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ORIGINAL ARTICLE

Manoeuvrability in adverse conditions: rational criteria and standards

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Abstract

The importance of norming manoeuvrability of ships in adverse weather conditions increased after the introduction of EEDI regulations, which raised concerns that manoeuvrability of ships in adverse conditions may become insufficient if EEDI requirements are achieved by simple reduction of the installed engine power. This paper addresses the definition of the required criteria (i.e. ship's abilities, relevant for the considered problem), measures (values quantifying ship's performance with respect to the criteria) and standards (acceptance limits for the measures). It is proposed to combine criteria that are based on the physics of the problem with standards that are empirical to some degree to reflect the existing safety level and operational practice and, at the same time, compensate for inevitable simplifications in the practical criteria. The paper reviews existing proposals, interviews of ship masters and accident data to define criteria for manoeuvrability in adverse conditions and summarises experience with their application, particularly addressing their practicality and redundancy with respect to each other. A practical assessment procedure is proposed, illustrated in examples and validated. A rational approach to fine-tune the standards, based on benchmarking of existing ships with respect to the new criteria, is proposed and tested on bulk carriers and tankers.

Keywords Manoeuvrability · Adverse Conditions · Criteria · Standards

1 Introduction

Below, the term *criterion* refers to a characteristic of the ship (such as ability to turn, ability to keep course, etc.) by which the ship's abilities, relevant for the considered problem, are judged. The criteria for manoeuvrability in adverse conditions are introduced below. The corresponding *measure* quantifies numerically the performance of the ship with respect to the considered criterion (e.g., turning diameter or overshoot angle). For manoeuvrability in adverse conditions, a convenient and frequently used measure is the marginal (i.e., maximum) weather severity (described by the significant wave height and wind force), up to which the ship can fulfil the criterion. Finally, the term *standard* (sometimes called *norm*) refers to a prescribed acceptance limit for the measure: here, the specified significant wave height and the related wind force at which the ship should be able to fulfil the corresponding criterion to be considered as sufficiently safe.

Manoeuvrability of ships may be presently normed according to the rules of classification societies, ship owner's requirements and non-mandatory (but gaining increasing acceptance by administrations and classification societies) IMO Standards for ship manoeuvrability [1], which address turning, initial turning, yaw checking, course keeping and emergence stopping abilities, which are evaluated in simple standard manoeuvres in calm water. These standards have been criticized for not addressing ship manoeuvring characteristics at limited speed, in restricted areas and in adverse weather conditions. To address ships' manoeuvrability in adverse weather, on the one hand, evaluation of the ship-specific environmental forces due to waves, wind and current is required, and, on the other hand, the assessment of the ability of the ship's steering and propulsion systems to overcome these forces. Several factors are relevant for this ability: first, the inherent manoeuvring characteristics of the ship's hull and its steering system, regulated e.g. by [1], using rational manoeuvrability criteria and empirical acceptance standards. Another relevant factor is the installed

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engine power and propulsion system in general, which are dimensioned according to commercial requirements to the speed in calm water and empirical margins (light propeller margin and sea margin). Peculiarities of the excitation forces in seaway for particular ship types, e.g., big windage area of some ship types, are addressed by increased requirements to the propulsion and steering system for certain ship types, also following from the experience. Despite the absence of rational requirements to ship manoeuvrability in adverse weather conditions, the safety level of modern ships in this respect is satisfactory: analysis [2] of the statistics of accidents due to insufficient manoeuvrability in heavy weather showed that the accident rates related to the fleet at risk are in the range of magnitude of 10^{-5} to 10^{-3} accidents per ship per year depending on ship type, i.e., by one order of magnitude lower than accident rates due to other reasons. The reason is, first, the empirical nature of how the above factors are considered and, second, the big role that operational practices play in ship manoeuvring.

The introduction of the Energy Efficiency Design Index (EEDI) represents a major step in improving energy efficiency and reducing greenhouse gas emissions of shipping. However, it has raised concerns that propulsion and steering abilities of ships may become insufficient to maintain manoeuvrability in adverse conditions if EEDI requirements are achieved by simple reduction of the installed engine power, which would abruptly change one of the important factors, whereas other factors, including design and operation practices, are still based on the pre-EEDI experience.

Whereas it may be tempting to simply put a minimum limit on the required installed power (i.e., use the installed power as a criterion), this solution would neglect other factors important for propulsion and steering in adverse conditions: ship size, relations of main dimensions, hull lines, propulsor (fixed or controllable pitch propeller, pods) and engine type (diesel or diesel–electric, type of turbocharging, propeller margin, etc.) and steering system.

To provide a rational basis for dimensioning of the propulsion and steering systems for manoeuvring in adverse conditions, criteria need to be developed concerning the relevant ship's abilities, as well as standards should be defined to assess the sufficiency of these abilities. As usual in the rule-making, standards must be empirical to some degree, while criteria require a rational approach based on the physics of the problem, because the standards reflect the existing safety level and, more important, depend on operational practices. Moreover, the developed criteria, although they address relevant ship parameters and characteristics, must be significantly simplified to remain practicable, therefore, the standards need to be fine-tuned in such a way that the resulting regulation feasibly reproduces differentiation between safe and unsafe vessels.

The work towards development of such criteria and standards was initiated by the International Association of Classification Societies (IACS) and led to the development of first draft guidelines in 2011, which resulted later in 2012 Interim Guidelines for determining minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions [3–5]. In 2013, these guidelines were updated and adopted by resolution [6] and further updated by [7, 8].

Although 2013 Interim Guidelines is an effective provision to prevent newly built ships from irrational reduction of installed power, their sufficiency was disputed, especially concerning the definition of the minimum power lines (MPL), strictness of standards and removal of comprehensive assessment. To support the development of a rational basis for regulations concerning manoeuvrability in adverse conditions, several research projects have been started worldwide, including the EU funded project SHOPERA (Energy Efficient Safe Ship Operation) [9, 10], a research project in Japan coordinated by the Japan Society of Naval Architects and Ocean Engineers (JASNAOE) together with ClassNK [11], project MacRAW (Short-sea Shipping Requirements: EEDI & Minimum Power Requirements) in the Netherlands [12], project PerSee (Performance of Ships in Seaway) in Germany and research projects in Greece [13, 14] and Korea. In 2017, a joint proposal was prepared by SHOPERA and JASNAOE projects concerning revised guidelines for bulk carriers and tankers [15–17], in which, however, standards have not been finalized yet.

This paper overviews criteria for manoeuvrability in adverse conditions and summarises experience with their application, particularly addressing their practicality and redundancy with respect to each other and describes the approach used to setting standards; practical assessment procedures and evaluation methods that are required for application of the developed criteria will be addressed elsewhere.

2 Manoeuvrability criteria

In [18], course-keeping ability in beam wind without waves was studied; the results show that the minimum required rudder area is defined by course-keeping in beam wind for slender ships with large windage area, turning in calm water for bulk carriers and tankers, and both requirements (depending on the loading condition) for general cargo ships. In paper [19], two criteria were proposed: leaving quay at low speed in wind 20 to 30 knots and 180° course change at 40% of maximum speed and rudder angle 2/3 of maximum in a seaway with significant wave height of 6.0 m. In [20], IACS put together requirements of classification societies related to the redundancy or duplication of the propulsion system to identify the relevant criteria and environmental conditions for steering and propulsion in adverse weather

Table 1 Criteria and weather conditions for redundancy and duplication of propulsion system according to requirements of classification societies from [20]

Class	Criteria	v_w	h_s
GL	Change and keep heading (weather-vaning)	21 m/s	5.4 m
GL	Advance speed ≥ min(7 knots, $v_d/2$)	11 m/s	2.8 m
LR	Steering ability, advance speed ≥ 7 knots	–	–
BV	Advance speed ≥ 7.0 knots	Bft 5 (8.0 to 10.7 m/s)	Corresp. to v_w
ABS	Weather-vaning without drifting	33 kn (17.0 m/s)	4.5 m
DNV	Weather-vaning at advance speed ≥ 6 knots	Bft 8 (17.2 to 20.7 m/s)	Corresp. to v_w

conditions; a summary in Table 1 (v_d means design speed, v_w wind speed, h_s significant wave height) indicates, basically, two requirements: ability of the ship to change or keep heading and ability to maintain some minimum advance speed. Further work by IACS on minimum power requirements for manoeuvrability in adverse weather conditions led to functional requirements to manoeuvrability in the open sea and coastal areas, concluding that manoeuvring in coastal waters is more challenging than in the open sea; the resulting criteria for ship propulsion and steering abilities were formulated in [3, 4], as follows: the ship should be able to (1) keep course in waves and wind from any direction and (2) keep advance speed of at least 4.0 knots in waves and wind from any direction. The required minimum advance speed of 4.0 knots was assumed to provide some minimum speed over ground to timely escape the coastal area in an increasing storm, and include some margin for current. To simplify the practical assessment procedure and replace the evaluation of the first criterion, which requires model tests in irregular waves and wind from all directions in a seakeeping basin, with simpler tests in head waves in a towing tank, an empirical relation was proposed, based on numerical simulations, between the rudder area, windage area and the required forward speed in head waves. This work led to the Interim guidelines for determining minimum propulsion power to maintain the manoeuvrability of ship in adverse conditions [5], updated in [6–8].

Investigations of accidents due to insufficient manoeuvrability in adverse weather conditions in [21] indicate, as the most frequent cause of heavy weather-related grounding accidents, too long waiting at anchor in an increasing storm and starting the engine too late or at a too low rate; in several accidents, however, vessels were not able to either move away from the coast (due to insufficient propulsion ability) or turn into seaway (due to insufficient course-changing ability) despite full engine power applied. Relevant criteria and weather conditions are summarised in [21]. Another source of data in [21] were interviews of masters of about 50 container ships, bulk carriers and tankers. They indicate that in the open sea, the captain has more freedom and can decide what severity of weather conditions is acceptable and what should be avoided, depending on the freeboard, cargo, stability and propulsion and steering characteristics of the ship. On the other hand, when caught in most violent storms, steering against seaway may be impossible for any vessel; in such circumstances, drifting with seaway was considered as an acceptable option for a limited time. Manoeuvring in coastal areas was reported as more challenging than in the open sea because, in principle, any manoeuvre may be required, sometimes in unfavourable seaway direction with respect to the ship. Steering problems were mentioned in the interviews as relevant for insufficient manoeuvrability in adverse conditions more often than propulsion problems (although insignificantly more often); insufficient engine power was mentioned more frequently as a relevant problem for bulk carriers and tankers, whereas insufficient steering ability was mentioned more frequently as a relevant problem for container vessels. As a very specific manoeuvring problem in restricted waters, manoeuvrability at limited speed due to navigational restrictions, e.g., during approaching ports, was mentioned, in strong wind and, sometimes, strong current, but usually without large waves.

