MANOEUVRING CRITERIA: MORE THAN IMO A751 REQUIREMENTS ALONE!

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In 1993, IMO resolution A751(18) was accepted. Since 1993, ship designs focussed on complying with these standards. For the Netherlands, MARIN gathered the full-scale results of about 100 ships. Performance with respect to IMO A751 requirements was demonstrated in the 2002 meeting of the IMO-DE. It was shown that most ships fulfilled the IMO recommendations. The ships not fulfilling the requirements sailed anyway, manually, or by using an advanced autopilot. Based on the gathered manoeuvring properties of the vessels, the following observations are made. The current standards are focussing much on conventional vessels: displacement ships propelled by standard propulsions (propeller(s) and rudder(s)). For vessels with other propulsion means, the rules are flexible. Also sailing in shallow and restricted water (most critical manoeuvring situations) are not dealt with. The impact of environment (wind, waves and other vessels) is also not taken into account. Because there are no criteria for that, under the economic pressure ships will be constructed "just" fulfilling the design criteria (so-called fit-for-purpose). However, other aspects are also important. On these subjects a set of criteria is proposed and ways to test or verify the designs are discussed.

1. INTRODUCTION

The danger of introducing manoeuvring criteria is that ships are designed that are just fulfilling the criteria. Under economic pressure it could then be said that the ship is "good" manoeuvrable, while this would be not the case as "good" manoeuvrable may also be defined by other factors.

When looking at criteria, one should make distinctions between safety criteria and mission related criteria. Safety criteria will define a minimum level of manoeuvrability. Ships not fulfilling these criteria are substandard and should obtain a penalty: more training is required, special means should be put on board or in the ultimate case, the ship would not be allowed to sail. This most severe penalty should not be carried out often, as that would jeopardise the common ground for solid criteria.

In this paper, the as-is situation is analysed. Some drawbacks are sketched and additional criteria (quantities and norms) are proposed. Furthermore, ways to verify compliance with these criteria are proposed. The objective remains that ships sailing in our waters should have adequate controllability, both for their own safety and the safety of others.

2. PRESENT CRITERIA: IMO A751(18) SINCE 1993

Since 10 years, IMO criteria are advised in many countries, although there is no obligatory character. Most national administrations take part in recommending that "IMO manoeuvres" are carried out on sea trials of newly built vessels. Also in the Netherlands, for every vessel built in the Netherlands or sailing under Dutch flag, IMO manoeuvres are carried out. The gathered results of about 5 years full-scale trials are summarised in Figures 1, 2 and 3.

MARIN gathered these results and made comparisons between the sea trial results and the IMO criteria. It is observed that for ships under Dutch flag or built by Dutch shipyards, most vessels comply with the criteria. Some ships are not fulfilling the criteria. For the "Dutch" vessels, the most difficult criterion is the criterion for the first overshoot angle of the 10/10 zigzag test. This means that there are ships that are course unstable up to an unsatisfactory degree (at least according to the IMO standards).

