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Analysis of manoeuvrability criteria and standards in view of environmental factors and EEDI impact

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ABSTRACT: A review and analysis of most significant earlier proposals on ship manoeuvring criteria are presented with the emphasis made on comparative significance and interconnection of inherent and environment-dependent criteria. It is demonstrated, mainly by means of plausible reasoning, that, besides possible toughening of the existing IMO standards based on purely inherent criteria for the turning ability and directional stability of ships, the only necessary additional criteria should be associated with the wind action and aerodynamic properties of the above-water part of the hull. A possible rational approach to formulating manoeuvrability criteria accounting for EEDI requirements is presented.
A detailed review of former proposals of Authors of papers to proceedings have to type these in a form suitable for direct photographic reproduction by the publisher. In order to ensure uniform style throughout the volume, all the papers have to be prepared strictly according to the instructions set below. A laser printer should be used to print the text. The publisher will reduce the camera-ready copy to 75% and print it in black only. For the convenience of the authors template files for MS Word 6.0 (and higher) are provided.

1 INTRODUCTION

The safety issue is undoubtedly very important for operation of any means of transportation including all ground vehicles, aircraft and marine craft. Although every branch of the "sea–air–land" triad has something in common with the other two, specifics are also evident and historically operation safety studies were carried out independently. However, at certain level of development some crossover of the concepts and results may become useful for better understanding of underlying differences and imperfections of currently adopted solutions.

All cases of compromised safety leading to disasters or minor accidents, e.g. (Guedes Soares & Teixeira 2001), are due to one or more of the following factors which, however, to some extent depend on each other:

1. **Force majeure** situation.
2. Deliberate **hostile actions**, most typical for wartime when the adversary action can be expected but terrorist attacks are possible during the peacetime as well.
3. **Insufficient reliability** of technical systems caused by inappropriate design and/or manufacturing.
4. **Human factor** which includes negligence in maintenance, as well as negligence in service duties, erroneous decisions and commands.
5. **Inadequate design** solutions and poor engineering.

In the present paper the focus will be made on the factor 5 mainly in application to water transportation and, even more specifically, to sea-going surface displacement ships.

Regarding this type of craft it seems natural to consider the following safety aspects which are highly dependent on the quality of the design decisions taken:

1. **Powering:** only sufficiently powered ships have good chances to withstand adverse external factors.
2. **Good seakeeping qualities:** a ship must not be prone to capsizing or loss of strength in heavy weather.
3. **Unsinkability:** certain level of the hull damage must not be fatal for the ship.
4. **Controllability:** manoeuvring qualities of any vessel must be sufficient for safe navigation under command of reasonably well qualified seafarers.

It is evident that the safety issue can never be considered as the only design objective and even hardly it can be viewed as the primary one. When it goes about merchant or fishing vessels, the primary goal of the industry is to design and build economically sound and competitive ships. It is obvious that to some extent safety and efficiency requirements are contradictory and the balance between the former and the latter is reached as result of a compromise which has been evolving during many centuries. Results of such a natural evolution are clearly visible on classic wooden sailing ships. But the 19^{th} century industrial revolution dramatically accelerated development of all means of transportation including the ships and the "natural selection" began to lag behind implemented changes and improvements. This resulted in the appearance of various rules and standards which were to be met independently of the agreement between the designer and the customer. It happened earlier for the strength and seakeeping issues while only relatively recently, and even not completely, when it goes about manoeuvrability.

As to powering, it has been traditionally associated not with safety but rather with economic issues depending mainly on the contractual speed and on the hydrodynamic quality of the hull and propulsor. While the latter have almost reached perfection due to extensive studies carried out in towing tanks and by the methods of Computational Fluid Dynamics (CFD) and possible gains are typically measured in few percent, the contractual speed value was mainly driven by traditions established by evolution for certain ship types although some elementary economic analysis was also often applicable.

While direct expenses are roughly proportional to the cube of the speed (at least, at low and moderate Froude numbers) and reduction of the latter may seriously reduce the per mile operational costs, the speed cannot be reduced indefinitely as part of the costs depend on the voyage time (like the crew's salary) and too slow transportation can be less attractive for the customers in spite of lower fees. It is not planned here to carry out detailed analysis of all possible factors defining a presumably optimal contractual speed value but it is clear that those factors are many and the weight of some of them is changing which can result in shifting that speed value to one or another direction. In particular, during 1–2 last decades two factors have become more significant than before:

1. Long period of elevated oil prices resulting in increased prices of the most common marine fuels.
2. Increased concern about emissions produced by water transport.

Both factors are concurrent in the sense that when other defining parameters of the engine are fixed, the volume of emissions is proportional to the amount of the fuel burnt. The difference is that the second factor is less volatile: currently (first quarter of 2016) the oil price keeps low values while the emission-related concern is remaining unchanged. These factors lead to appearance of the so-called "slow steaming" or "slow sailing" which meant reduction of the ship operation speed compared to what had been usual in former seamanship practice (Psarafitis and Kontovas 2010). This, however, resulted in the engines operated substantially off the design point at a lower efficiency and often with poorer composition of the emissions (Cariou 2011). The evident solution was to reduce the power of the newly built vessels which is in fact encouraged by introduction of the so-called Energy Efficiency Design Index (EEDI) for most newly built or heavily refurbished diesel-powered cargo ships (IMO 2013), (Carlton 2012) whose acceptable value is supposed to be gradually decreased in course of years.

It must be recognized that the introduction of the EEDI was accompanied by understanding that it can stimulate appearance of underpowered ships and that certain safe speed and minimum power requirements must be introduced in order to guarantee sufficient ship manoeuvrability and navigation safety in adverse weather conditions. De facto, this means that the existing manoeuvrability standards must be revised and, probably, some new or additional ones suggested (Papanikolaou et al, 2014).

In the two main sections of the present article, first, an analytic review of the most important contributions to development of ship manoeuvrability criteria and standards is given and then possible approaches to devising "adverse weather" manoeuvring standards are outlined.

2 REVIEW OF STUDIES ON MANOEUVRING CRITERIA AND STANDARDS

2.1 *General remarks*

Manoeuvrability of surface ships was the last area of ship hydrodynamics to appear and to get developed and, even so, its development followed earlier progress in dynamics of submarines and aircraft, see e.g. (Sutulo & Guedes Soares 2011). Obviously, this retardation applied also to formulation of manoeuvrability criteria let alone any manoeuvring standards.

