Review

Review on Ship Manoeuvrability Criteria and Standards

Serge Sutulo * and C. Guedes Soares [ID]

Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Av. Rovisco Pais 1, 1049-001 Lisbon, Portugal; c.guedes.soares@centec.tecnico.ulisboa.pt
* Correspondence: sutulo@centec.tecnico.ulisboa.pt

Abstract: Possible reduction of the installed power on newly designed merchant ships triggered by requirements of the Energy Efficiency Design Indices (EEDI) raised concern in possible safety degradation and revived interest in manoeuvrability standards to make them capable to compensate for negative effects of underpowering. A substantial part of the present article presents a detailed analytical review of general principles laid in the foundation of consistent safety standards in the naval architecture and analysis of the existing IMO manoeuvrability criteria and standards. Possible ways of extension of the existing standards to embrace situations associated with adverse sea and wind conditions are discussed and modification of the present standards related to the directional stability is considered as one of the possible solutions. At the same time, it was found that introduction of additional standards for the ship controllability in wind is justified, and the second part of the contribution is dedicated to developing a theoretical basis useful for devising such standards. This includes obtaining a set of analytical solutions related to the steady motion in wind and analysis of wind-tunnel data which resulted in simple equations for conservative generalized envelopes for the aerodynamic forces which are especially convenient for standardizing purposes. Possible design decisions aimed at augmentation of the ship's capacity to resist adverse environmental factors are outlined.

1. Introduction

There are no doubts that since ancient times the seafarers were able to discriminate between "good" and "not so good" vessels albeit this was only possible on a purely qualitative and intuitive level. Such discrimination was necessary and sufficient for a slow but steady evolution of various types of ships. As result, it became possible for ships to reach a certain undisputable level of perfection without any scientific support: medieval sailing ships were capable to perform very long voyages in rough sea waves including round-the-world trips. Of course, development based exclusively on traditions and some empiric rules was extremely slow.

Acceleration of development was not possible without certain scientific contributions unthinkable without quantification of the ship performance and seaworthiness. It can be noticed that the tangible raise of the "quantitative" phase of development of the naval architecture approximately coincided with the transition from sailing ships to mechanically powered ones. Likely, this was not only a coincidence associated with concurrent development of the naval architecture and ship theory but was also facilitated by the fact that any mechanically driven ship is, in many respects, a much simpler technical system than a sailing vessel. In particular, while the speed of a powered ship can be measured rather reliably at some specified standard testing conditions (deep water, calm sea, specified engine rpm) this is practically impossible for a tall ship whose speed depends substantially on the available wind. Further, as the aerodynamic configuration of a sailing ship is extremely variable, it is difficult to quantify its seaworthiness. Finally, it is practically impossible to

establish any reasonable measures of manoeuvring qualities of such ships as, for instance, a sail-driven ship is not able to perform steady turning circles and it is very difficult to reasonably define parameters of any turn executed through rather complex coordination between the rudder deflection and handling of the sails.

However, nowadays the sailing ships occupy a relatively narrow niche of recreational and training vessels and can be treated in some special way. As to the powered ships, all quantitative measures of their performance can be divided into two groups:

1. Contractual parameters whose values are established, first, as the customer's requirements and, further, as a compromise and agreement between the customer and the builder specified in the contract.
2. The parameters whose acceptable values are typically specified by various rules and regulations. Most of such regulated parameters are related to maritime safety.

All these parameters may be related to the ship hydrodynamics or the strength and reliability of a ship hull and other elements or other operational qualities. Only hydrodynamics-related parameters will be considered further. The most common parameter of the first group is the contractual or design speed of the ship. The inability of a newly built ship to reach the specified speed value in the trials is typically treated as incomplete fulfilment of the contract and, unless the problem is fixed, is penalized. Most parameters of the second group are related to seaworthiness and unsinkability although in the several last decades manoeuvring performance of ships also became subject to substantial efforts aimed at the development and implementation of manoeuvrability criteria and standards.

The present article contains an analysis of existing requirements to the manoeuvring performance of civil displacement ships with emphasis given to the well-known manoeuvrability standards of the International Maritime Organization (IMO) [1]. All studies related to the introduction of any standards are characterized by many poorly formalizable issues and they strongly depend on subjective opinions of numerous experts. Final solutions are typically reached after long discussions in form of a more or less acceptable compromise, a retrospective analysis of existing approved standards and criteria and various alternative proposals is rather important.

The authors deliberately abstain from formulating any completed specific proposals complementing or modifying the existing recognized system of manoeuvring criteria but rather focus on discussion of possible approaches and methodology. This discussion constitutes the main content of the present article.

Section 2 of the article is dedicated to the formulation of general requirements to any system of criteria and standards related to maritime safety with a brief review of the existing intact-stability criteria. In addition, relatively recent minimum powering criteria are briefly commented. Section 3 contains a brief review of some existing calm-water manoeuvring criteria and of some earlier published alternative proposals. The influence of accounting for adverse factors and external disturbances on the composition and acceptable values of manoeuvrability criteria is discussed in Section 4, where also some possible novel approaches are outlined.

While the first four sections are mainly of descriptive character, Section 5 is of a more specific nature presenting some analytical developments that can be useful for devising simplified manoeuvring standards accounting for the ship aerodynamic characteristics and wind action. Finally, Section 6 contains a concluding discussion.

2. General Principles of the Criteria and Standards in Naval Architecture

Most theoretical developments and methods in naval architecture are associated with problems of analysis or design. However, it is reasonable also to talk about the standardizing problem characterised by some specifics which justify placing this problem into a separate class.

Most standards in ship design are associated with various aspects of the ship safety depending on the global and local strength, seaworthiness and manoeuvrability where the latter area was embraced by standardizing activities relatively recently and possesses

a shorter historical record. At the same time, studies on the intact stability standards have been actively carried out since the 1930s and they provide rather rich material for comparative analysis of various approaches [2–4]. As a result of such analysis, it was possible to formulate the following reasonable requirements to any consistent set of safety standards independently of the application area.

A. **Simplicity:** Criteria must be as simple as possible and preferably described by relatively simple analytical formulae.
B. **Testability:** Criteria must be verifiable both in operation and in the design stage.
C. **Clearness:** Criteria must be crisp, prescriptive and preferably of "pass" vs "non-pass" binary type.
D. **Physical consistency:** Criteria must be based on transparent and consistent physical (mechanical) principles. This makes undesirable recourse to criteria based exclusively on failure statistics although verification on statistical data is indispensable.
E. **Realism:** No matter how solidly based is any new proposed standard, it should not be implemented if the fraction of the existing fleet for which it fails, exceeds a certain value: typically 5 or 10 per cent. Similarly, no one standard is acceptable if it leads to evidently excessive requirements.

Apparently, the most straightforward and intuitively transparent criterion of a ship's seaworthiness could be the expected duration of the ship's survival in certain severe weather conditions characterized by parameters of the sea and wind spectra but in practice, some better defined simplified scenarios are needed.

The so-called Second Generation Intact Stability Criteria [2,5–7] envisage 5 different basic failure scenarios including parametric roll and broaching to. However, the existing IMO Code [2] still in effect is based, besides direct requirements to the righting-arm curve, almost exclusively on the so-called weather criterion, i.e., on the estimation of dynamic stability of a dead ship under the action of resonant roll and an unfavourable wind gust. Despite its simplicity, this criterion is quite reasonable and reliable as in fact it resulted from several decades of evolution based on intensive research studies carried out in many countries. The criterion still survives despite considerable efforts aimed at accounting for, say, parametric rolling, broaching or just involving more sophisticated and accurate mathematical models [5,6]. It is also remarkable that while the direct statistical approach introduced by Rahola is considered outdated and no longer acceptable, statistical analysis keeps playing an important role [2,8].

Of course, all safety-aimed criteria and standards have a clear trend to involve more and more sophisticated mathematical models, scenarios and schemes which sometimes seems to be more driven by the interests of developers than by clear practical demands. In particular, it is envisaged that in the mentioned "Second-generation intact-stability criteria", see, e.g., [9], 3 levels or tiers of criteria are to be introduced with the level 1 corresponding to the most simple and conservative criteria while higher-level criteria presume involvement of rather sophisticated schemes and methods. It is supposed that a higher-level criterion is only invoked if the corresponding lower-level criterion is not satisfied. Whether such multi-level system of standards will be definitely beneficial for the overall safety of shipping is not so evident and some specialists reserved a somewhat sceptical attitude [10]. The authors of the present contribution tend to believe that any practical system of criteria and standards should be kept as simple and transparent as possible and, regarding the classification mentioned above, all ideas presented in this paper should be viewed as corresponding to the lowest level.

In addition to the aforementioned standardizing areas, relatively recently a completely new problem emerged—that of minimum installed power requirements [11]. It was triggered by the so-called Energy Efficiency Design Index (EEDI) requirements, see [12] for more details. These requirements encouraged reduction of the installed main engine power as the most effective mean of decreasing the fuel consumption and, concurrently, emissions of all kinds. As such a trend obviously leads to reduction of the capability of ships to withstand adverse conditions thus impairing navigational safety, it gave birth to

rather natural concerns. As result, considerable efforts have already been dedicated to working out certain minimum-power standards limiting the EEDI-driven reduction of the installed power [13].

The minimum-power requirements are connected with the seakeeping and manoeuvring qualities of ships. However, in this article, the authors avoid detailed discussion of the minimum-power problem limiting themselves to the short comments that follow.

Since the appearance of powered ships the required power of the main engine(s) has always been estimated as a compromise between a natural desire to reach the highest possible operation speed and safety and a desire to build a more economical vessel. It is obvious that the latter encourages the designer to reduce the ship's speed and the engine's rating. In some special cases (tugs, fishing vessels, icebreakers) the engine power is governed not by the design speed but by the required bollard pull. While the bollard pull-based power can be determined relatively straightforwardly, a more common task of setting the design speed is more complex and fuzzy. The value of this speed depends on the type of the ship, its size, actual and envisaged fuel prices, traditions and expectations of ship owners and seafarers.

A kind of natural selection during many decades resulted in several typical values of the design speed for various types and classes of ships although those typical values were subject to relatively small variations and corrections especially when new types of ships, engines and propulsors were introduced. However, so far they have never been conditioned by some legal requirements. Thus, in some sense, the introduction of EEDIs is breaking the existing dynamic equilibrium exerting substantial legal pressure that encourages the ship designers to decrease the power of main engines. It was soon understood that in some cases the newly built ships could become underpowered and excessively prone to exogenous factors. As result, the problem of standardizing also some minimum safe power of ships was formulated with the purpose of legal counterbalancing the unfavourable impact of EEDI requirements.

In addition to vulnerability to environmental factors, the underpowering may have one more negative effect related to the stopping distance in crash stop. While the stopping distance or the track reach from the speed at maximum continuous rating in calm water, as specified by the current IMO standards, may remain unchanged as long as poorer reversing capabilities come in certain harmony with the reduced speed, this is not so certain for partial speed and/or in presence of unfavourable wind, sea and current. This issue, closely related to the powering requirements is also dropped here.

As the danger of underpowering was realised, lately a concept of the reserved power to only be used in extreme conditions was discussed [13]. It may happen that this situation will finally lead to the appearance of more adaptable and flexible power plants.

Returning to the general standardization problem, it can be observed that there are three main different standardizing schemes:

1. **Explicit criteria scheme.** It is presumed that the limiting values of certain criteria are explicitly specified and the compliance to them is to be verified by some certified or generally recognized procedures which may include full-scale trials, model-scale tests and Computational Fluid Dynamics (CFD) modelling. For instance, regarding some manoeuvring criterion such as, e.g., the minimum turning radius, its value can be specified explicitly and their fulfilment is then verified by estimating the corresponding measures for the actual ship or design. This approach was realized in IMO standards [1,14] and STANAG standards [15]. The advantage of this scheme is that the standards in form of natural and meaningful manoeuvring qualities are verified directly and the estimation methods can be gradually improved in course of natural scientific progress without affecting the standards themselves. The evident disadvantage is the necessity to select and use some methods not incorporated into the text of the standards: this complicates application of the standards and may introduce additional uncertainty.

2. **Implicit scheme.** Alternatively, the standards can be formulated in form of a set of direct requirements to the rudder effectiveness. The latter must be defined within the standards in some unambiguous way allowing immediate verification at least for the most typical steering devices. This approach was followed in the implicit manoeuvring standards implemented within the Rules of the Russian Maritime Register of Shipping [8], see also [12,16]. In contrast with the IMO standards which were developed and adopted 14 years later, the Russian standards do account for aerodynamic loads albeit in a somewhat hidden way. However, although implementation of these standards was by all means somewhat useful, their straightforward reproduction in the part concerning controllability in wind cannot be recommended: the exploited mathematical models and prediction methods were too simplistic by all reasonable standards and even suffered from some inconsistencies. Even though these inconsistencies were traced by some experts, they practically could not be fixed as all the models and methods are embedded in the standards and their correction, modification and improvement is unthinkable without revision of the corresponding part of the Rules which is impossible without complicated bureaucratic procedures. This is one of the main reasons why the mentioned "hidden" manoeuvring standards remained unchanged since their embedment into the text of the Rules in 1982. Even though these Rules will keep these standards for an indefinite time, it is obvious that any new developments should follow a more "explicit" approach and it makes sense to realize them as some modifications and extensions of the existing IMO standards.

The task of specifying limiting values for criteria involved in any system of standards is also important and non-trivial. The following approaches can be followed:

1. **Statistical approach.** This approach is based on the assumption that for the existing successful ships values of the considered criteria are acceptable while those for ships that went through some kind of failure are not. In its direct form, this method had been applied by Rahola [2,3] for devising first-generation intact stability standards but rather soon this method was abandoned in favour of "mechanical" schemes. At the same time, statistical checks and corrective actions are considered mandatory for any set of standards. For instance, regarding any manoeuvrability standards, Norrbin [17] proposed the acceptability level as being worse by half of the standard deviation than the observed average value of this or that criterion over a representative set of vessels. Koyama and Kose [18] also have explicitly indicated that manoeuvring qualities of any ship must not deviate too much from average or typical which is especially important for marine pilots normally possessing very limited time to become acquainted with specifics of every piloted ship.

2. **Scenario approach.** This method is based on the faith that it is possible to formulate one or more operation scenarios that can be considered critical beyond any reasonable doubt and on the assumption that for every such scenario it is possible to develop sufficiently reliable prediction methods. Typically, simpler and more conservative methods are preferred to keep with the simplicity principle but also a hierarchy of methods with various degrees of accuracy and complexity may be envisaged by the already mentioned multi-level approach. A good example of the scenario approach for the turning ability standard was given by Mastushkin [19] who considered a scenario of avoiding the collision with a suddenly detected obstacle in form of an infinite wall crossing the ship's path. Starting from some assumed radar detection distance it was assumed that the evasion manoeuvre would be a sharp turn at full helm (this was found to be more efficient than a crash stop). The upper boundary for the advance in turning manoeuvre was defined setting in this way a standard for the turning ability. This and other considered scenarios were inevitably rather artificial and schematized. In addition, broad application of simplified mathematical models and empiric methods further increased uncertainties and final adjustment was performed "statistically" using data for the then existing fleet. The same procedure was applied to all scenarios considered. As result, the following general conclusion

can be drawn: although any of the meaningful scenarios provides reasonable and useful indicators, no one of those scenarios is guaranteed to be "played" successfully in real world even if the ship meets the finally adjusted standards.