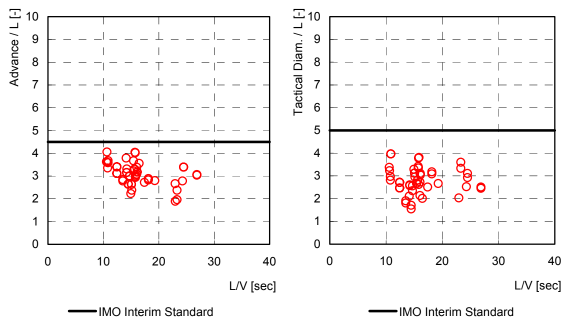

Fig. 1 Advance and tactical diameter obtained from turning circle tests

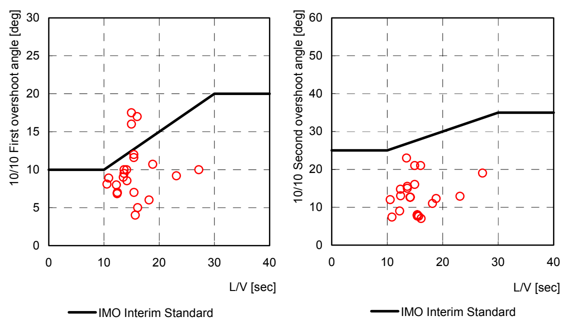

Fig. 2 First and second overshoot angles obtained from 10/10 zigzag tests

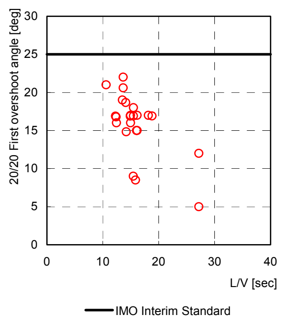

Fig. 3 First overshoot angle obtained from 20/20 zigzag tests

Although some vessels do not comply with the criteria, all ships are delivered and are sailing. The feeling of the designers and sailors is that the vessels are indeed course unstable. In general, it is the feeling of the designers that the criteria for overshoot angles is realistic. This is also confirmed by the conclusions by Rhee [1]. The vessels that do not comply with the criteria are indeed course unstable, although the degree of instability or unacceptability can be under discussion.
The following question arises: will, by pursuing the present line of IMO A751(18), substandard ships be eliminated? This is the motivation to investigate the other and enhanced criteria for manoeuvring.

3. MOTIVATION FOR A QUEST FOR MANOEUVRING CRITERIA

One of MARIN's core businesses is to perform an adequate judgement and if necessary improvement of a ship in the design stage. The request towards the ship's performance in terms of manoeuvrability is in general: “the ship shall be good manoeuvrable”. This means that IMO criteria have to be fulfilled. However, the “IMO A751 requirements” only relate to a small portion of the ship’s “safe manoeuvring”. The following highly relevant operational aspects are important as well and there are questions that need to be answered in MARIN's day-to-day business:

- Adequate manoeuvrability in shallow water.
- Maximum achievable wind forces for harbour manoeuvring.
- Low-speed manoeuvring capabilities.
- Steering in wind and waves at relatively high speeds. Ability to execute a 180 degrees. Turn in waves.
- Limited heel angles.
- Adequate straight-line stability.
- Low speed manoeuvring.

When judging the capabilities of each vessel on these items, one should make a distinction between the norm needed to achieve safe vessels and the norm to achieve that the ship is “adequate to the mission it has to perform”.
In some cases, these questions can be answered using statistics: comparison to similar vessels. MARIN is in the lucky position that an enormous amount of information has been compiled, either as full-scale measurements, basin model-scale measurements and bridge or fast-time simulations. This enabled us to build up a statistical database containing the behaviour of a large amount of vessels. Each new vessel can be rated against existing vessels of the same type and the same mission. The qualifications “superior to”, “comparable to” and “worse than” are related to this database.
However, databases alone are not enough. For vessels with special missions, or special designs, comparison is difficult. This means that in this case a more detailed study towards “which manoeuvring behaviour is acceptable” should be carried out. A bridge simulator is the best tool for this.
Having this in mind, a questionnaire has been put together. Using interviews, ship operators are asked their opinion on the minimum required steering behaviour of vessels. Students of the Dutch merchant academy have performed these interviews on a series of conning officers of Dutch-flag vessels. The interviews were especially focussed on obtaining information on both IMO types of manoeuvres and non-IMO manoeuvres. This gave us the lead to the importance of heel angles and the performance in shallow waters. This led to important conclusions:

- Ballast load is often the easiest condition, but especially the heel angle is of importance.
- Shallow water at moderate speeds (for example sailing in the Strait of Malacca).
- Heel angles during manoeuvres are of significant importance.
- Low speed manoeuvring is depending on the ship type. There is a class of vessels which always uses tugs (bulk carriers, large tankers). Another class preferably uses no tugs.

