

Maneuverability in Adverse Conditions: Assessment Framework and Examples

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ABSTRACT

Maneuverability of ships is presently regulated by the IMO Standards for Ship Maneuverability, which do not address ship maneuverability in adverse conditions. The importance of norming maneuverability in adverse conditions increased after the introduction of EEDI, which led to concerns that fulfilling EEDI by simply reducing ship's installed power may lead to insufficient maneuverability in adverse conditions. Responding to the need for norming the maneuverability in adverse conditions, *Shigunov and Papanikolaou (2013)* presented additional criteria and an assessment procedure ("Comprehensive Assessment"), which is based on a relatively simple mathematical model and allows using alternative methods (model tests, numerical simulations or empirical formulae, depending on designer's needs) for different components of the environmental forces and responses (waves, wind, maneuvering forces, rudder forces). This procedure is especially suitable for ships with innovative propulsion and steering solutions, but may be impracticable if it is to be applied to all ships. Therefore, two additional procedures were developed, namely the "Simplified Assessment", which has the complexity of a spreadsheet calculation but takes all relevant physics and ship particulars into account, and even a much simpler "check", which is based on empirical formulae (of the complexity of a pocket calculator), determining the required installed power as a function of ship's deadweight, windage area, rudder area, propeller characteristics and engine type. This paper outlines the rationale and status of these developments.

Keywords: *Manoeuvrability in Waves; Numerical Assessment Methods; Simplified Assessment*

INTRODUCTION

The implementation of the Energy Efficiency Design Index (EEDI) has raised justified concerns that some ship designers might choose to simply lower the installed power to achieve EEDI requirements, which can lead to insufficient manoeuvrability of ships under adverse weather conditions. A requirement was added to the Reg. 21, Ch. 4 of MARPOL Annex VI to verify that the installed propulsion power is sufficient to maintain manoeuvrability under adverse conditions. The first such verification procedure, provided in the *2012 Interim Guidelines*, issued in 2012 [1], was based on three levels of assessment (Level 3, Comprehensive Assessment, Level 2, Simplified Assessment and Level 1, Minimum Power Lines). In the revised, *2013 Interim Guidelines* [2], Level 3 was removed as too complex; in Level 2, numerical methods were replaced with model tests, which is too complex for this assessment level; besides, a

formulation of Level 1 was accepted, that does not relate to propulsion or steering characteristics of ships. In 2014, these were extended into Phase 1 of EEDI implementation (until December 31, 2019). Although *2013 Interim Guidelines* is an effective provision to prevent new built ships from underpowering, the mentioned elements can be improved. To address this, several research initiatives have started in EU (project SHOPERA [3], *Energy Efficient Safe Ship Operation*), Japan, Germany, The Netherlands, Korea and China.

Manoeuvrability of ships is presently addressed by IMO *Standards for Ship Manoeuvrability*, adopted in 2002 [4], which norm turning, initial turning, yaw-checking, course-keeping and emergence stopping abilities of ships, which are evaluated in simple manoeuvres in calm water. These Standards have been often criticized for not addressing ship manoeuvring characteristics at limited speed, in restricted areas and in adverse

weather conditions. Two questions arise: first, whether the acceptance limits of the existing criteria are strict enough to ensure sufficient manoeuvrability also at low speed and in adverse conditions, and second, whether all relevant ship characteristics are covered by the existing criteria or additional criteria are required. Whereas existing experience and knowledge do not provide clear answer to the first question, the answer to the second question is obvious when we note that one of tasks of steering is withstanding environmental forces; because different ships experience different environmental forces, the ship-specific assessment of ship's steering and propulsion abilities to withstand these forces appears a necessary part of minimum manoeuvrability requirements.

Based on the analysis of accident statistics, detailed accident reports, interviews of ship masters and existing proposals for manoeuvrability criteria in adverse conditions, work [5] proposed to consider three scenarios (manoeuvring in the open sea, manoeuvring in coastal areas and manoeuvring at limited speed in restricted areas); for each of these scenarios, the following practical criteria were proposed:

- In the open sea: (C1) *the ship should be able to keep heading in head to bow-quartering seaway up to 60° off-bow*;
- In coastal areas: *the ship should be able, in waves and wind from any direction, to keep (C2) a prescribed course and (C3) a prescribed advance speed*;
- At limited speed in restricted areas: *course-keeping at a specified low speed in strong wind in (C4) shallow water, (C5) shallow water near a bank and (C6) shallow water during overtaking by a quicker ship*.

ASSESSMENT FRAMEWORK

Whereas *IMO Manoeuvrability Standards* [4] are evaluated in full-scale trials, this is impossible in adverse weather conditions; model tests and numerical computations are possible alternatives. In principle, criteria C1-C6 can be directly evaluated in transient model experiments with self-propelled ship models in simulated irregular waves and wind, for all required combinations of wave direction and wave period. However, such an approach is impracticable at the present state of technology: First, reliable statistical predictions

require repeating tests in multiple long realisations of each seaway, which is too expensive. Second, only few suitable facilities exist world-wide, which makes such tests impractical for routine design and approval. Finally, verification of such tests by the Administration is impossible, especially in marginal cases (which are of interest in approval), where results strongly depend on steering time history. Alternatives to such model tests – direct numerical simulations of transient manoeuvres in irregular waves – are not mature enough yet for routine design and approval [6].