However, late appearance of these standards is explained not only by that natural historical delay but also by an increased complexity of the task. For instance, resistance of a ship to capsizing called usually "intact stability problem" could be relatively easily, at least in a reasonable first approximation, associated with the few parameters defining the righting arm curve and also with the parameters of the beam sea and of the wind gust. Nothing that simple and obvious could be formulated for ship manoeuvring qualities and although it was indisputable that there existed vessels with obviously "good" and "bad" manoeuvring properties, reasonable quantification of these properties was far from obvious.

One of fundamental differences between the standardization tasks in ship seakeeping and manoeuvrability is that while in the former case any non-trivial criterion must be based on external excitation from waves and wind, it is possible to talk about non-trivial manoeuvring criteria in still water without influence of any exogenous factors.

On the other hand, in the general case a manoeuvring ship represents a closed-loop system which is often ergatic i.e. containing a human operator in the control loop. Such a system is more complicated, somewhat fuzzy and less convenient for working out simple criteria and standards. For instance, a characteristic example of a criterion based on such approach was the minimum lateral deviation from the initial path at the end of Wiliamson's manoeuvre proposed by Nawrocki (1977).

So, possible approaches to devising manoeuvrability criteria are:

1. Devise the criteria on the basis of the closed-loop ergatic system representing a steered ship and implemented on a computerized real-time ship handling simulator.
2. Use a computer simulation system, not necessarily real-time, closed with some standard automatic controller implemented as a control law.
3. Base the manoeuvring criteria on only specially designed or historically recognized manoeuvres realizable with an open-loop feed-forward control.

The first approach has become practically standard in aeronautics (Stevens et al. 2016) where it was laid in the basis of the so-called Joint Airworthiness Requirements (Swatton 2005). In that field this method is quite natural as good interaction of a pilot with the plane is extremely important for its successful handling as all aircraft are characterized by very small values of the reference time constant $T_{\text{ref}} = L/V$, where L is the characteristic length and V is the speed of the craft. As for marine craft, this time constant is substantially larger, the man–machine interaction issue becomes much less critical and, in spite of a few attempts discussed below, the "ergatic" approach has not gained popularity in the surface ships manoeuvrability.

The second approach is simpler to implement as it does not require a full-scale bridge simulator and real-time simulations. Difficulties here are determined by dependence of the ship's simulated behaviour not only on its inherent manoeuvring qualities but also on the structure and parameters of the control law. These parameters must be determined from some optimality criterion that is not very simple and requires certain standardization of the synthesis procedure.

The third approach proved to be the most promising and convenient and most proposed criteria are based on a limited number of probe manoeuvres: turning circles, spiral manoeuvre, zigzag manoeuvres and some others. It must be noticed that the zigzag manoeuvre is, strictly speaking a closed-loop manoeuvre as the system is closed by the nonlinear control law:

$$\delta^* = \delta_z \operatorname{sign}\left(\psi_z \operatorname{sign} r - \psi\right), \tag{1}$$

where δ^* is the rudder order, δ_z, ψ_z are the zigzag parameters, r is the rate of yaw, and ψ is the current heading angle. However, as long as this control law does not contain any parameters depending on the ship dynamic properties, the zigzag manoeuvre is as free of uncertainties as any open-loop manoeuvre.

The downside of the third approach is that those test manoeuvres are artificial and are practically never used in navigation. As result, the criteria based on them cannot be linked directly to the seamanship requirements.

In the following subsections, a review of the most important manoeuvrability criteria and standardizing procedures proposed earlier is given. An attempt is made to present separately disturbances-free criteria characterizing inherent manoeuvring qualities and criteria considering interaction of the ship with environment although in some cases such a separation was difficult.

An attempt of a more or less substantiated analysis of those proposals is also undertaken. To a large extent, the analysis is supported by resolution of the following dilemmas:

1. Must a certain criterion be standardized by regulation bodies or must be included into the objective function(s) in course of design optimization process?
2. How difficult is to verify fulfilment of a standard for a given ship in full scale trials?
3. How meaningful is a criterion from the viewpoint of practical application?
4. Safety-oriented or mission-oriented standards are preferable?
5. Must a set of criteria be minimized or it is desirable to include all thinkable manoeuvrability measures?
6. Must the standards be of binary type (pass—nonpass) or rating-based?
7. Are the standards aimed exclusively at raising navigation safety or also must stimulate improvement of manoeuvring qualities of ships?
8. Are the criteria formulated explicitly or are implicit i.e. are hidden inside, say, requirements to the effectiveness of the rudder?
9. Regarding very large range of variations in ship dimensions, must the criteria be dimensional or dimensionless? Or both?
10. Is a particular criterion of the closed-loop or open-loop type?
11. Is the criterion based on some ship mathematical model which is supposed to be known or is model-independent?
12. Is the criterion directly observable during the manoeuvring trials or tests with free-running models or its value can only been established in course of some identification procedure?

Finally, it should be noticed that an excellent and still valuable exposure of the earliest developments in ship manoeuvrability emphasizing links to flight dynamics was presented by Norrbin (1960) while another brief reviews of proposals on ship manoeuvrability criteria and standards can be found in (Sutulo 1995, 1996).

2.2 *Inherent manoeuvrability criteria and proposals for corresponding standards*

One of the earliest publications dedicated to manoeuvrability criteria belongs to Gertler & Gover (1961), where the sequence of steps for working out criteria and standards practically was established. Also, formulated was the concept of a "definitive manoeuvre" viewed as a manoeuvre developed solely for quantifying certain manoeuvring qualities. The authors were already capable to understand that seemingly more realistic manoeuvres are all closed-loop and much more difficult to realize. In particular, an apparently obvious criterion of the practical course stability in a real seaway requires long trials or simulations to accumulate sufficient statistics which is not easy to realize. The following list of principal manoeuvring qualities was formulated:

1. **Operational or practical stability:** the ability to keep a straight path with small heading error and with small rudder activity.
2. **Heading change ability:** ability to change the course rapidly.
3. The ability to rapidly check the course alteration or turning.
4. **Turning ability:** ability to sail along highly curved trajectories which is traditionally measured by the so-called tactical diameter, advance and transfer.

In addition, it was suggested to consider the ability of the ship to accelerate and decelerate rapidly and the ability to manoeuvre at low speed in the harbour area without tug assistance. However, it is clear that the first of these two qualities is mainly about ship powering and characteristics of the main engine and is not associated with the manoeuvring performance per se. The second quality was formulated in a very unclear way and the low-speed manoeuvrability will be discussed more in detail later in view of later proposals.