Analysis of the statistics of accidents in SHOPERA [2] showed that the rate of accidents due to insufficient manoeuvrability in adverse conditions is in the range of 10^{-5} to 10^{-3} accidents per ship per year, i.e., by one order of magnitude lower than accident rates due to all reasons. The rate of accidents due to manoeuvring in heavy weather is the largest for general cargo vessels, followed by RoRo ships, cruise ships and pure car carriers and further by bulk carriers, gas carriers and tankers. Container ships, LNG carriers and refrigerated cargo carriers have the lowest rate of relevant accidents among the considered ship types. Factors increasing accident frequency are frequent port calls (general cargo vessels, RoRo ferries) and large windage area (cruise and RoRo vessels and car carriers). Majority of manoeuvrability-related accidents happen in coastal areas; the most relevant locations for all ship types are restricted waters and ports (57.3% of all relevant accidents happen in ports, 20.1% in other restricted waters and only 22.6% en route). Port areas are the almost exclusive location type for RoRo ferries and dominating accident location for RoRo cargo vessels, cruise vessels, general cargo vessels and bulk carriers. Other restricted waters relate to a significant portion of accidents for general cargo vessels and bulk carriers. The contribution of en route scenario is mostly relevant for tankers, bulk carriers, small general cargo vessels and RoRo cargo vessels and, to some extent, also for pure car carriers and gas carriers, and is very insignificant for the other vessel types. An important result of this study is that the inclusion of very rare abnormal weather events (such as hurricanes and typhoons) in the statistical analysis does not significantly alter the statistics.

In [22], it was proposed to differentiate three scenarios, in which steering and propulsion abilities of ships are challenged in a different way and thus, requiring different criteria: open sea, coastal areas and restricted areas (including ports). The open-sea scenario imposes less strict functional requirements on the manoeuvring, but in rather severe weather conditions. It is sufficient that the ship can weather-vane, i.e., change heading into a favourable one with respect to the environment and keep this heading. Arguably, the inability to manoeuvre in the open sea should not lead to a loss of the ship, because stability of ships unable to manoeuvre and drifting in beam sea should be ensured by the severe wind and rolling criterion (Weather Criterion) [23] in most severe weather. As a simpler practical criterion, the following weather-vaning ability criterion was proposed in [22]: the ship should be able to keep heading in head to bow-quartering seaway up to 60° off-bow.

Similarly to this weather-vaning requirement, heading recovery criterion was proposed in [12], meaning the ability of the ship to turn from beam into head seaway. However, this formulation is much more difficult to evaluate in practice, because it requires model tests (or numerical simulations) of transient manoeuvres in irregular waves and wind. Therefore, [12] proposes to develop an empirical requirement to bollard pull (i.e., propeller thrust at zero ship speed), which should ensure the weather-vaning ability in a seaway of a given severity, using model tests and numerical simulations of turning into seaway for sufficiently many ships. It is interesting to note that weather-vaning ability in bow seaways is rather a propulsion than steering problem: inability to complete a turn in bow seaway is always related to insufficient propulsion ability, unlike steering in beam or stern-quartering seaways; [12] confirms this, showing that results do not depend on the manoeuvring characteristics of the hull and rudder.

The second scenario proposed in [22], manoeuvring in coastal waters, imposes stronger functional requirements on ship's manoeuvrability: in principle, any manoeuvre may be required, frequently in a complex navigational situation and in a seaway from a direction unfavourable for manoeuvring. However, the relevant weather conditions are less severe than in the open sea, because in an increasing storm, ship masters timely search for shelter or leave to the open sea. This means, however, that not only a sufficient steering ability should be enforced but also a sufficient propulsion ability, to enable timely leaving the coastal area; both abilities are necessary in any seaway direction. Correspondingly, two criteria were proposed for coastal areas: steering ability criterion, the ship's ability to perform any manoeuvre in seaway from any direction, and propulsion ability criterion, the ship's ability to maintain a specified speed in seaway from any direction. The required ship speed in the propulsion criterion was increased from 4 knots [3] to 6 knots, to consider possibly strong currents in coastal areas.

Because the ability to perform any manoeuvre is impossible to evaluate in practice, an equivalent practical criterion was proposed in [22]: the ship should be able to overcome environmental forces to start or continue course change in seaway from any direction. Whereas this formulation is similar to the traditional course-keeping requirement, and this criterion is frequently referred to as course-keeping criterion [3], steering ability is understood here as the ability to overcome environmental forces and start (or continue) course change during an arbitrary manoeuvre, without considering whether each intermediate state during manoeuvre is stable or not, whereas the traditional definition of course-keeping addresses stability of straightforward motion. It may be argued that straightforward motion is one of "any manoeuvres" required by the criterion; note, however, that the proposed formulation does not exclude the ship's ability to perform straightforward motion: even if a ship is directionally unstable on some course, it will still be able to follow this course using rudder for course corrections. This is acceptable considering that the proposed criteria concern safety-relevant situations, occurring few times per operational life, and not operational efficiency which is addressed by the traditional course-keeping criterion.

It is also important to note that the steering ability and propulsion ability criteria are frequently misunderstood as a requirement to keep course at a specified forward speed. This is not so: these criteria are independent and, moreover, are usually challenged in different situations: propulsion ability in head seaways (where it is more difficult to keep forward speed, but requirements to steering are less demanding) and steering ability in stern-quartering to beam seaways (where steering is more difficult but achievable forward speed can be larger). Moreover, for many ship types, a requirement to keep arbitrary course at 6 knots forward speed is impossible to satisfy. Thus, the proposed steering ability criterion does not specify any forward speed: achievable speed is part of assessment, i.e., the capabilities of both the propulsion system (and thus, the attainable speed) and steering system in their interaction are integral parts of steering ability assessment.

Finally, note that instead of the requirement to be able to perform any manoeuvre proposed in [22], frequently some standard calm-water manoeuvres (e.g., turning) are simply transferred into waves without a rational reason. Apart from the practical problem of the need to carry out multiple realisations of such manoeuvre in irregular waves and wind to derive reliable statistical estimates, note that turning circle is not relevant as a practical manoeuvre in calm water and, especially, in adverse conditions. Whereas in calm water, this is still a convenient standard manoeuvre for norming, because it is easy to measure its parameters, such as tactical diameter and advance, this advantage disappears in seaway, where parameters of turning circle do not exist in marginal cases (i.e., in cases at the acceptance boundary, which are of interest in approval), when trajectories are far from a circle and sometimes erratic, so that it is even impossible to differentiate between "successful" and "unsuccessful" manoeuvres.

The third scenario considered in [22], manoeuvring at limited speed in restricted areas, concerns situations where the ship master must reduce the applied engine power (and thus forward speed) significantly below the available power due to navigational restrictions, e.g., during approaching to or entering ports, navigation in channels and rivers, etc. In [22], course-keeping at a specified low speed in strong wind in shallow water, in shallow water near a bank and in shallow water during overtaking by a quicker ship were proposed as practical criteria. Although this scenario was found relevant for majority (77.4%) of manoeuvrability-related accidents in adverse weather conditions [2] and is dominating accident scenario for RoRo and cruise vessels, container ships, pure car carriers, general cargo vessels and bulk carriers, it is not considered here, because the full available power cannot be applied in this scenario and therefore, this scenario is not affected by the EEDI requirements.

From the above, the following criteria seem appropriate for manoeuvrability in adverse conditions and, at the same time, are affected by the installed power: weather-vaning ability criterion for the open-sea scenario and two criteria, steering ability and propulsion ability, for manoeuvring in coastal waters. Note that the proposal for revised guidelines for bulk carriers and tankers [16] involves only propulsion ability criterion for manoeuvring in coastal waters; the reasons are discussed below.

3 Environmental conditions

Ship performance with respect to the criteria defined above can be quantified by the marginal wave height (and corresponding wind speed), up to which the ship can fulfil each criterion. To judge whether the ship is sufficiently safe, this marginal wave height should be compared with a standard, i.e., the minimum acceptable limit of ship's performance. In addition to the wave height, also the related wind speed, wave energy spectrum and wave period should be defined. The difficulty when using the available wave statistics to define the open-sea standards is that none of existing ships can weather-vane in all possible sea states, and, moreover, this is unnecessary because the safety of a ship, not able to weather-vane in a certain sea state in the open sea and thus drifting in beam seaway, should be ensured by the IMO Severe Wind and Rolling Criterion (Weather Criterion) [23]. Considering standards for coastal water criteria, one problem is that there are no unified recommendations for the seaway parameters in coastal areas. On the other hand, met-ocean climate of coastal areas strongly depends on the region and local bathymetry, which cannot be considered in regulations addressing ship safety in unrestricted service. Besides, measurements in coastal areas refer to fixed observation locations, whereas ship masters do not remain in a dangerous position near the coast in a growing storm, but either search for shelter or leave to the open sea, which influences the encountered environmental conditions. Therefore, also other sources must be used.

The well-known findings of the HARDER project, which were adopted in the new harmonized probabilistic damage ship stability regulation of SOLAS 2009 and the Stockholm Regional Agreement on the damage stability of passenger ships, indicate that more than 80% of collisions happened at significant wave heights below 2 m, and significant wave heights in excess of 4 m were practically not recorded during collision accidents.

The requirements of classification societies to redundancy of propulsion system [20], Table 1, indicate rather moderate standards: maximum wind speed 21 m/s and maximum significant wave height 5.4 m for weather-vaning and maximum wind force Bft 8 for 6.0 knots advance speed.

In the 2013 Interim Guidelines, standard wave heights were defined by benchmarking of tankers, bulk carriers and container ships in the EEDI database against the coastal waters propulsion and steering criteria, which led to the significant wave height 4.0 m and wind speed 15.7 m/s for ships with L_{pp}=200 m and less, and significant wave height 5.5 m and wind speed 19.0 m/s for ships with L_{pp}=250 m and greater, with a linear interpolation of wave height and wind speed for L_{pp} between 200 m and 250 m.