3. **Ergatic approach.** This approach is very common in aeronautics [20] where standardization focuses on ergatic issues, i.e., on the man–machine interaction presuming a definition of acceptable values of parameters of mathematical models of aircraft. Nowadays, this has become a rather routine practice and is performed with the help of interactive flight simulators operated by representative groups of pilots. Probably, for the first time, the idea of applying a similar approach to ship manoeuvring was expressed by Segel [21] and much later, though independently and in a more elaborated form, by Sutulo [22]. In fact, elements of this approach combined with the scenario of steering a ship in a complex bent canal were also used by Nobukawa et al. [23] to establish an acceptable level of directional stability and finally these results contributed to the IMO standards. However, in general, the significance of methods based on interactive simulations in ship manoeuvrability is much inferior to that in the flight dynamics because of substantial differences in dynamic properties, in particular in the values of time lags, between the surface displacement ships and aircraft. In addition, this approach is hardly suitable for standardizing any properties of the craft related to exogenous perturbations.

3. On Calm-Water Manoeuvrability Criteria and Corresponding Standards

3.1. General Specifics of Manoeuvring Standards

It should be noted that the parameters defining the manoeuvring performance of ships for a long time belonged to the first "contractual" group that is at best they were specified in the contract but it was clear that this situation could not last forever. As long as the manoeuvring qualities were related to the navigational safety, in the middle of the 20th century first attempts to establish manoeuvring criteria and to set corresponding standards were undertaken.

Even though ship seakeeping and ship manoeuvrability in some sense can be viewed as two faces of ship dynamics, the differences between possible standardizing strategies in both fields are, however, substantial:

1. It is possible to speak about manoeuvring qualities of a ship in still water, i.e., without any excitation at all while any seakeeping criterion is associated with a certain level of external excitation caused by wind and waves.

2. The tighter is any intact stability standard, the higher will be the safety level, which is always welcome unless the implementation costs are too high. The situation is more delicate with the manoeuvring performance as, for instance, an extremely good turning or stopping ability can increase the probability of collision as the behaviour of some surrounding vessels may become too unusual and unpredictable. This does not present any problems in deep-sea conditions and in absence of other craft but is highly undesirable in dense traffic conditions. In particular, that means that a rating-based system of standards encouraging the highest possible performance such as those suggested in [24,25] could produce unpredictable effects regarding the overall navigational safety.

3. The human factor is much more important when dealing with manoeuvring performance. It is even possible to say that, unless the manoeuvring qualities are extremely poor, competent operators after suitable training are capable to compensate for imperfections in manoeuvring properties and successfully and safely handle practically any ship although this adaptability is achieved at a price: difficulties and strain in controlling the ship may be very different and not always acceptable. In general, the human factor is very difficult to be accounted for but the ergatic approach mentioned in the previous section probably can be useful in handling this issue. Of course, in the seakeeping the human factor is also present in the sense that a high seasickness level may affect selection of the speed and of the heading but the difference is obvious.

4. While ship mathematical models serving as a basis for standardizing the intact stability may only consider one degree of freedom, i.e., accounting for the roll motion only, this cannot be allowed for the manoeuvring motion where a mathematical model must have at least two degrees of freedom, i.e., the coupled sway and yaw and often also the surge motion must be included. To prevent possible misunderstandings, it should be emphasized that the often-used Nomoto equations, contrary to their appearance, implicitly embrace two degrees of freedom.

Here the verifiability requirement may be very difficult to meet as long as it presumes the possibility to check any manoeuvring criterion in full-scale trials. This is not so easy even with calm-water criteria: high-quality measurements require practical absence of wind which is a rather rare situation and typically full-scale data suffer from considerable uncertainties. The difficulties are becoming even more serious for criteria related to the waves and wind as it is necessary to fix a certain level of external perturbations. This problem was discussed by Dand [26] who expressed the opinion that the requirement of the possibility of a full-scale verification of any particular standard could be lifted. He suggested that "a combination of a simulation model and suitable indices derived from past best practice, be used as a way of assessing manoeuvrability of vessels".

While the number of publications on the intact stability and unsinkability criteria is definitely superior to that on manoeuvring standards, the latter is also quite significant. Rather complete reviews on proposed manoeuvring criteria and standards can be found in [12,22] and the following text is mainly focusing on the sources related to the development and validation of the existing IMO standards [1].

There exists a more or less clear understanding of which calm-water manoeuvring qualities should be standardized although, e.g., Quadvlieg [27] tried to extend the list of standard criteria, aiming at the assessment of manoeuvring prediction methods. In the following, only classic, commonly recognized criteria will be discussed.

It is recognized that regarding manoeuvring qualities of surface displacement ships in calm water the following properties are of primary interest:

1. Turning ability
2. Directional stability

A ship is assessed as perfectly controllable if it can be characterized by a high level of these two properties at the same time although often one of them may be partly sacrificed. For all purposes, it is important to establish reasonable measures for these qualities.

3.2. Turning Ability

This quality can be subdivided into the turning ability per se which is also called sometimes the ultimate turning ability and the so-called initial turning ability (ITA).

The (ultimate) turning ability of a ship is its capability to describe a highly curved trajectory in absence of external factors. When the moderate manoeuvring (excluding crabbing and rotation with the help of side therusters) is considered, a very natural measure of the turning ability can be introduced which is the steady turning diameter at full helm non-dimensionalized by the ship length. In reality, the easier to register "tactical diameter" is usually preferred. It is, however, well correlated with the steady turning diameter.

According to the IMO standards, the tactical diameter is required to not exceed 5 ships length independently of the value of that length and of the speed of the ship.

Despite a certain terminological similarity, the initial turning ability is rather different from the ultimate turning ability discussed above: not the path curvature is here considered but the ability of a ship to rapidly change the heading enough. In most cases, the 10 deg heading change is considered, and no helm check is performed. The latter indicates that it does not go about a true course-changing manoeuvre. The meaning of standardizing the initial turning ability consists in preventing temptations to assure good turning ability at large helms at the expense of the inherent stability of the ship and without increasing the effectiveness of the rudder: despite technically good turning abilities such ships will be slow in responses to the rudder deflections or, in other words, they will be not well

controllable. The ITA is correlated with both the ultimate turning ability and with the ship directional stability although not in a quite straightforward way. It is clear, however, that a ship with a sufficiently large (say 3–4% of the centreplane area) rudder working outside of the propeller slipstream (a rather typical configuration for naval ships) is very likely to possess, at the same time, perfect directional stability combined with the good turning ability both ultimate and initial. With a smaller rudder in the slipstream the combination of manoeuvring qualities may turn out less favourable and then invoking the ITA criterion can serve as a good remedy against unsatisfactory controllability of the ship.

3.3. Directional Stability
3.3.1. Definitions and Criteria

The directional stability is, in practical terms, the capability of a ship to follow a straight path with moderate yawing, at a low average intensity of rudder orders and without an excessive strain of the human operator (helmsman) [22]. The ship is treated here as a closed-loop system and the course-keeping process is interpreted as continuing mitigation of deviations from the ordered heading caused by low-level excitations from sea waves. On directionally unstable ships this process can be accompanied by self-sustained oscillations whose admissible frequency and amplitude are to be standardized. Even though criteria of this type had been suggested, see, e.g., [28], they appeared to be impractical as the mentioned parameters of oscillations depend also on the parameters of the controller represented in this case by the helmsman. The undesirable influence of the controller is eliminated if the "inherent" stability of the ship with the rudder fixed in its neutral position is considered. Both the practical stability and the inherent stability are correlated: the higher is the degree of the inherent directional stability, the easier and better is the course keeping. However, quantitative criteria of the inherent directional stability are not obvious. The most natural criteria, at first sight, must be associated with the eigenvalues of the mathematical model of the sway-yaw motion linearized around the straight run. It is known that both eigenvalues are always real, and one of them has a relatively small absolute value and can be either positive or negative for different ships. The positive eigenvalue correspond to inherently unstable ships, the negative one—to inherently stable craft and it is obvious that the absolute value can serve as a measure of the stability/instability degree. Even though proposals to use the critical eigenvalue or the corresponding time lag as a stability criterion were made [29], its inconvenience became clear very soon: there is no way to check the value of this criterion directly from the results of full-scale or model-scale trials. As result, most of the proposals were exploiting more practical indirect measures.

3.3.2. Connection with Parameters of the Spiral Curve

The first of such indirect criteria is based on the configuration of the static characteristic (spiral curve) of a ship, which represents the dependence $r'(\delta_R)$ of the non-dimensional rate of yaw or the path curvature r' on the rudder angle δ_R in a steady turn. When the ship is directionally unstable, this curve possesses a hysteresis loop around the origin and the dimensions of this loop, i.e., its height and/or width can serve as measures of the degree of instability [12,22]. Some specialists believed that only some admissible degree of instability must be specified while all inherently stable ships are equally and unconditionally acceptable [30,31]. However, the stability margin can be very different and, aiming at standardizing directional stability of naval combatants and trying to keep the spiral curve as the main source of information on manoeuvring qualities, it was proposed by Sutulo [22] to standardize the value of the spiral curve derivative at the origin, i.e., $\frac{\mathrm{d}r'}{\mathrm{d}\delta_R}\Big|_{\delta_R=0}$ or of its normalized modification $\frac{\delta_m}{r'(\delta_m)} \cdot \frac{\mathrm{d}r'}{\mathrm{d}\delta_R}\Big|_{\delta_R=0}$, where δ_m is the maximum rudder angle.

There are reasons to believe that the optimal value of the latter normalized parameter should be 1.0 which corresponds to an absolutely straight spiral curve. This can be viewed as an educated guess but this guess is, however, indirectly confirmed by the fact that all

high-speed moving objects, e.g., steady-wing aircraft, are highly linear. The aircraft are not only always inherently stable but typically a certain margin of the so-called static directional stability is required [20]. It is interesting to note that Oltmann [32] also considered a similar though inversed criterion $\left.\frac{d\delta_R}{dr'}\right|_{\delta_R=0}$ and he demonstrated invoking multiple full-scale data for unstable ships that this criterion is only weakly correlated with the hysteresis loop width.

However, such "initial tangent" criteria have not gained recognition. One of the causes is that it is difficult to estimate these quantities from full-scale trials that must include the Bech reverse spiral test being rather difficult to execute let alone that the obtained estimates of the derivatives can be highly uncertain. Regarding the fact that most civil ships indeed remain well steerable even at some moderate degree of inherent instability, the dimensions of the hysteresis loop can serve as suitable indicators of acceptable directional stability at least for merchant ships.

However, the analysis based on the spiral curve configuration also has inconveniences related to full-scale trials. The Dieudonné spiral manoeuvre is not the easiest manoeuvre to execute as it requires substantial water area and is long in duration. The presence of wind is especially unfavourable for this manoeuvre as it makes practically impossible reaching the steady turn regime at each rudder deflection. To obtain more or less reliable averaged results in wind, it is necessary to perform at least two full turns at each helm which would increase the duration of the trials to unacceptable values. That is why, while requirements to the parameters of the spiral manoeuvre are formulated in the Explanatory Notes to the IMO manoeuvring standards [33] they were not even mentioned in the main text of the Standards [1] where an alternative in form of overshoot angles in zigzag tests was preferred [34]. However, Norrbin [35] characterized the fact that the spiral characteristic finally did not enter the main text of the IMO standards as "unfortunate".

3.3.3. Connection with Parameters of the Zigzag Manoeuvre

As long as there is no way to establish an analytical connection between the overshoot angles and, say, traditional stability indices, this solution raises, however, the following questions:

1. Whether both the width and the height of the hysteresis loop influence the actual steerability and the overshoot angles of a ship or one of them can be neglected?
2. Are the overshoot angles highly correlated with the parameters of the loop or they should be treated as additional and independent criteria?

As will be seen from the review below, the existing data are rather contradictory and this fact alone was sufficient for stimulating some criticism with respect to the existing IMO standards [1,23,33]. For instance, the data presented in [23] indicated that the relation between the loop width and the overshoot angles is rather rigid: the larger is the former, the larger are the latter. Norrbin [17] discussed the relative importance of the loop width and height and pointed out that the overshoot angles are better correlated with the loop width than with its height. Nikolayev et al. [36] discovered that the correspondence between the overshoot angles and the loop width alone can be very poor but can be improved if the loop height is used as an additional factor.

It is generally recognized that the following 3 overshoot angles adopted as standard measures are significant: the first overshoot angle in the 10°–10° zigzag (OS1), the second overshoot angle in the same zigzag (OS2) and the first overshoot angle in the 20°–20° zigzag (OS3). It is not possible to link analytically the parameters of Kempf's zigzag manoeuvres to other measures of the inherent directional stability, multiple simulations and trials confirm that typically the higher is the directional stability, the smaller are values of the overshoot angles. There is also a direct evidence that reduction of OS1 is beneficial for steering. In particular, such a conclusion was obtained in [37] based on multiple interactive simulations in the conditions of a straight and double-bent channel under influence of current. Many specialists suspected that these three criteria are not of equal significance.

For instance, Ræstad [38] came to the conclusion that the necessity of inclusion of OS3 into the Standards was not confirmed by analysis of full-scale data and by polling the seafarers although OS3 is typically considered important as a measure of the turn checking ability. At least, Yoshimura et al. [39], on the other hand, concluded that the OS1 requirement is less restrictive than OS3 while the least restrictive is OS2. At the same time, according to [40] OS1 is the strictest criterion.

Yoshimura et al. [39] showed that the correlation between the loop width and the overshoot angles OS1 and OS2 was confirmed by full-scale trials carried out with 50 ships. It can be noticed, however, that the shown correlation was better than in most other sources. Rhee et al. [41] performed a rather detailed study of the width–height correlations. Simulations showed a rather strong correlation with the width and a somewhat weaker one with the height of the loop. At the same time, the full-scale data demonstrated substantially inferior correlation in general and with OS3 it was even practically absent. As to the $10°$–$10°$ zigzag overshoots, OS1 correlated better with the loop height while OS2—with its width. Haraguchi and Nimura [42] have found, performing simulations based on tank data, a definitely positive width–angles correlation for pod-driven ships. A good correlation between the loop width and the overshoot angles was obtained by Sohn et al. [43] for a number of simulated ships but Yamada [44] pointed out that his data do not confirm such correlation.

The brief review above might leave an impression that the correlation between the parameters of the hysteresis loop is uncertain as the available data are controversial especially regarding full-scale sea trials data. However, it must be taken into account that such data are always given without uncertainty estimates while the uncertainties may be considerable for measurements taken in real sea conditions. In addition, there is sufficient evidence that the hysteresis loop height though ignored by the existing standards also influences the ship's behaviour in steering and the values of the overshoot angles thus impairing their correlation with the loop width. It must be admitted that detailed study of the influence of the loop width–height relation is still the matter of future research and so far even qualitative discussions such as that by Norrbin [17] are very rare.

