be 1.0 for the time being.

4 Utilizing the trial period of using the draft EEDI Guidelines, the Japanese Government, in cooperation with its industries, is rigorously working on the overall refinement of the EEDI Guidelines (other than fw coefficient), by identifying uncertainty and technical difficulties of calculation and their solution, considering the appropriate baseline, and developing proper verification procedure. In parallel to these works, Japan intends to continue its task relating to

fw coefficient, trying to widen the understanding on the usefulness and benefits of assessing the ship performance in actual sea condition through the use of *fw* coefficient.

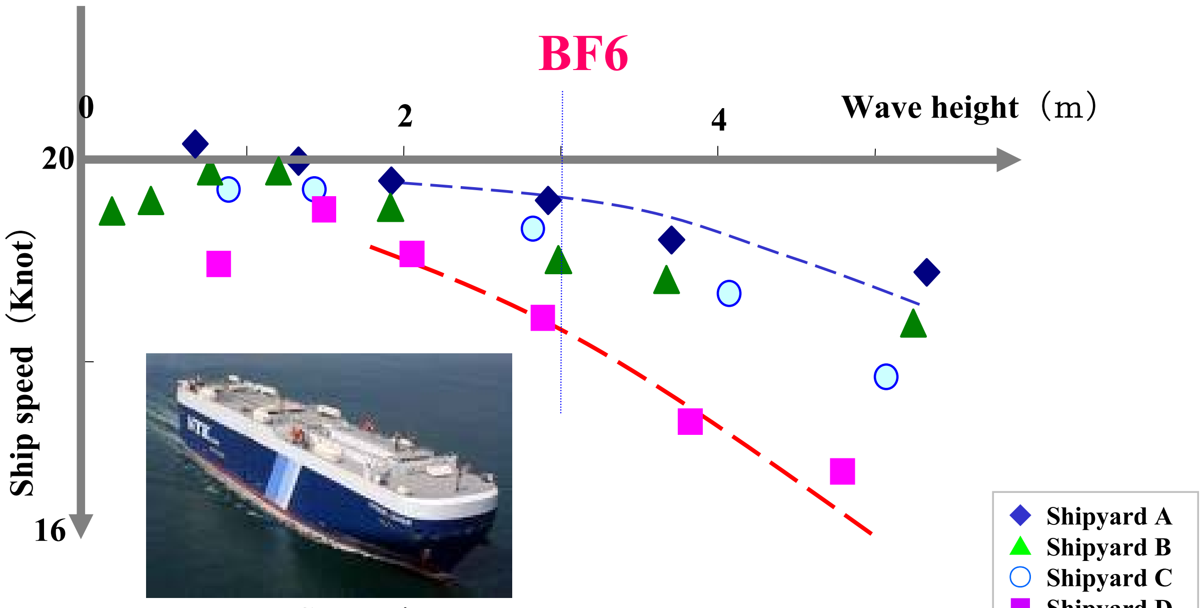
5 More specifically, in this note and the attached fw Simulation Guidelines as well as the sample programme, we would like to solicit the cooperation from shipbuilding industry, maritime research institute and academic institute in major shipbuilding countries in the fine tuning of the fw Simulation Guidelines by conducting trial use of the fw Guidelines.

Review of the importance of taking into account the actual sea condition

6 In the presentation given at the intersessional meeting of the GHG-WG 1 in Oslo and at MEPC 58, Japan emphasized that the performance of ships in actual sea shows a wide variation even if the ships have the same principal particulars and similar specification.

Example of Ship Performance in Actual Sea

- Speed loss is not the same even if the ships are designed under the same specification