Analysis of interviews of ship masters and accident investigation reports in [21] (see also references herein) shows that 50% of ship masters leave coastal areas before wind speed reaches Bft 8 and significant wave height achieves 5 m according to interviews; however, some ship masters reported wind force up to Bft 10 and significant wave height up to 11 m as relevant for manoeuvrability problems. Accident investigation reports indicate wind force up to Bft 10 (more than 23 m/s) and significant wave heights above

6.0 m during accidents in coastal areas. However, the well-documented case [24], where the significant wave height exceeded 6.0 m, clearly indicates too long waiting of the vessel at anchor in an increasing storm as one of the reasons of the accident. The study of this accident in [21] shows that at the significant wave height of 4.5 m, about 80% of the initial number of vessels were still at anchor, whereas 50% of the vessels left anchorage before significant wave height achieved about 5.5 m. The two vessels, which have been waiting at anchor until significant wave height exceeded 6 m, experienced an accident and a near-accident.

Statistics of accident rates, locations and corresponding weather conditions during accidents due to insufficient manoeuvrability in adverse conditions collected by SHOPERA [2] shows remarkably mild environmental conditions during accidents (mean wind speed of about 10 m/s and mean significant wave height about 1.5 m). On the other hand, maximum significant wave height and wind speed during manoeuvrability-related accidents achieve, according to SHOPERA statistics, in rare cases 7.0 m (the case considered above) and 20 m/s, respectively.

The scatter in the wave heights relevant for manoeuvrability between different sources is not surprising considering that manoeuvrability performance depends significantly on characteristics of the vessel, on the operational experience and practices of the ship master and other environmental conditions, such as wave period. Therefore, although statistical information, evidence and interviews are important to estimate the relevant severity of environmental conditions, benchmarking of the existing fleet with respect to the new criteria is an appropriate way to fine-tune the standards: namely, considering that the present safety level with respect to manoeuvrability-related accidents in heavy weather is satisfactory according to statistics, e.g. [2], standards should be selected such that majority of existing vessels can satisfy them.

The need for benchmarking is evident considering that worst possible conditions in coastal areas are avoided by ship masters, whereas in the open sea, ship's inability to manoeuvre in the worst possible storms should not lead to negative outcomes due to the intact stability regulations. Moreover, manoeuvrability in general and, especially, manoeuvring in heavy weather depend to large degree on the established operational practices, which will be reflected by the benchmarking. More importantly, note that practical design assessment cannot address all possible variability of navigational situations encountered during operational life; therefore, whereas the proposed criteria address relevant design parameters and characteristics of a ship hull, steering and propulsion systems and engine for manoeuvrability in adverse conditions, as well as relevant environmental factors, they are simplified to remain practicable. Thus, the proposed criteria should not be confused with operational guidance: particularly, they cannot say what adverse conditions are safe for specific manoeuvres in specific navigational situations. Rather, the proposed criteria and corresponding marginal wave heights represent metrics for rational comparison between ships with regard to their manoeuvrability in adverse conditions and, consequently, for the definition of standard wave heights (because the standards are, essentially, based on marginal wave heights of ships known to be sufficiently safe). Therefore, the definition of the standards should be considered as fine-tuning of the criteria to reliably differentiate between sufficiently and insufficiently safe ships, and not as an identification of safe or unsafe operational conditions. Finally, note that the combination of rational criteria and empirical standards is the usual way used to develop rational regulations. Results of benchmarking and studies concerning standards are shown below.

The influence of wind forces on propulsion and steering ability in seaway is comparable to the influence of the time-average wave forces for ships with a large windage area, such as container vessels and pure car and truck carriers, and is less important (but not negligible) for vessels with moderate windage area, such as bulk carriers and tankers [21]. For practical assessment, it is convenient to use a unified wind speed-wave height relationship (different between the open sea and coastal areas) rather than use an additional standard for the wind speed. The problem in the definition of such unified relationships is that the relation between wind speed and wave height strongly depends on the fetch (i.e., the length of water surface over which a given wind blows), wind duration and relative contributions of wind sea and swell; all these factors strongly depend on location even when considered in a statistical sense.

For the open sea, the well-known semi-empirical formula $h_{\mathrm{s}} = 0.243(v_{\mathrm{w}}^2/g)\mathrm{th}\left(0.011\sqrt{gF/v_{\mathrm{w}}^2}\right)$ by Bretschneider for the wind sea can be used, where F, m, is the fetch length, and v_{w}, m/s, is the wind speed at 10 m above the free surface; for an unlimited fetch this gives

$$v_{\mathrm{w}} = 6.354 \cdot h_{\mathrm{s}}^{0.5} \tag{1}$$

Figure 1 (left) compares this formula with hindcast data for two typical North Atlantic open-sea locations, West Shetland (generated by Oceanweather Inc. for the period from 1988 to 1998) and South-East of Iceland (generated by MET Norway for the period from 1955 to 2009, denoted SE Iceland), and shows that it agrees well with the hindcast data for the both locations and provides slightly conservative estimation of the wind speed for a given significant wave height for $h_{\mathrm{s}} < 10$ m, perhaps due to the presence of swell in the hindcast data. Relation (1) was recommended by SHOPERA for the open sea.

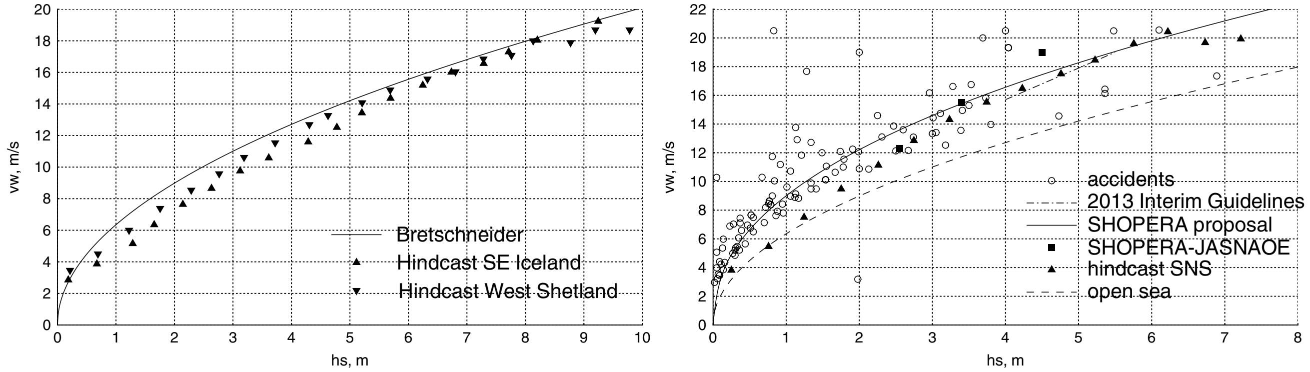


Fig. 1 Wind speed-significant wave height relationships in open sea (left) and coastal areas (right)

In coastal areas, the influence of limited fetch is significant for offshore wind (which, however, rarely leads to problems when leaving coastal areas). For onshore wind, more relevant for accidents, limited fetch is usually not relevant, but the limited storm duration needs to be considered to reflect the fact that ships leave coastal areas in growing storms, especially because this increases wind speed for a given wave height. To define this relation, SHOPERA used statistics of wind speed and wave height during accidents in coastal areas [10], shown in Fig. 1 (right) together with the resulting recommendation by SHOPERA for coastal areas,

$$v_{\mathrm{w}} = 9 \cdot h_{\mathrm{s}}^{0.44} \tag{2}$$

in comparison with the 2013 Interim Guidelines, hindcast data for a location in the North Sea off Dutch coast (simulated by Oceanweather Inc. for a period from 1964 to 1995, denoted Hindcast SNS) and the relation (1) for unlimited fetch and duration in the open sea (denoted as Unlimited Fetch). In the proposal [16] prepared by SHOPERA and JASNAOE projects, statistics of wind speeds and corresponding wave heights for the Pacific coast of Japan and the North Sea coast of Great Britain were used; the former data were provided by the National Maritime Research Institute of Japan for a period of 10 years from February 1994 to January 2004 [25], and the latter data by the Health and Safety Executive of UK [26], based on hindcast wind and wave data for the periods from January 1977 to December 1979 and from January 1989 to December 1994. The proposal from [16] is also shown. The accident data show a considerable number of accidents in strong wind and under-developed waves; in such conditions, wind force at a given significant wave height increases considerably compared to Eq. (1). The hindcast data for the south coast of North Sea agrees well with the accident data in the relevant region of wave heights but shows significantly smaller wind speeds in low to moderate seaways. The 2013 Interim Guidelines agree well with the SHOPERA proposal, whereas the SHOPERA-JASNAOE proposal provides higher wind speeds in the relevant region of wave heights.

Regarding wave energy spectra, noting that in a severe storm, the influence of swell is usually insignificant compared to the wind and for simplicity, [5, 6, 10, 16] propose using a unimodal spectrum. For the assessment of weather-vaning ability in the open sea, it is reasonable to assume a situation of a ship weather-vaning for a prolonged time, i.e., a developed storm, thus a two-parameter Pierson-Moskowitz spectrum is suitable, as recommended by SHOPERA [10]. For propulsion and steering criteria in coastal waters, the relevant scenario is rather different: ship masters do not remain near the coast in a growing storm but either search for shelter or leave to the open sea, thus a developing storm situation is more typical. Therefore, [5, 6] employ the JONSWAP spectrum with the peak parameter of 3.3, which is also proposed by SHOPERA [10] and SHOPERA-JASNAOE [16]. Regarding the remaining factor, the directional

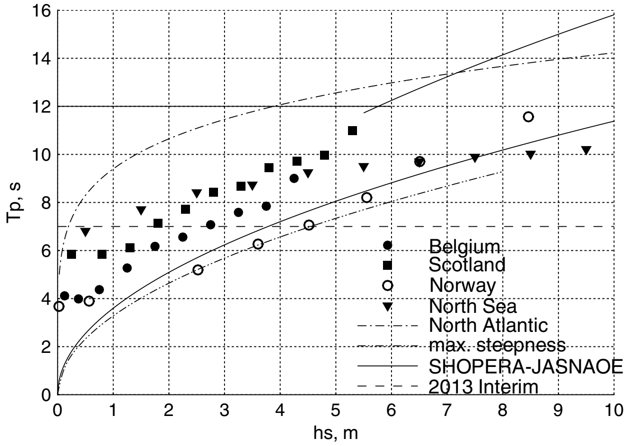


Fig. 2 Most likely peak wave periods in coastal areas and open sea compared to SHOPERA-JASNAOE proposal [16] and 2013 Interim Guidelines [6]

spreading of wave energy, note that whereas the assumption of short-crested waves is recommendable as more realistic, long-crested waves can also be used (when it is more conservative) when the long-crested waves assumption is more practicable for designers [10].