However, in practice, there is no doubt that both the loop width and the overshoot angles can serve as reasonable measures of the directional stability of ships and the overshoot angles have the advantage to suit not only unstable but also directionally stable vessels. Remarkably, Ræstad [38] demonstrated using full-scale measurements and questionnaires distributed among seafarers that ships with subjectively abnormal behaviour indeed exhibit especially large overshoot angles.

3.4. Analysis of IMO Criteria of Directional Stability

The measures of the ship's directional stability used in the IMO standards [1,33] are reviewed and analysed in this subsubsection. It is important to keep in mind that these standards had been devised for calm-water steering.

The measures for the turning ability in IMO standards in terms of the ship length are fixed for all vessels but the required degree of the directional stability depends on the ship reference time $T_{\mathrm{ref}} = L/V$, where V is the speed specified in the standards. The stability requirements can be formulated either in terms of the hysteresis loop width (Figure 1) or in terms of the overshoot angle OS1 (Figure 2). The IMO requirements are shown on the plots as a solid line (graphs plotted in dotted and dash-dot lines and the meaning of $L_{1,2,3}$ will be discussed below, in the next section). If the reference time is smaller than 9 or 10 s, the requirement becomes flat. In particular, every inherently stable ship unconditionally satisfies the spiral loop requirement although further tightening of the inherent stability standard for small values of the reference time would seem more natural. However, any extrapolation on the plot for the loop width can only result in unrealizable negative values, see the dotted line in Figure 1 and application of alternative parameters of the spiral curve, such as its initial slope, discussed in the previous section is not compatible with the IMO

standard. At the same time, a reasonable extrapolation can be performed on the overshoot angle plot, see the dashed line in Figure 2.
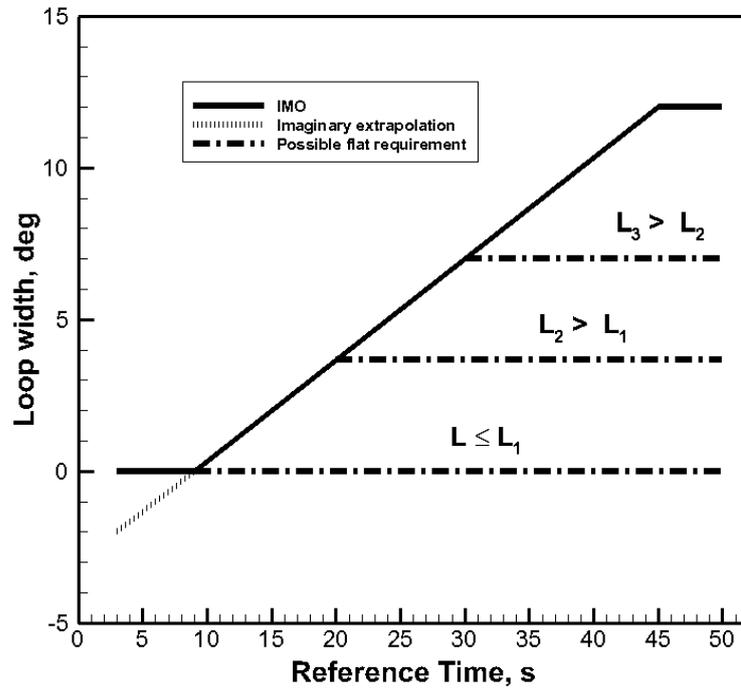

Figure 1. Standards for hysteresis loop width according to IMO standards and alternative requirements.
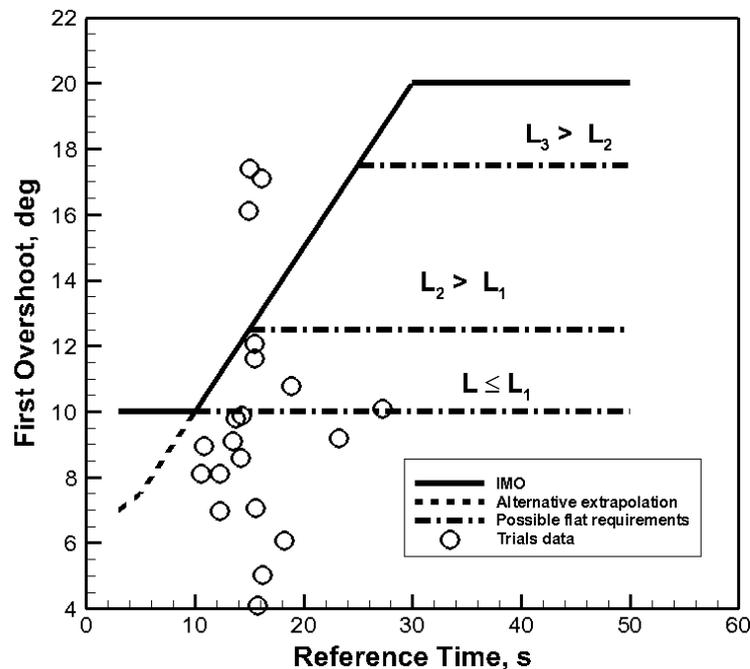

Figure 2. Existing and proposed standards for the first overshoot angle in 10°–10° zigzag.

As to the reference time exceeding 9 s, such ships are allowed to be directionally unstable and only the degree of instability is limited. As the reference time is increasing further, the inherent stability requirements according to the existing IMO standards are becoming looser and looser which looks consistent for manoeuvring in calm water. Constant limiting

values applied again for $T_{\mathrm{ref}} > 30$ s are explained by the necessity to have some helm margin at large loop width.

Dependence of the stability criteria on the ship reference time looks quite logical from the viewpoint of the ergatic approach: the smaller and faster is the craft, the higher is the required degree of directional stability. This is explained by the obvious fact that smaller time lags of the controlled object require also smaller time lags of the controller. Even though the human operator is adaptable in a rather wide range of dynamic properties of the controlled object, steering faster and smaller craft requires from the operator a higher degree of concentration and tension which cannot be completely eliminated even after intense and long training.

The IMO-adopted standardizing numerical values of the manoeuvring criteria are a result of intense and long research work and of multiple discussions carried out over many years. So, it can be saidthat they represent some acceptable compromise [34]. However, they should not be viewed as a kind of dogma and alternative values of the manoeuvrability measures were proposed not only before but also after the interim and even definitive standards were approved. For instance, in one of the earlier proposals [45] it was suggested to allow the hysteresis loop width not exceeding 4 degrees as a measure of an acceptable degree of instability for all ships independently of the reference time. A number of values of the parameters of the hysteresis loop proposed from 1959 to 1987 were listed by Norrbin [17]. Li and Wu [41] suggested to consider manoeuvring criteria as fuzzy variables but this suggestion did not have any impact apparently because it was unclear how to use fuzzy requirements in a document of legal nature.

Yoshimura et al. [39] analysed full-scale data for 50 ships and came to the conclusion that OS2 should be increased by 5 deg and OS3 should be defined as doubled OS2 while in fact it was fixed at 25 deg which looked too strict for ships with $T_{\mathrm{ref}} > 12$ s. On the other hand, Rhee et al. [41] suggested easing the overshoot angles requirements for small T_{ref} having pointed out that the smaller ships are easier to operate in narrow waterways without considering, however, external disturbances. Sohn et al. [43] performed interactive simulations in a narrow waterway under the action of wind and current and discovered that in discordance with the IMO standards ships with larger T_{ref} and with the same loop width were more difficult to steer (Nishimura and Kobayashi [46] came to similar conclusions). Alternative flat standards, 20° for OS1 and 40° for OS2 independently of the T_{ref} value, were proposed in [43] on the basis of subjective assessments and data on mean rudder deflections. Another flat standard for only OS1 was proposed by Oltmann [32]: the suggested value of 17° was close to the average of the IMO standard over the whole T_{ref} interval. In theory, a lower speed must not impair either the turning ability or the directional stability in calm conditions although such effect was traced by Yasukawa et al. [47] in the case when the propeller loading was substantially reduced. However, as the reference time of the ship $T_{\mathrm{ref}} = L/V$ at a lower operational speed V becomes larger, the standard related to the stability will be easier to meet according to the existing IMO requirements (Figures 1 and 2).

It is worth noting that the ship reference time can serve, to some extent, as an indirect measure of the degree of powering: the smaller is T_{ref}, the better powered is the ship. Hence, according to the existing IMO standards, the less powered is the ship, the less directionally stable it may be. Of course, such simple and general parameter as T_{ref} is not capable to account for all specifics reflecting the capability of this or that ship to withstand adverse conditions but in general it captures that capability fairly enough to be used in first-level standards: the smaller is T_{ref} the faster is the ship at the same length and, in general, the higher is the disposable power. All specifics related to the characteristics of the propulsion complex (different configurations can reveal very different reactions to augmentation of the resistance) should be accounted for in higher-level criteria or, even preferably, within special design and simulation procedures.

Looser directional stability requirements for larger and slower ships have always been considered beneficial for the designers as in this case good turning ability can be achieved

with less effective steering devices. However, when external loads of any nature, roughly independent of the ship speed, are taken into consideration, it can be expected quite the opposite: as the proper hydrodynamic forces on the ship hull and the rudder are roughly proportional to the square of the speed, a more effective steering device must be required. In other words, if one needs to keep the resisting capacity of a ship to given external factors at a lower speed, one must stimulate installation of a more effective steering device. Stimulation can be achieved by augmenting the directional stability requirements without easing (or maybe even with tightening) those for the turning ability. This task is always feasible although not always very easy.

Possible solutions for a single-screw vessel could be:

1.   Installation of sufficiently large twin rudders working outside of the propeller slipstream.
2.   An azipod arrangement with enlarged skeg and/or installation of additional stabilizing fins.
3.   A steering nozzle with additional stabilizers.
4.   A high-lift rudder (flapped, Schilling) with additional stabilizing fins.

It is expected that all these solutions may presume augmentation of maximum deflection angles as compared to the orthodox 35 degrees. Of course, these solutions make the steering complex heavier, bulkier and more expensive but this is inevitable as a definite improvement of the steering ability has its price.

4. Accounting for Adverse Conditions and External Perturbations in Manoeuvrability Criteria

4.1. Earlier Proposals

As has already been noticed, the existing IMO manoeuvrability standards [1,33] had been devised without account for external disturbances.

The authors are not aware of any reasons for such a decision and of any related discussions. In fact, it is possible to avoid including requirements into official standards presuming that the environmental factors can be taken into account for each design individually using available prediction methods whenever it is considered necessary by the customer. In particular, this viewpoint was discussed and recognized with some hesitation as preferable by the first author 25 years ago [48].

However, the current trend is exactly to complement the existing IMO set of standards with additional environment-dependent requirements [9,30,49,50].

Even though the existing IMO standards are formulated for calm water, the importance of accounting for environmental factors had been discussed in the literature more than once. These factors, first of all, are disturbances caused by wind, sea waves and current although in a more general sense variations of the ship draught and trim, shallow water effects and hydrodynamic interaction with other borders and bodies can also be interpreted as perturbations.

Norrbin [17] underlining the importance of accounting for the wind action pointed out that "some passenger ferries have the relative windage area comparable to that of the old windjammers". Spyrou and Vassalos [51] remarked that while a ship may have good manoeuvring performance in calm sea and even keel, its behaviour may become unacceptable under external disturbances and/or in a trim-by-the-bow condition.

Lowry [52] formulated a general definition that "a vessel is controllable if the forces and moments generated by the vessel can overcome the [external] aero/hydrodynamic forces acting on the vessel". As the "forces generated by the vessel" are also hydrodynamic, this statement may look not very exact but it is clear that the author meant here disturbances from sea waves.

Li and Wu [37] also paid attention to the necessity of the introduction of criteria related to environmental factors. Koyama and Kose [18] stated that in developing manoeuvring standards the current should not be considered at all as long as strong tidal currents presumably can be avoided while the wind effects can not and must be taken into account. It was proposed to consider the wind speed 15 m/s for the course keeping at 5 kn speed of

advance. A similar steering-in-the wind formulation was also discussed in [40]. Zaky and Yasukawa [30], studying the effects of the load condition for the virtual tanker KVLCC2, discovered that the wind balancing rudder angle becomes smaller in ballast condition with a stern trim than in full load in spite of a substantially larger relative windage area. Some researchers, including the first author of the present paper, see [48], tended to believe that the capacity of a ship to withstand external factors in the sense of manoeuvrability should not be standardized but, in any necessary case, must be subject to design specifications and special analysis.

Latest studies on manoeuvrability in adverse weather conditions mainly focused on second-order wave excitation effects including added resistance in waves [13]. The latter is really important in the formulation of minimum-power requirements which include the ability of the ship to keep controllability under adverse conditions characterised by the significant wave height varying from 4.5 to 6.0 m and for the wind speed from 19 to 22.6 m/s depending on the ship's length. The controllability must be demonstrated using some trusted prediction method in the sense that at some small speed, e.g., 2 knots, the ship is capable to maintain heading advancing into head seas [13]. Regarding that "trusted method," it is clear that at present the only reliable method for predicting a ship's behaviour in waves is an application of CFD codes which are, however, prohibitively slow for performing systematic calculations, especially in irregular seas. However, as will be discussed below, there is a possibility to bypass this difficulty.

The latest case of interest in manoeuvring criteria accounting for external factors is associated with expected underpowering caused by EEDI requirements while "low-powered" tankers designed to minimize the costs of construction, operation and maintenance had been already mentioned by Norrbin [17]. It still does not mean, however, that EEDI-compliant ships require some special sets of criteria and standards but they are more likely to become vulnerable to external factors and the existing standards are supposed to be revised and extended in such a way that this vulnerability is limited to acceptable levels.

Of course, any kind of hydrodynamic and aerodynamic perturbations must be somehow checked and counteracted and the effectiveness of the ship control device must be sufficient for that purpose. The hydrodynamic interaction issues (such as the ship-to-ship interaction) may be quite important per se but they are hardly associated with the underpowering as in this case all categories of forces will be simultaneously proportional to the squared ship speed.

If the minimum-power requirements lead in this or that case to the reduction of the installed power and of the ship design speed as compared to those selected without the influence of such requirements, it may happen that either the IMO standards must be somehow modified or complemented with standards based on additional criteria.

In general, the following external factors can be considered:

1. Hydrodynamic interaction with other vessels, banks, steady and floating structures and the seabed.
2. Excitation from the sea waves.
3. Aerodynamic loads caused by wind.
4. Additional forces that may be significant for certain special ships: reaction from the towline for tugs, reaction from towed acoustic arrays, trawls, sweeps and other towed devices.

It is interesting to note that all (!) these factors had been considered during the development of earlier Russian national manoeuvring standards as presented by Mastushkin [19] who led and supervised that development. As those national standards, see [8], in no way influenced the development of the IMO criteria, the issue of the external factors practically had never been discussed on the international level before studies on the STANAG standards [15]. These standards, however, were driven by a desire to account for all possible navigational situations and missions sensitive to the manoeuvring performance of naval combatants and auxiliary ships. While this approach is understandable, it is hardly rational as long as the simplicity principle is definitely neglected.