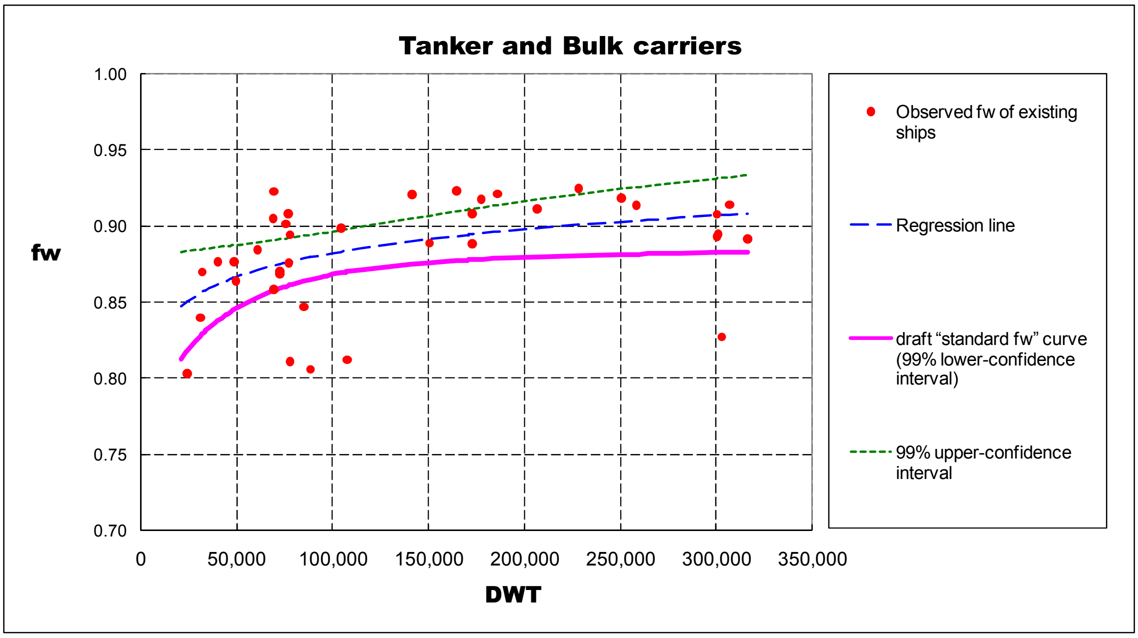
Pure Car carrier

7 The chart above is based on the experiences of a Japanese shipping company which operates Pure Car Carriers in North Pacific Ocean routes. It found that those PCCs <u>having similar specifications, thus having the same design speed in calm sea condition, have shown large deviation in the speed reduction in actual sea</u>, thus resulting in the deviation in fuel consumption, which amounts to 10% difference in yearly fuel cost. The bottom line is to make a distinction between the ship showing superior performance (upper blue line above) and the ship showing inferior performance (lower red line above).

8 The *fw* coefficient was designed to take care of this situation: it is defined as the ratio of speed reduction from the calm sea condition to the representative sea condition (Beaufort Scale 6). In the above example, the Ship A (upper blue line) has the *fw* value of about 0.98 (19.6 kt in BF6 divided by 20 kt in calm sea), while the Ship B (lower red line) has the *fw* value of about 0.91 (18.2 kt in BF6 divided by 20 kt in calm sea). The difference in *fw* values can represent the difference in ship performance.

9 The *fw* can be obtained by conducting a ship-specific simulation following the procedure explained in the attached fw Simulation Guidelines. The sample programme, as attached, was developed based on the simulation methodology and procedure described in the fw simulation Guidelines, and can be used to obtain a fw value for an individual vessel.

10 If the simulation is not conducted, the "standard *fw*" curve can be used to obtain "average" *fw* value for a particular ship type and size. MEPC 58/4/29 shows the basic concept of obtaining "Standard *fw*" curve (figure 1 below is an excerpt from MEPC 58/4/29).



<Figure 1 – Example of "standard fw" curve>

11 The red spots represent the calculated *fw* values of individual existing ships of Japanese shipping companies. The regression lines have been drawn and the lower red line was proposed as provisional "standard *fw*" curve. For example, if a bulk carrier of 200,000 DWT is going to be constructed, its "standard *fw*" would be 0.88 by reading the corresponding point on the red line. This is "average" *fw* based on the existing ship data, and if a ship-specific simulation is conducted, the calculated *fw* for that particular ship may be 0.95 (in such a case, *fw* is higher than average, thus the ship has superior performance, or it may be 0.80 (in this case, lower than average, thus inferior performance).

Request for trial use of the fw Simulation Guidelines

12 You are kindly requested:

.1 to test the fw simulation sample programme by using your own ships' data or using the sample ship data that is attached as example;

.2 to send us the results of simulation by filling in the attached Excel file, with comments, if any, on the practical aspects of simulation programme such as difficulties that you encountered during the trial use;

.3 to examine the fw Simulation Guidelines, in light of the simulation results as well as your own experiences of estimating the ship performance under wave and winds; and

.4 to send us any comments and suggestions for possible improvement of the fw Simulation Guidelines, as a result of the above-mentioned trial and consideration.