Besides the standard turning circles, which were recommended to be executed at various helms including 35°, until the 540° heading change is reached and must be followed by a pull-out, the incomplete (within ±15° rudder angle) Diedonné spiral was suggested as a mandatory manoeuvre. The width and the height of the hysteresis loop, if present, were proposed as measures of the inherent directional instability. As to directionally stable ships, two possible measures of the directional stability were indicated, though on the level of a somewhat vague idea: (1) the slope of the spiral curve at zero yaw and (2) the settling time in the pull-out manoeuvre. Apparently, no one of these two measures was later brought to practical use although the first of them could be easily generalized to cover also unstable ships if the unstable branch of the spiral curve is also recovered with the Bech inverse spiral manoeuvre.

The overshoot angles and the "time to reach execute" in zigzag manoeuvres were considered as measures of the course-checking capability and of the initial turning ability. Apparently, their connection with the inherent directional (in)stability was not yet completely understood but on the basis of the then available trial data it was noticed that "the excessively large overshoot angles were always obtained with the ships that had a high degree of the directional instability".

Some very tentative numerical values of the manoeuvring quality measures were formulated: the height of the hysteresis loop was recommended not to exceed 0.2deg/s for a 167m length ship and its width should not exceed 4deg. The first overshoot angle in the $20° - 20°$ zigzag was recommended to remain below 5.5° at 8kn and 8.5° at 16 kn (this difference is likely caused by the influence of the finite rudder deflection rate). The tactical diameter at 35° helm was to be limited by 4.5 ship lengths and the corresponding advance—to 3.35 lengths. In addition, it was suggested to limit the speed loss in turning (not more than 37.5% at the 180° heading change) and the time to reach this point. These two criteria, however, were not supported in later studies.

Of course, the later suggestions could set different numerical values for the mentioned criteria and propose some new ones. For instance, Doerffer (1980) reported about Manoeuvrability Requirements of the International Maritime Pilots' Association (IMPA) that required $D \leq 5L$, where D is the steady turning diameter and L is the ship length while Doerffer himself proposed a tighter standard: $D \leq \min(3L,\ 1389\text{m})$. IMPA also proposed a higher rudder deflection rate (3.5deg/s instead of 2.33deg/s required by virtually all classification societies and the most interesting was the proposal to standardize minimum values of the stable speed through water: 5kn for a ship with the diesel engine, 3kn for a ship moved by the steam turbine and 2kn for all ships equipped with the controllable pitch propellers independent of the type of the main engine.

In general, it is obvious that the task of setting standardizing values for manoeuvrability criteria contains some arbitrariness although sometimes more or less natural reference value can be found. For instance, the standards for river-going vessels existing as a guide of the Russian River Register and commented by Pavlenko (1979) presume the following condition for the dimensionless steady turning diameter:

$$D/L \leq \min\left(2,\ 1.4k_W R_W/L\right), \tag{2}$$

where k_W is a correction factor and R_W is the minimum curvature radius of the fairway depending mainly on the meandering of the river in which the ship in design is planned to operate. Such a natural measure for the turning diameter has never been proposed for sea-going ships. According to the mentioned standards for inland vessels, there are also limited steady turning diameters at the rudder angles $\delta_R = 0,\ 10°, 20°$: $D_0/L \geq 10$; $D_{10}/L \geq 4$, and $D_{20}/L \geq 2$. The meaning of these requirements is to limit the degree of the directional instability (most inland ships are directionally unstable) and the steepness of the spiral curve.

Manoeuvrability standards of sea-going vessels implicitly embedded into the Rules of the Russian Maritime Register of Shipping (RS 2016) presume only two spiral curve requirements: $D_{\min}/L \leq 4$ and $D_0/L \geq 26.7$ (Mastushkin 1981), (Baquero 1982). Initially, an attempt was made to link the first requirement with the necessity to avoid collision with a suddenly detected obstacle of infinite transverse dimension but in fact the criterion was faired with values of this criterion observed on already existing vessels. It was also assumed that there existed a sufficiently strong correlation between the steady turning diameter and the advance in spite of the latter being dependent also on the rudder deflection rate.

It is evident that better turning abilities increase the safety of navigation. For instance, Kwick (1979) demonstrated that in situations of congested traffic reduction of the dimensional turning diameter from 6.8 to 2.8 cables yields a two-fold reduction of the probability of collision.

Yudin (1967) studied steering capabilities of merchant ships with the help of analogue computers and came to conclusion that acceptable degree of the directional stability is reached when $D_0/D_{30} \geq 5$, where D_{30} is the steady turning diameter at 30deg helm, independently of the absolute values of those quantities.

Many specialists have criticised the attention paid to the spiral curves and turning circles indicating that in this way dynamic properties of ships cannot be taken into account properly enough and more consistent would be to use certain parameters of mathematical models typically described by sets of ordinary differential equations. Such approach was followed in flight dynamics where, for instance, parameters of simple linear models for short-period motions in the longitudinal plane were standardized with the help of interactive flight simulators. Apparently, for the first time a proposal to apply similar approach to surface ships was made by Segel (1960). Much later a similar proposal was made independently and in a somewhat more elaborate way by Sutulo (1995). As the number of parameters defining more or less full ship mathematical models is typically too large (20–30 and more), it was proposed to base the criteria on the simplified dimensionless input-output models usually called Norrbin equations, see e.g. (Sutulo & Guedes Soares 2011):

$$T_1'T_2'\ddot{r}' + \left(T_1' + T_2'\right)\dot{r}' + r' + f\left(r'\right) = K'\left(\delta_R + T_3'\dot{\delta}_R\right) \qquad (3)$$

and

$$T'\dot{r}' + r' + f\left(r'\right) = K'\delta_R; \qquad T' = T_1' + T_2' - T_3'. \qquad (4)$$

Both equations are written for the easily observable dimensionless rate of yaw r' and its derivatives, with the constants T_1', T_2', T_3', T' being the dimensionless time lags, K'—the ship gain and the function $f(r')$ is defined in such a way that $r' + f(r') = K'\delta_R$ describe the actual spiral curve including with the unsteady branch when it is present. At $|r'| \to 0$ influence of the nonlinear function vanishes, the Norrbin equations reduce to the linear Nomoto equations and the remaining parameters characterize dynamic behaviour of the ship in such gentle manoeuvres as the course keeping or slight heading changes. It was suggested to implement the model on a ship handling simulator, variate the parameters and obtain subjective estimates from statistically meaningful groups of professional human operators thus tracing in the parameter space boundaries separating good, acceptable and unacceptable combinations of the parameters. More details associated with this process are given in (Sutulo 1995), where presented is even a tentative adaptation of the aeronautical Cooper–Harper handling qualities rating scale (Stevens et al. 2016) which could facilitate rating of the mathematical models. Although the approach still looks promising, especially for smaller and faster craft, it has never been realised. Partly this can be explained by economical obstacles: practically all full-scale bridge simulators are supposed to train operators, often on the commercial basis, not to perform research studies. On the other hand, as was mentioned above, a necessity for such interactive study is really less critical for ships than for aircraft as in the former case the object's reference time is much larger and the interaction between the operator and the craft is much less immediate and critical.