The range of wave periods used in the assessment has a significant influence on the assessment results. For propulsion and weather-vaning abilities, the upper (long waves) boundary of the employed wave periods defines how much of the added resistance peak is considered, whereas the lower boundary of wave periods (short waves) is important for larger, especially blunt, vessels, for which a significant part of added resistance comes from short waves. For the steering ability, relevant external forces (per wave height squared) increase with increasing wave frequency, therefore, it is important how the lower boundary of the employed wave periods (short waves) is defined.

Waves are typically short in coastal areas: Fig. 2 shows most likely peak wave periods vs. significant wave height for several coastal locations: west of Shetland Islands (Scotland), Belgium and Norway, collected by SHOPERA [10], together with North Sea coastal areas data according to [27] in comparison with the theoretical maximum storm steepness boundary $T_z = 8 \cdot (h_s/g)^{0.5}$ [28] ($T_p = 3.282 \cdot h_s^{0.5}$ for a JONSWAP spectrum with $\gamma = 3.3$) and with the most likely peak wave periods in North Atlantic [29]. The range of peak wave periods proposed by SHOPERA [10] and JASNAOE [16] projects for the assessment of propulsion and steering abilities in coastal areas, from $3.6h_s^{0.5}$ to $5.0h_s^{0.5}$ (or 12 s, whichever larger), captures the most likely wave periods in various coastal areas and, at the same time, covers the wave periods which are most critical for added resistance (whereas waves in the open sea are predominately longer). The lower boundary of peak wave periods used in the 2013 Interim Guidelines, 7.0 s, shown for comparison in Fig. 2, is very conservative in the relevant range of significant wave heights (which, however, can be compensated by fine-tuning of standards anyway).

4 Evaluation of criteria

To define marginal wave heights, the proposed criteria should be applied to selected ships at systematically varied wave heights; this requires a practical assessment framework, which consists of assessment procedures (i.e., algorithms to determine marginal wave heights for each of the criteria defined above) and evaluation methods (experimental, numerical or empirical methods required to define input elements for these procedures). SHOPERA has developed a flexible assessment framework which will be described elsewhere; in this paper, the most accurate procedure, comprehensive assessment, is applied. It is based on separate evaluation of different acting forces (due to waves, wind, propeller, rudder, etc.) in simple model tests, numerical calculations or empirical formulae and combination of these components in a simple numerical model. The numerical model follows from neglecting oscillatory forces and moments due to waves and thus considering only average in time forces, moments and other variables (propeller thrust, torque and rotation rate, required and available power, drift angle and rudder angle), assuming the time scale of such oscillations shorter than the time scale of manoeuvring motions. This reduces the evaluation of manoeuvrability criteria to a solution of coupled motion equations in the horizontal plane under the action of time-average wave-induced forces and moments (index d), as well as wind forces and moments (w), calm-water reactions (s), 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. 3, leads to a system of motion equations, which converges to a steady state described by the following equation system (note that achieving converged solution can be realised in various ways, including time-domain simulation):

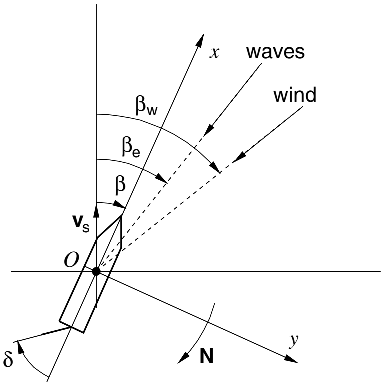


Fig. 3 Coordinate system and definitions

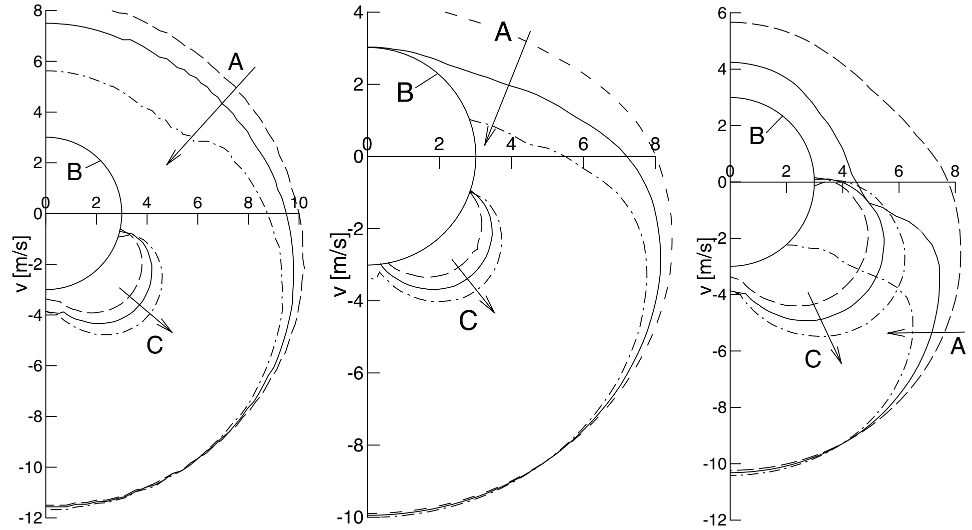
$$X_s + X_w + X_d + X_R + T(1 - t) = 0 \tag{3}$$

$$Y_s + Y_w + Y_d + Y_R = 0 \tag{4}$$

$$N_s + N_w + N_d - Y_R l_R = 0 \tag{5}$$

The coordinate system has an origin O in the main section at the water plane; x-, y- and z-axes point towards bow, starboard and downward, respectively (positive rotations and moments with respect to z-axis are clockwise when seen from above). The ship sails with a 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; rudder angle δ is positive to port. The lever l_R in the yaw moment due to rudder $-Y_R l_R$ in Eq. (5) in general differs from $L_{pp}/2$ due

Fig. 4 Examples of results of comprehensive assessment



to pressure redistribution on the ship stern due to rudder influence.

A converged solution, described by the equation system (3)-(5), provides the required propeller thrust (from which, 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.

To satisfy the criteria defined above, maximum of the ratio $P_\mathrm{B}\big/P_\mathrm{B}^\mathrm{av}$ along the line corresponding to the maximum available steering effort (for the steering ability criterion) or line corresponding to forward speed 6.0 knots (for the propulsion ability criterion) should not exceed 1.0. Figure 4 shows examples of converged solutions and application of the steering and propulsion criteria in polar coordinates ship speed (radial coordinate)—seaway direction (circumferential coordinate): along line A, $P_\mathrm{B}\big/P_\mathrm{B}^\mathrm{av} = 1$, line B corresponds to the required advance speed in the propulsion criterion (6.0 knots), and line C limits the area within which the required steering effort exceeds the available one (here, rudder angle exceeds 35°). For illustration, lines A and C are shown for the considered example (solid line) and for 1 m lower and 1 m greater significant wave height (dashed and dash-dot lines, respectively); arrows indicate increasing wave height for each group of three lines. The left plot corresponds to a seaway in which the vessel fulfils both criteria (lines A do not cross lines B and C); in the middle plot, the installed power is marginally sufficient to provide advance speed of 6.0 knots in head seaway (where solid line A touches line B); in the right plot, the installed power is marginally sufficient for steering in nearly beam seaway (where solid line A touches solid line C).

An important question is how to define the maximum steering effort: for example, maximum rudder angle can be used or the maximum lift coefficient of the rudder. In some cases, special treatment is required, e.g., for vectorised propulsion. Treatment of particular cases should in any case be agreed with the regulatory approval; an important question related to the steering ability criterion is whether a safety margin is required for the maximum available steering effort, e.g., by reducing the maximum available rudder angle in the assessment. Such margin seems unnecessary for two reasons: first, unless such steering margin is ship-specific, its effect will be lost due to fine-tuning of standards anyway; second, absence of such safety margin means that the ship will not be able to start course change when it is sailing exactly in the marginal condition corresponding to the crossing point of solid lines A and C in Fig. 4, right, i.e., when $P_\mathrm{B}\big/P_\mathrm{B}^\mathrm{av} = 1$ at exactly one point on the line corresponding to the maximum steering effort, and ship is in exactly this condition. Note, however, that if the ship starts course change when sailing in exactly this condition, any resulting deviation will lead to a more favourable condition with respect to propulsion and steering, thus the ship will

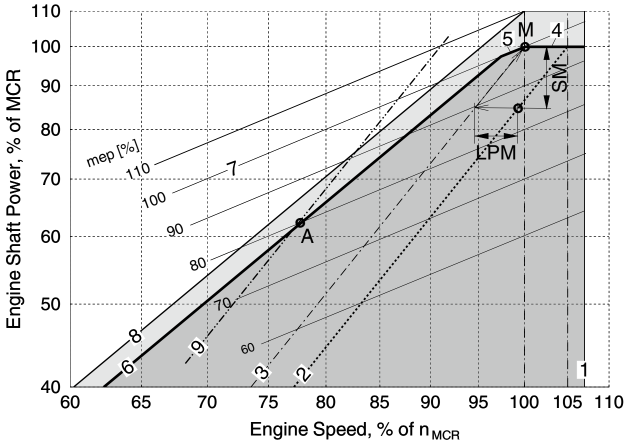


Fig. 5 Diesel engine diagram

be able to continue the started course change, i.e. a safety margin is not necessary.

One of critical aspects of manoeuvrability of ships in adverse conditions is modelling of the main engine and the propulsion system under high load due to increased resistance in adverse conditions. Frequently used assumptions of constant torque, constant power or constant rotation speed can lead to non-conservative predictions. To evaluate the manoeuvrability criteria, the required brake power P_{B} should be compared with the available brake power $P_{\mathrm{B}}^{\mathrm{av}}$ at the actual propulsion point. The former is the result of the assessment procedure, and the latter depends on the characteristics of the main engine and should be provided by the engine manufacturer.