13 In order to allow us the time to summarize the comments and the data, the data and comment submission by 28 February 2009 would be appreciated.

14 Since our main target is ocean-going and large-sized vessels of which contribution to CO_2 emission is relatively large, we would appreciate it if the trial calculation is conducted for a variety of large-sized and major category ships, such as tankers, bulk carriers, container ships and gas carriers.

15 The provided zip file consists of three folders: 1) DOC, 2) PRG and 3) INPUT. In the folder "DOC", there are documents of "fw guideline" and "programme outline". Please read carefully these documents at first for the use of the fw Guidelines and programmes. "PRG" holder contains four programme files for the simulation. And "INPUT" holder includes input data for three different ship types: a large container ship, a PCC and a Panamax bulk carrier, as examples for the programmes.

Confidentiality

16 The data for individual ships, to be supplied in the attached EXCEL file, will strictly be kept inside MLIT and National Maritime Research Institute (NMRI), while your comments and insights as well as the calculated fw values (without disclosing the ship ID including shipbuilder and shipbuilding country) may be reflected and incorporated in a future Japanese submission which will consist of the report of fw simulation trial and the revised fw Simulation Guidelines.

Contacts

17 The comments, suggestions or questions should be sent to the contact points below via e-mail. These contacts would be pleased to answer any technical and policy questions relating to this note.

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ANNEX 2

THE DRAFT GUIDELINES FOR THE CALCULATION OF THE COEFFICIENT(*fw*) FOR THE DECREASE OF SHIP SPEED IN REPRESENTATIVE SEA CONDITION

1 General

1.1 Application

.1 These guidelines are intended as guidance on conducting the simulation to obtain the f_W coefficient, which is contained in the energy efficiency design index, for an individual ship;

.2 these guidelines apply to ships of which ship resistance as well as brake power in a calm sea condition (no wind and no waves) is estimated by a tank test or an alternative method equivalent in terms of accuracy; and

.3 the design parameters and the assumed conditions in the performance simulation should be consistent with those used in calculating the other components in the energy efficiency design index.

1.2 Method of calculation

Symbols

P_B : Brake power
R_T : Total resistance in calm sea condition (no wind and no waves)
V_{ref} : Design ship speed when the ship is in operation in calm sea condition (no wind and no waves)
V_w: Design ship speed when the ship is in operation under the representative sea conditions
ΔR_{wave}: Added resistance due to waves
ΔR_{wind} : Added resistance due to wind
η_D: Propulsion efficiency
η_S : Transmission efficiency

Subscript *w* refers to wind and wave sea conditions.

.1 The basic procedures in calculating the decrease of ship speed is shown in Figure 1.1. (See section 4 for more information.)