The alternative procedure proposed in SHOPERA (referred further to as Comprehensive Assessment) is based on separate simple model tests, numerical simulations or empirical formulae to account for different effects (wave forces, wind forces, manoeuvrability coefficients, rudder forces), which are combined in a relatively simple numerical model for ship motions. The procedure is based on neglecting oscillatory forces and moments due to waves and thus considering only time-average forces, moments and other variables, assuming that the time scale of their oscillations is shorter than the time scale of manoeuvring motions.

This reduces the evaluation of criteria C1-C6 to a solution of coupled equations of motion in the horizontal plane under the action of time-average wave-induced forces and moments (index *d*), wind forces and moments (*w*), calm-water forces and moments (*s*), including interaction effects, rudder forces (*R*) and propeller thrust (*T*). Projecting forces on the *x*- and *y*-axes and moments on the *z*-axis of the ship-fixed coordinate system, Fig. 1, leads to a system of equations, converging to a steady state described by the following system (note that achieving a converged solution can be realised in different ways, including time-domain simulation):

$$X_s + X_w + X_d + X_R + T(1-t) = 0 \quad (1)$$

$$Y_s + Y_w + Y_d + Y_R = 0 \quad (2)$$

$$N_s + N_w + N_d - Y_R I_R = 0; \quad (3)$$

I_R is the lever of the yaw moment due to rudder, which in general differs from $L_{pp}/2$ due to the pressure redistribution on the ship stern due to rudder influence.

Figure 1 shows the coordinate system: origin *O* in the main section at the water plane; *x*-, *y*- and

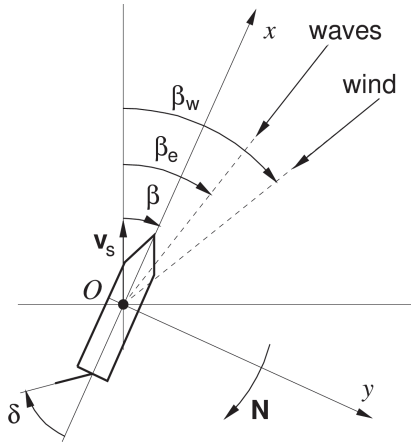


Figure 1. Coordinate system and definitions

z -axes point towards bow, starboard and downward, respectively (positive rotations and moments with respect to z -axis are clockwise when seen from above). For simplicity of description and without loss of generality, the ship is assumed to sail in the north direction with the speed v_s ; its heading deviates from the course by the drift angle β (positive clockwise when seen from above). The main wave and wind directions are described by angles β_e and β_w , respectively (0, 90 and 180° for waves and wind from the north, east and south, respectively); rudder angle δ is positive to port.

The converged solution, described by the equation system (1)-(3), provides the required propeller thrust T (from which, the advance ratio J , rotation speed n of the propeller, and required P_D and available P_D^{av} delivered power are found), drift angle β and rudder angle δ .

Any contribution in the system (1)-(3) can be defined individually, with the most suitable methods (empirical, numerical or experimental), depending on the designer needs and available technology. Innovative propulsion and steering solutions can be directly leveraged when necessary, by using high-fidelity results for the corresponding components. If, in the future, better numerical or experimental methods or empirical formulae are developed, they can be accommodated by the procedure without the need to revise Guidelines. The procedure is also easily verifiable in approval, because each of the contributions can be easily verified or updated, if necessary.

Note that a methodologically similar approach is used for the different problem of ship capsizing in

dead ship condition [7], [8]: even though seakeeping tests in beam seaway at zero forward speed are much easier to carry out and to evaluate than transient manoeuvres in seaway, still a simpler method is used, which is more accurate and more efficient. It is based on series of separate simple tests in well-controlled conditions (steady drift in beam wind, roll decay in calm water and roll in regular beam waves) which are used to define separately different elements (heel angle, roll damping and effective wave slope), which are put together in a simple analytical model.

Figure 2 shows examples of converged solutions described (1)-(3), corresponding to the application of the manoeuvring criteria in coastal areas C2 and C3 in polar coordinates *ship speed* (radial coordinate) – *seaway direction* (circumferential coordinate, head waves and wind come from the top). Along the line A, the required delivered power P_D is equal to the available delivered power P_D^{av} , along line B the speed is equal to the required minimum advance speed (here 4.0 knots), and line C limits the highlighted area in which the required rudder angle for course-keeping exceeds the maximum rudder angle (assumed here 25° as an example).

The left plot corresponds to a seaway in which the installed power is sufficient to fulfil both criteria C2 and C3 (line A does not cross lines B and C). Further to the right, the following combinations of wave height and period are shown: installed power is marginally sufficient to provide 4.0 knots advance speed in head seaway (line A crosses line B in head seaway); installed power is marginally sufficient to provide 4.0 knots advance speed in bow-quartering seaway (line A crosses line B in bow-quartering seaway); and installed power is marginally sufficient for course-keeping in nearly beam seaway (line A crosses line C).

An important question is how the accuracy of each of the components of system (1)-(3) influences the final result. To investigate this, each of the coefficients of forces and moments in the system (1)-(3) was disturbed by $\pm 10\%$ in turn, and the maximum ratio P_D/P_D^{av} was evaluated at the significant wave height 5.5 m and zero-upcrossing wave periods from 7 to 15 s along the lines 4.0 knots (criterion C2) and rudder angle 25° (criterion C3).