Having observed this, it is the work of the hydrodynamicists to translate this information in "objective" limiting values. The target should not be to obtain a method to express the manoeuvring qualities in one number (such as propagated amongst others in [2] and [3]). It is preferred to have individual criteria for each quality. With individual criteria, it can be recognised which qualities of the ship are fulfilled and which qualities need to be improved. In that way the hydrodynamic opti-misation can focus on the criteria that are not fulfilled. Furthermore, the criteria should be such that they can be checked by objective tests. In this respect, free sailing model tests are the best methods, giving high quality results within a short time.
While performing the research, it became apparent that the quest for criteria is answered in a different way for ship designers and for ship operators. Operators tend to require answers to "knowing how the ship reacts". In a way, a much more enhanced "wheelhouse poster" is required. From the operator's side, amongst other, the following questions were rated important:

- How different does my ship react in shallow water?
- Up to which speed is my ship reacting on its rudder?
- How much bow thruster force can I expect as function of the forward speed?
- At which wind speed do I need tugs?

The designers (with the hydrodynamicists on their side) are, however, trying to derive criteria from that in order to build ships adequate for sailing and fit for purpose:

- What is the required size and type of my rudder?
- How many bow and stern thrusters are required and which power is necessary?
- Which heel angles are acceptable?

Having recognised these aspects, it became clear that two aspects are important: guaranteeing a minimum level of manoeuvrability (depending on minimum safety level and on mission requirements) and supplying more information with respect to the manoeuvrability to the crew.

In the following sections, several criteria for non-IMO conditions are treated. Each of the individual hydrodynamic aspects are indicated as points of attention indicated by the interviews. The knowledge on the subject is fed from experience in the basins and from full-scale observations. We are focussing on the safety issues, and not on individual requirements for the mission. Subsequently, the following aspects are discussed:

- Shallow water
- Straight-line stability
- Heel angles due to steering
- Steering with special devices
- Steering (controllability) in wind
- Steering (controllability) in waves

4. INFLUENCE OF SHALLOW WATER

Manoeuvring properties are of particular importance in shallow water. The following three aspects play an important role:

- Due to squat, caused by increased velocities under the vessel, the ship will trim and sink, causing a different submerged portion of the vessel and causing (in case of bow down trim) a more course unstable vessel.
- The flow of water around the aft ship will become much more difficult, especially for a beamy vessel. This could cause flow separation and therefore undesired loss of effectiveness of the rudder. The different wake fields in deep and shallow water are illustrated in Figure 4. This figure illustrates the wake field at the location of the propeller for deep water (left-hand side) and for shallow water (right-hand side). This has been calculated using MARIN's RANS calcu-lation software PARNASSOS [4].

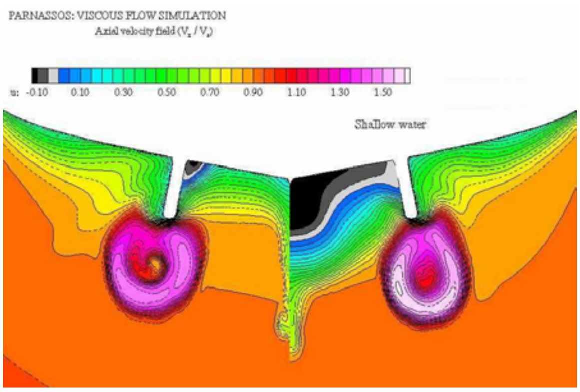

Fig. 4 Wake field in deep and shallow water (Courtesy of IHC Holland N.V. Dredgers)

- Due to the larger overflow velocities under the vessel, the forces due to drifting and rotating are changing. This results in increasing lift and drag coefficients (see the excellent work of the ITTC in [5]).

A well-known example is the Esso Osaka, which demonstrated an increase of the advance and tactical diameter with decreasing water depth. Most cases are indicating the increase in course keeping stability in shallow water. However, many ships also encounter decrease of course keeping ability in shallow water. As an illustration, we refer to Figures 5 and 6, in which it is demonstrated with a computer simulation model based on cross flow drag theory and adaptation of the hydrodynamic coefficient based on the shallow water coefficients, that the course instability grows. While for the directionally stable vessel, the overshoot angles decrease from 6 degrees to 4 degrees, for the course unstable vessel, the second overshoot angle increases from 29 degrees to 38 degrees (the criterion for the second overshoot angle was 34 degrees).

