# Evaluation of stability criteria limiting the angle of heel due to turning, in the light of ship motion simulation results

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**ABSTRACT**

The sudden turns of ships may introduce unsafe stability conditions, as occasionally evidenced by the capsizing or cargo damage enroute. Therefore, this well-known threat to ship stability consisting in possible large heeling during turning is addressed within the 2008 IS Code based criteria framework. Several proposals for amendments to that regulation were submitted to the International Maritime Organization in past years. Also, a number of military-originated solution as well as some historical regulations issued by classification societies exist. All versions of a criterion designed to prevent excessive heeling during rapid course alterations constitute a set of similar solutions though they vary in details and in the resultant quantitative outcome. Two identified versions of the criterion related to the angle of heel due to turning have been examined. Furthermore, a historical proposal utilizing the dynamic angle of heel has been considered as well. The evaluation is based on credible results of numerical simulations of ship motions. The state-of-the-art, successfully benchmarked, 6DoF ship dynamics model LaiDyn has been utilized. Both the instantaneous maximum angle of heel and the quasi-static angle of heel developing during steady turning have been captured from the simulation results. The main intended objective of this article is to develop a discussion on both, first on the possible improvements to the contemporary criterion assessing stability during turning of the ship; second, on the potential future extension of the Second Generation Intact Stability Criteria in order to cover the risk due to ship turning.

**Keywords:** *stability criteria evaluation, stability during turning, heel due to ship turn, ship operational stability.*

## 1. INTRODUCTION

Despite vast majority of seagoing ships spend most of their operation time lying on a steady course, with some yaw oscillations, they need to turn at times in order to execute the transportation tasks. From the tactical perspective, the intended course alterations are expected and executed in accordance with a voyage plan. Therefore, typical rudder settings are minor, the resultant rate of turn is relatively low, and eventually, the turn-induced angle of heel does not jeopardize the ship safety in terms of its stability. However, from the operational control point of view, occasionally ships have to undertake ad hoc maneuvers when underway, which reflect the proper reaction to varying navigational situations. The most common reason for a sharp turn to starboard is a collision evasive maneuver, although other causes may occur as well, for instance man overboard action. Data recorded in real operation reveal that the rate of turn reaching up to 3 degrees per second and rapid course alteration by even more than 90 degrees are not exceptional (Gil et al., 2022; Mestl et al., 2016). Such sharp turns may occur by the action of a massive heeling moment due to the centrifugal force, potentially causing an angle of heel that should not be neglected from the ship stability assessment perspective. The incidents record shows that occasionally ships experience an insufficient stability conditions exposing them to the turn-related threat, like for instance in case of ro-ro ship *Hoegh Osaka* (MAIB, 2016), the trawler *Dimitrios* (Voytenko, 2015) or the general cargo vessel *Mosvik* (Voytenko, 2017). The most tragic accident strictly related to a rapid turn was the disaster of the ferry *Sewol* in 2014 with 294 deaths (Kee et al., 2017).

The International Maritime Organization undertook relevant efforts in order to prevent excessive heeling of ships during a rapid alteration of their course. To date, the adopted instrument addresses the issue with regards to passenger vessels only. The International Code on Intact Stability, 2008 (2008 IS Code) contains a mandatory criterion for passenger vessels restricting the maximum allowed angle of heel in turns to 10 degrees (International Maritime Organization (IMO), 2008). The heeling moment on account of turning shall be obtained from the following formula.

$$M_R = c \cdot \frac{v_0^2}{L_{WL}} \cdot \Delta \cdot \left(KG - \frac{d}{2}\right) \quad (1)$$

where:

$M_R$ - heeling moment (kNm);

$c$ – coefficient equal to 0.2 (-);

$v_o$ - service speed (m/s);

$L_{WL}$ - length of ship at waterline (m);

$\Delta$ - displacement (t);

$d$ - mean draft (m);

$KG$ - height of center of gravity (m).

The corresponding formula describing the heeling lever, with respect to proper units, is the following.

$$l_R = c \cdot \frac{v_0^2}{g \cdot L_{WL}} \cdot \left(KG - \frac{d}{2}\right) \quad (2)$$

where:

$g$ – gravitational acceleration (m/s$^2$).

The 2008 IS Code based approach is straightforward as the static moments balance is considered. Moreover, the formula does not include several associated hydrodynamic effects caused by the hull and the rudder.