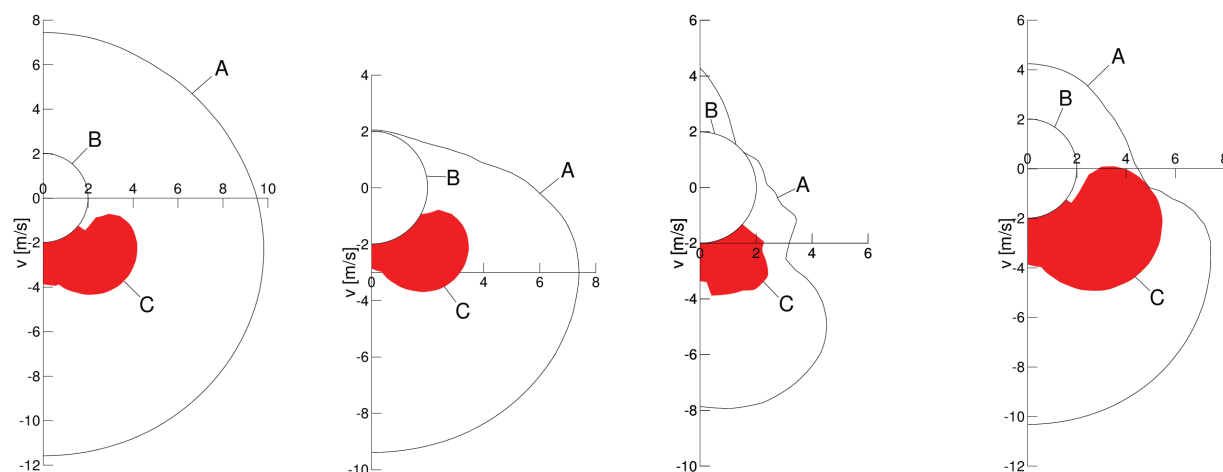


Figure 2. Examples of assessment results in polar coordinates *ship speed* (radial coordinate) – *seaway direction* (circumferential coordinate, head waves and wind come from the top): line “required power equal to available power” (line A), line “advance speed 4.0 knots” (line B) and line “rudder angle 25°” (line C)

The results, shown in Table 2 as percentage of the change of the ratio P_D/P_D^{av} due to change of each force or moment coefficient by 10%, indicate that the most important contribution is the time-average wave x -force (added resistance), followed by calm-water z -moment, calm-water y -force, time-average wave y -force and x -force on the rudder.

Table 2. Change of ratio of required to available delivered power in percent due to 10%-change of different components of forces and moments

Contributions	x -force	y -force	z -moment
Calm-water	0.7	1.7	1.8
Wind	1.4	0.6	0.4
Waves	3.5	1.7	0.3
Rudder	1.7	0.0	

If empirical formulae are used for all contributions, this assessment (*Comprehensive Assessment*) is not expensive; still it requires the solution of a nonlinear system of 3 equations for many cases (combinations of forward speeds and seaway headings). Whereas acceptable for a designer, consultancy or Class, this may be still too complex for Administrations to verify. Therefore, it is suggested that even simpler alternative assessment procedures are disposed. The Comprehensive Assessment will be anyway required for cases with large uncertainties, such as innovative propulsion and steering design solutions;

for the majority of conventional vessels, however, simple checks should be sufficient. In particular, it is foreseen to develop two simpler assessment procedures: a *Simplified Assessment* procedure, which is based on significant simplifications, such as reduced number of assessment cases and reduced complexity of the motion equations, but still takes into account all relevant physics for propulsion and steering (similar in complexity to the existing Level 2 assessment in the *2013 Interim Guidelines*); and another, simplest assessment procedure, based on the definition of the required minimum installed power as an empirical function of main ship parameters (similar in complexity to the existing Level 1 assessment in the *2013 Interim Guidelines*, but taking into account *propulsion* and *steering* characteristics of vessels).

SIMPLIFIED ASSESSMENT PROCEDURES

Principles

The aim of the simplification is to reduce the number of solution cases, as well as, if possible, the number of terms in motion equations (1) to (3). However, the procedure should still remain a first-principles assessment, keeping all relevant physics from the Comprehensive Assessment. In particular, this procedure evaluates the same criteria (C1-C6) as those enforced in the Comprehensive Assessment. In this paper, such Simplified Assessment procedures are presented concerning the following two criteria: propulsion ability (advance speed at least 4.0 knots in all seaway directions) and steering ability (course keeping in all seaway directions).

Propulsion Ability

The starting point is the system of equations (1)-(3), which has to be solved for all relevant forward speeds and all possible seaway directions to demonstrate that the ship is able to keep forward speed of at least 4.0 knots in seaway from any direction. Noting that bow seaways are most critical for required power at a given speed (Fig. 2, second and third plots from left), it is enough to consider only seaways from 0 to about 60° off-bow in the assessment. Further, neglecting the influence of drift on the required thrust and required power allows omitting equations (2) and (3). Thus only eq. (1) needs to be considered in head waves:

$$X_s + X_w + X_d + X_R + T(1 - t_H) = 0 \quad (4)$$

However, it is important to keep in mind that the time-average longitudinal force due to waves X_d in eq. (4) should be taken as the maximum force in mean wave directions between 0 and 60° off-bow.

The contributions X_s , X_w , X_d , X_R and thrust T in eq. (4) can be found using any method from the Comprehensive Assessment (empirical, numerical or experimental). However, it seems logical to allow using also simpler approximations for these terms in the Simplified Assessment.