The ship time lags and the ship gain were considered by Bassin (1968) as direct measures of the initial turning ability both in the sense of steady turn at small rudder angles and also as the rate of response of the ship to the rudder deflection. However, more promising looked the use of two combinations proposed by Sobolev (1978) which have the sense of the dimensionless and normalized initial angular acceleration resulting from an instantaneous deflection of the rudder by 1 radian:

$$q_0 = \frac{K'}{T'}; \qquad q = \frac{K'T_3'}{T_1'T_2'} = \frac{T'T_3'}{T_1'T_2'}q_0. \qquad (5)$$

Sobolev indicated that the “normal” statistically based value should be $q_0 \approx 0.45 - 0.5$. Whether these numerical values are well based or not is, however, disputable as much earlier Nomoto (1960) proposed the so-called $K' - T'$ diagram which is de facto equivalent to the linear dependency:

$$\frac{K'}{T'} \approx 5\frac{A_R L}{\nabla}, \qquad (6)$$

where A_R is the rudder area and ∇ is the ship displacement. It can be seen that for a typical cargo ship eq. (6) indeed will produce numerical values close to the given above but the dependence on the relative rudder area seems to be natural and essential. On the other hand, eq. (6) was obtained as result of a not impeccable analysis of some zigzag data let alone that they now correspond to almost 60 years old ship configurations and forms.

However, collection of more recent data while applying more rigorous procedures probably makes sense as such a criterion as the initial angular acceleration is well observable and has practical meaning. The difference between q and q_0 is that the former reflects the behaviour of the ship at the very beginning of the process or in the initial “boundary layer” part of the transient. Whether this parameter is important for the adequate perception of the vessel by the operator or q_0 alone is quite sufficient, still remains uncertain. As to the parameter q_0, its significance seems to be undoubted but no serious, simulator-supported research aimed at establishing its admissible range and sensitivity to the scale has ever been undertaken.

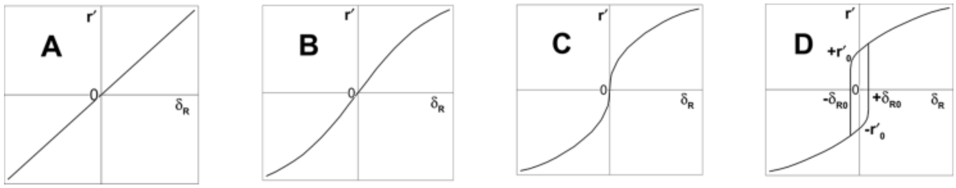

Figure 1. Various types of ship steady turning characteristics (spiral curves): A—ideal linear; B—typical for highly stable ship; C—for marginally stable ship; D—for substantially unstable ship.

All criteria based on the parameters of even the simplest ship mathematical models have a drawback of not being directly measurable in free-running model tests or in full-scale trials as they require a certain identification procedure which also must be standardized and certified to avoid additional uncertainties. That is why, in the actual IMO standards (IMO 2002a) direct measures were preferred: the relative tactical diameter $D_T/L \leq 5$ and the relative advance should not exceed 4.5. The steady turning diameter was present in earlier versions of the Standards but was removed as it is tightly correlated with the tactical diameter being more difficult for estimation. Also, the Standards contain limitations on the zigzags overshoots. It is remarkable that the values of allowable overshoots in the $10° - 10°$ zigzag depend on the ship reference time T_{ref}. For instance, the first overshoot must not exceed 10 degrees as $T_{\text{ref}} < 10$s but can be up to 20 degrees when $T_{\text{ref}} > 30$s with linear interpolation between these values in between. The meaning of this dependency is clarified in the Explanatory Notes to the Standards (IMO 2002b) where the Dieudonné spiral is recommended as additional criterial manoeuvre and the width of its hysteresis loop is then standardized in such a way that it must be zero for $T_{\text{ref}} < 9$s and must not exceed 12 degrees when $T_{\text{ref}} > 45$s with linear interpolation between these values.

The similarity between these two standards is evident (differences in the numerical values of the reference time are likely of historical origin and do not undermine the analysis that follows). However, while the spiral-based requirement of the directional stability of the ship without any additional discrimination for all $T_{\text{ref}} < 9$s is quite understandable as the directional stability margin had never been quantified in terms of the spiral curve's shape presuming that all directionally stable ships are undistinguishably acceptable, this is less evident for the overshoot angles. Much more natural would be to require their further continuous, although not necessarily linear, reduction for smaller values of the reference time.

Although the loop height was mentioned in the Explanatory Notes as alternative measure of the directional instability, it was not standardized likely assuming that some correlation between the width and the height exists although this connection so far has never been investigated with due thoroughness. As to the loop width, its upper limit looks reasonable as it means that the ship will be always controlled with certainty if only the applied helms exceed 6 degrees which is quite moderate. The hypothesis about the indistinguishability of all inherently directionally stable ships mentioned above is in no way evident as one could expect that smaller and faster vessels would require some stability margin for comfortable manual steering. Indeed, considering the full set of possible and qualitatively different spiral curves (Figure 1), it is intuitively evident that, for instance, the vessels with the static response described by the curves A or B, and C will have in practice very different responses although that difference is not captured by any of the existing manoeuvrability criteria.

However, while the loop-based criterion cannot be directly extended to the ships with $T_{\text{ref}} < 9$s, there are no obstacles to doing this with the criteria based on the zigzag overshoot. Quadvlieg and van Coeverden (2003) presented data gathered from full-scale trials of a number of Dutch ships demonstrating for many vessels the first overshoot angle well below 10 degrees and sometimes as low as 4–6 degrees and the second overshoot 8–12 degrees instead of the lowest limiting value of 25 degrees. This means that a smooth continuation of the zigzag overshoots requirements to the domain of smaller reference time is practically possible and this circumstance may turn out very important in view of possible conversion of the IMO standards to account for exogenous factors. In terms of the spiral curve properties such a continuation would probably mean reduction of the maximum or average curvature of the spiral curve but corresponding suitable numerical measures are yet to be established and recognized.

Any such measure should serve over the whole range of the degree of the directional stability as it was demonstrated by Sutulo (1989) that the reaction of a ship to small helms does not change qualitatively or discontinuously when passing from a marginally stable (spiral curve type C in Figure 1) to a slightly unstable configuration (like type D but with a smaller hysteresis loop, than is sketched in the figure).