The available delivered power on the propeller $P_{\mathrm{D}}^{\mathrm{av}}$ can be calculated as $P_{\mathrm{D}}^{\mathrm{av}} = \eta_{\mathrm{s}}\eta_{\mathrm{g}}P_{\mathrm{B}}^{\mathrm{av}} - P_{\mathrm{PTO}}$, where P_{D} is the delivered power to the propeller, P_{B} is the brake power of the engine, η_{s} is the shaft efficiency, η_{g} is the gear efficiency, and P_{PTO} is the power take-off. In an assessment procedure based on convergence to a steady state, i.e., not considering ship motions in waves and transient responses of the engine, a steady engine model, defined by the engine diagram, can be used to define $P_{\mathrm{B}}^{\mathrm{av}}$ as a function of the engine rotation rate. Figure 5 shows an example of the engine diagram for a two-stroke low-speed turbocharged marine diesel engine. The horizontal axis corresponds to the rotation speed as percentage of rotation speed at the maximum continuous rating (MCR), and the vertical axis shows shaft power as percentage of MCR (note logarithmic scales used for both axes). Line 1 corresponds to the maximum rotation speed (shown as an example at 105% of the engine layout point rotation speed following recommendations in [30]); the minimum rotation speed limit, or idle limit, corresponding to 25–30% of the nominal rotation speed, is not shown. Curve 2 is called the light propeller curve and corresponds to resistance and propulsion characteristics of a clean hull and propeller in calm water. Along this line, shaft power is defined by the hull resistance curve, open-water propeller characteristics and hull-propeller interaction coefficients and is approximately proportional to n^3. Curve 3 is referred to as the heavy propeller curve, and is assumed in design as a propeller curve corresponding to fouled hull in heavy weather. This curve is obtained by shifting the light propeller curve to the left by the so-called light propeller margin (LPM), typically about 4% of the nominal rotation rate, and upwards by a sea margin (SM), typically about 15% of MCR, up to point M; point M corresponds to MCR and is the layout point for the engine. In the assessment of the sufficiency of the installed engine for manoeuvrability in adverse conditions, it is necessary to consider that the maximum continuous output of a diesel engine is bounded, depending on its rotation speed, by several limits. The power limit, line 4, is relevant at maximum rotation rates. At this limit, maximum power continuously provided by the engine is constant and equal to MCR. The maximum torque limit (also called maximum mep limit), line 5, is defined by the shafting system bearing strength, and is relevant at the moderately reduced rotation rates. At this limit, torque is constant and thus the maximum engine output is proportional to rotation speed n. The surge limit (also called air limit), line 6, is relevant at low rotation rates. To the left of line 6, the engine will lack air from the turbocharger for the combustion process. Surge limit depends on the turbocharging technology used, thus, manufacturer data should be referred to for its definition.

Diesel engine is controlled by changing pressure in cylinders; constant mean effective pressure (mep) lines are the lines parallel to line 7, which corresponds to the mep limit of 100%; along these lines, shaft power is proportional to the rotation speed n, and, correspondingly, the torque is constant. Line 8 is the engine overload limit (typically about 10% of MCR at point M): whereas the area between lines 2, 4, 5 and 6 is available for continuous operation in adverse conditions or during manoeuvres without time limitation, the area between lines 4, 5, 6 and 8 is available for overload running for limited periods (1 h per 12 h according to recommendations in [30]); this area should be considered as not available for manoeuvring in adverse conditions.

Due to increased resistance in adverse conditions or during manoeuvres, line 2 shifts upwards (up to line 9, for example), and the maximum engine output is defined by the intersection point A of line 9 with one of the engine limit curves 5 or 6: at low added resistance, e.g., in normal operation in low to moderate sea states, maximum torque line 5 is relevant, whereas for propulsion and manoeuvring in heavy weather, i.e., at a greater added resistance, surge limit line 6 becomes the limiting curve.

The above concerns low-speed two-stroke diesel engines working directly on a fixed-pitch propeller. Although in the practical approval, verified manufacturer data describing engine limit curves and propeller characteristics should be used, a summary of approaches used for other types of the engine and propulsion is given here for information. For a diesel-electric propulsion, it was assumed that the diesel works at a constant rotation speed (corresponding to full MCR in emergency), whereas the power output of an electric motor is independent from the rotation speed; however, maximum output of the electric motor is limited by the maximum torque due to strength limits of shaft bearings. For a vessel equipped with a controllable-pitch propeller, it was assumed that in an emergency the captain will use the full available power, i.e., operate propeller at a constant (nominal) rotation speed and adjust the pitch of propeller blades to the required forward speed and thrust.

Validation of the methods to define the force components required in the assessment was one of the main concerns in the SHOPERA and JASNAOE projects; detailed results

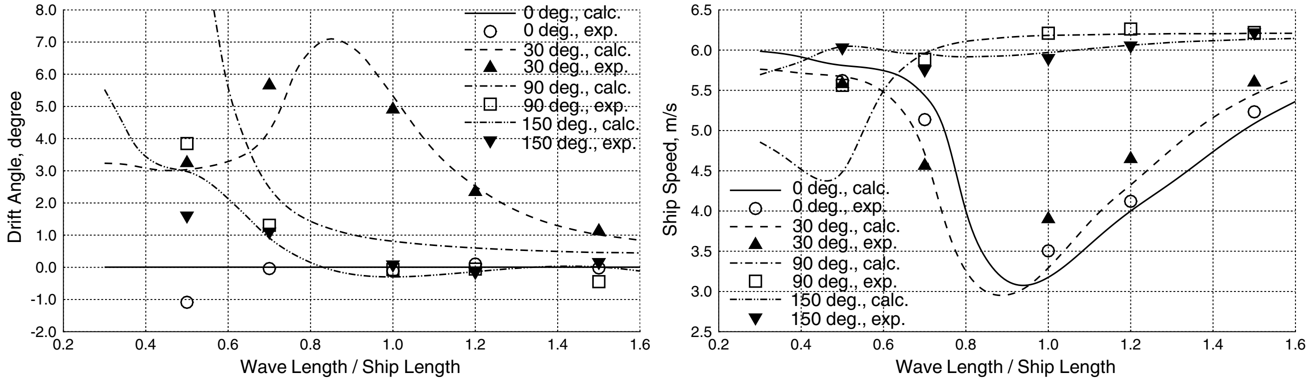


Fig. 6 Computed (lines) vs. measured in [31] (symbols) drift angle (left) and maximum attainable speed (right) for S-175 model depending on ratio of wave length to ship length in waves of various directions (0 degree corresponds to head waves)

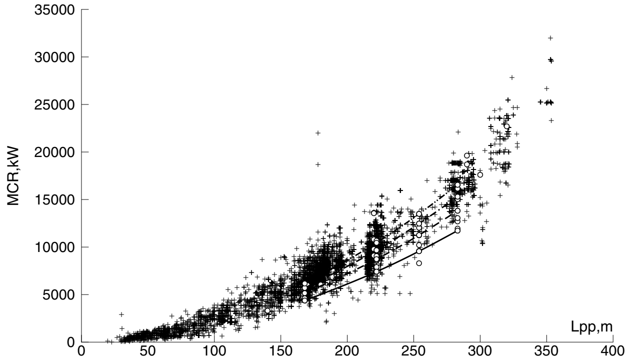


Fig. 7 IHS-FairPlay database per March 2016 (+), studied ships (circle) and 5% (solid line), 10% (dashed line), 20% (dash-dotted lines) and 30% (dash-double-dotted line) low-power lines for bulk carriers

can be found elsewhere. Here, an illustration of the validation of the comprehensive assessment procedure involving all components (apart from wind forces) is included, for which course-keeping and speed loss model tests [31] for S-175 model at a straight course in regular waves of various lengths and directions were used. Calm-water reactions were computed with RANS-CFD, the time-average wave-induced forces and moments with the Rankine-source code GL Rankine [32], propeller characteristics were taken from [31], and rudder forces were modelled with a semi-empirical approach from [33]. Figure 6 compares drift angle and maximum attainable speed between computations and model tests.

5 Application and standards

Above, met-ocean data, statistics of environmental conditions during accidents and detailed accident reports, as well as interviews with ship masters were used to define reference values for standards, i.e., wave heights at which the defined criteria should be satisfied. Here, approach to benchmarking of existing fleet with respect to the new criteria is described, to fine-tune the standards. One difficulty is that existing ships differ in type and size, the other one is that installed power differs significantly between ships of the same type and size. This leads to a significant scatter in the marginal wave heights between ship types and sizes and between ships of the same type and size. Thus, to fine-tune the standards,

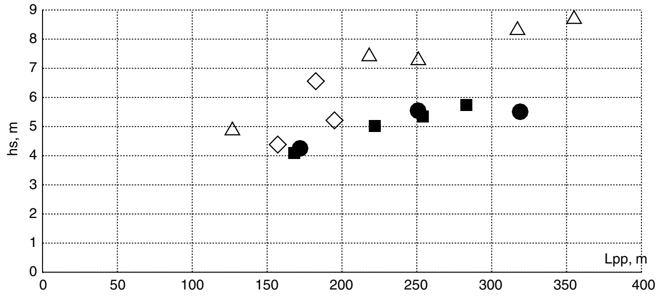


Fig. 8 Marginal significant wave heights for propulsion (left) and steering (right) criteria for bulk carriers (filled squares), tankers (filled circles), container ships (empty triangles) and general cargo vessels (empty diamonds) with installed power along the 5% low-power boundaries of their IHS-FairPlay databases

some reference ships of all relevant sizes of each type in the EEDI framework should be selected. However, the selection of such reference ships is influenced by various stakeholders and is still under discussion at IMO, which delays the finalisation of standards. To provide a rational basis for this discussion, the following way was proposed by SHOPERA [10]: select reference ships along regression lines in axes L_{pp}—installed power, cutting 5, 10, 20% etc. of low-power ships, see an example for bulk carriers in Fig. 7.