For example, using semi-empirical models for the rudder resistance X_R , e.g. [9], [10], will lead to an implicit dependence of X_R on the propeller thrust T , requiring an iterative solution of eq. (4). To allow a simpler, non-iterative solution, assume $X_R = -t_R T$, where t_R is an empirical constant. In bow-quartering waves, a significant rudder angle may be required for steering, which leads to $t_R = 0.2$ (based on Comprehensive Assessment for 15 vessels). This results in a simple non-iterative equation for the required thrust T :

$$T = -\frac{X_s + X_w + X_d}{1 - t_H - t_R}, \quad (5)$$

where t_H is the thrust deduction on the ship hull.

At 4.0 knots advance speed, the influence of forward speed on propeller can be neglected, i.e. using the bollard pull assumption (K_T and K_Q at zero advance ratio $J=0$) instead of full open-water propeller curves provides accurate enough results, Fig. 3.

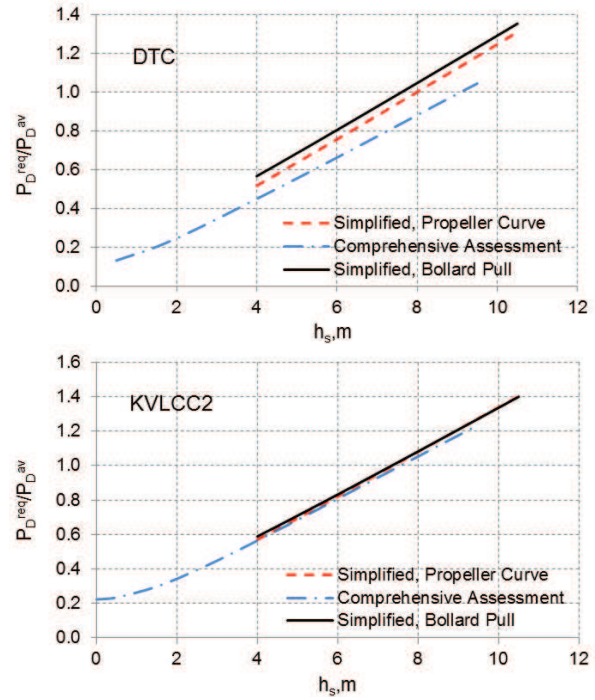


Figure 3: P_D/P_D^{av} vs. h_s according to Comprehensive and Simplified Assessments; the latter using propeller curves and bollard pull assumption

To define the calm-water resistance X_s at 4.0 knots advance speed, the ITTC regression line is accurate enough:

$$X_s = -C_F(1+k)0.5\rho v_s^2 A_0, \quad (6)$$

where $C_F = 0.075(\log_{10} Re - 2)^{-2}$ is the friction coefficient, $Re = v_s L_{pp}/\nu$ is the Reynolds number, k is the form-factor, v_s is ship speed, and A_0 is the wetted surface of the hull.

Wind resistance $X_w = -0.5X'_w \rho_a (v_s + v_w)^2 A_F$ can be defined using the air density ρ_a , wind speed v_w , frontal windage area A_F , and head wind resistance coefficient X'_w , which can be assumed conservatively as 1.0 in the Simplified Assessment.

The most challenging term in eq. (5) is the time-average longitudinal force in short-crested irregular waves (“added resistance”) X_d , taken as the maximum over the wave directions 0 to 60° off bow. In the 2013 *Interim Guidelines*, it can be defined only using model tests. According to the SHOPERA approach, it can be defined using any method from Comprehensive Assessment (empirical, numerical or experimental) to define quadratic transfer functions of X_d in regular waves, combined with a spectral integration. Again, using

alternative simpler approximations seems to be appropriate in the Simplified Assessment; here, an empirical expression is proposed, based on computations with the software *GL Rankine* [11], a spectral integration using JONSWAP spectrum with $\gamma = 3.3$ and \cos^2 -wave energy spreading and taken as maximum over mean wave directions 0 to 60° off-bow and peak wave periods from 7.0 to 15.0 s:

$$X_d = -83L_{pp}C_B^{1.5} \left(1 + \sqrt{Fr}\right) h_s^2; \quad (7)$$

$Fr = v_s(gL_{pp})^{-1/2}$ is the Froude number. Figure 4 shows results of eq. (7), y-axis, vs. numerical computation, x-axis, for 14 bulk carriers (BC), tankers (TA) and container vessels (CV).

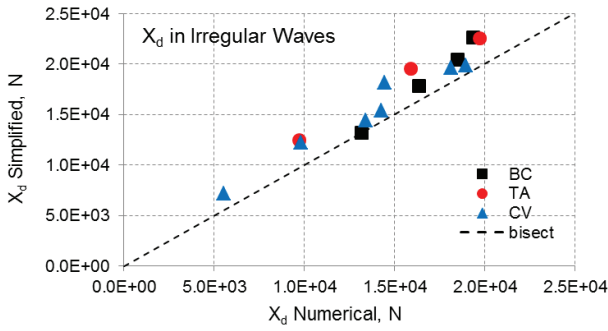


Figure 4: X_d in irregular short-crested waves according to eq. (7) vs. numerical computations.