Probably, the first study where the dependence of the required degree of the directional stability and the ship reference time was established on the basis of simulations carried out with a group of marine pilots was that by Nobukawa et al. (1990) and the there suggested dependence of the loop width was very close to that finally set by the IMO Standards.

A more detailed discussion of the interconnection between the admissible degree of directional stability and the ship reference time can be found in (Sutulo 1995)

It makes sense to compare the IMO requirements with the manoeuvrability standards recently approved for NATO naval ships—the so-called STANAG manoeuvrability requirements (Örnfelt 2009), (Armaoğlu et al. 2010), (Quadvlieg et al. 2010). These standards are declared to be both safety and mission oriented and, as result, they have a "Christmas tree" appearance reflecting the attempt to cover all possible situations and scenarios corresponding to merely all thinkable missions and tasks which resulted in 88 different criteria. Regarding the turning ability, the requirements to the relative tactical diameter vary from approximately 3.8 to 6.0 depending on the mission and the Froude number: at higher Froude numbers the ships tend to trim by the stern which reduces their ability to turn. No direct criteria of the directional stability are considered as in fact practically all naval ships are directionally stable. Instead of the zigzag overshoot angles, standardized is the time of the yaw check in the $20° - 20°$ zigzag after the second rudder execute, non-dimensionalized by the ship reference time. The required value of this criterion varies from 1 to 2.5 depending on the ship reference time, ship type and mission.

Belenky & Falzarano (2006) have de facto expanded the IMO standards having introduced a system of integer-valued rating indices depending on the reached values of the criteria. Although this rating system can serve as a useful guide for ship designers, it cannot be viewed as a set of true standards which must be of binary nature. An additional problem is caused by the fact that the authors have based part of their research on the linearized version of eq. (4) where it is assumed $f(r') \equiv 0$ and used statistical data for K' and T' obtained by Barr et al. (1981). However, even a superficial inspection of the cited report clearly indicates on heavy and evident biases in the statistical data on K' and T': they had been determined from zigzag tests assuming that each ship's mathematical model is strictly linear which is simply not true. As result, all estimated values of these two parameters were positive thus giving illusion that all tested vessels had been directionally stable which is in fact highly unlikely. Because of this, in this part the study by Belenky and Falzarano cannot be recognized as credible. On the other hand, the cited publication presents certain interest as long as it discusses issues related to the influence of the environmental factors.

2.3 *Manoeuvrability criteria depending on external factors*

In relation to manoeuvrability criteria and standards it is possible to consider 4 main kinds of exogenous factors: (1) wind, (2) hydrodynamic interaction, (3) sea waves, and (4) current.

2.3.1 *Wind*

The wind is characterized by its absolute speed and direction, and it can be either favourable or unfavourable for steaming depending mainly on the relationship between the wind direction and the required ship course. For instance, Knight (1912) talks about possibilities to exploit the wind action for performing certain complicated manoeuvres although in most cases the wind complicates ship handling or even makes it impossible.

Loss of controllability, which may happen at sufficiently strong wind, can be interpreted in two ways:

1. The ship is not able to go straight with any desired course angle, or, in other words, there are some unreachable courses or headings.
2. The ship is not capable to perform any desired manoeuvre, in particular the full turn is not possible.

The second interpretation of the controllability loss may seem more general and was preferred by some researchers (Sobolev 1978) but it was demonstrated (Pershitz 1983) that in fact the both formulations are equivalent and, hence, the first approach is certainly preferable as long as the manoeuvre to be verified looks simpler.

However, organization of direct full-scale trials or even free-running model tests aimed at more or less systematic studies of manoeuvrability in wind is prohibitively difficult, if at all possible, and no one study of this kind is familiar to the authors. On the contrary, presence of significant wind during the trials is normally viewed as nothing more than undesirable disturbance.

Most of investigations of the manoeuvrability in wind including those aimed at establishing corresponding criteria have followed practically one and the same scheme:

1. Some more or less detailed ship mathematical model is assumed. In the case of the steady straight motion the model is supported by the set of equilibrium algebraic equations. The required ship aerodynamic characteristics are typically determined by means of wind-tunnel tests but use of databases or CFD computations is also possible.
2. The set of equilibrium equations is solved with respect to the ship speed, drift angle and the balancing rudder angle. The input parameters can be different but for standardizing purposes the most typical are: (1) the relative wind speed $\bar{V}_w = V_w/V$, where V_w is the absolute wind speed, and (2) the ship air drift angle β_A which is more often called the relative wind angle, see (Sutulo & Guedes Soares 2015b) for details.
3. When it goes about manoeuvrability standards, typically the whole range of possible values of $\bar{V}_w$ and β_A is explored to capture the largest magnitude of the required balancing rudder angle $|\delta_R^0|$. If for some combination of the input parameters the equilibrium solution does not exist or—in simpler formulations—the balancing rudder angle exceeds by its absolute value the admissible value δ_R^{adm}, then controllability is considered as lost. The admissible rudder angle is smaller than the maximum one by some more or less arbitrary steering margin.

The maximum absolute wind speed $V_w^{\max}$ at which the controllability is never lost in the sense described above, is a typical criterion of ship controllability in wind.

In particular, a criterion of this type served as basis for the requirement to controllability in wind implicitly embedded into the Rules of the Russian Maritime Register of Shipping (RS 2016). Namely, the main wind criterion is supposed to be satisfied if the estimated rudder effectiveness index E (depends on the relative rudder area, lift gradient, and also on the relative propeller diameter and its thrust if the rudder works in the slipstream) is not less than the required effectiveness E_2 defined by the formula:

$$E_2 = \frac{\overline{A}_w^b}{V^2}\left(1 - \tfrac{1}{15}\overline{A}_w^b\right) \times \left\{1 + (k_R - 1)\left[\tfrac{1}{3} + 0.029(V - 3.85)\right] - 5x'_{wb}\right\}, \quad (7)$$

where V is the ship design speed, $\bar{A}_w^b = A_w^b / A_b$ is the relative lateral windage area, A_w^b and A_b are respectively the absolute windage area and the lateral submerged area corresponding to the minimum draught at which the rudder is completely submerged, k_R is the rudder aspect ratio, and x'_{wb} is the relative abscissa of the centroid of the area A_w^b.

The formula (7) was obtained fixing the absolute wind speed at 25m/s and the following rather strong additional assumptions were made:

1. The air drift angle was fixed at $\beta_A = 130°$ as multiple calculations indicated that in most cases the ship is then most sensitive to wind.
2. A simple generic mathematical model with only one quadratic nonlinearity in the sway force (Pershitz 1983) which permitted to obtain an analytic solution for the equilibrium.
3. The significant wave height was assumed to be 4.5m which predetermined setting the rudder angle steering margin equal to 7 degrees on the basis of statistics available to the developers.