There were some attempts to improve the criterion at IMO. In IMO document MSC 89/22/8, the U.K. delegation suggested to change the '$c$' coefficient from 0.2 to 0.4 (International Maritime Organization:, 2011a). They also proposed the possibility of acceptance of other equivalent methods specific to various types of ships, i.e. full-scale trials, model scale testing and the use of simulations. In documents SLF 54/11 from 2011 and then SLF 55/12 from 2012, RINA submitted a revised proposal for the criterion modification (International Maritime Organization:, 2012, 2011b). The distinction between the initial dynamic angle of heel and the static 'steady-state' heel was raised and the inspiration by the criterion applied by the navy (International Maritime Organization:, 2012) was emphasized. In the document SDC 1/14, Japan expressed their concern about a shortage of examples based on actual full-scale trials in the earlier U.K. proposal (International Maritime Organization:, 2013a). An alternative proposal for modification of the criterion was submitted by Poland in the document SDC 1/14/1 (International Maritime Organization:, 2013b). The suggested critical determinant to be examined was the initial transient maximum angle of heel in turn, instead of the static one. The IACS document SDC 2/INF.5 criticized the proposal presented in SDC 1/14/1 (International Maritime Organization:, 2014). The briefly described discussion shows that the issue is not commonly recognized as unambiguous in terms of the preferred approach. The analysis presented in (Hinz et al., 2021) confirms the discrepancies between the different approaches.

Besides the formula (1) provided by the 2008 IS Code, there are numerous regulations applicable for naval ships and some intended for European inland vessels based on the Directive 82/714/EEC (European Council, 2015). However, these regulations are to a large degree similar, as utilizing the same simplified model of the phenomenon. Apparently, the formulas may appear different, although they can be easily transformed into the form close to the formula (1). For instance, the heeling lever due to a turn shall be, according to naval regulations by Bureau Veritas, estimated according to the following formula.

$$IL = \left(\frac{V^2}{\mathrm{R}}\right) \times \frac{a \cos\theta}{g} \quad (3)$$

where:

$V$ – speed of the vessel during turning operation; this may be assumed 80% of the maximum speed when vessel start turning (m/s);

$R$ - turning radius, which may be assumed to be 3.3Lbp (length between perpendiculars) (m);

$a$ - vertical distance between drifting center and center of gravity of the vessel (m);

$\Theta$ – angle of heel (deg).

As the speed $V$ from the formula (3) equals to $0.8V_0$ from the formulas (1) and (2), $g$ = 9,81 m/s$^2$, the vertical distance $a$ may be assumed as $KG$ - $d$/2, and the turning radius may be assumed to be 3.3 of the ship's length, another form of the formula (3) is as follows.

$$l_R = c_{BV} \cdot \frac{v_0^2}{g \cdot L_{bp}} \cdot \left(KG - \frac{d}{2}\right) \cos\theta \qquad (4)$$

where $c_{BV}$ = 0.194, which is pretty close to 0.2 from the formula (1). The ship length between perpendiculars is close to the length at waterline and the cosine of the heel angle is very close to 1. Actually, the heel limit is set to 10 degrees (for passenger ships) in the 2008 IS Code, which makes the value $\cos\theta$ not less than 0.985, while, in case of the Bureau Veritas regulation, the threshold is set to 15 degrees (for naval ships), so $\cos\theta$ is not less than 0.966. In any of those two cases the cosine characteristics of the heeling moment does not significantly vary from the simplified assumption of the constant heeling moment adopted in 2008 IS Code. Thus, the comparison of the formula (2) to (4) and indirectly to (3) shows that they are almost the same in terms of results.

The review of contemporary regulations reveals that from the practical point of view the adopted formulas for the heeling moment or the heeling lever calculation are equivalent, regardless of the technical formulation. The following standards were considered: the 2008 IS Code and the classification societies which incorporated this Code, the Australian Navy, the U.S. Navy, the U.K. Royal Navy, the Polish Register of Shipping inland rules that are fully based on the European inland vessels regulations. The only meaningful difference consists in various values of the coefficient '$c$', which equals typically around 0.2 for seagoing ships (IMO, 2008) and $0.45C_B$ (block coefficient) for inland vessels, which produces the number around 0.4, i.e. roughly twice the 2008 IS Code based value (European Council, 2015).

The research question derived from the described contemporary approach to regulations preventing excessive heeling of ships during rapid turns, focuses on the assessment of the accuracy of the simplified practical formulas. This may be achieved with the use of a sophisticated model allowing for a credible simulation of ship motions. In order to address these objectives in an organized manner, the rest of the paper is structured as follows: Section 2 introduces the method adopted in the study comprising ship motion simulations and turning scenarios, as well as the considered ships particulars; Section 3 presents obtained results, to be discussed in Section 4; while Section 5 concludes.