Figure 5 compares results of the proposed simplified propulsion ability assessment procedure with the Comprehensive Assessment for 4 bulk

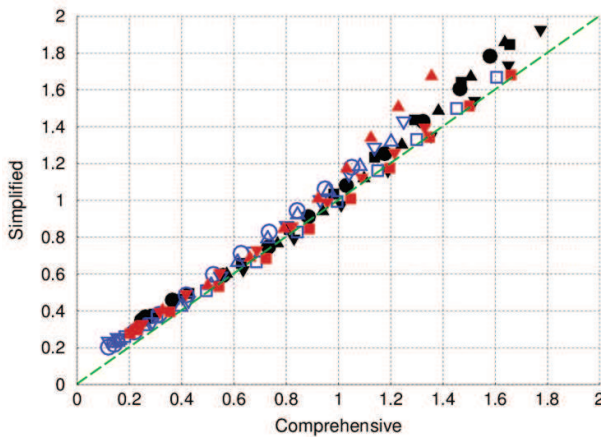


Figure 5: Ratio of required to available delivered power according to Simplified (y-axis) vs. Comprehensive (x-axis) Propulsion Ability Assessment for 4 bulk carriers (■, ▲, ▼, ●), 3 tankers (■, ▲, ▼) and 4 container ships (□, △, ▽, ○) in waves of significant wave heights from 0.0 to 9.5 m.

carriers, 3 tankers and 4 container ships at $h_s = 0$ to 9.5 m. The plot shows the ratio of the required to available delivered power $P_D/P_D^{av} > 1$ according to the Simplified (y-axis) vs. Comprehensive (x-axis) Assessment. The proposed Simplified Assessment procedure is sufficiently accurate to slightly conservative, especially for $P_D/P_D^{av} > 1$ (which is not relevant anyway). This procedure was implemented in MS Excel for practical use.

Steering Ability

The starting point is the system (1)-(3), which is being solved for all relevant forward speeds and all seaway directions to check that *the ship is able to keep course in seaway from any direction*. Note that for the steering ability, both the steering system and propulsion (which influences steering ability) are required and should be integral parts of the assessment: e.g. ships with powerful propulsion may have a smaller rudder, whereas ships with weaker propulsion may compensate this with larger or more effective steering devices.

The first simplification stems from an observation, which based on the results of Comprehensive Assessment for about 15 ships, that the steering ability is challenged to the largest degree in seaway directions close to beam (Fig. 2, right), i.e. the point with the maximum ratio of the required to available delivered power along the line of maximum rudder angle (further referred to as *critical conditions for steering* for brevity) is close to beam seaway. This allows reducing the simplified steering ability assessment to beam seaways only (from the norming point of view: ships with better steering ability in beam seaway will also have better steering ability in all seaway directions). Thus the system (1)-(3) results in the following system:

$$X_s + X_w^{90} + X_d^{90} + X_R + T(1 - t_H) = 0 \quad (8)$$

$$Y_s + Y_w^{90} + Y_d^{90} + Y_R = 0 \quad (9)$$

$$N_s + N_w^{90} + N_d^{90} - Y_R I_R = 0 \quad (10)$$

solved only in beam seaways; superscript 90 at the time-average wave and wind forces means that their evaluation is required only in beam waves and transverse winds, respectively.

To validate the simplification (8)-(10), the ratio of the required to available delivered power P_D/P_D^{av} computed using this simplification was compared

with the comprehensive steering ability assessment using system (1)-(3) for 15 vessels; results for a 14000 TEU container ship (DTC, top) and a very large crude oil carrier (KVLCC2, bottom) in Fig. 6 show that the simplification (8)-(10) is sufficiently accurate.

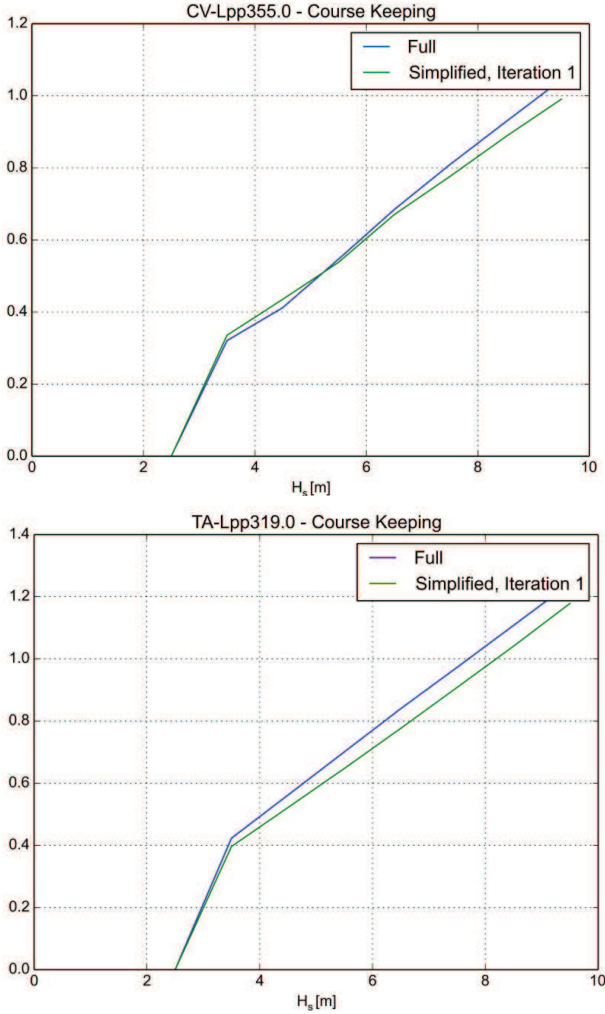


Figure 6: Ratio of required to available delivered power vs. significant wave height according to comprehensive steering ability assessment (blue line) and simplified system (8)-(10) (red line) for DTC (top) and KVLCC2 (bottom) in full load.