Of course, the thus formulated criterion cannot be interpreted literally regarding numerous assumptions and simplifications applied: if some ship satisfies the criterion, it still does not mean that that the ship will never lose controllability at 25m/s wind at the specified draught and when advancing at the design speed. However, multiple test calculations have demonstrated that that requirement is not trivial and it reasonably well captures the influence of the ship speed, relative windage area and of the position of its centroid. The wind speed value $V_w = 25\text{m / s}$ is rather arbitrary and was adjusted in such a way that most of the fishing and cargo fleet existing in the mid of 70s satisfied the criterion.

The mentioned Rules (RS 2016) contained another wind criterion E_3 presuming the ship in full load (meaning smaller relative windage area) advancing at the 6kn speed under action of 12m/s wind in a shallow canal with a rectangular cross-section, with negligible seas (hence, no steering margin is required) but shifted to one of the banks so that the hydrodynamic interaction was also taken into account. The formula for this criterion is:

$$E_3 = 0.03 + 0.01(k_R - 1) + 0.01A_w^0(1 - 3x'_{w0}), \quad (8)$$

where A_w^0 is the lateral windage area in full load and x'_{w0} is the corresponding dimensionless abscissa of its centroid. Non-triviality of this criterion was also demonstrated by means of test calculations.

Quadvlieg (2003) proposed for the open sea case to allow maximum balancing rudder angle 20 degrees when the wind speed is at least 20.5m/s and the ship speed 8kn i.e. speed reduction caused by wind and sea is assumed. No evidence of practicality of this criterion is known to the authors. Quadvlieg mentioned yet another wind-conditioned criterion as the ability of a ship to leave the quay without tug assistance under unfavourable wind with the speed from 20 to 40 knots depending on the ship type. This is, however, a too specific criterion related to low speed manoeuvring looking more like a design scenario.

It is worth mentioning probably the simplest possible criterion for controllability loss in wind proposed by Barr et al. (1981):

$$V_w^2 \overline{A}_w^2 / V^2 \le 125 \quad (9)$$

but this formula cannot serve as a useful manoeuvring criterion as it is not sensitive to the actual rudder effectiveness being based on some averaged statistical data.

It must be noted that although manoeuvrability at slow speed is in fact directly connected with some wind present and no specific controllability problems would be observed in still air, sometimes special low-speed manoeuvrability criteria are introduced but are not well defined. For instance, in STANAG Standards (Örnfelt 2009) the slow speed ability criterion is defined as “minimum required speed for safe manoeuvring” without any association with some wind velocity that hardly makes sense.

2.3.2 *Hydrodynamic interaction*

Concerning the influence of various hydrodynamic boundaries, Bindel (1960) proposed the following specific criteria worked out on the basis of tests with a free-running model steered by a human operator within a simulated canal:

1. The model can (or cannot) be steered without striking the banks.
2. The maximum values of the rudder angle, heading deviation and lateral deviation do not exceed certain level.
3. Similar as above but average values are standardized as being more resistant to occasional human errors.

It was also noticed that for every combination of the ship and the canal exists a certain speed called critical at which the probability of bad steering becomes substantially higher. It remained unclear whether this speed is related to the usual critical shallow water speed or not and no suggestions on numerical values of any criterion were made.

Quadvlieg (2003) noticed that fulfilment of the IMO standards only in deep water, as is required, may become insufficient and proposed to impose the same standards also in shallow water with depth equal to $1.3T$, where T is the draught. Of course, this will make the requirements considerably stricter but practical applicability of the resulting standards is unclear.

2.3.3 *Seas*

In most cases standards were based on imposing certain restrictions on the heading error during the straight course steering process. For instance, the STANAG Standards prescribe the maximum admissible levels of the 95% heading deviation which can be reached with not more than 50 helm adjustments per minute (Örnfelt 2009). The required deviation varies from $\pm 2°$ to $\pm 5°$ depending on the mission (Armaoğlu et al. 2010). That deviation must be checked for the sea state, which must be defined in every particular case individually but typical sea state values used in (Quadvlieg et al. 2010) varied from 4 to 5.

It makes sense to compare the mentioned requirements with the data on the ship yawing in a natural seaway obtained from questioning 87 Dutch navigators (Amerongen & Prins 1979). For the sea state varying from 0 to 8 and the ship speed varying from 6 to 24 knots the reported peak heading deviations varied from 1 to 15 degrees and the required maximum rudder angles were from 1 to 26 degrees. Somewhat strange is that much larger helms were reported for the naval ships than for merchant ones.

2.3.4 *EEDI-oriented proposal*

The most systematic analysis of environmental manoeuvrability criteria called also "criteria of manoeuvrability in adverse conditions" and with particular account for EEDI requirements was recently performed by Shigunov & Papanikolau (2015) who propose to consider the following manoevrability criteria (these are somewhat re-formulated by the authors of the present paper but their meaning is carefully preserved):

1. A criterion related to very rough (extreme) open sea conditions: maximum sea state and wind speed at which the ship is able to maintain arbitrary heading against sea and wind which are coming from directions within the $\pm 60°$ sector.
2. A criterion related to the necessity of manoeuvring in the coastal area in growing storm: maximum sea state and wind speed at which the ship is capable to sail at 4kn speed with arbitrary course independent of the direction of seas and wind.
3. Criteria related to manoeuvring in restricted partially sheltered areas in absence of tangible seas (like harbours) with substantially reduced speed under action of wind and current:
   - 3.1. Maximum wind speed at which the ship at minimum draught loading condition is able to sail an arbitrary straight course at a specified low speed.
   - 3.2. As above but the ship is in full load advancing at some other specified low speed parallel to and at a specified lateral distance to a vertical wall.
   - 3.3. As above but instead of the wall a faster overtaking vessel is considered.

Of course, it is supposed that all listed criteria, after their concretization, must be benchmarked against the existing fleet. The authors of the cited source discuss also possibilities and tools that can be used to evaluate the criterial values but it is evident that this is not an easy task even when it goes about predictions on the design stage let alone their direct verification. Hence, although these criteria look quite reasonable, it makes sense to try to design a simple and more practical set.

In the next section the authors make an attempt to outline an alternative approach to standardizing ship manoeuvrability in adverse conditions on the basis of some logical re-thinking of the array of earlier formulated criteria and standards and exploiting the authors' inherent understanding and feeling of manoeuvring qualities of ships.