A comparison of marginal wave heights for ships of all sizes and all types in EEDI framework [10] (an example in Fig. 8 compares marginal wave heights for bulk carriers, tankers, container ships and general cargo vessels along the 5% low-power boundaries of their IHS-FairPlay databases) shows that marginal wave heights are ship size-dependent: larger vessels can fulfil both propulsion and steering criteria at greater wave heights than smaller vessels. This is understandable physically—the impact of seaway on ship's maneuverability in waves diminishes with increasing ship size; besides, this reflects existing design and operation practices, because the results refer to the existing fleet: obviously, smaller vessels do not operate in storms of the same severity as larger ones. Note that standard wave heights in the 2013 Interim Guidelines [6] are also ship-size dependent; however, the dependency of standards on ship size is a subject of ongoing discussion. Another observation is that marginal wave heights differ, sometimes substantially, between different ship types: bulk carriers and tankers show similar marginal wave heights, which are lower than the marginal wave heights of other vessel types, due to their lower installed power per displacement compared to vessels of other types of the same size as well as advanced propulsion and steering concepts typical for some other vessel types. Reaching a conclusion regarding ship type dependency of standards also requires a discussion with all interested stakeholders; the arguments in favour of ship type-dependent standards are that the differences in the marginal wave heights between different ship types follow from studies for existing vessels, thus they reflect established design and operation practices, and that the consequences of accidents differ, sometimes significantly, between different ship types (e.g., between passenger and cargo vessels). On the other hand, the differences in the manoeuvrability characteristics in adverse conditions also reflect, at least partially, differences in the economic performance profiles of the various ship types, which should not affect the required minimum safety level.

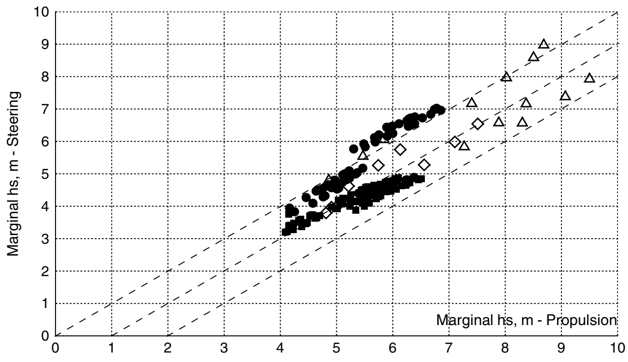


Fig. 9 Marginal significant wave height for propulsion (x axis) and steering (y axis) criteria for bulk carriers (filled squares), tankers (filled circles), container ships (empty triangles) and general cargo vessels (empty diamonds)

The results of case studies [10] show that the most critical ship types regarding manoeuvrability in adverse weather conditions are bulk carriers and tankers; therefore, these ship types are addressed first by the joint SHOPERA-JASNAOE proposal [16]; general cargo vessels seem as a relevant next step. Whereas finalisation of standards for bulk carriers and tankers is still under discussion at IMO, the results shown below for reference ships along lines cutting 5, 10% etc. of low-power ships provide a rational basis for an informed decision.

One observation relates to the obvious correlation between the marginal wave heights for propulsion and steering criteria in coastal areas. Figure 9 illustrates this correlation for bulk carriers, tankers, container ships and general cargo vessels; marginal significant wave height according to the propulsion criterion may exceed the marginal significant wave height according to the steering criterion by about 1.0 m (for smaller bulk carriers) to about 2.0 m (for big container ships). Note, however, that this correlation is not automatic but stems from the fact that the steering systems of the considered ships are properly dimensioned according to other requirements, e.g., [1] or classification rules. Note also note that in practical terms, the difference in the marginal wave heights between the steering and propulsion criteria means that the requirement to be able to perform any manoeuvre in seaway from any direction is more conservative than the requirement to be able to advance with a speed of 6 knots in seaway from any direction. Obviously, the ability to perform any manoeuvre in seaway from any direction may not always be necessary: depending on situation, it may be sufficient to perform a specific manoeuvre in a narrow range of seaway headings. However, design assessment cannot consider all specific situations that may be encountered during operational life of individual ships, therefore, a universal (but because of this, conservative) formulation of the steering ability criterion seems appropriate.

Another note concerns the relationship between the required advance speed in the propulsion criterion and the marginal wave height: increasing the speed reduces the corresponding marginal wave height, Fig. 10, therefore, fine-tuning of standards should be considered together with fine-tuning of the required forward speed.

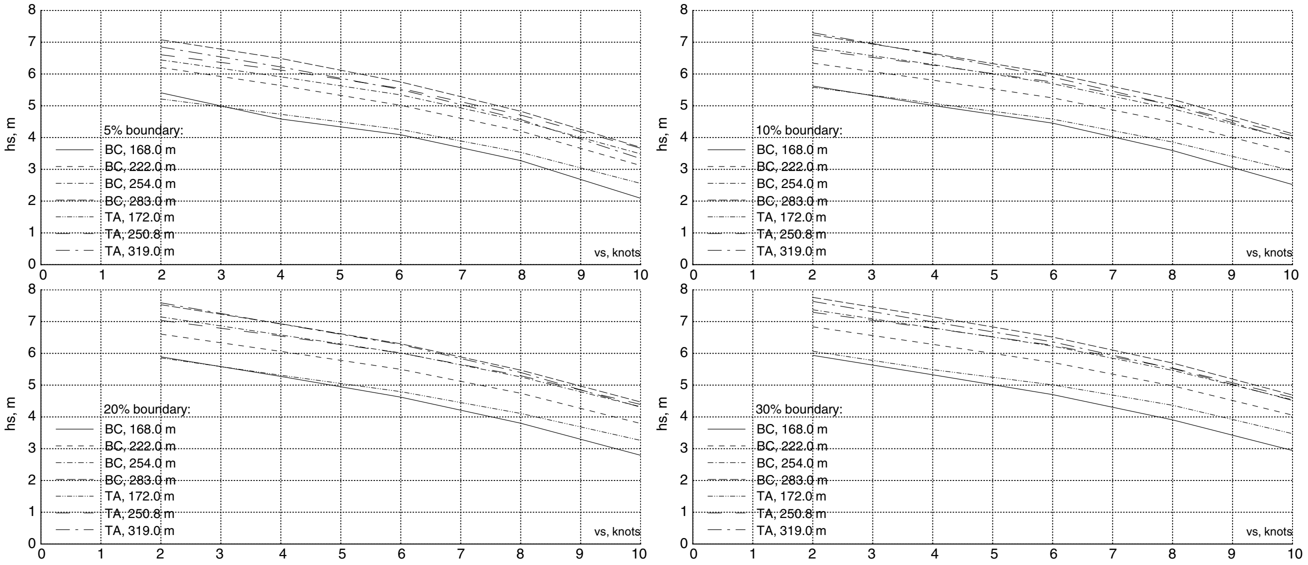


Fig. 10 Marginal significant wave height for propulsion at various forward speeds v_s (x axis) for bulk carriers and tankers along 5, 10, 20 and 30% low-power boundaries of their IHS-FairPlay databases

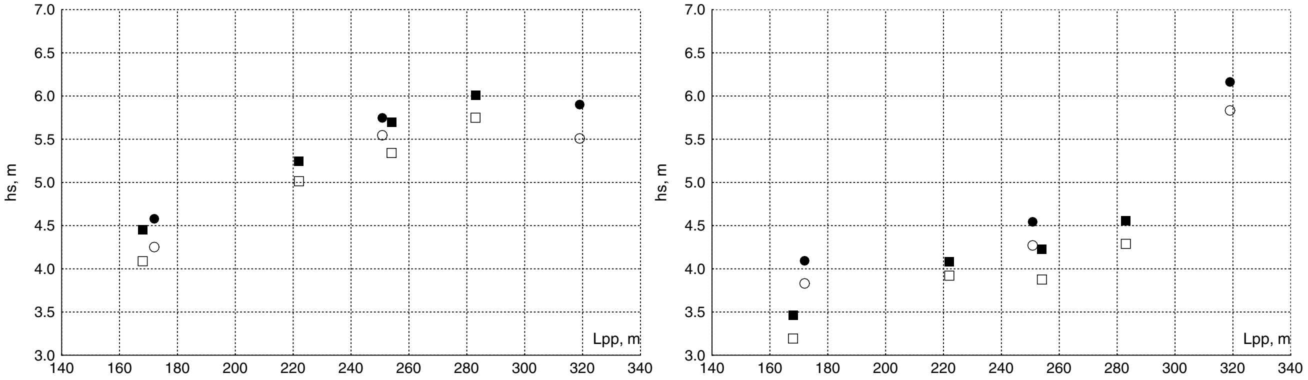


Fig. 11 Marginal significant wave height for propulsion at 6 knots forward speed (left) and steering (right) criteria for bulk carriers (squares) and tankers (circles) along 5% (empty symbols) and 10% (filled symbols) low-power boundaries of their IHS-FairPlay databases

Figure 11 shows marginal significant wave heights for propulsion (at 6 knots forward speed) and steering criteria for bulk carriers and tankers selected along the 5 and 10% low-power boundaries of their IHS-FairPlay databases. Because, according to the statistics of manoeuvrability-related accidents in adverse weather conditions [2], existing ships are in general sufficiently safe in this respect, the selected ships may be assumed representative for defining standards. However, the 5%-boundary may be influenced by wrong reporting in the IHS-FairPlay database; for 10%-low power boundary bulk carriers and tankers, marginal significant wave height is about 4.5 m (for propulsion) and 3.5 m (for steering) at L_{pp} of 170 m to about 6.0 and 4.5 m, respectively, at L_{pp} of 275 m. Underline again that prescribing standard wave heights based on reference ships does not mean fixing the minimum installed power to the installed power of the reference ships: the installed power can be reduced if standards can be satisfied by other technical solutions, e.g., optimised hull lines, increased propeller margin, advanced turbocharging, power take-in etc.

The above results concerned propulsion and steering criteria in coastal waters; regarding the weather-vaning criterion for the open sea, one question to consider is whether manoeuvrability in adverse conditions in the open sea should be normed at all, because loss of manoeuvrability for a limited time in the open sea should not lead to negative outcomes since ship safety in dead ship condition should be controlled by the severe wind

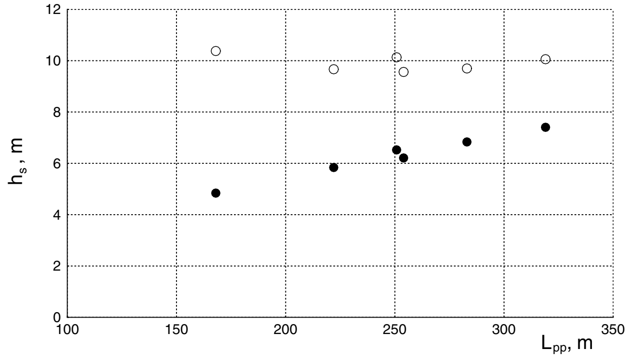


Fig. 12 Marginal significant wave height for bulk carriers and tankers on MPL for 6 knots propulsion in coastal areas (filled circles) and weather-vaning in open sea (empty circles)

and rolling criterion (Weather Criterion) of the IS Code [23]. Irrespectively of this question, two concerns raised by ship operators regarding ship's manoeuvrability in the open sea require explanation. First, what weather-vaning abilities should be expected in possibly encountered high to extreme sea states for ships marginally fulfilling the coastal waters criteria, compared to their seakeeping, loads and other characteristics relevant in the open sea—in other words, whether manoeuvrability in the open sea may become a limiting factor in operation, compared to other characteristics, even if it is not safety relevant. Second, the following contradiction needs to be explained: according to observations reported by ship masters, they have no difficulties when sailing in significantly higher waves than the marginal wave heights with respect to the propulsion and steering criteria reported above. This is also observed in the wide scatter of the environmental conditions relevant for steering and propulsion problems in [21], following from interviews of ship masters.