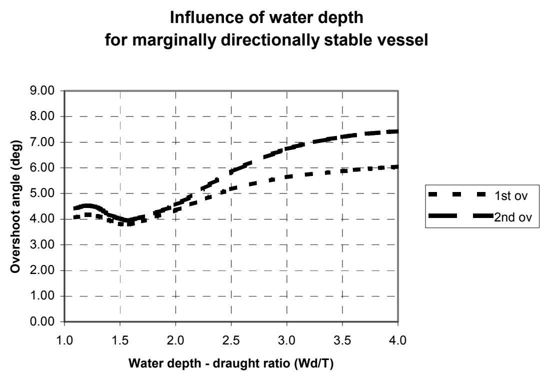

Fig. 5 Overshoot angles for a directionally stable vessel

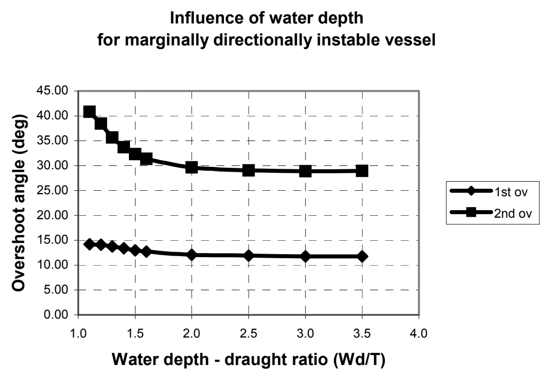

Fig. 6 Overshoot angles for a marginally directionally unstable vessel

This means that (without attempting to generalise the problem) that course unstable ships will become more course unstable and course stable vessels will become more course stable. This means that course unstable vessels will have more difficulty fulfilling the IMO criteria towards overshoot angles in shallow water. Course stable vessels will, however, have more difficulty in achieving the manoeuvring towards advance and tactical diameter.

Vessels that will have to sail in shallow water, which are 90% of the vessels, should therefore fulfil not just the IMO criteria, but should remain significantly under the criterion to have enough margin to fulfil the criteria in shallow water as well. The target is that the vessel should have enough course stability and turning ability to fulfil the IMO requirements with respect to overshoot angles and turning circle dimensions in shallow water. The criteria should be fulfilled in water depths larger than 1.3 times the draught of the vessel ($Wd/T > 1.3$). At this water depth, the speed is obviously lower than the speed used for the tests at deep water. With this decreasing speed, the overshoot angles decrease as well.

A set of free sailing model tests or captive (PMM or rotating arm) tests at both water depths (deep water and the lowest keel clearance) will give these results.

5. STRAIGHT-LINE STABILITY: THE RESIDUAL RATE OF TURN RATIO

When free sailing tests are performed, it is a normal procedure to perform the turning circle test and the pull-out test in one procedure. During model tests, this is standard procedure (at least with large enough basins). During full-scale trials, this could be more problematic due to the influence of the wind on the "residual rate of turn". The residual rate of turn ratio can be derived from a turning circle test at hard over rudder (35 degrees or the maximum rudder angle, whichever is the smallest) with a pull-out manoeuvre. In Figure 7 such a manoeuvre is given.

The time trace of the rate of turn of a turning circle / pull-out manoeuvre will show that the rate of turn decreases from the constant rate of turn during the turn after the rudder has been put to zero to a rate of turn which stabilises after having travelled a few ship lengths (between 10 to 15 ship lengths). This rate of turn at zero rudder angle is called the residual rate of turn. The residual rate of turn ratio is the ratio between the rate of turn at zero rudder angle and the rate of turn at the maximum rudder angle. Such a value is related to the height of the instability curve as illustrated in Figure 8.