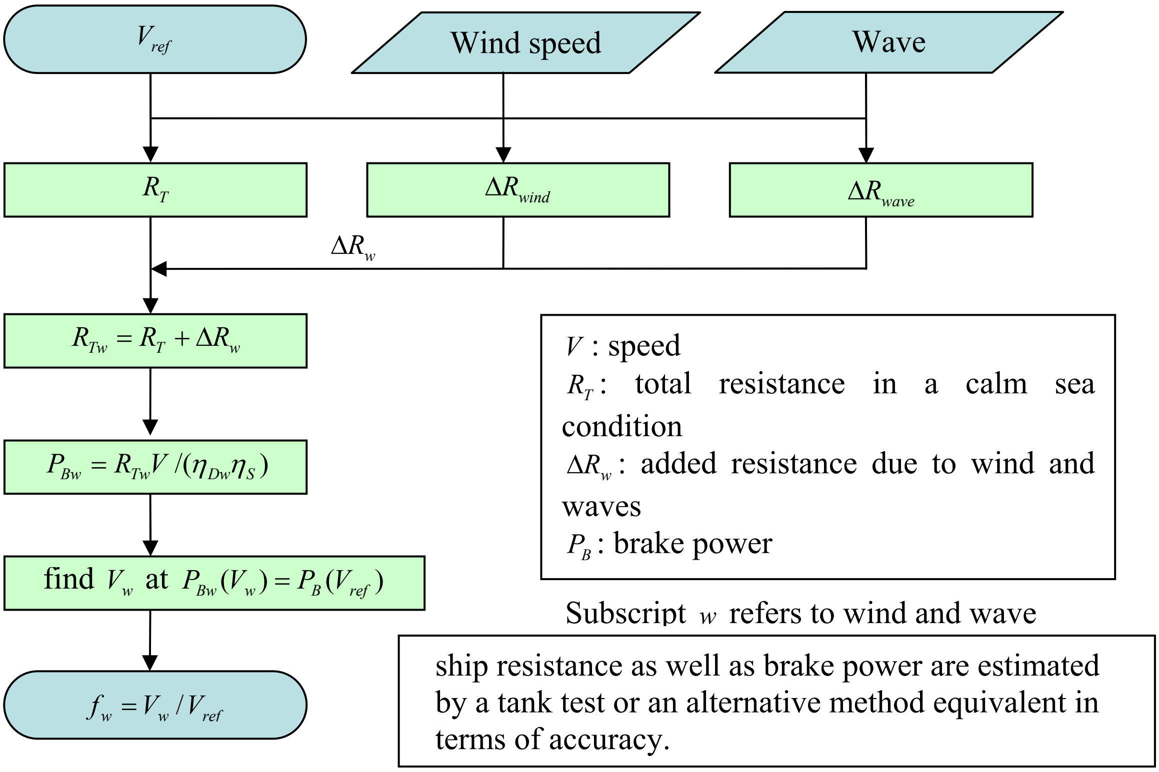


Figure 1.1 – Flow chart of calculation for the decrease of ship speed

.2 Relation between the power and the decrease of ship speed is shown in figure 1.2

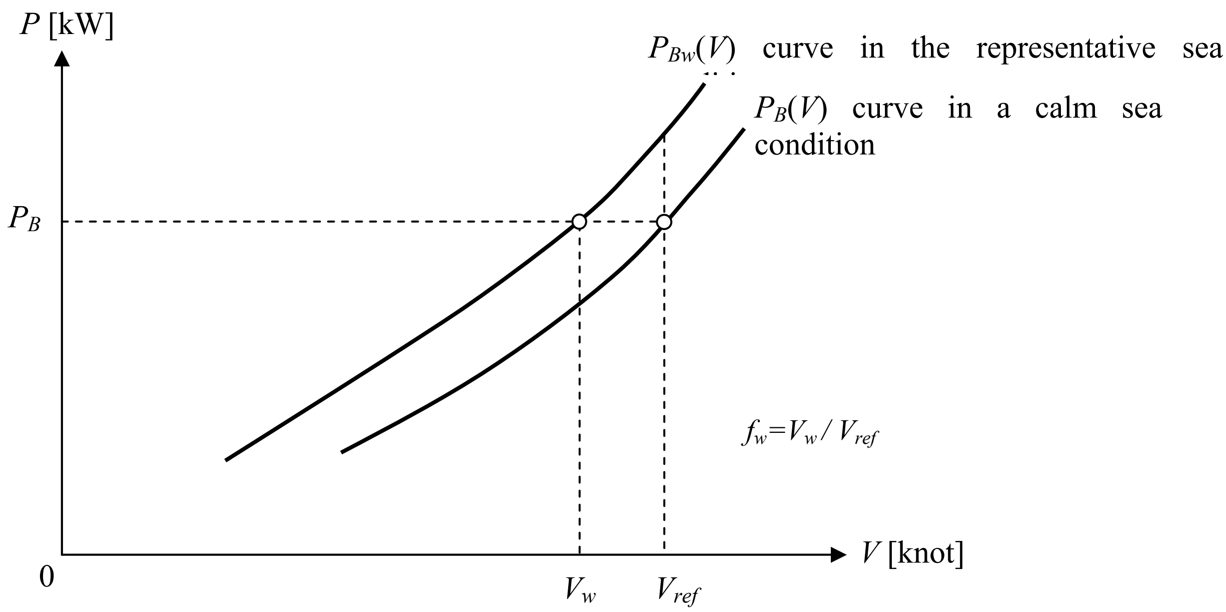


Figure 1.2 – Relation between power and the decrease of ship speed

2 Representative sea condition

2.1 Representative sea condition

.1 The representative sea conditions are provided in table 2.1 based on the Beaufort Scale.

.2 The direction of wind and waves are defined as heading direction, which has the most significant effect on the speed reduction.