4.2. Standards Accounting for Disturbances from Sea Waves

The task of developing manoeuvrability criteria accounting for the wave action is more complex and contains more uncertainties than it could seem at first sight. It is only evident and known from the seamanship practice that less powered (slower) ships are more sensitive to the action of the sea. The scenario approach followed by some researchers [49,50] looks quite natural and suitable. However, the selection of critical scenarios is not easy. Probably, an adequate understanding of the complexity of the task of handling a ship in rough sea waves can be obtained from the following abridged quotation [53], (pp. 118–121):

> "The great wave flung the bows up, pushed the *Ulysses* far over to starboard, then passed under. The *Ulysses* staggered over the top, corkscrewed wickedly down the other side, her masts, great gleaming tree trunks thick and heavy with ice, swinging in a great arc as she rolled over, burying her port rails in the rising shoulder of the next sea.
>
> 'Full ahead port!' . . . 'Starboard 30!'
>
> The next sea, passing beneath, merely straightened the *Ulysses* up. Next, at last, Nicholls understood. Incredibly, because it had been impossible to see so far ahead, Carrington had known that two opposing wave systems were due to interlock in an area of comparative calm: how he had sensed it, no one knew, would ever know, not even Carrington himself: but he was a great seaman and he had known. For 15, 20 s, the sea was a seething white mass of violently disturbed, conflicting waves—of the type usually found, on a small scale, in tidal races and overfalls—and the *Ulysses* curved gratefully through. Then another great sea, towering almost to bridge height, caught her on the far turn of the quarter circle. It struck the entire length of the *Ulysses* for the first time that night—with tremendous weight. It threw her far over on her side, the lee rails vanishing. [. . .]
>
> And still, the great wave had not passed. It towered high above the trough into which the *Ulysses*, now heeled far over to 40°, had been so contemptuously flung, bore down remorselessly from above and sought, in a lethal silence and with an almost animistic savagery, to press her under. The inclinometer swung relentlessly over—45°, 50°, 53° and hung there an eternity, while men stood on the side of the ship, braced with their hands on the deck, numbed minds barely grasping the inevitable. This was the end. The *Ulysses* could never come back. [. . .] . . . the *Ulysses* shuddered, then imperceptibly, then slowly, then with vicious speed lurched back and whipped through an arc of 90°, then back again. [. . .] 'Slow ahead both! Midships!' 'Steady as she goes!' The *Ulysses* was round."

The quoted fragment is an artist's description of a turn in heavy seas of a cruiser participating in a WW2 arctic convoy. However, this description is based on personal experience of its author and in fact it well agrees with recommendations given in seamanship manuals, see, e.g., [54]. This indicates that the selection of ship handling scenarios and formulation of explicit criteria for manoeuvrability in sea waves may become a prohibitively difficult task with plenty of uncertainties. However, even if some reasonable scenarios are established, it will be very difficult to verify compliance of a given ship with the corresponding criteria: there is no chance to perform full-scale trials, scaled model experiments of this nature are very complex and the existing theoretical and numerical methods are not matured enough to provide reliable estimates. Of course, there are some ways to bypass those difficulties.

The first way was de facto followed in several later proposals for manoeuvrability criteria in adverse conditions and consists, first, in lifting the requirement of direct verifiability of each criterion in the spirit of the philosophy proposed in [26] and, second, in simplifying the model for the wave action, which is very complex. Considering the hull forces, it is possible to separate the first-order and second-order effects of sea waves. The first-order excitation forces are of primary importance in ship seakeeping and also are the

main cause of the ship's yawing in a seaway. In regular waves, they result in ship responses with the wave encounter frequency and are roughly proportional to the wave amplitude at least when the nonlinear effects are not very pronounced. From the point of view of manoeuvrability, the most unfavourable is the case of long following waves. Possible loss of controllability in extreme seas and situations similar to that described in the quotation above are also caused by first-order effects. The second-order reactions result in regular waves in time-averaged steady forces and moments which, of course, will affect the motion of the ship in the horizontal plane. In particular, they will result in the added resistance in waves but also in the additional constant sway force and yaw moment. These forces and moment are roughly proportional to the square of the wave amplitude and reach their maxima in relatively short waves. In irregular seas the second-order excitation is more complex and, besides the steady component, results in low-frequency excitation which can cause resonant motions of moored or anchored ships.

Most latest proposals on manoeuvring criteria and standards are based on the methods predicting only second-order wave forces possibly combined with the steady current and wind action while the first-order effects are accounted for indirectly by setting some sea margin to the maximum rudder deflection angle, see, e.g., [9,11,49,50,55]. Apparently, for the power standardization problem, this approach is completely justified but it is less evident for the ship controllability in waves. In particular, the extreme situation described above cannot be captured in this way.

However, there are reasons to believe that it is possible to bypass the difficulties related to accounting for wave disturbances. Such alternative is based on two rather evident observations concerning possible outcomes of the analysis of each possible sea waves scenario:

1. The rudder effectiveness required by the scenario is superior to that conditioned by the existing standards for the turning ability and directional stability in calm water.
2. The effectiveness of the rudder required by the sea scenario is inferior to or is absorbed by the effectiveness required by the calm-water criteria.

It is clear that in the latter case any additional criterion turns out excessive and can be ignored but in the former case, a more effective rudder should be required.

Another evident observation is that such a more effective rudder will also improve the indices of the turning ability and directional stability. This means that this additional requirement can be accounted for implicitly, through appropriate tightening of the main manoeuvring standards, i.e., decreasing the allowed values of the advance, tactical diameter and zigzag overshoot angles. Does that mean that no additional separate or explicit criteria accounting for the seas and hydrodynamic interaction would then be necessary? The answer would be definitely "no" if and only if it were possible to reduce the impact of the mentioned external factors without enhancing the effectiveness of the steering device. This looks, however, highly unlikely.

Of course, the shape of the hull and especially its fullness may influence the interaction and wave excitation forces but this shape is almost entirely determined by resistance, propulsion and other design considerations. Similarly, it is practically impossible to alter the gyration radius in yaw motion through redistribution of mass along the hull. The only realistic modification consists of increasing the size of the stabilizing skeg or installation of additional stabilizers which improves the directional stability but inevitably at the expense of the turning ability. An objection may arise that, for instance, ships with different values of the block coefficient are subject to different levels of excitation loads and would require different requirements to the rudder effectiveness but this difference can be accounted for both by explicit or implicit criteria.

Hence, it can be assumed that the resistive capacity of a ship with respect to the action of hydrodynamic exogenous factors (sea waves) can only be augmented by increasing the effectiveness of the rudder which, in its turn, is guaranteed if the turning ability and the directional stability are increased simultaneously. It means that the existing standards of the turning ability and stability are to be revised and maybe tightened but no additional

special explicit standards are necessary. It must be emphasized that ships with a good turning ability alone can easily show poor resistance against external factors including sea waves if these ships are not directionally stable or even stable but with insufficient stability margin. This may happen with full-bodied vessels and, as long as the external factors are ignored, can be even viewed as beneficial because a less effective small rudder is then sufficient for good turning qualities but such rudder will not be able to appropriately counteract external forces especially at low speed.

4.3. Standards for Controllability in Wind

The same principle of increasing the rudder effectiveness through tightening the calm-water standards could be also applied to the aerodynamic (wind) factors but here the situation looks somewhat different because, contrary to hydrodynamic loads, it is possible to define several very evident and significant parameters affecting the level of sensitivity of a ship to wind. Since long ago, it has been established with certainty, see, e.g., [12,56–58], that the manoeuvring sensitivity to the wind depends on the following four fundamental dimensionless parameters: the relative density of the air $\overline{\rho}_A = \rho_A / \rho$, where ρ_A is the air density and ρ is the water density; the relative lateral windage area $A_L' = A_L / (LT)$, where A_L is the lateral windage area, L is the ship waterline length, T is the ship draught; the relative longitudinal position of the centroid of A_L defined as $x_A' = x_A / L_{OA}$, where x_A is the abscissa of the centroid and L_{OA} is the length overall; and the relative wind speed $\overline{V}_w = V_w / V$, where V_w is the absolute wind speed and V is the actual speed of the ship with respect to water. The air relative density is practically constant and its variability can be ignored while the remaining parameters can vary in a wide range and are extremely important as they influence the mentioned sensitivity substantially. This fact is quite transparent intuitively and well familiar to all seafarers. In particular, it has always been known that slow vessels with a large windage area and small draught are especially difficult for handling in wind and even the controllability can be lost completely.

It seems that contrary to the criteria driven by sea waves excitation it is easier to introduce a separate standard based on the criterion of controllability in the wind than to establish some additional rules for tightening calm-water criteria, which must capture dependence on the windage area parameters mentioned above. In fact, two additional wind-controllability requirements were developed by Mastushkin [19] and these are up to present embedded into the Rules of the Russian Maritime Register of Shipping [8], see also [12,16]. Multiple test calculations performed with more than 100 ships showed that after appropriate adjustment this criterion became non-trivial: some existing ships that did not satisfy it did really suffer from controllability problems in wind. Of course, for the majority of ships that criterion looked excessive, as the requirements of turning ability/stability in calm water were for them more strict. A similar situation will be with any consistent wind criterion. In particular, it will be certainly redundant for ships with high draught and low windage area: for such ships, second-order wave loads may often exceed aerodynamic ones. On the other hand, many ships in ballast condition, passenger ships and ferries will be more prone to aerodynamic loads than to any other type of excitation and then that additional requirement turns out significant. For instance, it was found by Zaky and Yasukawa [30] that while the second-order wave forces for a typical tanker in full load exceeded by 50% the wind forces, for the same ship in ballast the wave force was 10% lower than the wind force.

4.4. Modification of Calm-Water Standards

4.4.1. Simplified Approach

Recognizing that simultaneous improvement of the turning ability and directional stability definitely improves the ship's capability to counteract external factors, it can be sufficient to modify the required (standardizing) values of the turning ability and directional stability criteria. Regarding the turning ability, as a zero approximation the existing values (5 ship lengths for the tactical diameter and 4.5 lengths for the advance, both

independent of the reference time) can be conserved or somewhat tightened regarding that they are satisfied with the majority of existing ships with a tangible margin [29]. However, the values of the measures of directional stability apparently must be revised. Given the previous discussion in Section 3, it goes about the dependence of the width of the hysteresis loop or of the zigzag 1st overshoot on the ship reference time T_{ref}. Again, as a zero approximation, it could be recommended to eliminate this dependence by introducing flat standards, see Figures 1 and 2. This modification seems quite appropriate as most existing ships already satisfy the thus modified standard: a sampling of existing vessels presented in [40] demonstrated compliance with the "flat" standard for most ships and did not show definite dependence on T_{ref} while the scatter is substantial.

It is remarkable that such deep revision and tightening of IMO standards apparently would not result in any serious problems regarding compliance difficulties as multiple sources (see [40,59–61] and Figure 2 where full-scale data from [40] are plotted as circle symbols) indicate that while the scatter of full-scale data is substantial, the dependence of the overshoot angles and/or loop width on T_{ref} is weak and often even absent. In the majority of cases, the standards are satisfied with a considerable margin. Exceptions are mainly associated with very specific vessels, such as hopper dredgers [62] but these hardly can be treated in a common way.

While Gong et al. [59] detected a larger scatter of trials data at low Froude numbers, the data in the cited source indicate that OS1 rarely exceeds 10–11 degrees. The same authors have also found by means of interactive simulation that reduction of OS1 from 13 to, say, 8 degrees with simultaneous reduction of the tactical diameter from 4.3 to 3.7 lengths definitely resulted in safer and more accurate steering.

Even though such modifications of the IMO standards would be, most likely, beneficial even in this form, it would be hardly the best possible solution.

4.4.2. Improved Modifications

Before an extended numerical study, see the next Subsubsection, is undertaken some heuristic improvements can be made. In particular, the same value of the reference time can correspond to larger and faster vessels or to smaller and slower ones. It is, however, evident that in the first case sensitivity to waves at the same sea state will be weaker, which means that the directional stability requirement can be eased (but not necessarily!) for larger ships and probably the ship length can then be introduced as additional parameter although for each L the requirement may remain flat as far as it is stricter than the existing IMO standard. This is illustrated by additional dash-dot lines in Figures 1 and 2 where it is supposed that the base requirement described by the lowest dash-dot line must be applied for all ships with the length not exceeding some value L_1, which must be specified, while the two remaining dash-dot lines show possible looser requirements for some larger ship lengths L_2 and L_3. These eased requirements can be viewed as a compromise between the existing and completely "flat" standards. The flatness of the standard, at least above some value of the reference time, makes less critical selection of the speed V: the IMO standards define it as 0.9 of the speed corresponding to 0.85 of the maximum continuous rating of the engine(s) and the same definition can be kept although the actual reachable speed in waves may be lower than that.

4.4.3. Supporting Studies

Regarding a better account for sea waves, development of more sophisticated and better substantiated requirements to the measures of directional stability, multiple simulations in waves must be performed for a set of generic ship mathematical models with varying indices of the turning ability and inherent directional stability must be performed and followed by appropriate analysis. Moreover, any representative set of mathematical models must embrace not only various values of the shaft power but also different types of propulsors (fixed- or controllable-pitch propellers) and various typical engine characteristics as, e.g., the loss of actual power will be very different for a DC electric motor and a

common turbocharged 2-stroke Diesel engine. It does not mean that the resulting standards must be differentiated for all possible configurations but differences in behaviour must be captured and analysed. Such numerical study must be, however, preceded by the development of a sufficiently accurate, fast and commonly recognized program for simulating the arbitrary motion of a ship in waves. Existing codes of this kind can hardly be applied as they suffer from various limitations and uncertainties. Application of Reynolds-Averaged Navier–Stokes Equations (RANSE) CFD codes or model tests looks unrealistic because of unacceptable time requirements: at least real-time or even accelerated-time simulations must be feasible. Unfortunately, no one of faster existing available codes can guarantee capturing all substantial effects accompanying manoeuvring in waves. For instance, one of the latest and relatively consistent developments [63] is fully linear (except for the account for 2nd-order excitation forces) and neglects many coupling effects, let alone variations of the hydrodynamic characteristics of propellers and rudders and interaction coefficients. The 2nd-order wave forces combined with the linear seakeeping model were used by Chillece and el Moctar [55] and by Kobayashi [64]. Only second-order forces were modelled for a tanker by Zaky and Yasukawa [30] who combined the sea with the wind action.

4.4.4. Design Implications for Steering Arrangement

Even though most ships apparently will satisfy even modified and tighter manoeuvring criteria, situations in which design decisions aimed at strengthening the ship's controllability are required may happen and then various solutions are possible. It is important to emphasize one more time that the directional stability must be augmented together (concurrently) with the turning ability of the ship design in consideration as only in this case the ship capacity to resist adverse factors will be improved. Augmentation of the rudder area is the most evident and straightforward solution. Simulations under wave and wind disturbances performed by Ohtagaki and Tanaka [44] demonstrated that the mean course deviation could be reduced from approximately 10 to 5 degrees with simultaneous reduction of the square-root mean rudder deflections from 13 to 8 degrees when the rudder relative area was increased from 1.2% to 2.5%. Norrbin [17] suggested using skegs or fixed fins to improve the directional stability. Haraguchi and Nimura [42] demonstrated direct reduction of the OS1 and OS2 overshoot angles by the factor of 3 and reduction of the OS3 angle by the factor of 2 when the relative rudder area was increased from 1% to 1.5%.