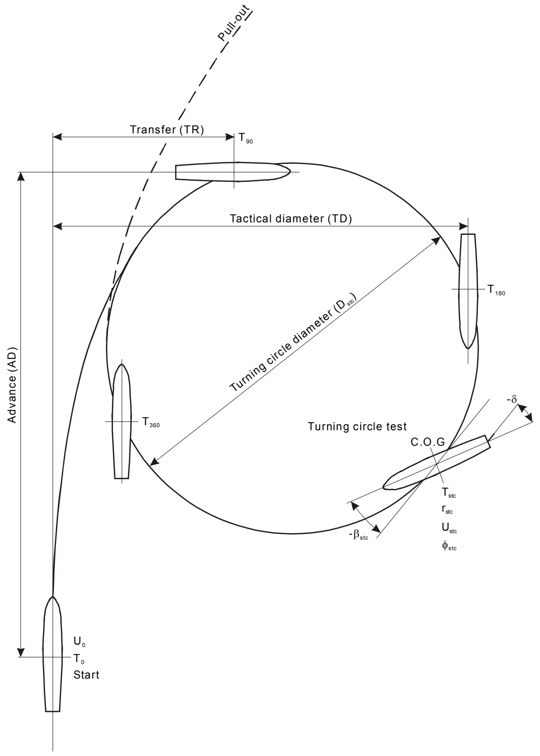

Fig. 7 Turning circle / pull-out test

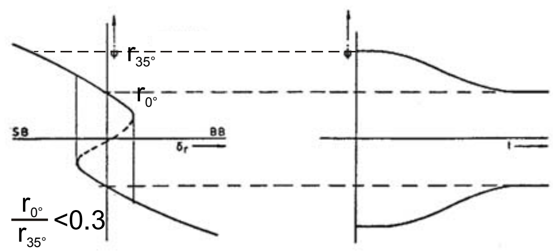

Fig. 8 Residual rate of turn ratio

The criterion is that the rate of turn ratio should be smaller than 0.3. The psychology behind this criterion is that the helmsman should encounter a large difference in visual perception (in general: the rate of turn) between steering with maximum rudder and steering with smaller rudder angles. Therefore, the rate of turn achieved with maximum rudder should be significantly higher than the rate of turn with a small rudder angle. This has been reduced to a single criterion derived based on bridge simulations in the eighties at MARIN, being the factor 0.3.
This criterion can be determined using free sailing model tests or captive tests followed by simulations.

6. HEEL ANGLES

The heel angle during turns is much more important than it received attention in previous criteria. The maximum heel angle is of importance. It needs to be said that the maximum heel angle is often much larger (factor 2 to 4) than the constant heel angle during a turn. The maximum heel angle is a function of speed, drift angles, roll damping and build-up of the dynamic manoeuvre.
From interviews, it appears that a heel angle of 10 degrees is much higher than acceptable. In Figures 9 and 10, these heel angles are illustrated. An IMO resolution has been written on the maximum heel angle: the criterion was set at 10 degrees. Furthermore, the "panic" angle has been determined at 9 degrees. If this angle is present for a longer time, and builds up slowly, this is a frightening effect. Therefore, it needs to be avoided. From a lot of model tests at MARIN, it was observed that heel angles are achieved up to 30 degrees.
To keep things practical, the maximum heel angle during a turning circle test is set at 13 degrees. This is valid for any steering angle. The maximum angle during the constant turning is set at 8 degrees, as it should be clearly below the panic angle.
The best way to verify this before the sea trials is to use free sailing model tests. It is also possible to do this using captive tests, but it is more elaborate and requires a larger set of tests.

Fig. 9 Heel angle during forced roll tests seen through bridge window

Fig. 10 Heel angle during turning circle on frigate (source: internet)

7. SPECIAL STEERING DEVICES

As the IMO criteria are defined for ships with rudders, one could say that they are not valid for ships with pods, azimuthing thrusters or other units with vectored thrust. However, from an operator point of view, there is no distinction between "hard-over rudder" or "hard-over pod", just as there is no difference in criteria for normal rudders and high-lift rudders. So, also podded driven vessels should fulfil the IMO criteria. The values of 10 degrees rudder angles apply to 10 degrees pod or thruster angles in the same way. In general, ships equipped with vectored thrust devices do not have problems with respect to their turning ability. It is, however, a myth that there are no "manoeuvring problems". Ships with vectored thrust devices often have course keeping problems. It should always be kept in mind that the role of the rudder is namely not only to steer the vessel, but also to stabilise the vessel. The stabilising effect of a thruster or a pod is in general less than the combination of a rudder with a propeller in front of it. Toxopeus and Loeff [6] have demonstrated that the overshoot angles of vessels with pods are larger than the overshoot angles of vessels with rudders. Therefore, the course keeping ability of vessels equipped with thrusters or pods needs to be investigated.