Table 2.1 – Representative sea condition

	Mean wind speed U_{wind} (m/s)	Mean wind direction γ(deg)	Significant wave height H (m)	Mean wave period T (s)	Mean wave direction θ(deg)
BF6	12.6	0	3.0	6.7	0

2.2 Wind condition

.1 The mean wind speed and wind direction are given in table 2.1.

2.3 Wave condition

Symbols

D : Angular distribution function
E : Directional spectrum
H : Significant wave height
S : Frequency spectrum
T : Mean wave period
α : Angle between ship course and regular waves (angle 0(deg.) is defined as the heading wave direction)
θ : Mean wave direction
ω : Circular frequency of incident regular waves

.1 As ocean waves are characterized as irregular ones, the directional spectrum should be considered.

.2 The mean wave speed and wave direction are given in table 2.1. To obtain the mean wave period from the Beaufort Scale, the following formula derived from a frequency spectrum for fully-developed wind waves is used.

$$T = 3.86\sqrt{H}$$

where, H is significant wave height in meter and T is mean wave period in second.

.3 The directional spectrum (E) is composed of frequency spectrum(S) and angular distribution function (D).

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

$$S(\omega;H,T)=\frac{A_S}{\omega^5}\mathrm{e}^{-\frac{B_S}{\omega^4}}$$

where,

$$A_S=\frac{H^2}{4\pi}\left(\frac{2\pi}{T_z}\right)^4,\ B_S=\frac{1}{\pi}\left(\frac{2\pi}{T_z}\right)^4,\ T_z=0.920T$$

$$D(\alpha,\theta)=\begin{cases}\frac{2}{\pi}\cos^2(\theta-\alpha) & \left(|\theta-\alpha|\le\frac{\pi}{2}\right)\\ 0 & (\text{others})\end{cases}$$

3 Ship condition

.1 The assumed ship conditions are summer full load, constant main engine output (e.g., 75% of MCR, to be consistent with the one used in the calculation of the design index), and operation in steady navigating condition on the fixed course; and

.2 the current effect is not considered.

4 Method of calculation

4.1 General

.1 Resistance in the representative sea condition, R_{Tw}, is calculated by adding ΔR_w, which is the added resistance due to wind and waves derived from the section 2.3, to the resistance R_T derived from a tank test in a calm sea condition or an alternative method equivalent in terms of accuracy;

.2 the design ship speed V_w is the value of V where the main engine power $P_{Bw}(V_w)$ under the aforementioned resistance under wind and waves equals $P_B(V_{ref})$, which is the brake power required for achieving the speed of V_{ref} in calm sea condition;

.3 in calculating P_{Bw} from the total resistance R_{Tw}, the properties for propellers and propulsion efficiency (η_D) should be derived from the formulas obtained from a tank test or an alternative method equivalent in terms of accuracy, and transmission efficiency (η_S) should be the proven value as verifiable as possible; and

$$P_B=R_TV/(\eta_D\eta_S)$$

.4 the coefficient of the decrease of ship speed (f_W) is calculated by dividing V_w by V_{ref} as follows:

$$f_w=V_w/V_{ref}\qquad \text{at } P_B(V_{ref})=P_{Bw}(V_w)$$

4.2 Total resistance in a calm sea condition: R_T

.1 The total resistance in a calm sea condition is derived from a tank test in a calm sea condition as the function of speed.

4.3 Resistance in the representative sea condition: R_{TW}

.1 Resistance in the representative sea condition, R_{Tw}, is calculated by adding ΔR_{wind}, which is the added resistance due to wind, and ΔR_{wave}, which is the added resistance due to waves, to the total resistance in a calm sea condition R_T.

$$R_{TW} = R_T + \Delta R_w = R_T + \Delta R_{wind} + \Delta R_{wave}$$

4.3.1 Added resistance due to wind : ΔR_{wind}

Symbols

A_L : Projected lateral area above the summer load line
A_T : Projected transverse area above the summer load line
B : Ship breadth
C : Distance from the midship section to the centre of projected lateral area (A_L); a positive value of C means that the centre of the projected lateral area is located ahead of the midship section
C_{Dwind} : Drag coefficient due to wind
L_{OA} : Length overall
U_{wind} : Mean wind speed
ρ_a : Air density (1.226(kg/m^3))

.1 Added resistance due to wind is calculated by the following formula on the basis of the mean wind speed and wind direction given in table 2.1.