To address these concerns, the ability to weather-vane in the open sea was evaluated for the bulk carriers and tankers selected along the 5% and 10% low-power boundaries. In the practical assessment, weather-vaning criterion was treated in a simplified way as the ability of the ship to keep position in bow to bow-quartering seaway; this simplification follows from the observation that a ship (with the traditional steering devices) is not able to keep heading under the action of environmental forces if its forward speed is not sufficiently large, because of reduced manoeuvring reactions on the hull and steering force on the rudder. As a first insight, Fig. 12 compares marginal significant wave heights for 6 knots propulsion ability criterion in coastal waters with marginal significant wave heights for weather-vaning at the most likely wave periods in the North Atlantic wave climate [29] for a series of bulk carriers and tankers with the length between perpendiculars between 160 and 320 m, selected on the minimum power line (MPL) [6–8]. The results show that marginal significant wave heights for weather-vaning at the most likely peak wave periods in the open sea are significantly larger than those for 6 knots propulsion in coastal areas, especially for small ships: the difference is more than 5 m for the smallest ship to 3 m for the largest ship.

Because of a wide variety of possible wave periods in the open sea, a more rational way to address the above questions is to use a probabilistic assessment. Here, the percentage of time (from the total time at sea) was calculated when ships can fulfil the weather-vaning criterion in the North-Atlantic wave climate [29] (neglecting routing and heavy-weather avoidance, i.e., the results are very conservative). Table 2 shows results for bulk carriers and tankers with L_{pp}

Table 2 Percentage of time that bulk carriers and tankers along 5% and 10% low-power boundaries and MPL can weather-vane in North Atlantic

Type	BC	BC	BC	BC	TA	TA	TA
L_{pp}, m	168.0	222.0	254.0	283.0	172.0	250.8	319.0
5% low-power	99.4	98.6	99.0	99.2	99.4	98.9	98.9
10% low-power	99.4	99.5	99.5	99.6	99.6	99.5	99.3
MPL	99.8	99.5	99.5	99.6	99.9	99.6	99.9

Table 3 Percentage of time when bulk carriers and tankers on MPL can fulfil 6 knots propulsion criterion in various coastal areas of North Sea (NS6 to NS20) and in North Atlantic (NA) wave climate

Type	BC	BC	BC	BC	TA	TA	TA
L_{pp}, m	168.0	222.0	254.0	283.0	172.0	250.8	319.0
NS6	93	96	96	98	97	98	99
NS11	94	97	97	99	97	99	99
NS13	94	98	98	99	97	99	99
NS14	96	98	98	99	98	99	100
NS17	96	98	98	99	98	99	100
NS20	99	100	100	100	99	100	100
NA	98	99	99	99	99	99	99

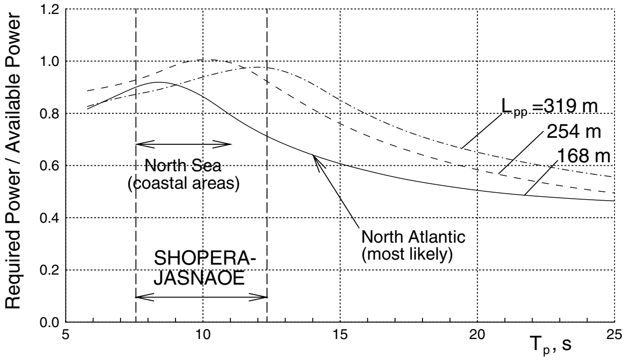


Fig. 13 Ratio of required to available power for weather-vaning at constant significant wave height vs. peak wave period

from 172 to 319 m selected along the 5 and 10% low-power boundaries of their IHS-FairPlay databases (their marginal significant wave heights with respect to the propulsion and steering criteria in coastal waters are shown in Fig. 11) and along their MPL. These results indicate that ships satisfying the coastal-water criteria up to rather moderate wave heights, Fig. 11, can weather-vane in the open sea in North Atlantic (including unrealistically high sea states since routing and heavy-weather avoidance are not considered) about 99% and more time, which means that manoeuvrability is a smaller problem in the open sea for such ships compared to other issues (motions, loads etc.); this means that open-sea manoeuvring criteria do not need to be considered, and also explains observations of ship masters that ships can manoeuvre at severer sea states than Fig. 11 suggests.

Because this comparison is partially influenced by the difference between the criteria used, to exclude this influence and thus compare the influence of the environmental conditions alone, the 6 knots propulsion criterion was applied in a probabilistic sense to coastal waters of the North Sea [27] and to the open sea described by the North Atlantics wave climate [29] to the bulk carriers and tankers from Table 2 selected along MPL; Table 3 shows that almost all coastal areas in the North Sea are significantly more challenging than the open sea with respect to the propulsion criterion.

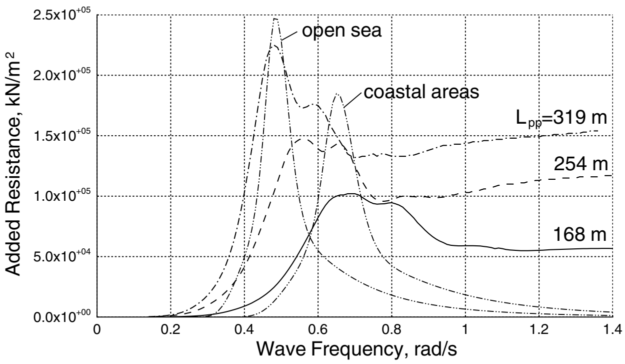


Fig. 14 Transfer functions of added resistance (solid, dashed and dash-dot lines) and typical wave energy spectra in open sea and coastal areas (dash-dot-dot lines, vertical scale has no meaning for wave energy spectra)

The reason is the difference in wave periods, which are in coastal waters typically shorter than in the open sea, Fig. 2. Figure 13, comparing the ratio of the required to available power for weather-vaning vs. peak wave period at the same significant wave height for ships of three sizes, shows that in short waves, the required power is significantly larger than in longer waves. The peak wave periods proposed in [10, 16] correspond to the most critical wave periods with respect to the required power. From the point of view of added resistance, typical wave periods in coastal areas are close to the peak of added resistance, especially for smaller ships, whereas in the open sea, typical wave periods are outside of the resistance peak range and are, therefore, less critical, Fig. 14.

Validation of numerical methods for the definition of force components was an important task in SHOPERA and JASNAOE projects; it is interesting, however, to verify these methods together with the verification of more general assumptions concerning scenarios, criteria, environmental conditions and standards by comparison with real operation. Accidents due to insufficient manoeuvrability in adverse conditions represent useful test cases, even though the full information about the ship condition, course of accident and environmental conditions is never available. A study of a grounding accident of a capesize bulk carrier Ocean Victory off Kashima port in Japan in [34] shows a good agreement between the computed marginal wave height and the real wave climate. Here, grounding of a panamax bulk carrier Pasha Bulker [24] off Newcastle, Australia is considered. The 225 m-long bulk carrier with a deadweight of 76,781 t and installed power 9230 kW was anchored and waiting for loading in ballast together with 56 other ships when weather conditions started worsening. Ships started to depart the anchorage (many of them after noticing anchor dragging), whereas Pasha Bulker remained at anchor until

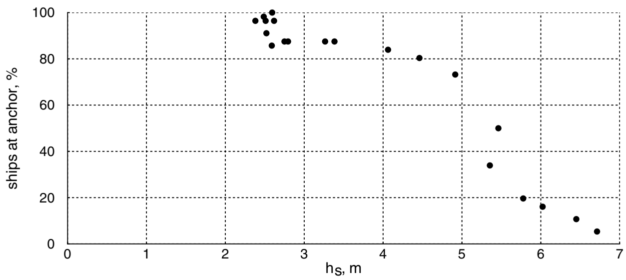


Fig. 15 Number of vessels at anchor as percentage of the initial number of anchored vessels vs. significant wave height during an increasing storm according to data in [24]

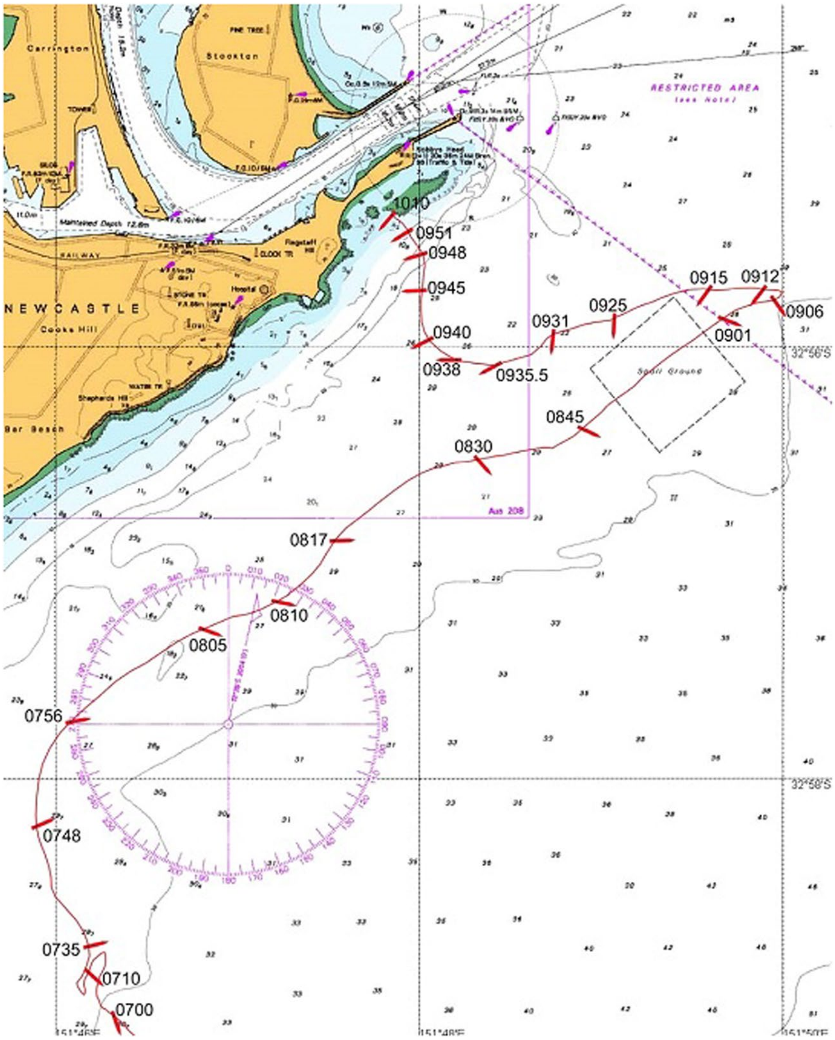


Fig. 16 Track and positions of Pasha Bulker on 2007-06-08 from [24]