8. LOW SPEED MANOEUVRING

Ships have to call in port regularly. A minimum sideways performance has to be guaranteed by the vessels. The low speed manoeuvring performance is, however, not a priori a safety criterion, but a mission criterion. Some vessels do not need low speed manoeuvring capability, as they are guided by tugs during the complete port entry process. For vessels like this (large tankers and large bulk carriers), escort tugs are required and are becoming more and more standard (see [7]).

For a larger group of vessels a minimum level of lateral control at zero speed is required. Owner requirements tend to pay more attention to this aspect. It was summarised by Quadvlieg and Toxopeus ([8]) that there was a minimum wind speed of 20 knots wind defined for ships leaving the quay. For ferries and cruise liners, 30 knots is used often, and even sometimes 40 knots. Another criterion that is seen more and more is the ability to turn on the spot within a square area of 2 ship lengths within a certain time frame. The way to verify this requirement is to perform model tests. Especially close to the quay, so many interactions are taking place that no satisfactory easy calculation methods are present. In [8], it was demonstrated that error margins of 100% can be found in this way. The best way to verify this is to perform static tests, eventually combined with bridge simulations.

9. STEERING IN WIND

When a ship slows down in wind, its heading will come up into, or pay off from the wind. This will depend on the design of the ship and the heading with respect to the wind. Roughly above a critical ratio of wind speed to ship speed, the ship looses "steerageway" and all headings cannot be held, even with full rudder and all power applied. Publications like [9] refer to methods to calculate the "control boundaries", the wind velocity at which the rudder angle exceeds 20 or 35 degrees.

When vessels are sailing in wind, and this wind is coming from an oblique direction, the vessel will have to maintain a minimum speed in order to be able to counteract the wind forces. Given a certain speed (say 6 knots) and a certain wind velocity (say 20 knots) from any direction (from bow wind to stern wind), this results in drift angles and rudder angles. These drift and rudder angles can be calculated. The additional resistance is calculated as well. This is demonstrated in Figure 11, showing the performance of two different ship concepts (a podded ship and a conventional ship) while sailing in wind (see also [6]). It demonstrates that in stern quartering wind, the required rudder angle to keep control is 25 degrees, while the pod angle of the same concept would be 15 degrees. This means in this case that the rudder configuration would not be acceptable. Only 10 degrees rudder angle left as margin for dynamic effects is not enough. The experience learns that a maximum rudder angle of 20 degrees is just acceptable. A second aspect that could lead to unacceptability is the increase of the added resistance and a possible insufficient engine power. In case the engine power is insufficient to keep speed, an unacceptable situation is found.

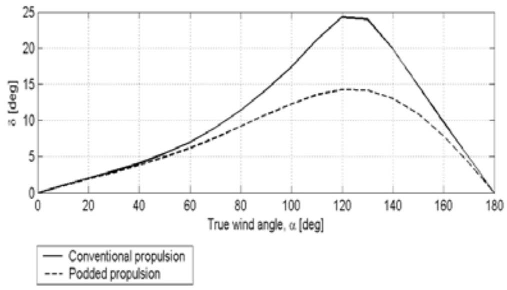

Fig. 11 Required steering angle to keep course for a pod-driven vessel versus a conventionally propelled vessel

These wind control boundaries can be calculated based on the derivation (calculation or model measurement) of the so-called current forces and wind forces, the rudder forces as function of pro-peller loading and so on.

This results in three equations (X, Y and N) and three unknowns (drift angle, rudder angle and propulsion power) for each wind speed and ship speed.

10. STEERING IN WAVES

The control in waves can be analysed to boil down to three issues: (1) How much rudder action is needed in moderate waves with a realistic autopilot? (2) Is a ship still controllable in extreme waves or will the ship broach too easily and what are the limiting wave conditions for uncontrollability? (3) What are the limiting wave conditions for adjusting the ships heading (changing from following waves to head waves for example)?

Issue (1) is an aspect that concerns economics. With to many rudder actions, resistance and hence fuel consumption increases. If the rudder angle oscillations become too high, issue (1) becomes automatically issue (2). Issues (2) and (3) are both aspects related to safety. Fortunately, more and more attention is drawn to the subjects, not only from a hydrodynamic point of view (see amongst others [10] and [11]), but also from the regulatory bodies (see [12]).