The main objective of this paper is to initiate a discussion among experts, whether the current version of the criterion limiting an angle of heel due to the ship turn, is sufficient, or a simulation-based alternative proposal would be justified. This might contribute to the potential future extension of the SGISC to address stability failure during the ship turning.

## 2. METHOD AND MATERIALS

The adopted comparative method is straightforward as the heeling lever due to the ship turn needs to be compared to the corresponding one that comes from a credible numerical simulation of the ship motion. Actually, as shown in previous section, the coefficients '$c$' may be compared since the remaining parts of the formulas (2) and (4) are practically equivalent. For that reason a set of simulations was carried out.

### *6DoF ship's motion modeling*

The motion model incorporated in LaiDyn software has been utilized to simulate the ship turning (Matusiak, 2002). LaiDyn has been developed as a 6 DoF hybrid non-linear model for time domain simulations comprising not only the ship response to the external excitation by waves, but also the propulsion and steering forces. It is crucial that the model comprises a maneuvering nonlinear sub-model including hull loads, rudder loads and propulsion action. It was further developed and validated in line with (Taimuri et al., 2020). The model also includes nonlinear formulations for hydrostatic and hydrodynamic forces, including wave excitation (Matusiak, 2011). The performance of the method was validated by model tests conducted at Aalto University (Matusiak, 2003; Matusiak and Stigler, 2012), which makes this computational tool reliable.

### *Considered ships and turning scenarios*

The motion simulations have been carried out for two sample passenger cruise-ships, called 'ship A' and 'ship B'. The former is over 300 meters long while the length of the latter is over 200 meters, as shown in Table 1. For each vessel a number of *KG* values has been considered (Table 1) along with three values of speed (10.28 m/s, 8.22 m/s, 6.17 m/s) and one rudder setting (35 degrees). These loading conditions are assumed, and their KGs are below and above the limiting value for a given draught.. The rudder setting hard to starboard reflects the condition assumed in the scenario considered for both merchant ships and naval ships in the course of stability assessment according to the criteria described in Section 1. Calm seas have been assumed for the sake of comparison of results.

**Table 1: Characteristics of considered ships**

| Ship | *LOA* (m) / Beam (m) / $C_B$ (-) | Draft (m) / Mass (t) | *KG* (m) / GM (m) |
|---|---|---|---|
| A | 327 / 37.4 / 0.69 | 8.5 / 69289 | 17.730 / 3.05<br>18.130 / 2.65<br>18.530 / 2.25<br>18.779 / 2.00<br>19.279 / 1.50<br>19.778 / 1.00 |
| B | 238 / 32.2 / 0.66 | 7.2 / 34054 | 14.888 / 2.92<br>15.039 / 2.77<br>15.190 / 2.62<br>15.813 / 2.00<br>16.316 / 1.50<br>16.818 / 1.00 |

For each considered scenario, the transient angle of heel and the steady state resultant angle of heel have been recorded. The transient angle develops dynamically in the initial stage of turning, while the static angle of heel remains constant once the 'steady state' of turning is achieved.

Having the angles of heel determined for the ships with known metacentric heights and *GZ* curves, it is easy to calculate the value of the '*c*' coefficient that should be used in the formula (2) to satisfy the exact heel for each considered scenario. The closer the result to the adopted value 0.2 (or 0.4 for inland vessels), the more accurate the simplified formula is, for that particular ship and scenario.

## 3. RESULTS

The basic results of the performed ship motion simulations are two values of the heel angles, as described in previous section. Furthermore, the shape of the ship's trajectory (a sample result is shown in Figure 1), the rudder force and the reduction in speed have been captured as well ( sample results are presented in Figure 2).