$$\Delta R_{wind} = \frac{1}{2}\rho_a A_T C_{Dwind}\left\{\left(U_{wind} + V_w\right)^2 - V_{ref}{}^2\right\}$$

.2 C_{Dwind}, should be calculated by a formula with considerable accuracy, which has been confirmed by model tests in a wind tunnel. The following formula is known for the expression of C_{Dwind}, for example:

$$C_{Dwind} = 0.922 - 0.507\frac{A_L}{L_{OA}B} - 1.162\frac{C}{L_{OA}}$$

4.3.2 Added resistance due to waves : ΔR_{wave}

Symbols

H : Significant wave height
T : Mean wave period
V : Ship speed

α : Angle between ship course and regular waves (angle 0(deg.) is defined as the heading wave direction)

β : Oblique wave angle

θ : Mean wave direction

ζ_a : Amplitude of regular waves

ω : Circular frequency of incident regular waves

.1 Irregular waves can be represented as linear superposition of the components of regular waves. Therefore added resistance due to waves ΔR_{wave} is also calculated by linear superposition of the directional spectrum (E) and added resistance in regular waves (R_{wave}) for waves described in section 2.3.

$$\Delta R_{wave} = \int_0^{2\pi}\int_0^{\infty} \frac{R_{wave}(\omega,\alpha;V)}{\zeta_a^{\ 2}} E(\omega,\alpha;H,T,\theta)\,\mathrm{d}\omega\,\mathrm{d}\alpha$$

.2 Added resistance in regular waves, R_{wave}, should be determined by a tank test or a formula equivalent in terms of accuracy.

In case of applying the theoretical formula, added resistance in regular waves R_{wave} is calculated from the components of added resistance due to ship motion in regular waves, R_{wm} and added resistance due to wave reflection in regular waves R_{wr} as an example.

$$R_{wave} = R_{wm} + R_{wr}$$

As an example, R_{wm} and R_{wr} are calculated by the method in 4.3.2.1 and 4.3.2.2.

4.3.2.1 Added resistance due to ship motion in regular waves

Symbols

g : Gravitational acceleration

$H(m)$: Function to be determined by the distribution of singularities which represents periodical disturbance by the ship

V : Ship speed

α : Angle between ship course and regular waves (angle 0(deg.) is defined as the heading wave direction)

ρ : Fluid density

ω : Circular frequency of incident regular waves

.1 Added resistance due to ship motion in regular waves, R_{wm}, is calculated as follows:

$$R_{wm} = \begin{cases} 4\pi\rho\left(-\int_{-\infty}^{m_3} + \int_{m_4}^{\infty}\right)\left|H(m)\right|^2 \dfrac{(m+K_0\Omega_e)^2(m+K\cos\alpha)}{\sqrt{(m+K_0\Omega_e)^4 - m^2K_0^{\ 2}}}\,\mathrm{d}m & \left(\Omega_e \le \dfrac{1}{4}\right) \\ 4\pi\rho\left(-\int_{-\infty}^{m_3} + \int_{m_4}^{m_2} + \int_{m_1}^{\infty}\right)\left|H(m)\right|^2 \dfrac{(m+K_0\Omega_e)^2(m+K\cos\alpha)}{\sqrt{(m+K_0\Omega_e)^4 - m^2K_0^{\ 2}}}\,\mathrm{d}m & \left(\Omega_e > \dfrac{1}{4}\right) \end{cases}$$

$$\Omega_e = \frac{\omega_e V}{g} \quad , \quad K = \frac{\omega^2}{g} \quad , \quad K_0 = \frac{g}{V^2}$$

$$\omega_e = \omega + KV\cos\alpha$$

$$m_1 = \frac{K_0\left(1 - 2\Omega_e + \sqrt{1 - 4\Omega_e}\right)}{2}$$

$$m_2 = \frac{K_0\left(1 - 2\Omega_e - \sqrt{1 - 4\Omega_e}\right)}{2}$$

$$m_3 = -\frac{K_0\left(1 + 2\Omega_e + \sqrt{1 + 4\Omega_e}\right)}{2}$$

$$m_4 = -\frac{K_0\left(1 + 2\Omega_e - \sqrt{1 + 4\Omega_e}\right)}{2}$$

4.3.2.2 Added resistance due to wave reflection in regular waves

Symbols

B : Ship breadth

B_f : Bluntness coefficient, which is derived from the shape of water plane and wave direction