3 RATIONAL MANOEUVRABILITY CRITERIA IN ADVERSE CONDITIONS

In order to work out a rational approach to defining a suitable set of manoeuvrability criteria accounting for adverse conditions, it is helpful to explicitly formulate certain more or less evident propositions:

1. The less powered is the ship, the more vulnerable it is with respect to various exogenous factors. In a rather general form this vulnerability can be associated with the ratio of the moving craft's kinetic energy to the energy of the air flux caused by wind and/or to the energy of the water flux caused by seas both corresponding approximately to some characteristic areas of the ship. Some external factors, such as the hydrodynamic interaction, cannot be directly described in this way but their influence does not depend on the ship's powering.
2. Independently of what is the nature of exogenous factors, these are observed in form of some undesirable forces and moments acting upon the ship. These loads must be counteracted with the help of the propulsors and control devices whose effectiveness is crucial for the ship's ability to withstand the adverse influence.
3. It is more or less evident that the reduction of the speed of the ship driven by the EEDI requirements can be, at least in theory, compensated by a corresponding boost in the effectiveness of the steering device installed on that ship.
4. In particular, if it goes about such active control devices as the lateral or azimuthal thrusters, it is sufficient to make them powerful enough to compensate for any external forces. Of course certain power limitations may exist but in any case if active means of control are involved, the task

becomes closer to the dynamic positioning system design problem than to the standardization problem limited by use of more traditional passive means of control. As the rudder remains the most common steering device, the following discussion will be focused on rudder-equipped ships to avoid, at least at this stage, unnecessary complications. Extensions to, say, pod-driven ships can be realised following, for instance, methodology developed by Woodward et al. (2009).

5. The effectiveness of a rudder is roughly directly proportional to its area. It is evident that if this area is A_{R1} for a ship with the design propulsion power P_1, reduction of this power to $P_2 < P_1$ will require the rudder area

$$A_{R2} = A_{R1}\left(\frac{P_1}{P_2}\right)^{2/3} \tag{10}$$

to keep the capacity of the ship to withstand external loads unchanged.

6. As long as the rudder area is increased with all significant dimensionless hydrodynamic characteristics kept (almost) unchanged, it will also affect the inherent manoeuvring qualities of the ship: both the directional stability and the turning ability of the ship in calm water will improve. In terms of the corresponding numerical measures, the tactical diameter, advance, zigzag overshoots and the time to 10 degrees heading change will all decrease. This was confirmed directly by some comparative simulations performed by the authors but is in fact rather obvious. In particular, the zigzag overshoot angles are reduced due to increased checking power of a larger rudder.
7. This rather evident observation in the previous item is very important as it permits to consider tightening the existing IMO standards instead of introducing some additional standards directly related to some adverse conditions scenarios.

The latter conclusion requires, however, some additional discussion. Considering the influence of sea waves it is necessary to notice that both the wave excitation forces and the forces caused by the rudder deflection are of hydrodynamic nature and depend, besides the characteristics of the rudder, on the shape of the underwater part of the hull. It seems highly unlikely that any realistic hull shape variations compliant with other design requirements would lead to a tangible reduction of the excitation force and moment impairing at the same time main manoeuvring qualities in still water. That is why the coherence between the inherent manoeuvring qualities of ships i.e. the fixed-rudder directional stability together with the turning ability and the ship's controllability in waves can be assumed as a viable hypothesis although its direct confirmation through systematic comparative simulations is desirable.

It must be emphasized that, to improve controllability in waves, both the directional stability and the turning ability must be enhanced: the well know method of boosting the turning ability at the expense of the stability cannot be applied.

To comply with the "2/3-law" defined by eq. (10), it is necessary to reduce the allowable $10° - 10°$zigzag overshoot angles when the main engine's power and the corresponding ship speed decrease. However, this would contradict the requirement of reducing allowed overshoot angles when the ship's reference time decreases what happens when the ship speed is increased. This contradiction can be resolved either by adapting a flat and rather severe overshoot angles limit or through introduction of two independent curves defining the overshoots with the least of two values taken as the standard. At this moment, no quantitative measures for the sea-governed overshoots are established and apparently this can be achieved with systematic simulations. However, as the final benchmarking is in any way inevitable, it can be also used directly for setting the standards not on the physical but on the statistical basis.

As long as it goes about the wave action, it makes sense to distinguish between the first- and the second-order effects. While the former excites yawing in the seaway but may also hamper turning and heading changes especially in following seas, the latter results in constant (in regular waves) or slowly varying (in irregular seas) drift loads which will create additional drag and may also require some non-zero average helm to compensate for this action. It is, however, evident that augmentation of the rudder effectiveness will be beneficial for counteracting each of these factors.

However, the approach based on modification of the IMO criterial values for the directional stability and turning ability as described above is not able to appropriately handle a ship's resistance to wind action as it does not capture the evident influence of the relative windage area and on the position of its centroid as is seen from eq. (7). That is why, it is necessary to complement the modified IMO requirements with a criterion reflecting the ability of the ship to steam with arbitrary course at some prescribed values of the wind and ship speeds. As any criterion must be benchmarked against the existing fleet and tuned accordingly, the accuracy of the mathematical model used that verification is not so important as long as it remains qualitatively consistent. Even a linearized model as was used by Sutulo & Guedes Soares (2015b) can be applied. It was also demonstrated in the cited publication that the conditions of arbitrary course, arbitrary heading and arbitrary air drift angle are all equivalent that makes possible further simplifications of the analysis.

As to estimation of the aerodynamic forces and moments, it makes sense to use the following simple generic formulae (Pershitz 1983), (Sutulo & Guedes Soares 2015a) for the standard aerodynamic coefficients C_{XA}, C_{YA}, C_{NA} as these are defined in (Brix 1993):

$$C_{XA} = -c_X \cos\beta_A, \qquad C_{YA} = c_Y \sin\beta_A,$$
$$C_{NA} = C_{YA}\left(x'_w + x'_0 - \frac{|\beta_A|}{2\pi}\right), \tag{11}$$

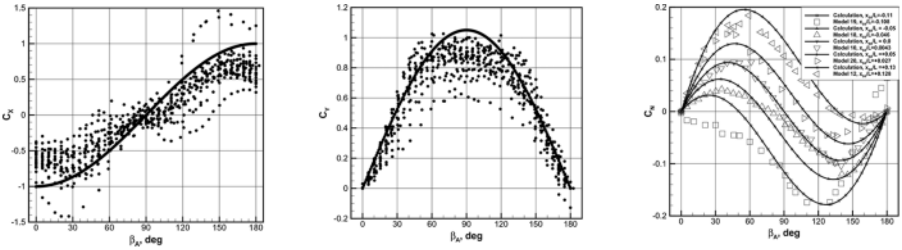

Figure 2. Coefficients of aerodynamic forces and moment: predictions by eq. (11) vs wind-tunnel data.

where c_X, c_Y, x_0' are the constant parameters. In spite of extreme simplicity, these formulae give reasonable estimates in many cases. Plots in Figure 2 show responses computed with eq. (11) at standard recommended values $c_X = 1.0$, $c_Y = 1.05$, and $x_0' = 0.25$ together with the wind tunnel data for 21 various ship forms from (Brix 1993). Only 5 characteristic cases are, however, shown for the yaw moment coefficients as in this case the results depend additionally on the longitudinal position of the windage area's centroid and plotting results for all ships would make the plot unreadable.