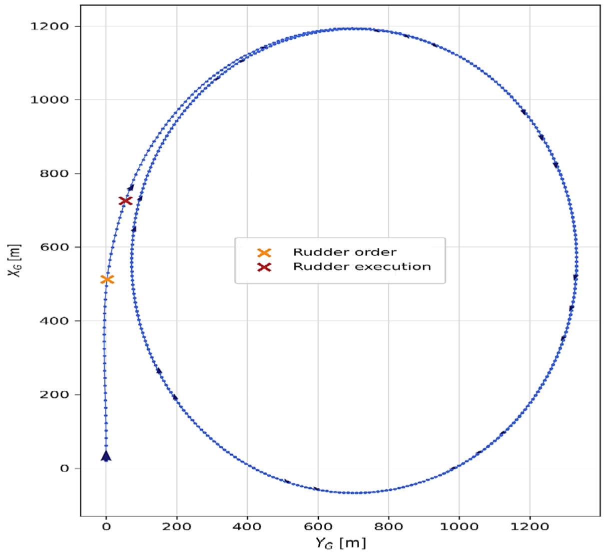


**Figure 1: Sample trajectory simulated for the ship A for one of the scenarios.**

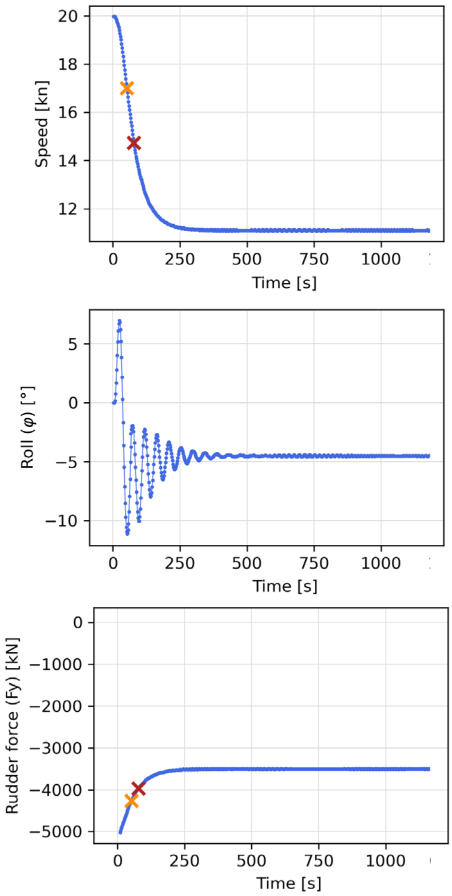


**Figure 2: Sample simulation outcome in terms of the time history of speed, roll and rudder force – Ship A.**

The values of the transient angle of heel and the steady state angle of heel have been obtained for each considered ship and the scenario of turn. The values of the heel angle are provided in Table 2 for the ship A and in Table 3 for the ship B, respectively.

**Table 2: Results of turning simulations for the ship A.**

| Initial speed (m/s) | *GM* (m) | Steady state heel (deg) | Dynamic heel (deg) |
|---|---|---|---|
| 10,3 | 3,05 | 1,3 | 3,1 |
| 8,2 | 3,05 | 0,9 | 2,0 |
| 6,2 | 3,05 | 0,5 | 1,3 |
| 10,3 | 2,25 | 1,9 | 4,1 |
| 8,2 | 2,25 | 1,3 | 3,0 |
| 6,2 | 2,25 | 0,8 | 1,8 |
| 10,3 | 1,00 | 4,5 | 11,2 |
| 8,2 | 1,00 | 3,2 | 7,4 |
| 6,2 | 1,00 | 1,8 | 3,9 |

**Table 3: Results of turning simulations for the ship B.**

| Initial speed (m/s) | *GM* (m) | Steady state heel (deg) | Dynamic heel (deg) |
|---|---|---|---|
| 10,3 | 2,92 | 1,2 | 2,9 |
| 8,2 | 2,92 | 0,7 | 2,1 |
| 6,2 | 2,92 | 0,4 | 0,9 |
| 10,3 | 2,77 | 1,3 | 3,3 |
| 8,2 | 2,77 | 0,8 | 2,2 |
| 6,2 | 2,77 | 0,4 | 1,0 |
| 10,3 | 2,62 | 1,4 | 3,6 |
| 8,2 | 2,62 | 0,8 | 2,3 |
| 6,2 | 2,62 | 0,4 | 1,1 |

The conclusive results of this research are quotients '$c_{regulatory}$' coefficient calculated according to the regulatory formula over '$c_{sim}$' determined from the results of simulations. The possible value $c_{regulatory} / c_{sim} = 1$ would mean a perfect agreement of the heeling moments. The ratio below 1 refers to an underestimation of the heeling moment calculated according to the regulatory requirements, while the ratio above 1 reveals conservatism of the regulation, which would overestimate the heeling moment due to the ship turn, thus the regulatory formula would be 'on a safe side' from the safety assessment point of view.

The obtained results are shown in Figures 3, 4, 5 and 6, with respect to the steady state angle of heel. The reference value named $c_{IMO}$ reflects the 2008 IS Code regulation while $c_{PRS}$ refers to the regulation by Polish Register of Shipping that are entirely based on the European inland navigation directive. The ship speed marked at the relevant axes are the initial ones.