It must be said that in a rather typical situation of a normal rudder working in the propeller slipstream augmentation of the rudder area will definitely increase the turning ability while improvement of the directional stability may become much less pronounced. In this case, simultaneous augmentation of the rudder and the skeg areas may be recommended [38]. Similar solutions can be very promising in the case of pod-driven ships [42,65]. However, it makes sense to keep in mind the natural improvement of controllability in some defining loading conditions. For instance, Zaky and Yasukawa [30] obtained that a typical ballast condition often results in simultaneous growth of the turning ability (due to larger relative rudder area) and of the directional stability (due to trim by the stern). Finally, the so-called high-lift rudders and other steering devices can be applied. For instance, Yamada [44] indicated that the application of the high-lift Schilling rudder permits considerable reduction of the OS2 angle. Eda and Numano [66] demonstrated the effectiveness of twin flap rudders.

5. Manoeuvrability Criteria in Wind: Theoretical Support

5.1. Ship Wind Resisting Capacity Criterion and Standardization Scheme

5.1.1. Preliminary Comments

As was discussed above, although in theory the approach based on adjustment of the existing IMO criteria can also be applied to account for wind perturbations, the special nature of aerodynamic exogenous factors and, in particular, the existence of few well-defined parameters characterizing aerodynamic peculiarities of ships makes reasonable the intro-

duction of an additional criterion. Even though a straightforward approach has inclined many researchers to require direct demonstration of the capability of a ship to perform arbitrary manoeuvres in a given wind [67], since long ago it has been understood that the ship remains controllable in wind of some specified velocity if it is capable to maintain any required course in straight run [56]. It was also demonstrated with the help of direct computations [58] that the ability to maintain an arbitrary course is equivalent to the ability of maintaining an arbitrary heading or arbitrary air drift angle. This scenario had been used by Mastushkin [19] for developing wind controllability criteria implicitly contained in the Rules [8], see also their concise description in [12]. Those criteria were applied using some simplified manoeuvring models under the assumption of the presence of constant wind with a certain specified speed. In general, the scheme turned out reasonable and practical although certain additional simplifications, such as the assumption that the rudder effectiveness is unconditionally higher for rudders with a higher aspect ratio, somewhat impair the quality and consistency of the standard. The approach followed here is similar in some respects but the authors tried to avoid evident drawbacks of earlier suggestions and to leave more flexibility in the standardizing scheme. Any wind controllability standard is supposed to be applied indiscriminately to all ships but in the case of underpowered ships, the corresponding criterion is more likely to become critical, i.e., leading to augmentation of the rudder effectiveness. The following material assembles practically all theoretical elements necessary for devising a rational and relatively simple standard for ship resistance to wind action, but the corresponding standard itself presumes specification of the wind speed value through a statistical adjustment to some representative subset of the existing fleet of vessels is left beyond the scope of the present article.

5.1.2. Formulation and Main Relations

The gustiness of the wind can be neglected in manoeuvring problems as the ship in the horizontal plane represents an aperiodic system with relatively large time lags and possessing no resonant frequencies. Similarly, self-sustained oscillations of the loads observed on non-steamlined bodies even in a sready flow will not have any significant effect. Assuming also that the wind-induced roll does not affect significantly the behaviour of the ship in the horizontal plane, the most general modular mathematical model for the steady ship motion in wind is described by the following set of nonlinear algebraic equations:

$$
\begin{aligned}
&X_H(u,v) + X_P(u,v,n) + X_R(u,v,n,\delta_R) + X_A(u_A,v_A) = 0,\\
&Y_H(u,v) + Y_R(u,v,n,\delta_R) + Y_A(u_A,v_A) = 0,\\
&N_H(u,v) + N_R(u,v,n,\delta_R) + N_A(u_A,v_A) = 0,\\
&Q_P(u,v,n) + Q_E(n^*,n) = 0,
\end{aligned}
\tag{1}
$$

where X, Y, N, Q stand for the surge force, sway force, yaw moment and the shaft torque, respectively; the subscripts H, P, R, A, E correspond to the hull, propeller, rudder, air (or aerodynamic) and engine, respectively; u and v are the velocities of surge and sway; n is the actual propeller rotation frequency (rps), and n^* is the ordered rotation frequency.

The kinematic parameters present in the set (1) are most convenient for the description of involved forces and are related to alternative parameters, which may be more suitable for human perception:

$$
\begin{aligned}
&u = V\cos\beta,\ v = -V\sin\beta,\\
&u_A = V_A\cos\beta_A,\ v_A = -V_A\sin\beta_A,
\end{aligned}
\tag{2}
$$

where $V = \sqrt{u^2 + v^2}$ is the ship speed relative to the water, β is the drift angle, $V_A = \sqrt{u_A^2 + v_A^2}$ is the airspeed of the ship or the relative wind speed and β_A is the air drift angle or the apparent wind angle.

In the case of absence of current, the following relations are valid:

$$u_A = u + V_w \cos(\chi_w - \psi),$$
$$v_A = v - V_w \sin(\chi_w - \psi), \qquad (3)$$

where V_w is the absolute wind speed, χ_w is the absolute wind direction angle, ψ is the ship heading angle.

The aerodynamic surge force X_A, sway force Y_A and yaw moment N_A are represented in the standard way:

$$X_A = C_{XA}(\beta_A)\frac{\rho V_A^2}{2} A_T, \ Y_A = C_{YA}(\beta_A)\frac{\rho V_A^2}{2} A_L, \ N_A = C_{NA}(\beta_A)\frac{\rho V_A^2}{2} A_L L_{OA}, \qquad (4)$$

where C_{XA}, C_{YA}, C_{NA} are the force/moment coefficients, A_T is the transverse projection of the above-water part of the hull, A_L is its longitudinal projection and L_{OA} is the length overall.

The dependencies of the forces and moments in (1) are closing the ship mathematical model and can be specified in various ways. In general, these dependencies can be very complicated and highly nonlinear. So far, the only simplifying assumption was that the propeller sway force and yaw moment could be neglected. A comprehensive nonlinear mathematical model is suitable and even desirable for simulating the ship manoeuvring motion in wind but seems to be excessively complicated for standardizing purposes. The following simplification seems to be adequate for that task: the speed of the ship with respect to water V is fixed and specified. In this case, the equations for the surge forces and shaft torques can be separated from the remaining two and are often ignored.

The assumption about the fixed speed V is sometimes doubted as in reality it also depends on the wind and in more detailed mathematical models used in simulation systems, it is continuously estimated and depends not only on the relative wind but also on the sea state, type and limiting characteristics of the main engine, type of the propulsor and on the throttle settings while the latter may be conditioned by voluntary reduction of speed to avoid resonances, reduce slamming and green water on deck. However, in simplified models oriented at the definition of manoeuvring criteria not only the assumption of a fixed ship speed is acceptable but the specific value of this speed is less important than it could seem because what matters is its magnitude relative to the wind speed V_w and the standardizing value for the latter is supposed to be adjusted to the existing fleet.

Most empiric methods use linearized or relatively easily linearizable rudder models [56,68,69] which is sufficiently appropriate for a standardizing problem. Then the sway–yaw equilibrium equations can be represented as

$$Y'_H(v') \cdot \tfrac{1}{2}\rho V^2 LT - C_{RN}^\alpha \cdot \tfrac{1}{2}\rho V_R^2 A_R \alpha_R \cos \delta_R + C_{AY}(\beta_A) \cdot \tfrac{1}{2}\rho_A V_A^2 A_L = 0,$$
$$N'_H(v') \cdot \tfrac{1}{2}\rho V^2 L^2 T - C_{RN}^\alpha \cdot \tfrac{1}{2}\rho V_R^2 A_R \alpha_R x_R \cos \delta_R + C_{AN}(\beta_A) \cdot \tfrac{1}{2}\rho_A V_A^2 A_L L_{OA} = 0, \qquad (5)$$

where Y'_H and N'_H are the hull sway force and yaw moment coefficients, $v' = v/V$ is the dimensionless sway velocity, V_R is the magnitude of the rudder velocity with respect to water, A_R is the rudder area, $\alpha_R = \delta_R - \kappa\beta$ is the rudder attack angle, κ is the flow straightening factor, x_R is effective rudder abscissa in the body frame, ρ and ρ_A are the water and air density, respectively. It is assumed here that the linear rudder model is characterized by the normal force coefficient gradient C_{RN}^α. As the minimum value of the function $\cos \delta_R$ is 0.85 in most cases, this factor can be dropped. In addition, it can be assumed that $L_{OA} \approx L$.

The set (5) can then be represented in the following non-dimensional form:

$$Y'_H(v') - C_{RN}^\alpha \overline{V}_R^2 A'_R(\delta_R + \kappa v') + C_{AY}(\beta_A)\overline{\rho}_A \overline{V}_A^2 A'_L = 0,$$
$$N'_H(v') - C_{RN}^\alpha \overline{V}_R^2 A'_R(\delta_R + \kappa v')x'_R + C_{AN}(\beta_A)\overline{\rho}_A \overline{V}_A^2 A'_L = 0, \qquad (6)$$

where $\overline{V}_R = V_R/V$, $A'_R = A_R/(LT)$ is the relative rudder area, $\overline{\rho}_A = \rho_A/\rho$, $\overline{V}_A = V_A/V$ and $A'_L = A_L/(LT)$.

The difference between V_R and V is caused by the influence of the wake behind the hull and by the influence of the propeller slipstream. The total effect can be positive (more typical for merchant ships) or negative depending on which part of the rudder is working in the propeller race and on the configuration of the stern. The straightening coefficient κ depends on the same factors but never exceeds 1.0.

The ideal propulsor model typically used by empiric methods, see e.g., [69,70], for modelling the influence of the propeller slipstream on the rudder will yield:

$$\overline{V}_R^2 = \overline{A}_{R0} + \overline{A}_{RP}(1 + C_{TA}),$$
$$\kappa = \kappa_H \frac{\overline{A}_{R0} + \overline{A}_{RP}\sqrt{1 + C_{TA}}}{\overline{A}_{R0} + \overline{A}_{RP}(1 + C_{TA})}, \tag{7}$$

where $\overline{A}_{R0} = A_{R0}/A_R$, A_{R0} and A_{RP} are the parts of the rudder area A_R outside and inside the slipstream, respectively, κ_H is the hull straightening factor varying from 0.3 to 1.0, C_{TA} is the propeller loading coefficient defined as:

$$C_{TA} = \frac{8T_P}{\rho \pi D_P^2 V^2}, \tag{8}$$

where T_P is the propeller thrust and D_P is the propeller diameter.

The hull straightening factor is assumed following the general recommendations [57,69] or it can be adjusted. The propeller thrust and the ship speed in (8) should correspond to the actual ship motion in wind and be obtained from the surge equation but, in first approximation and for standardizing purpose, it is possible to assume that the thrust corresponds to the free run with the speed V, which is then a free parameter.

As the drift angle of the ship advancing along a straight path in wind practically never exceeds 30 degrees, polynomial approximations for the functions $Y'_H(v')$ and $N'_H(v')$ will be adequate. It makes sense to apply the simplest approximations used in the Pershitz empiric method [12,56]:

$$Y'_H(v') = Y'_v v' + Y'_{vv} v'|v'|,$$
$$N'_H(v') = N'_v v', \tag{9}$$

where the coefficients ("hydrodynamic derivatives") can be estimated using the procedure described in [57,69]. This model exploits the fact that the drift angle nonlinearity is much weaker for the yaw moment than for the sway force and is the nonlinear model of minimum complexity. A fully linearized model is also possible and was used in [58] but, as the substantially more accurate model (9) still permits analytical solutions, its application may be preferable. If the primary mathematical model for the sway force and yaw moment has a different structure, it always can be reasonably approximated with (9). For instance, suppose that the coefficients of a very common cubic model

$$Y'_{H3}(v') = Y'_{v3} v' + Y'_{vvv} v'^3,$$
$$N'_{H3}(v') = N'_{v3} v' + N'_{vvv} v'^3, \tag{10}$$

are known. Then, requiring direct matching at the values of the dimensionless sway velocity v'_1 and v'_2 (for instance, they may correspond to 10 deg and 20 deg values of the drift angle) for the sway force and only at v'_2. it is possible to obtain the approximating formulae:

$$Y'_v = Y'_{v3} - Y'_{vvv} v'_1 v'_2,$$
$$Y'_{vv} = Y'_{vvv}(v'_1 + v'_2),$$
$$N'_v = N'_{v3} + N'_{vvv} v'^2_2. \tag{11}$$

Of course, the approximation can be performed in different ways including the application of the least-square method.

Substituting (9) into (6) and performing obvious transformations it is possible to bring the equilibrium equations to the following form:

$$
\begin{aligned}
C_Y^v v' + Y'_{vv} v'|v'| + C_Y^\delta \delta_R &= f_Y(\overline{V}_A, \beta_A), \\
C_N^v v' \qquad\qquad + C_N^\delta \delta_R &= f_N(\overline{V}_A, \beta_A),
\end{aligned}
\tag{12}
$$

where

$$
\begin{aligned}
C_Y^v = Y'_v - \kappa E_R, &\qquad C_Y^\delta = -E_R, &\qquad f_Y(\ ) = -K_{AY}(\beta_A)\overline{V}_{AL}^2, \\
C_N^v = N'_v - \kappa E_R x'_R, &\qquad C_N^\delta = -E_R x'_R, &\qquad f_N(\ ) = -K_{AN}(\beta_A)\overline{V}_{AL}^2,
\end{aligned}
\tag{13}
$$

where

$$
E_R = C_{Rn}^\alpha \overline{V}_R^2 A'_R; \; K_{AY}(\beta_A) = C_{AY}(\beta_A)\overline{\rho}_A A'_L; \; K_{AN}(\beta_A) = C_{AN}(\beta_A)\overline{\rho}_A A'_L,
\tag{14}
$$

and where E_R has the meaning of the rudder effectiveness index.

5.1.3. Useful Analytical Solutions

Standard analysis based on the Equation (12) presumes computation of equilibrium values of v' (or β) and δ_R as functions of β_A at some fixed value of $\overline{V}_A$. The solution always exists for this model but when the values of the parameters A'_L and $\overline{V}_A$ are large enough, the required equilibrium rudder deflection angle can exceed the maximum possible value δ_m within a certain interval of the air drift angle β_A and this is then interpreted as a loss of controllability in wind. This analysis can be complemented by an investigation of the inherent local stability of attainable equilibrium regimes, see, e.g., [71–74] and such analysis is of considerable theoretical interest. However, it is not relevant for estimation of controllability in the sense formulated above as the steered ship represents a closed-loop system and can be stabilized on any reachable course with the helmsman or autopilot. Necessary allowance for the rudder oscillatory motions (sea margin) is accounted for in setting the value of δ_m which is assumed to be smaller by 5–7 degrees than the maximum deflection angle of the rudder.