the significant wave height achieved 6 m and was the last ship to depart, Fig. 15. Despite its heading offshore, the ship has moved nearly parallel to the coast for more than an hour in wind and waves from starboard bow, not able to leave to the open sea, Fig. 16 from [24]; during this drifting, the significant wave height has grown up to 6.6 m. After that, the captain has undertaken several turning manoeuvres

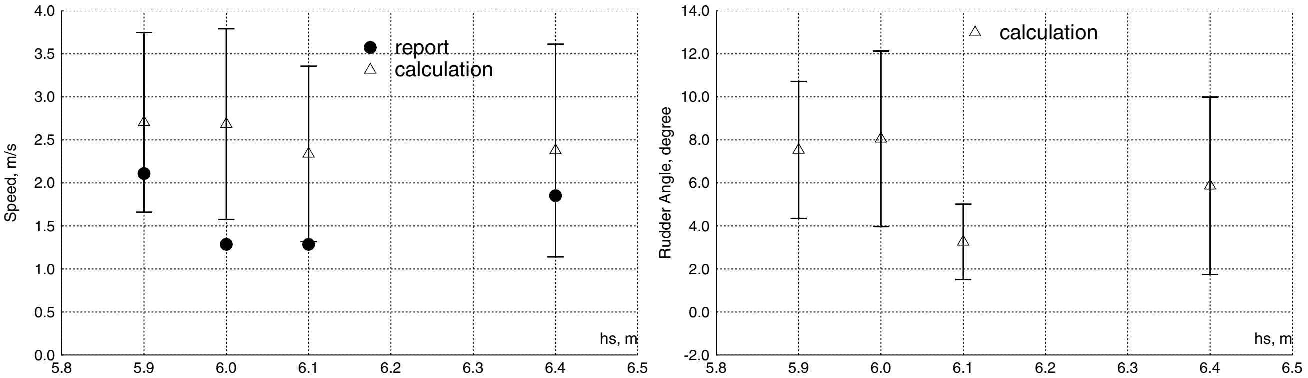


Fig. 17 Computed attainable speed (left) and rudder angle (right) compared to data from report [24]

which reduced the distance to the shore and eventually led to grounding.

The course of accident confirms the feasibility of the scenario of leaving coastal area in a growing storm and, in this case, relevance of the propulsion criterion. The wave height during the accident, however, appears to be greater than it should be appropriate: departing anchorage as the last of 56 ships suggests worse than normal operation (it should be noted that using anchor in heavy weather until it starts dragging is a typical error and a frequent cause of accidents, even though anchor is not supposed to be used in heavy weather).

Figure 17 shows computed maximum attainable speed (left), compared with data from [24], and rudder angle (right) for time instants, for which the speed and course could be reconstructed from [24]. The vertical bars correspond to the variation of the peak wave period (not reported in [24]) from $3.6h_s^{0.5}$ to $5.0h_s^{0.5}$. The estimated attainable speed agrees with the report data; the slight over-estimation may be due to several reasons: difference in wave height between the measurement station and instantaneous ship positions, aging of the hull, engine and propeller (not considered in the calculations), propeller pitching in ballast and, perhaps, not always full available power applied during the accident. This comparison verifies the numerical methods used as well as the relevance of the propulsion criterion and of the assumed scenario; on the other hand, a recommendation for the standard significant wave height following from this case should be below than the 6 m wave height during the accident due to the reasons discussed above (note that the marginal significant wave height with respect to the propulsion criterion for reference ships of this size, selected along the 10%-low power line, is about 5.3 m).

6 Conclusions

Manoeuvrability of ships is presently normed according to the rules of classification societies, ship owner's requirements and non-mandatory, but gaining increasing acceptance by administrations and classification societies, IMO Standards for ship manoeuvrability [1], which, however, do not address manoeuvrability at low speed, in restricted waters and in adverse weather conditions. The importance of the latter issue increased after the introduction of EEDI regulations, which raised concerns that propulsion and steering abilities of ships may become insufficient for manoeuvrability in adverse conditions if EEDI requirements are achieved by simple reduction of the installed engine power.

The following elements are required to regulate ship manoeuvrability in adverse conditions: criteria (characteristics by which ship's abilities, relevant for the considered problem, are judged), measures (values quantifying the performance of ship with respect to the considered criterion—here, marginal, i.e., maximum, weather severity at which the ship can fulfil the criterion) and standards (acceptance limits of the measures for the ship to be considered as fulfilling the defined criteria).

Review of existing regulations, interviews of ship masters, analysis of accident statistics and accident investigations led to the following criteria: weather-vaning in the open sea, understood as the ship's ability to change and keep heading in head to bow-quartering seaway; steering ability in coastal areas, understood, in a general sense, as the ship's ability to perform any manoeuvre in seaway from any direction; propulsion ability in coastal areas, i.e., ship's ability to maintain a specified speed in seaway from any direction to escape a dangerous area; and manoeuvring at limited speed in strong wind in restricted areas, which concerns situations where the ship master must reduce the applied engine power (the latter scenario does not impose any restrictions on the installed power and thus was not considered here).

Whereas criteria require a rational approach, based on the physics of the problem, standards must be empirical to some degree, because they reflect the existing safety level and operational practices and, moreover, they should compensate for inevitable simplifications in the practical criteria. Therefore, whereas existing regulations, met-ocean data, statistics of environmental conditions during accidents, accident reports and interviews with ship masters were used to estimate appropriate standards, their ultimate fine-tuning was based on benchmarking of existing ships with respect to the new criteria: because existing ships are in general safe with respect to manoeuvrability in adverse weather, majority of them should be able to satisfy the proposed standards. The difficulty is that existing ships differ in type and size, installed power and type of propulsion and steering system, which leads to a significant scatter in the marginal wave heights. Therefore, reference ships of all representative sizes were selected for each ship type in the EEDI framework. Still, this leaves the problem that the installed power differs significantly between ships of the same type and size. To provide a rational basis for fine-tuning of standards, the following way was proposed: select reference ships along regression lines in axes ship size – installed power, cutting 5, 10, 20% etc. of low-power ships of each type and size.

A similar approach, used in the 2013 Interim Guidelines, led to the significant wave height 4.0 m and wind speed 15.7 m/s at L_{pp}=200 m and less to 5.5 m and 19.0 m/s, respectively, at L_{pp}=250 m and greater (for shorter, i.e., more conservative, wave periods than those proposed by SHOPERA and JASNAOE projects). The requirements of classification societies to redundancy of propulsion system employ rather moderate standards: maximum wind speed 21 m/s and significant wave height 5.4 m for weather-vaning and maximum wind force Bft 8 for 6.0 knots advance speed requirement. Interviews of ship masters indicate that 50% of ship masters leave coastal areas before wind speed reaches Bft 8 and the significant wave height achieves 5 m. Statistics of accident rates, locations and corresponding weather conditions during accidents due to insufficient manoeuvrability in adverse conditions collected in SHOPERA shows mean wind speed of about 10 m/s and mean significant wave height about 1.5 m during accidents; this agrees with the well-known findings of the HARDER project that more than 80% of collisions happened at significant wave heights below 2 m, and significant wave heights in excess of 4 m were practically never recorded during collisions.

The results of benchmarking of existing fleet show that marginal wave heights differ, sometimes substantially, between different ship types: bulk carriers and tankers show very similar marginal wave heights, which are lower than the marginal wave heights of other vessel types, therefore, these ship types were addressed first by the joint SHOPERA-JASNAOE proposal [16]. Whereas finalisation of standards for these ship types is still under discussion at IMO, a rational basis for informed decision can be provided by the proposed methodology: for example, bulk carriers and tankers along the 10%-low power boundary of their IHS-FairPlay databases demonstrate marginal significant wave height of about 4.5 m at L_{pp} = 170 m to 6.0 m at L_{pp} = 275 m.

The results show correlation between marginal wave heights for propulsion and steering criteria in coastal areas: fulfillment of the propulsion criterion at a certain significant wave height guarantees fulfillment of the steering criterion at a significant wave height of about 1.0 m (for small ships) to 2.0 m (for big ships) smaller. Therefore, the proposal prepared by SHOPERA and JASNAOE applies only the propulsion criterion (also because the steering criterion is more difficult to evaluate in practice).

Regarding weather-vaning in the open sea, note that loss of manoeuvrability for a limited time in the open sea should not lead to negative outcomes, because ship safety in dead ship condition should be controlled by the severe wind and rolling criterion. Nevertheless, a comparison study was carried out, showing that bulk carriers and tankers selected along the 5 and 10% low-power boundaries and along MPL can weather-vane more than 99% of time and move at 6 knots against seaway more than 98% of time in the North-Atlantic winter wave climate including unrealistically high sea states (because routing and heavy-weather avoidance were not considered). Thus, for ships satisfying the coastal-water criteria at the wave heights reported above, manoeuvrability is a smaller problem in the open sea compared to other issues (motions, loads etc.), i.e., open-sea manoeuvring criteria are not necessary. The reason is the rather short (and thus steep) waves, characteristic for coastal waters, applied in the propulsion and steering criteria.

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