It is evident that the discrepancy for a particular geometry can be significant but the formulae (11) give a rather reliable upper estimate for coefficients of the surge and sway force coefficients for the majority of tested vessels. The plots for the yaw moment coefficient demonstrate that its dependence on the position of the centroid is captured qualitatively correctly. This makes the aerodynamic loads model (11) very suitable for standardization purposes. Of course, it would be desirable to perform additional validation using a later database published in (Blendermann 1996) and the model's constant parameters can be adjusted. Also, the cloud of experimental data for the sway force could be better contoured if the corresponding formula is complemented with the third harmonic $c_{3Y} \sin 3\beta_A$ containing an additional constant coefficient.

The external factors related to the hydrodynamic interaction with the canal bank or other wall-type fixed boundary can be ignored in the standardization process as the interaction forces will depend on the ship speed similarly to the rudder steering forces and the ship under-powering will not affect the rudder effectiveness depending on this factor. Practically the same remains true for the ship-to-ship interaction as the most critical situation is the overtaking with small difference between the speed values of the both participating vessels.

Finally, it makes sense to discuss possible influence of current on the required effectiveness of control surfaces. It is necessary to distinguish between the cases of non-homogenous and homogenous current. In the first case, the current velocity is substantially non-constant within the ship's length, the influence of the current is complicated, non-trivial and can be compared with the influence of waves. Behaviour of a ship in such current is poorly studied but for sea-going ships it is a relatively rare scenario and its consideration can be postponed. As to the homogenous steady current, its influence is purely kinematical and does not affect controllability by itself. At the same time, it is clear that any ship must be able to counteract the translational motion caused by the current in presence of adverse wind and sea maintaining certain speed over the ground and this may influence the powering requirements.

Of course, installation of more effective steering devices can only come at some cost. First, a larger rudder requires larger space in aft area of the ship hull and it may happen that it will be impossible to accommodate it without violating some natural rules: for most ships a rudder protruding below the base plane is inacceptable. In such cases installation of two rudders even at a single screw ship may become a way out. In any case, however, a more powerful, more heavy and spacy steering gear will be required and additional accommodation problems may arise. Of course, a reduced maximum speed of the ship reduces also the maximum stock moment and this can somewhat alleviate the design problem.

The controllability of a ship depends also on the rudder deflection rate which must be chosen appropriately. Of course, the faster is the rudder, the better but higher deflection rates require more powerful drives while too fast deflections make no sense for large and slow ships. Mandel (1965) proposed to standardize the dimensionless rudder deflection rate $\varepsilon_m' = \varepsilon_m T_{\text{ref}}$, where ε_m is the usual deflection rate typically measured in deg/s. Mandel himself proposed the standard value $\varepsilon_m' = 60°$ although other proposal were 46.7 and even 35.6 degrees. As $\varepsilon_m = \varepsilon_m' / T_{\text{ref}}$, it is clear that reduced speed of the ship and increased reference time could relieve requirements to the steering gear. However, this will not be possible for ships with the reference time at the design speed larger than 15–25s (depending on which of the standards mentioned above is adopted) as, according to the Rules of practically all classification societies, the rudder dimensional deflection rate must be not less than 2.33deg/s independent of the ship's length and speed. In addition, it must be noted that the recommended values of the dimensionless deflection rate were established analysing its influence on the measures of the turning and zigzag manoeuvres in calm water while it is still not quite clear which requirements could be worked out on the basis of studies of manoeuvring under action of sea waves and wind.

4 CONCLUSIONS

The detailed, though in no way exhaustive, analysis of suggested and partly implemented manoeuvrability criteria and standards, covering the period of more than five decades, made possible outlining rational ways to working out modified manoeuvrability criteria in the spirit of EEDI requirements.

The proposed standardization scheme is ultimately simple, accounts, explicitly or implicitly, for all significant adverse conditions, is free of contradictions, is practically realizable and is compatible with the existing IMO standards for calm-water manoeuvrability.

Its application presumes the following steps:

1. The requirements for the advance and tactical diameter in turning, for the zigzag overshoot angles and for the initial turning measure are re-defined statistically on the basis of data collected for relatively new ships. The earliest building year and the size of the sample collection should be agreed upon and approved. Apparently, the new standards must be set in such a way that, say, 95% of the ships form the collection satisfy them. It is desirable to investigate possible peculiarities of the vessels off the limit.
2. A standard procedure for checking the ship controllability in wind must be adopted and approved. It can be based on a non-linear or linearized ship mathematical model, must cover the whole range of the air drift angles (or, alternatively, heading or course angles) and must account for the main parameters of the windage area when the ship is in the ballast or heavy ballast condition. The aerodynamic loads can be estimated by means of the generic model (11) or some other universal model may be approved.
3. The mentioned standardized procedure is to be applied to a statistically significant sample collection of ships (the same as before or different depending on the data availability) at some selected and approved speed of advance, and for each ship the maximum wind speed, at which it still remains fully controllable, must be computed.
4. Again, the agreed standardizing value of the wind speed must be chosen in such a way that 95% of the collection be recognized as controllable in wind. It must be emphasized that this criterial wind speed should not be treated as a real limiting or critical wind speed.
5. Finally, the worked out new criteria must be benchmarked against an independent collection of ships and, as result, certain corrections may be introduced.

However, it must be recognized that better understanding of the correspondence between the degree of inherent directional (in)stability and the behaviour of a ship in a seaway is highly desirable and should be studied by means of systematic simulations with some sufficiently consistent modular mathematical models. Meanwhile, it should be emphasized that in this paper, apparently for the first time, was established such an interesting and important fact that the dependence of the required degree of (in)stability on the ship speed obtained earlier for the calm water (the faster is the ship, the more stable it must be) is quite opposite to the dependence imposed by the adverse conditions in which case the inherent stability requirements must become stronger at smaller speed.

Finally, it can be foreseen that implementation of modified and/or additional manoeuvrability standards may require more effective, heavier and more expensive steering devices from the ships underpowered under influence of the EEDI requirements which may stimulate some correction of the latter.

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