The set (12) can be solved analytically. First, physical considerations and computations performed with the linearized model show that at positive β_A the drift angle β must be negative, which corresponds to $v' > 0$ which makes possible substituting $v'|v'|$ with v'^2 as, due to symmetry, it is sufficient to consider only non-negative values of the air drift angle. Then, expressing the rudder angle from the second equation and substituting it into the first one the following quadric equation is obtained:

$$
Y'_{vv} v'^2 + (C_Y^v - C_N^v / x'_R) v' + f_N / x'_R - f_Y = 0.
\tag{15}
$$

The assumption that always $x'_R = -\frac{1}{2}$ will not lead to substantial errors and is justified in approximate analysis. Then, the non-negative solution to this equation is given by the formulae:

$$
\begin{aligned}
v' &= \frac{-2C_N^v - C_Y^v - \sqrt{\left(C_Y^v + 2C_N^v\right)^2 + Y'_{vv}[f_Y(\beta_A) + 2f_N(\beta_A)]}}{2Y'_{vv}}, \\
\delta_R &= \left[f_N(\beta_A) - C_N^v v'\right] / C_N^\delta.
\end{aligned}
\tag{16}
$$

These formulae should be applied for a set of values of $\beta_A \in [0, \pi]$ to check whether the controllability can be lost or not. However, the equilibrium Equation (12) can also be interpreted in other ways.

First, assuming that the ship sails at the controllability limit, i.e., $\delta_R = \delta_m$ and that the value of $\overline{V}_A$ is fixed, it will be possible to solve the set (12) with respect to v' and β_A. However, due to nonlinear dependencies $C_{AY}(\beta_A)$ and $C_{AN}(\beta_A)$ this can only be performed numerically and it is clear that the solution does not exist if at a given $\overline{V}_A$ the ship is controllable with some margin.

In addition, under the same assumption $\delta_R = \delta_m$ it is possible to eliminate v' and to obtain a single equivalent equation which can be represented in one of the following two forms:

$$C_{VVVV}\overline{V}_A^4 + C_{VV}\overline{V}_A^2 + C_{V0} = 0 \tag{17}$$

or,

$$C_{EE}E_R^2 + C_E E_R + C_{R0} = 0, \tag{18}$$

where,

$$
\begin{aligned}
&C_{VVVV} = Y'_{vv}K_{AN}^2, \; C_{VV} = A_{VVEE}E_R^2 + A_{VVE}E_R + A_{VV}, \; C_{V0} = A_{EE}E_R^2 + A_E E_R, \\
&C_{EE} = A_{VVEE}\overline{V}_A^2 + A_{EE}, \; C_E = A_{VVE}\overline{V}_A^2 + A_E, \; C_{R0} = C_{VVVV}\overline{V}_A^4 + A_{VV}\overline{V}_A^2, \\
&A_{VVEE} = \kappa^2 x'_R(K_{AY}x'_R - K_{AN}), \\
&A_{VVE} = \kappa K_{AN}(N'_v + Y'_v x'_R) - 2x'_R(Y'_{vv}K_{AN}\delta_m + \kappa N'_v K_{AY}), \\
&A_{VV} = N'_v(K_{AY}N'_v - K_{AN}Y'_v), \; A_{EE} = x'_R\delta_m(Y'_{vv}x'_R\delta_m - \kappa Y'_v x'_R + \kappa N'_v), \\
&A_E = N'_v\delta_m(Y'_v x'_R - N'_v).
\end{aligned} \tag{19}
$$

The bi-quadric Equation (17) can be easily solved analytically with respect to the relative critical airspeed $\overline{V}_A(\beta_A)$, which corresponds to the maximum ship air speed at which no loss of controllability occurs for the current ship configuration. It is often assumed [19] that the maximum sensitivity to the wind is observed at $\beta_A \approx \frac{3}{4}\pi$. However, while on average this assumption is justified, the most "dangerous" air drift angle can be substantially different and it makes sense to search for $\beta_A = \mathrm{argmin}\overline{V}_A$ which is rather simple in the one-dimensional problem and can be performed, e.g., by means of a dichotomy algorithm. Once the critical values of V_A and β_A are determined, it is possible to determine the minimum value of the absolute wind speed V_w at which controllability can be lost.

A solution to the quadric Equation (18) at fixed values of $\overline{V}_A$ and β_A will provide the minimum required rudder effectiveness index E_R which is always positive. Once the required value of E_R is fixed, the designer can adjust the actual rudder effectiveness mainly through variating the effective rudder area A'_{RE} or the rudder normal force gradient C_{RN}^α. The latter can be increased by increasing the rudder aspect ratio but this must be performed with care as the higher is the aspect ratio, the lower is the stall angle and this highly undesirable stall may then occur at moderately large rudder attack angles.

To close the schemes described above it is necessary to define the dimensionless aerodynamic characteristics of the ship hull $C_{XA}(\beta_A), C_{YA}(\beta_A), C_{NA}(\beta_A)$.

5.2. Aerodynamic Characteristics of Ships for Standardizing Purposes

While ship mathematical models used in ship handling simulators require the most accurate prediction of aerodynamic loads to obtain a more realistic reaction of the model to the simulated wind, the logic of developing manoeuvring standards often permits some conservative approximate estimates which somewhat facilitates the task. In this section, methods for estimating the aerodynamic characteristic of ships are mainly discussed from this viewpoint.

In contrast with the submerged part of the hull of a surface displacement ship, the above-water part is rarely streamlined and very often possesses a rather complicated, edged and peculiar shape especially bearing in mind that not only it includes the hull per se but also superstructures, deckhouses and, possibly, other structures and equipment.

As result, during several decades the aerodynamic characteristics of ships were mainly determined using wind-tunnel tests although lately application of CFD methods is gaining popularity and it is recognized that the credibility of physical and numerical modelling has become comparable [75].

Fortunately, the dependence of the aerodynamic characteristics on the angular velocity of yaw can be neglected and, besides the Reynolds number, the aerodynamic force coefficients will only depend on the air drift (or attack, or sideslip) angle. As most above-water shapes are edged, the separation lines will be fixed and dependence on the Reynolds number is then insignificant. On the other hand, the following circumstances lead to various complications and uncertainties:

1. The natural wind over the sea surface is always more or less gusty which is difficult to reproduce in physical or numerical modelling. However, the frequency of fluctuations either is too high to trigger a more or less significant response of the vessel or they can be handled on the basis of the quasi-steadiness principle. Moreover, while in the classic intact stability weather criterion the gustiness factor is accounted for as the duration of the gust can be comparable with the natural period of roll, the filtering property of the ship in the horizontal plane is much superior as the ship represents then an aperiodic system without any resonant frequencies, the responses will be weaker and the gusts are typically neglected. Of course, in any realistic simulation, at least relatively low-frequency gusts must be modelled and even the quasi-steady part of the load must be complemented with the inertial one [75]. This can be performed using various wind spectra such as those suggested by Davenport, and Harris and Kaimal for gusts along the main wind direction and the spectrum proposed by Lumly and Panofsky for the transverse components, see [75]. However, as mentioned above, the account for realistic air velocity fluctuations is hardly important for manoeuvring standardizing purposes when just some constant wind velocity can be specified.

2. When a typical above-water shape is subject to an absolutely steady and uniform flow, the resulting perturbed flow will not remain steady and the observed loads will not be constant because of unsteady vortex shedding. However, the resulting fluctuations are always of relatively high frequency and will not affect the ship motion. In wind-tunnel experiments and in the CFD modelling, the observed time series are filtered and averaged resulting in average steady values of the forces.

3. The full-scale Reynolds number cannot be reached in atmospheric wind tunnels used in ship hydrodynamics applications. On edged forms typical for ship superstructures the scale effect is negligible what was directly confirmed by comparative CFD computations performed at model and full-scale values of the Reynolds number. However, if a ship contains substantial non-edged elements similar to cylinders or spheres, application of appropriately placed turbulence stimulators is recommended. In general, the results of well performed wind-tunnel tests can be taken with sufficient credibility and applied for estimating loads on full-scale ships.

4. When the wind blows over the sea surface, a boundary layer is formed resulting in a sheared flow with the velocity distribution typically following the 1/7 power law [75]. If the wind tunnel tests are carried out using a ground plate, the situation is similar but the relative thickness of the boundary layer is different. Typically, the wind-tunnel data are brought to the uniform flow and the apparent wind in simulations is also supposed to be uniform with the equivalent speed corresponding to the 10 m height above the sea level. In most cases, this will yield somewhat conservative estimates that seem to be beneficial for standardizing purposes.

5. The apparent wind is composed of the true wind and and of that originating from the motion of the ship with respect to the still air. In the second case, the flow is not sheared and the resulting relative flow can have different directions on various heights forming the so-called "twisted wind". This effect practically cannot be reproduced in the wind tunnel but can be modelled with CFD. However, as long as so far no data on this phenomenon were reported, the common practice is to neglect the effect.

It can be assumed, that as long as results of appropriate wind-tunnel tests or CFD computations for a given configuration are available, they can be effectively applied for simulating the manoeuvring motion of the corresponding ship in wind or for checking compliance with some wind related criteria. The experimental option is nowadays relatively costly not because of wind-tunnel tests per se, which are in this case simple and not excessively time-consuming, but because of the necessity of manufacturing required scaled models although maybe rapid development of the 3D printing will reduce this cost considerably.

If the above-water configuration of a ship is close to one of the models tested before and the corresponding aerodynamic coefficients are available, these can be used with a rather high degree of certainty. However, the prototype approach is not always possible and several attempts to devise "universal" methods were undertaken. For instance, the method developed by Melkozerova and Pershitz, see [57], provides approximations for the sway force and moment coefficients for single-island and twin-island superstructures whose relative lengths and positions of the centroids serve as defining factors.

Later two alternative empiric methods were developed on the basis of systematic wind-tunnel tests: the method of parametric loading functions developed by Blendermann and the method of trigonometric series. Both methods are described in detail by Blendermann [75] and are only outlined below.

The method of loading functions is a specific approximation of tabulated aerodynamic characteristics performed over 15 ship types and allowing corrections for the longitudinal position of the centroid of the lateral windage area. The method of trigonometric series was developed by Fujiwara and it presumes approximation of the aerodynamic coefficients with 3 or 4-terms trigonometric polynomials over the whole range of the sideslip angle. The coefficients of these trigonometric polynomials are algebraic polynomial regressions on a set of geometric parameters. Specifics of the latter is the separate treatment of the geometry of the above-water hull per se and of the superstructures. Recently, an interesting and promising method based on the combination of elliptic Fourier descriptors with artificial neural networks was proposed [76] but still not brought to the practical tool level.

The methods outlined above are more suitable for simulation applications requiring accurate predictions of aerodynamic loads. As was mentioned earlier, standardization tasks can be often effectively handled using some approximate or upper-end conservative estimates and a simple method aiming at possessing such properties is proposed below.

A simple generic model for the surge and sway force coefficients is based on the evident fact that all loads are 2π-periodic. Then, accounting for the evident symmetry properties and retaining only the first non-zero terms in the Fourier expansion of the coefficients it is obtained:

$$C_{AX} = -C_{AX0} \cos \beta_A, \ C_{AY} = C_{AY0} \sin \beta_{A,} \tag{20}$$

where C_{AX0} and C_{AY0} are some positive constant parameters representing the magnitude of the aerodynamic force in head/stern or beam apparent wind, respectively.

The average recommended values of these parameters are [57]:

$$C_{AX0} = 1.0, \ C_{AY0} = 1.05. \tag{21}$$

Of course, these values are approximate, suggested many decades ago and reflect the averaged properties of the then existing hull shapes. In addition, an alternative and even more obsolete value $C_{AY0} = 1.2$ is mentioned in the book [56].

To estimate possible uncertainties associated with approximations (20), it makes sense to check them against recent experimental data. The richest available database of this kind is that collected by Blendermann on the basis of his own wind tunnel tests. Blenedermann's data can be found in 3 sources: in the reference book [77], in the report [78] and the manual [75]. The cited report describes the most complete database containing data for 48 configurations (in some cases two different configurations correspond to the same ship

but at different loading conditions). A thorough comparison carried out by the authors showed that 21 of these configurations were also presented in [77], and 21—in [75]. All data from the report [78] were checked against alternative sources and digitized by the authors using the available tables of values. The book [77] contained one additional configuration not present in the report and it was decided to ignore it.

The experimental data for C_{AX} are plotted as symbols in Figure 3 where also the response provided by (20) is shown as a dashed line. It is evident that this simple model provides a fair averaged estimation for the set of empiric data but in many cases, the magnitude of the surge force is substantially underestimated. To provide more conservative estimates, the following two-term equation can be proposed:

$$C_{AX} = -C_{AX0}^M \cos \beta_A + C_{AX0}^5 \cos 5\beta_A \tag{22}$$

with $C_{AX0}^M = 1.35$ and $C_{AX0}^5 = 0.2$, and the corresponding response is shown in Figure 3 with a solid line. It is obvious that the formula (22) does really provide an upper limit for the absolute value of the surge force for most configurations, The experimental points more or less significantly dropping outside the envelope at air drift angles around 30 and 150 degrees correspond not exactly to a ship but to an empty floating dock with rather high walls but with a relatively small transverse section area. So, Equation (22) with the indicated values of the constant parameters can be recommended if really conservative estimates are desirable. A similar analysis was also performed for the sway force coefficient in Figure 4 where the dashed line represents the response provided by the Equation (20) and the solid line—by the following model:

$$C_{AY} = C_{AY0}^M \sin \beta_A + C_{AY}^3 \sin 3\beta_A \tag{23}$$

with $C_{AY0}^M = 1.17$ and $C_{AY}^3 = 0.15$.

The latter formula produces a rather clear envelope for almost all experimental data except those corresponding to the same floating dock and, at $\beta_A = 60°$, to a car carrier with an exceptionally high freeboard.

Analysis of data for the yaw moment coefficient turns out somewhat more complicated as an additional parameter comes into play. The generic model for the yaw moment coefficient is [57]:

$$C_{AN}(\beta_A) = C_{AY}(\beta_A) \cdot x_A'(\beta_A), \tag{24}$$

where x_A' is the relative lever of the sway force which, in its turn, is represented as

$$x_A'(\beta_A) = x_w' + \Delta x_A'(|\beta_A|), \tag{25}$$

where $x_w' = x_w / L_{OA}$ is the relative abscissa of the centroid of the lateral windage area and the function $\Delta x_A'()$ accounts for the displacement of the sway force application point and can be approximated as

$$\Delta x_A' = k_x \left(\frac{1}{4} - \frac{|\beta_A|}{2\pi} \right), \tag{26}$$

which is generalization of the equation recommended in [56,57] where it is assumed that $k_x \equiv 1.0$.