The analysis of the terms of system (1)-(3) using Comprehensive Assessment shows that none of terms is negligible compared to the other terms, thus none of the terms can be simply omitted. To identify possible simplifications, introduce the levers of yaw moments as follows:

$$l_s \equiv N_s/Y_s, \quad l_w \equiv N_w/Y_w, \quad l_d \equiv N_d/Y_d, \quad (11)$$

and rewrite eq. (10) using these definitions as

$$l_s Y_s + l_w Y_w^{90} + l_d Y_d^{90} - Y_R l_R = 0 \quad (12)$$

Express Y_s from eq. (9) as

$$Y_s = -Y_w^{90} - Y_d^{90} - Y_R \quad (13)$$

Introducing eq. (13) into eq. (12) leads to the following combination of equations (9) and (10):

$$Y_w^{90} (l_w - l_s) + Y_d^{90} (l_d - l_s) = Y_R (l_s + l_R) \quad (14)$$

Analysis of the terms of converged solutions of the system (1)-(3) in the critical conditions for steering ability (i.e. forward speeds and seaway directions, for which P_D/P_D^{av} is maximum along the line $\delta = \delta_{max}$, see Fig. 2, right) shows that

$$l_s \sim L_{pp}/2, \quad l_w \ll l_s, \quad l_d \ll l_s, \quad (15)$$

Fig. 7, thus eq. (14) can be simplified as

$$Y_w^{90} (0 - l_s) + Y_d^{90} (0 - l_s) = Y_R (l_s + l_R)$$

or

$$Y_R = -b (Y_w^{90} + Y_d^{90}) \quad (16)$$

where

$$b = l_s / (l_s + l_R) \quad (17)$$

As a result, the system of equations (8)-(10) reduces to one equation

$$X_s + X_w^{90} + X_d^{90} + X_R + T(1 - t_H) = 0 \quad (18)$$

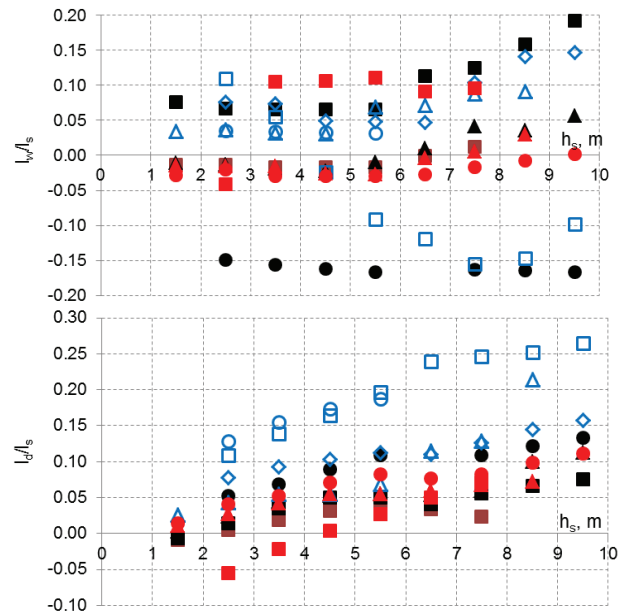


Figure 7: Ratios of levers l_w/l_s (top) and l_d/l_s (bottom) in the critical conditions for steering ability (combinations of forward speeds and seaway directions, for which P_D/P_D^{av} is maximum along the line $\delta = \delta_{max}$)

This equation is solved only for beam seaway; its solution (the maximum attainable speed and corresponding propeller rotation speed and thrust) defines the maximum available lateral steering force on the rudder Y_R^{av} . This steering force should not be less than the required lateral steering force defined by eq. (16), $Y_R^{req} = -b(Y_w^{90} + Y_d^{90})$.

As an approximation, assume $l_R \approx 0.5L_{pp}$, then definition (17) simplifies to

$$b = -l_s / (l_s + 0.5L_{pp}), \quad (19)$$

which can also be written as

$$b = \frac{Y_s l_s}{Y_s l_s + Y_s 0.5L_{pp}} = \frac{N_s}{N_s + 0.5Y_s L_{pp}} = \frac{N'_s}{N'_s + 0.5Y'_s} \quad (20)$$

where $Y'_s = Y_s / (0.5\rho L_{pp} T_m v_s^2)$, $N'_s = N_s / (0.5\rho L_{pp}^2 T_m v_s^2)$ are the coefficients of calm-water side force and yaw moment, respectively; note that they depend only on drift angle β .

To validate these approximations, Fig. 8 compares the ratio of the required to available delivered power according to approximations (16), (18) and (20) with the same ratio from the Comprehensive Assessment for the 15 sample ships. In the Simplified Assessment, the value of b is taken from the Comprehensive Assessment, as the exact value $b = N_s / (N_s + 0.5Y_s L_{pp})$ in critical conditions for steering ability; the approximation provides accurate to slightly conservative results.

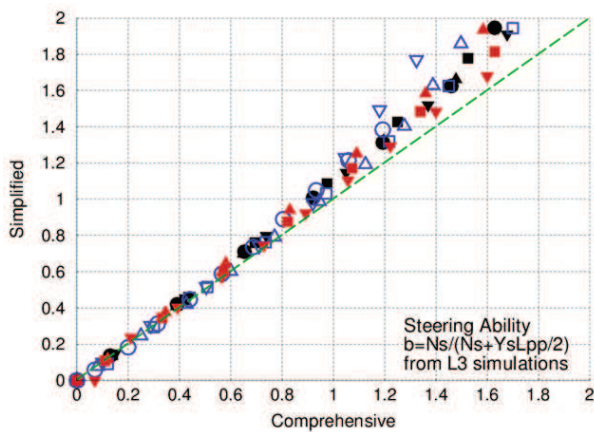


Figure 8: Ratio of required to available delivered power according to Simplified Assessment (16),(18),(20) with exact value of $b = N_s / (N_s + 0.5Y_s L_{pp})$ taken from Comprehensive Assessment (1)-(3) (y axis) vs. the same ratio from Comprehensive Assessment (x axis) for 4 bulk carriers (■,▲,▼,●), 3 tankers (■,▲,▼) and 4 container ships (□,△,▽,○) in waves of h_s from 0.0 to 9.5 m.