C_U : Coefficient of advance speed, which is determined on the basis of the guidance for a tank test

d : Ship draft

$F_n = V / \sqrt{L_{pp} g}$: Froude number (non-dimensional number in relation to ship speed)

g : Gravitational acceleration

I_1 : Modified Bessel function of the first kind of order 1

K : Wave number of regular waves

K_1 : Modified Bessel function of the second kind of order 1

L_{pp} : Ship length between perpendiculars

V : Ship speed

α : Angle between ship course and regular waves (angle 0(deg.) is defined as the heading wave direction)

α_d : Effect of draft and frequency

ρ : Fluid density

ζ_a : Amplitude of regular waves

ω : Circular frequency of incident regular waves

.1 Added resistance due to wave reflection in regular waves is calculated as follows:

$$R_{wr} = \frac{1}{2}\rho g \zeta_a{}^2 B B_f (1 + C_U F_n)\alpha_d$$

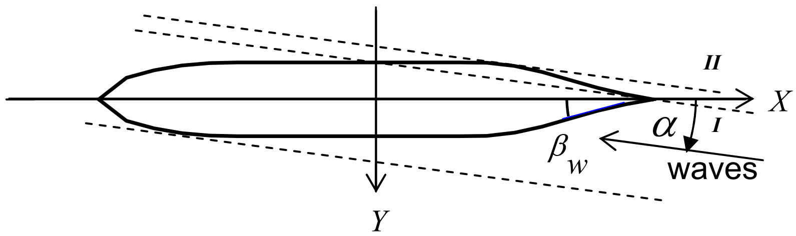
$$\alpha_d = \frac{\pi^2 I_1^2(K_e d)}{\pi^2 I_1^2(K_e d) + K_1^2(K_e d)}$$

$$K_e = K\left(1 + \Omega\cos\alpha\right)^2$$

$$\Omega = \frac{\omega V}{g}$$

$$B_f = \frac{1}{B}\left\{\int_I \sin^2(\alpha+\beta_w)\sin\beta_w dl + \int_{II} \sin^2(\alpha-\beta_w)\sin\beta_w dl\right\}$$

where, *dl* is a line element along the water plane, and domains of integration is shown in the following figure.



Effect of advance speed, α_U, is determined as follows:

$$\alpha_U = C_U(\alpha)F_n$$

The coefficient of advance speed in oblique waves, $C_U(\alpha)$, is calculated as follows:

$$C_U(\alpha) = \mathrm{Max}\left[F_S, F_C\right]$$

(i) $B_f(\alpha=0) < B_{fc}$ or $B_f(\alpha=0) < B_{fs}$

$$F_S = C_U(\alpha=0) - 310\left\{B_f(\alpha) - B_f(\alpha=0)\right\}$$
$$F_C = \mathrm{Min}\left[C_U(\alpha=0), 10\right]$$

(ii) $B_f(\alpha=0) \geq B_{fc}$ and $B_f(\alpha=0) \geq B_{fs}$

$$F_S = 68 - 310 B_f(\alpha)$$
$$F_C = C_U(\alpha=0)$$

where, $B_{fc} = \frac{58}{310}$, $B_{fs} = \frac{68 - C_U(\alpha=0)}{310}$.

.2 The aforementioned coefficient, $C_U(\alpha=0)$, is determined by a tank test. The tank test should be carried out in short waves since R_{wr} mainly works in short waves. The length of short waves should be $0.5L_{pp}$ or less.

.3 Effect of advance speed in regular heading waves, α_U, is calculated by the following equation where R_{wave}^{EXP} is added resistance obtained by the tank test in regular heading waves, and R_{wm} is added resistance due to ship motion in regular waves calculated by 4.3.2.1.

$$\alpha_U(F_n) = C_U F_n = \frac{R_{wave}^{EXP}(F_n) - R_{wm}(F_n)}{\frac{1}{2}\rho g \zeta_a{}^2 B B_f \alpha_d} - 1$$

.4 Effect of advance speed, α_U, is obtained for each speed of the experiment by the aforementioned equation. Thereafter the coefficient of advance speed, $C_U(\alpha = 0)$, is determined by the least square method against F_n; see figure below. The tank test should be conducted under at least three different points of F_n. Such points of F_n should be selected so that the speed in representative sea condition should lie between the lowest selected F_n and the highest selected F_n.