Blendermann's data on the sway force and yaw moment coefficients were used to generate experimental values of $\Delta x_A'$ using the evident relation:

$$\Delta x_A' = C_{AN}(\beta_A) / C_{AY}(\beta_A) - x_w' \tag{27}$$

and the resulting values are plotted as symbols in Figure 5 except for the values corresponding to the drift angles close to 0 or 180 degrees as the absolute values of C_{AY} and C_{AN} are very small which may lead to unnaturally high relative errors in $\Delta x_A'$.
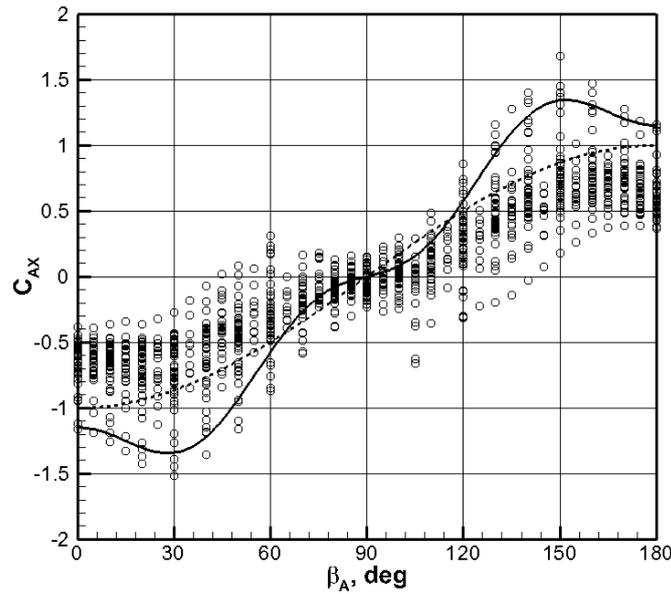
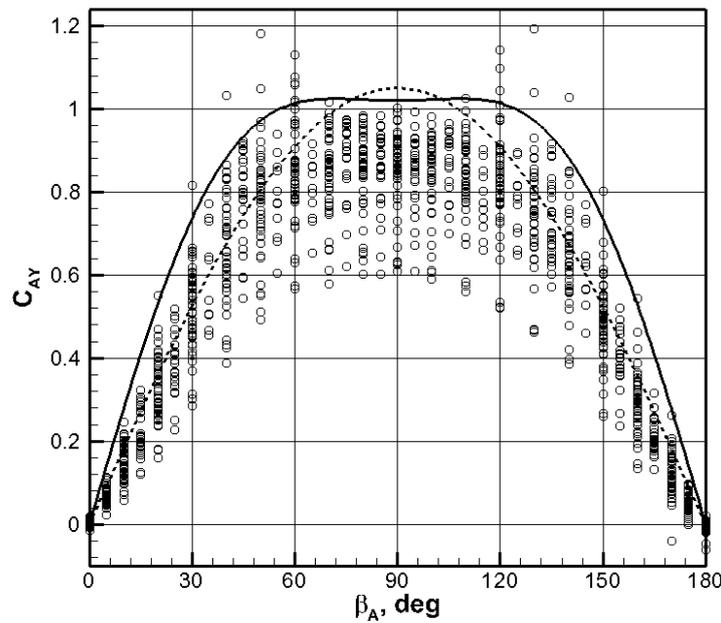**Figure 3.** Experimental (circles) and analytical (lines) data for surge force coefficient.

Figure 4. Experimental (circles) and analytical (lines) data for sway force coefficient.

The responses provided by (24) at $k_x = 1.0$ (dashed line) and $k_x = 0.8$ (solid line) are also plotted there. It is obvious that the scatter of empiric data is considerable, and in any particular case, the error caused by using (24) can be very large. However, in general, the linear approximation looks reasonably adequate and the value $k_x = 1$ leads to somewhat more conservative estimates. At the same time, the value $k_x = 0.8$ worked somewhat better delimiting the stripe of the x'_A values for various x'_w. The lower line in Figure 6 was obtained from (24) at $k_x = 0.8$ and $x'_w = -0.11$ which is the lowest value of the centroid's abscissa for all configurations presented in [78] while the upper line corresponds to $x'_w = +0.13$ which is the highest value.
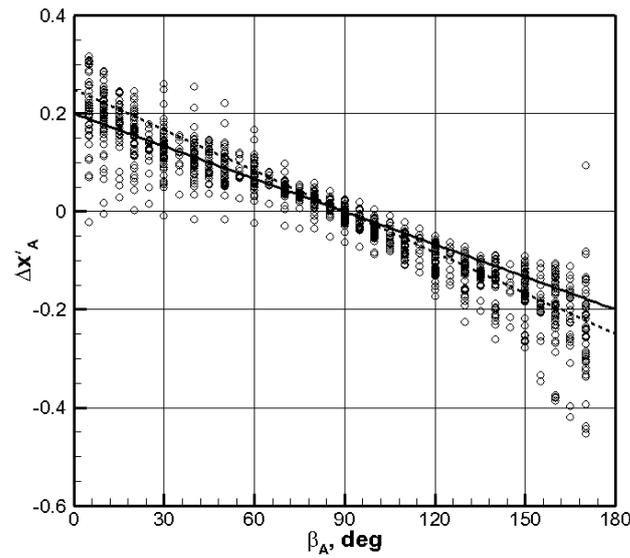
Figure 5. Increment of sway force lever as a function of the air drift angle.
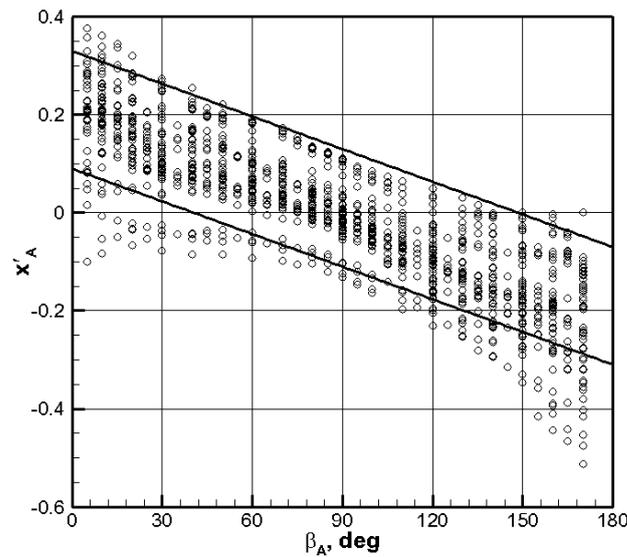
Figure 6. Sway force lever as a function of the air drift angle.

Finally, the measured values of the yaw moment coefficients C_{AN} are plotted in Figure 7 together with the predictions obtained with the formula (24) at $x'_w = -0.11$ (lower line), $x'_w = 0$ (middle line) and $x'_w = 0.13$ (upper line). The outlying empiric values correspond to a ro-ro/lo-lo ship, to a tanker with the aft superstructures and to the floating dock mentioned above.

Regarding some possible future developments, it makes sense to note that Dand [26] proposed two additional parameters describing the windage area geometry: the lateral aspect ratio $k_{AL} = 2A_L/L_{OA}^2$ and the transverse aspect ratio $k_{AT} = 2A_T/L_{OA}^2$. Unfortunately, the authors are not aware of any attempts to use these parameters for the classification and clusterization of ship aerodynamic data.
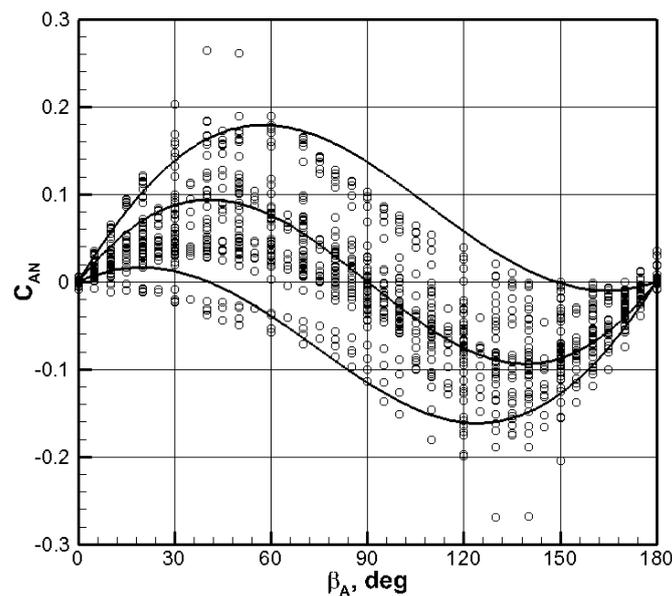
Figure 7. Experimental (circles) and analytical (lines) data for yaw moment coefficient.

6. Discussion and Conclusions

An attempt to work out rational approaches to the development of manoeuvrability criteria and standards was undertaken and is described in the present article. A definite emphasis was put on additional "environmental" criteria, which aim at complementing the existing IMO set of standards. Even though primarily it was found more rational to avoid criteria related to the resisting capacity of a ship to exogenous factors leaving this issue to performance specifications supposed to be formulated by the customer, the recently emerged danger of the appearance of underpowered and more prone to external factors ships stimulated revision of that attitude. As long as the introduction of the Energy Efficiency Design Indices stimulating the under-powering was performed on the level of officially introduced IMO regulations, it is quite natural to balance those indices with some counter-weighting requirements in order to prevent unacceptable reduction of safety.

A natural solution could be to accompany the reduction of the engine power and the design speed with appropriate augmentation of the effectiveness of the main control device in such a way that the resistance capacity of the ship to external factors remains unchanged. In some respects, such formulation of the manoeuvrability standardization problem is not typical and requires a special analysis, which is presented in this article. The main result of this analysis is an outline of a procedure for modification and extension of the IMO set of manoeuvring standards which seems to be relatively simple and promising. The procedure presumes execution of the following steps:

1. The existing turning ability standards, i.e., the limiting values for the relative advance and tactical diameter must be somewhat tightened on the basis of statistical data corresponding to the vessels currently in operation. Collection of these data may present certain organizational difficulties but, as long as all ships are now equipped with GPS units, it is, likely, possible, first, to create appropriate guides for shipmasters and to find means for stimulating them to perform necessary tests which are rather simple. In addition to the objective numerical data, it is also important to collect information about the subjective linguistic evaluation of manoeuvring qualities of ships by their operators.

2. The same as stated in the previous item applies to the directional stability measured by the values of the overshoot angles in zigzag manoeuvres which are relatively simple to be carried out during the operation of ships. It is expected that the existing IMO requirements could be re-considered and tightened.

3. The ship wind resisting capacity should be standardized separately on the basis of an additional criterion and some suitable standardization schemes must be adopted. It is suggested to use the classic criterion, i.e., the ability of a ship to sail with an arbitrary course (or heading, or apparent wind angle) under the action of wind with a certain specified speed. The wind controllability problem was formulated in the general form and it was further subject to reduction aiming at simplification of the standardizing procedure while still capturing correctly dependence on the most important parameters, i.e., on the ship speed and on its relative windage area. Likely, the most practical approach should be based on Equation (18) whose solution will provide a requirement to the relative rudder effectiveness defined by (14). The actual rudder effectiveness index is supposed to be estimated using any approved or commonly acknowledged method. Of course, the term "rudder" must be interpreted in the generalized sense embracing also steering nozzles and azipods. The standardizing value of the wind speed should be set from statistical considerations and, judging from the earlier standardization experience, its expected value may lie in the interval from 15 to 30 m/s.

4. Estimation of aerodynamic loads is part of any wind controllability standardization scheme. While the wind tunnel or CFD data are preferable when the ship configuration is fixed with certainty, simpler empiric methods can be recommended for early design stages. A very simple conservative method especially suitable for standardizing tasks and based on envelopes constructed on the wind tunnel data is suggested in the present article.

5. Reduction of the available engine power of newly built ships stimulated by the EEDI requirements can and must be compensated by increasing the effectiveness of the main steering device in order to keep the same level of resistibility of ships to the external factors. A direct appropriate augmentation of the rudder area in theory always solves the problem but may become unacceptable from the viewpoint of arrangement of the steering complex. In such cases, implementation of rudders with increased effectiveness such as the Schilling or flap rudder possibly combined with the installation of additional skegs or fixed fins may become a more suitable alternative. Other novel developments such as the so-called gate rudders [79] may be considered. Less evident possible solutions could be based on arrangements used on inland (river-going) ships that can include multiple rudders, combinations of rudders with steering nozzles, flanking rudders etc., see, e.g., [80]. However, these "inland" arrangements must be adapted with caution as a rather high degree of directional instability is often tolerable for river-going vessels rarely subject to perturbations from waves and the inherent stability of the resulting configuration must be verified with care.

6. It is evident that compensation of negative effects of the reduced powering through augmentation of the effectiveness of the steering device always comes at some cost. It is not clear whether these extra costs were considered when the EEDI requirements were worked out. However, much earlier Lowry [35] discussed possible costs of improving controllability and remarked that they will be hardly acceptable if exceed the overall construction and operation costs by more than 1–2%. Of course, this estimate is very crude and may be reconsidered.

It can be concluded from the present study that future progress in developing consistent and practical manoeuvring standards depends on development of a fast, reliable and validated method for simulating manoeuvring motion in waves. Systematic simulations with various hull forms are expected to provide sufficient information for confirming or disproving the hypothesis of concurrency of manoeuvring qualities in still water and of behaviour of a ship in waves. If the hypothesis is confirmed, modification of IMO standards can be carried out. Of course, such modification, as well as development of additional standards for controllability in wind, will require adjustment to statistical data on the existing fleet.