Obviously, the value of b depends on drift angle β in critical conditions for steering ability (b is a decreasing function of β), which depends on ship size and geometry, installed power and wave height and period. To provide a conservative recommendation for the value of b , it was evaluated in critical conditions for the steering ability using the Comprehensive Assessment and compared with its values at various drift angles for 11 ships (4 bulk carriers, 4 container ships, 3 tankers). This comparison shows that using the value of b at drift angle of $\beta = 5^\circ$ leads to a maximum conservative error (overestimation) for b of up to 16%, and to acceptable accuracy results of the Simplified Assessment, Fig. 9.

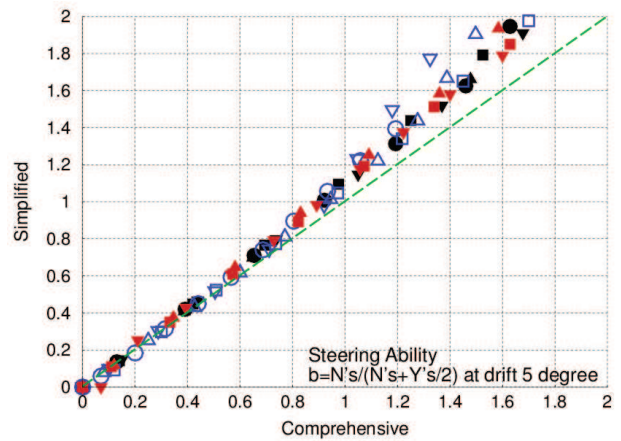


Figure 9: Ratio of required to available delivered power according to Simplified Assessment (16),(18),(20) using value of $b = N'_s / (N'_s + 0.5Y'_s)$ at drift angle $\beta = 5^\circ$ (y axis) vs. the same ratio according to Comprehensive Assessment (x axis) for 4 bulk carriers (■,▲,▼,●), 3 tankers (■,▲,▼) and 4 container ships (□,△,▽,○) at h_s from 0.0 to 9.5 m.

If even calm-water manoeuvring derivatives Y'_s and N'_s are not available, it is useful to have a conservative assumption for b . It proves that a maximum value of $b = 0.4$ could be used based on the results for the 11 sample ships, Fig. 10 (here, even a more conservative assumption $b = 0.5$ was used). This assumption actually leads to very conservative results for container ships (for DTC, RANSE-computed value of b at drift angle 5° is 0.25). An empirical formula for b at $\beta = 5^\circ$ as a function of main ship particulars is required and needs to be developed.

To define the other terms in equations (16), (18), in addition to Comprehensive Assessment

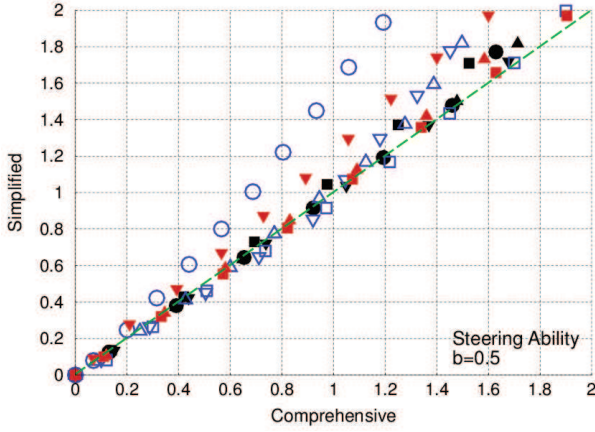


Figure 10: Ratio of required to available delivered power according to Simplified Assessment (16),(18) employing value of $b=0.5$ (y axis) vs. the same ratio according to Comprehensive Assessment (x axis) for 4 bulk carriers (■,▲,▼,●), 3 tankers (■,▲,▼) and 4 container ships (□,△,▽,○) in waves of h_s from 0.0 to 9.5 m.

methods (empirical, numerical and experimental), it is logical to introduce simplified approximations, consistent with the complexity of the Simplified Assessment, which are considered below.

The increase in rudder resistance X_R is significant in critical conditions for steering, because both rudder angle and the ratio P_D/P_D^{av} are maximal. Because X_R implicitly depends on thrust, which is itself part of solution, a simple assumption $X_R = -t_R T$ is used to avoid iterative solution of eq. (18). According to Comprehensive Assessment results for 15 vessels, $t_R = 0.3$ is recommended.

To calculate the available lateral force on rudder Y_R , model by Söding [9] was used with $\delta_{max} = 25^\circ$ as a conservative assumption.

The lateral force due to beam wind is calculated as $Y_w^{90} = -0.5Y_w^{90} \rho_a A_L v_w^2$; where $Y_w^{90} = 1$ can be used as a conservative assumption for the lateral wind force coefficient. The longitudinal component of the wind resistance in beam seaway X_w^{90} can be neglected, thus $X_w^{90} = -0.5X_w^{90} \rho_a A_F v_s^2$.