Within the CRNavies research forum of MARIN, FREDYN is developed (see amongst others [10] and [13]) which is used to study the aspects related to steered vessels sailing in extreme waves. The controllability in extreme waves is a subtle combination of very good craftsmanship and difficult hydrodynamics. The study to verify whether heading changes are still possible in certain waves is therefore difficult. Criteria are not set yet. A research effort is, however, made to do so. The FREDYN code (accurate predictions of broaches and capsizes) was developed as a fast time simulation program, is also mounted to a full mission simulator. In this simulator, now extensive possibilities are present to study these phenomena. Even better, if the study comes up with a good guidance, officers can be trained on keeping control in extreme waves, which they will hopefully never encounter in real life. This guidance could be in the form of a two-dimensional chart with ship speed on one axis and wave height on the other. Areas in the chart would then define the combinations of speed and wave height that allow the ship to turn easily, or combinations which could endanger the ship and crew.

Criteria of how good the ship performance should minimally be, are not yet defined; but a criterion could possibly read like this: “The ship must be able to execute a 180 degrees course change with an initial speed of 40% of the maximum speed and at a rudder angle of 2/3 of the maximum rudder angle in waves of say 6 metres height.”

This leaves the crew with a margin in ship speed and rudder angle to play with in order to be able to execute this difficult manoeuvre.

11. MANOEUVRES IN CONFINED WATERS

As stated by many authors, manoeuvring in confined waters may be most critical. Interaction effects between banks and other vessels are causing impulses on the own ship and on other vessels. The hindrance causes undesired motions and sometimes uncontrollable motions. Especially since today's economics are pushing us on one hand to perform economy of scale on the ship size and on the other hand to save money on dredging (to increase canal depths) and infrastructure investments (locks and bridges). Ships sailing in these restricted areas require special treatment to assure a minimum level of controllability. Traditional inland vessels on the European inland water system will also comply with this: their rudder designs and rudder areas are advanced compared to seagoing vessels. Dijkhuis et al. [14] illustrate how the Dutch government is dealing with the admittance policy and with the criteria for this. In the mean time, criteria are developed and acting. These criteria are posed on course keeping ability, turning ability and minimum achievable speed. Criteria are valid for the lowest and highest loading condition and for different water depths.

12. LIST OF CRITERIA

Based on the discussion of manoeuvring aspects above, the following list of criteria should be considered:

- The IMO criteria with respect to course keeping and turning should be met, also at any water depth up to Wd/T=1.3.
- The residual rate of turn ratio should be below 0.3.
- The maximum heel angle due to steering should be below 13 degrees.
- The constant heel angle due to steering should be below 8 degrees.
- Ships having special steering devices should also fulfil the requirements. The steering angles are equal to the steering angles of rudders. That means that the criteria for a 10/10 zigzag test are valid for 10 degrees pod angle, waterjet or thruster angle as well.
- Depending on the mission of the vessel: leaving the quay should be possible at wind speeds below 20 knots, 30 knots or sometimes 40 knots.
- Necessary rudder angle in wind of 40 knots at 8 knots ship speed should be less than 20 degrees.
- The ship must be able to execute a 180 degrees course change with an initial speed of 40% of the maximum speed and at a rudder angle of 2/3 of the maximum rudder angle in waves of say 6 metres height.

13. CONCLUSIONS AND RECOMMENDATIONS

When examining the requirements regarding the manoeuvring behaviour of the ship during its full operational life, the following conclusions and recommendations are made regarding applying criteria to the manoeuvrability of ships:

- The “IMO A751 requirements” only relate to a small portion of what should be considered as “safe manoeuvring”.
- A set of other criteria is proposed that cover a larger area of ship operations than the aspects covered by IMO resolution A751(18).
- Despite that designers can design ships fulfilling minimum manoeuvring requirements, it does not eliminate the need to provide better guidance to the operators of the vessel. The pilot card, wheelhouse poster and manoeuvring booklet should be provided with better information and assist the operators in their daily work.

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