References

1. *Standards for Ship Manoeuvrability*; International Maritime Organization (IMO); Resolution MSC.137(76)4. Available online: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.137(76).pdf (accessed on 16 August 2021).
2. Biran, A.; Pulido, R.L. *Ship Hydrostatics and Stability*; Butterworth–Heinemann: Amsterdam, The Netherlands, 2003.
3. Lugovsky, V.V. *Theoretical Foundation of Standardization of Intact Stability of Sea-Going Vessels*; Sudostroyeniye Publ.: Leningrad, Russia, 1971. (In Russian)
4. The Stability in Waves Committee: Final Report and Recommendations to the 29th ITTC. 2021. 57p. Available online: https://ittc.info/media/9110/stability-in-waves-committee.pdf (accessed on 16 August 2021).
5. Jensen, J.J.; Choi, J.-H.; Kristinsen, H.O.; Nielsen, H.O.; Nielsen, U.D.; Erichsen, H.; Tvedt, E.I. An attempt to define critical wave and wind scenarios leading to capsize in beam sea. In Proceedings of the 13th International Symposium on Practical Design of Ships and Other Floating Structures (PRADS'2016), Copenhagen, Denmark, 4–8 September 2016; 8p.
6. Mironiuk, W. A research model of a ship's angle of heel. *Zeshyty Naukowe Akademii Morskiej w Szczecinie* **2016**, *46*, 43–48.
7. IMO Resolution MSC.267(85). Adoption of the International Code on Intact Stability, 2008 (2008 IS Code). Adopted on 4 December 2008. Available online: https://wwwcdn.imo.org/localresources/en/KnowledgeCentre/IndexofIMOResolutions/MSCResolutions/MSC.267(85).pdf (accessed on 16 August 2021).
8. Rules for Classification and Construction of Sea-Going Ships. In *Part III: Equipment, Arrangements and Outfit*; ND No. 2-020101-138-E; Russian Maritime Register of Shipping: St. Petersburg, Russia, 2021.
9. Shigunov, V. Direct stability assessment pragmatic solutions. *Ship Technol. Res.* **2017**, *64*, 144–162. [CrossRef]
10. Kobyliński, L. Stability criteria—Present status and perspectives of improvement. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2014**, *8*, 281–286. [CrossRef]
11. Shigunov, V.; Papanikolaou, A. Criteria for minimum powering and maneuverability in adverse weather conditions. *Ship Technol. Res.* **2015**, *62*, 140–147. [CrossRef]
12. Sutulo, S.; Guedes Soares, C. Analysis of manoeuvrability criteria and standards in view of environmental factors and EEDI impact. In *Maritime Technology and Engineering 3*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2016; pp. 371–383.
13. The Specialist Committee on Manoeuvring in Waves: Final Report and recommendations to the 29th ITTC. 2021. 33p. Available online: https://ittc.info/media/9106/sc-manoeuvring-in-waves.pdf (accessed on 16 August 2021).
14. Sutulo, S.; Guedes Soares, C. Mathematical models for simulation of manoeuvring performance of ships. In *Marine Technology and Engineering*; Guedes Soares, C., Garbatov, Y., Fonseca, N., Teixeira, A.P., Eds.; Taylor & Francis Group: London, UK, 2011; pp. 661–698.
15. Quadvlieg, F.H.H.A.; Armaoğlu, E.; Eggers, R.; van Coeverden, P. Prediction and verification of the maneuverability of naval surface ships. *Trans. Soc. Nav. Archit. Mar. Eng.* **2010**, *118*, 180–197.
16. Baquero, A. Consideration of ship manoeuvrability in the preliminary design phase (in Spanish). *Ing. Nav.* **1982**, *50*, 284–295.

17. Norrbin, N.H. Ship handling standards—Capabilities and requirements. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 37–50.

18. Koyama, T.; Kose, K. Recent studies and proposals of the manoeuvring standards. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 545–553.

19. Mastushkin, Y.M. *Manoeuvrability of Fishing Vessels*; Lyogkaya i Pishchevaya Promyshlennost Publ.: Moscow, Russia, 1981. (In Russian)

20. Stevens, B.; Lewis, F.L.; Johnson, E.N. *Aircraft Control and Simulation*; John Wiley and Sons: Hoboken, NJ, USA, 2016.

21. Segel, L. Ship maneuverability as influenced by the transient response to the helm. In Proceedings of the First Symposium on Ship Maneuvering, David Taylor Model Basin, Washington, DC, USA, 24–25 May 1960; pp. 151–177.

22. Sutulo, S.V. On the ergonomic approach to evaluation of ship manoeuvring criteria, Trans. In Proceedings of the International Symposium Manoeuvrability'95", Iława, Poland, 16–19 October 1995; pp. 93–118.

23. Nobukawa, T.; Kato, T.; Motomura, K.; Yoshimura, Y. Studies on manoeuvrability standards from the viewpoint of marine pilots. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 59–66.

24. Biancardi, C.G.; Cavazzi, D.; Grazziano, G.; Mosullo, M.T. Full scale measurements of a set of yaw/sway manoeuvring Q-indices. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 1996 (MARSIM'96), Copenhagen, Denmark, 9–13 September 1996; pp. 635–642.

25. Belenky, V.; Falzarano, J. Rating-based maneuverability standards. *ABS Tech. Pap.* **2006**, 227–246. Available online: https://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.432.5803&rep=rep1&type=pdf (accessed on 16 August 2021).

26. Dand, I. Low speed manoevring criteria: Some considerations. In Proceedings of the International Conference on Marine Simulation and Ship Maneuverability, MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. KN-4-1–KN-4-8.

27. Quadvlieg, F. Current status of manoeuvring prediction methods, their mutual pros and cons and ways to quantify the capabilities. In Proceedings of the Yücel Odabaşı Colloquium Series—2nd International Meeting "Recent Advances in Prediction Techniques for Safe Manoeuvring of Ships and Submarines", Istanbul, Turkey, 17–18 November 2016; pp. 1–9.

28. McCallum, I.R. "Which model?"—A critical survey of ship simulator mathematical models. In Proceedings of the Third International Conference on Marine Simulation (MARSIM'84), Rotterdam, The Netherlands, 19–22 June 1984; pp. 375–387.

29. Bassin, A.M. *Ship Propulsion and Manoeuvrability: Manoeuvrability*; Transport Publ.: Moscow, Russia, 1968. (In Russian)

30. Zaky, M.; Yasukawa, H. Effect of load condition on zig-zag manoeuvres of a VLCC in adverse weather conditions. In Proceedings of the International Conference on Ship Manoeuvrability and Maritime Simulation (MARSIM'2018), Halifax, NS, Canada, 12–16 August 2018; Paper 2, 10p.

31. Yudin, E.B. Measure of operational directional stability of ships. *Trans. Krylov Ship Res. Inst.* **1967**, *239*, 72–81. (In Russian)

32. Oltmann, P. Identification of hydrodynamic damping derivatives—A pragmatic approach. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. 575–583.

33. International Maritime Organization: Explanatory notes to the standards for ship manoeuvrability. MSC/Circ. 1053. 16 December 2002. 41p. Available online: https://www.register-iri.com/wp-content/uploads/MSC.1-Circ.1053.pdf (accessed on 16 August 2021).

34. Srivastava, S.D. IMO's activities on ship manoeuvring. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability (MARSIM'93), St. John's, NL, Canada, 26 September–2 October 1993; pp. 527–541.

35. Norrbin, N.H. Ship geometry, a dynamic stability parameter and standard test analysis. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability (MARSIM'93), St. John's, NL, Canada, 26 September–2 October 1993; pp. 447–456.

36. Nikolayev, E.; Inutina, T.; Lebedeva, M. On ship manoeuvrability estimation based on IMO resolution No. A.751(18). In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 1996 (MARSIM'96), Copenhagen, Denmark, 9–13 September 1996; pp. 303–307.

37. Li, M.; Wu, X. Simulation calcu;ation and comprehensive assessment of ship manoeuvrabilities in wind, wave, current and shallow water. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 403–411.

38. Ræstad, A.E. A classification society's experience with IMO resolution No. A.751(18). In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 1996 (MARSIM'96), Copenhagen, Denmark, 9–13 September 1996; pp. 309–318.

39. Yoshimura, Y.; Kose, K.; Haraguchi, T. Criteria for yaw-checking and course-keeping abilities in IMO's Interima standards for ship manoeuvrability. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 2000 (MARSIM 2000), Orlando, FL, USA, 8–12 May 2000; pp. 367–378.

40. Quadvlieg, F.H.H.A.; van Coeverden, P. Manoeuvring criteria: More than IMO A751 requirements alone! In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; Volume 2, pp. 291–298.

41. Rhee, K.P.; Kim, S.Y.; Sung, Y.J.; Son, N.S. On the correlation between the overshoot angles in zigzag tests and the navigational difficulty. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; Volume 2, pp. 299–307.

42. Haraguchi, T.; Nimura, T. A study on manoeuvrability standards for a ship with a POD propulsion system. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. 308–315.

43. Sohn, K.; Yang, S.; Lee, D.; Bae, J. A simulator study on yaw-checking and course-keeping ability of unstable ships. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; Volume 2, pp. 327–333.

44. Yamada, K. Application of ship-handling/manoeuvrability criteria to stern configuration and rudder area design. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; Volume 2, pp. 316–326.

45. Ohtakagi, Y.; Tanaka, M. Application of real-time ship manoeuvring simulator in the past ten years. In Proceedings of the Third International Conference on Marine Simulation (MARSIM'84), Rotterdam, The Netherlands, 19–22 June 1984; pp. 25–37.

46. Nishimura, T.; Kobayashi, H. The estimation of ship manoeuvrability for controlling position of unstable ships. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. 334–343.

47. Yasukawa, H.; Zaky, M.; Yonemasu, I.; Miyake, R. Effect of engine output on maneuverability of a VLCC in still water and adverse weather conditions. *J. Mar. Sci. Technol.* **2017**, *22*, 574–586. [CrossRef]

48. Sutulo, S.V. On the manoeuvring standards for sea-going vessels. *Trans. Russ. Marit. Regist. Shipp.* **1996**, *19*, 109–121. (In Russian)

49. Shigunov, V. Norming manoeuvrability in adverse conditions. *J. Offshore Mech. Arct. Eng.* **2017**, *139*, 1–10. [CrossRef]

50. Shigunov, V. Manoeuvrability in adverse conditions: Rational criteria and standards. *J. Mar. Sci. Technol.* **2018**. [CrossRef]

51. Spyrou, K.; Vassalos, D. Recent advances in the development of ship manoeuvring standards. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 51–58.

52. Lowry, I.J. Ship of Japan controllability: An industrial perception. In Proceedings of the MARSIM and ICSM 90 (Joint International Conference on Marine Simulation and Ship Manoeuvrability), Tokyo, Japan, 4–7 June 1990; pp. 333–340.

53. MacLean, A. *HMS "Ulysses"*; Harper Collins Publ.: London, UK, 1994.

54. Alekseyev, L.L. *Practical Manual on Handling Seagoing Vessels*; CNIIMF Publ.: St. Petersburg, Russia, 2003. (In Russian)

55. Chillcce, G.; el Moctar, O. A numerical method for manoeuvring simulation in regular waves. *Ocean. Eng.* **2018**, *170*, 434–444. [CrossRef]

56. Pershitz, R.Y. *Ship Manoeuvrability and Steering*; Sudostroyeniye Publ.: Leningrad, Russia, 1983. (In Russian)

57. Voytkunsky, Y.I. (Ed.) *Handbook on Ship Hydrodynamics*; Sudostroyeniye Publ.: Leningrad, Russia, 1985. (In Russian)

58. Sutulo, S.; Guedes Soares, C. Preliminary analysis of ship manoeuvrability criteria in wind. In *Maritime Technology and Engineering*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2015; pp. 933–946.

59. Gong, I.-Y.; Yang, Y.-H.; Yun, K.-H.; Park, S.-K.; Oh, J.-Y.; Kim, S.-Y.; Jeong, M.-H.; Seo, T.-H.; Baek, M.-S. The influence of ship maneuverability modelling on the navigational safety assessment result. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 2012 (MARSIM'2012), Singapore, 23–27 April 2012; pp. 740–748.

60. Kang, C.-G.; Kim, J.-H. Assessment of ship manoeuvrability based on IMO resolution No. A.751. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 1996 (MARSIM'96), Copenhagen, Denmark, 9–13 September 1996; pp. 293–302.

61. Capurro, G.; Sodomaco, P. Applications of the manoeuvring prediction program SIMSUP to meet the new IMO standards. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability 1996 (MARSIM'96), Copenhagen, Denmark, 9–13 September 1996; pp. 563–576.

62. Jurgens, A.J.; de Jager, A. Controllability at too high speeds in too shallow water. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM 2006, Terschelling, The Netherlands, 25–30 June 2006; pp. 393–404.

63. Zhang, W.; Zou, Z.-J.; Deng, D.-H. A study on prediction of ship maneuvering in regular waves. *Ocean. Eng.* **2017**, *137*, 367–381. [CrossRef]

64. Kobayashi, E. Development of a simulation system to evaluate ship manoeuvrability in waves. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability (MARSIM'93), St. John's, NL, Canada, 26 September–2 October 1993; pp. 295–303.

65. Woodward, M.D.; Clarke, D.; Atlar, W. On the manoeuvring prediction of pod driven ships. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. 344–352.

66. Eda, H.; Numano, M. Analysis of major marine disasters. In Proceedings of the International Conference on Marine Simulation and Ship Manoeuvrability MARSIM'03, Kanazawa, Japan, 25–28 August 2003; pp. 547–554.

67. Martin, L.L. Ship Maneuvering and control in wind. *SNAME Trans.* **1980**, *88*, 257–281.

68. Yasukawa, H.; Yoshimura, Y. Introduction of MMG standard method for ship maneuvering predictions. *J. Mar. Sci. Technol.* **2015**, *20*, 37–52. [CrossRef]

69. Sutulo, S.; Guedes Soares, C. On the application of empiric methods for prediction of ship manoeuvring properties and associated uncertainties. *Ocean. Eng.* **2019**, *186*, 106111. [CrossRef]

70. Sutulo, S.; Guedes Soares, C. Comparative simulation of definitive manoeuvres of the KVLCC2 benchmark ship using different empiric mathematical models. In *Maritime Transportation and Harvesting of Sea Resources*; Guedes Soares, C., Teixeira, A.P., Eds.; Taylor & Francis Group: London, UK, 2018; Volume 1, pp. 571–579.
71. Eda, H. Low-speed controllability of ships in wind. *J. Ship Res.* **1968**, *80*, 181–200. [CrossRef]
72. Benedict, K. Wind influence on directional stability and turning of ships. In Proceedings of the 14th Scientific and Methodological Seminar on Ship Hydrodynamics (SMSSH), Varna, Bulgaria, 24–27 September 1985; Volume 1, pp. 11.1–11.11.
73. Sutulo, S.V. A study on the course keeping of a ship in wind. In Proceedings of the 14th Scientific and Methodological Seminar on Ship Hydrodynamics (SMSSH), Varna, Bulgaria, 24–27 September 1985; Volume 1, pp. 12.1–12.8. (In Russian)
74. Spyrou, K. Yaw stability of ships in steady wind. *Schiffstechnik/Ship Technol. Res.* **1995**, *42*, 21–30.
75. Blendermann, W. *Practical Ship and Offshore Structure Aerodynamics*; Technische Universität Hamburg-Harburg: Hamburg, Germany, 2013.
76. Prpić-Oršić, J.; Valčić, M. Sensitivity analysis of wind load estimation method based on elliptic Fourier descriptors. In *Maritime Technology and Engineering 3*; Guedes Soares, C., Santos, T.A., Eds.; Taylor & Francis Group: London, UK, 2016; pp. 151–160.
77. Brix, J. (Ed.) *Manoeuvring Technical Manual*; Seehafen Verlag: Hamburg, Germany, 1993.
78. Blendermann, W. *Wind Loading of Ships—Collected Data from Wind Tunnel Tests in Uniform Flow*; Technical Report Nr. 574; Institut für Schiffbau der Universität Hamburg: Hamburg, Germany, 1996.
79. Carchen, A.; Turkmena, S.; Piaggiob, B.; Shia, W.; Sasakic, N.; Atlarc, M. Investigation of the manoeuvrability characteristics of a Gate Rudder system using numerical, experimental, and full-scale techniques. *Appl. Ocean. Res.* **2020**, *106*, 102419. [CrossRef]
80. Quadvlieg, F.H.H.A. Mathematical models for the prediction of manoeuvres of inland ships: Does the ship fit in the river. In Proceedings of the "Smart Rivers 2013", Liège, Belgium, 23–27 September 2013; Paper 187, pp. 1–9.