Approximation of the calm-water resistance in eq. (18) is more difficult than in eq. (5): the ITTC regression line cannot be used, because it would under-estimate resistance at the (rather high) forward speeds relevant in critical conditions for steering. If the resistance curve is available e.g. from model tests, it can be directly used; alternatively, resistance curve should be approximated in such a way as to fit those

parameters that are used in approval and are available to Administration, e.g. the maximum continuous rating (MCR) of the engine, corresponding propeller rotation speed n_{MCR} and ship speed at MCR v_{MCR} . In this case, the calm-water resistance curve can be „calibrated“ as

$$X_s = -C_F(1+k)0.5\rho v_s^2 A_0 \left(1 + c_{MCR} v_s^2 / v_{MCR}^2\right) \quad (21)$$

where parameter c_{MCR} is adjusted in such a way that $P_B = \text{MCR}$ when $n = n_{MCR}$ and $v_s = v_{MCR}$.

For the time-average longitudinal wave force in irregular short-crested beam waves X_d^{90} , a simple empirical formula is proposed, obtained from numerical computations with *GL Rankine* and spectral integration for JONSWAP spectrum with $\gamma=3.3$ with \cos^2 -spreading, as a maximum over peak wave periods from 7.0 to 15.0 s:

$$X_d^{90} = -380L_{pp} C_B^{1.5} (0.1 + Fr) h_s^2 \quad (22)$$

Comparison of results of eq. (22) with numerical computations is shown in Fig. 11 at the forward speed of 4.0 m/s.

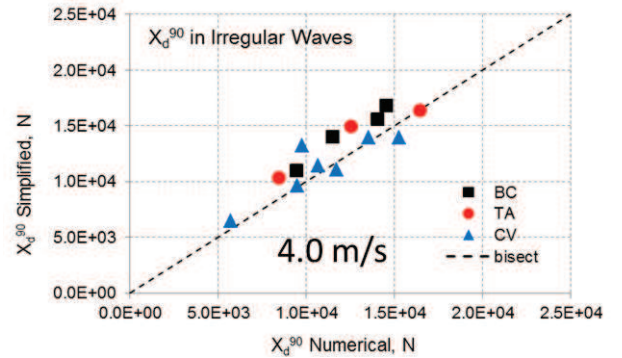


Figure 11: X_d^{90} in irregular short-crested beam seaway according to eq. (22) (y-axis) vs. numerical method (x-axis) for 4 bulk carriers (BC), 3 tankers (TA) and 7 container ships (CV).

Similarly, a simple empirical formula for the time-average lateral wave force Y_d^{90} in irregular short-crested beam seaway, obtained for JONSWAP spectrum with $\gamma=3.3$ and \cos^2 -spreading, is proposed as the following function of peak wave period:

$$Y_d^{90} = -\frac{540L_{pp} h_s^2}{1 + T_p^5 / (C_B L_{pp}^{0.5})^5}; \quad (23)$$

Fig. 12 compares results of eq. (23) with numerical computations with *GL Rankine* followed by spectral integration.

This procedure was implemented in a MS Excel for practical use.

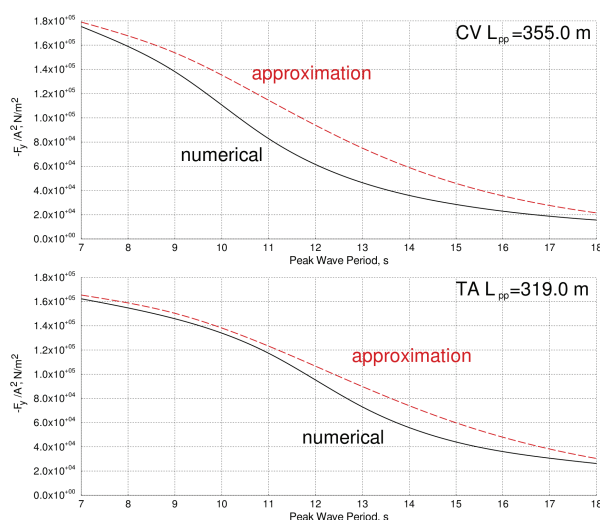


Figure 12: Y_d^{90} at significant wave height of 1.0 m according to eq. (23) (dashed red line) and numerical method (solid black line) vs. peak wave period for DTC (top) and KVLCC2 (bottom).

OUTLOOK

The herein outlined Simplified Assessment procedure for the maneuverability of ships in adverse weather conditions is currently under finalization and validation in the project SHOPERA; it requires, however, the following developments: First, the extension on ships with unconventional steering and propulsion arrangements (twin propellers, twin rudders, controlled-pitch propellers, diesel-electric and turbine propulsion and ships with pod drives). Second, the development of the Simplified Procedure for weather-vaning ability (criterion C1) and maneuverability at limited speed in restricted areas (criteria C4-C6). Third, the finalization of “simplified” empirical methods, consistent with the Simplified Assessment, for the time-average wave forces in irregular short-crested waves: X_d in bow and in beam waves and Y_d in beam waves, in addition to the numerical and empirical methods required for the Comprehensive Assessment. Finally, the development of an empirical formula for b , as a function of main ship particulars.

The next level of simplification, namely a simple empirical formula, is currently being developed in the project SHOPERA based on results of the Comprehensive Assessment for a large number of sample vessels, see e.g. the approach used in [12].

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