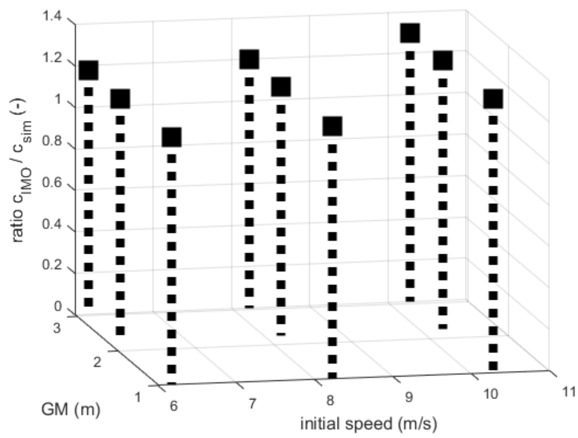


**Figure 3: Coefficients ratio $c_{IMO}$ (IMO 2008 IS Code originated) over $c_{sim}$ (simulations-based) for the ship A within the considered range of *GM* and initial speed.**

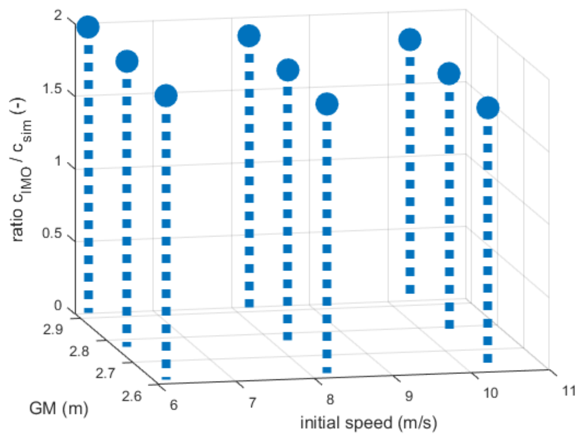


**Figure 4: Coefficients ratio $c_{IMO}$ (IMO 2008 IS Code originated) over $c_{sim}$ (simulations-based) for the ship B within the considered range of *GM* and initial speed.**

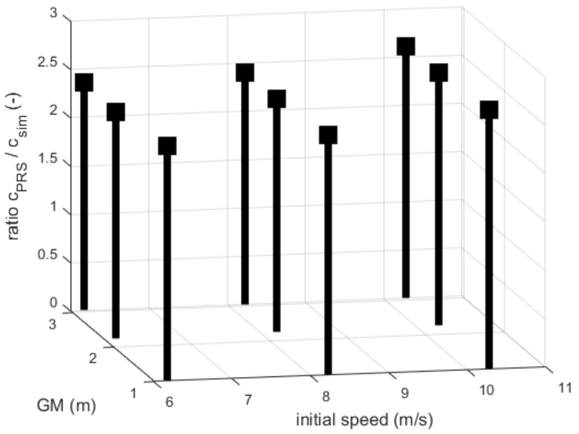


**Figure 5: Coefficients ratio $c_{PRS}$ (PRS inland ships) over $c_{sim}$ (simulations-based) for the ship A within the considered range of *GM* and initial speed.**

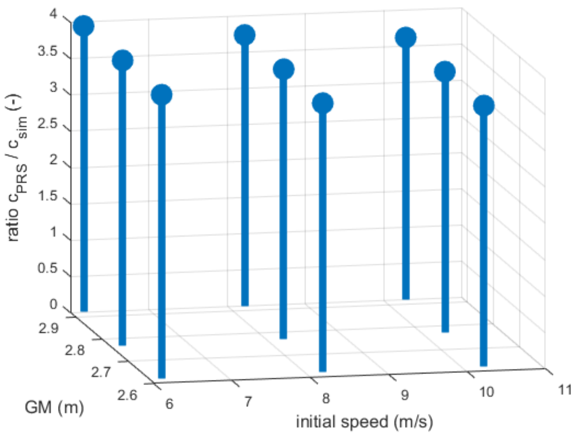


**Figure 6: Coefficients ratio $c_{PRS}$ (PRS inland ships) over $c_{sim}$ (simulations-based) for the ship B within the considered range of *GM* and initial speed.**

As the contemporary regulations do not comprise the transient angle of heel due to turning, the results reflecting the dynamic angle of heel need to be compared to the relevant reference value, i.e. also dynamic. As described in Section 1, RINA proposed consideration of such dynamic heel, as did the Polish proposal submitted as SDC 1/14/1. In this paper we utilize the SDC 1/14/1 proposal as the reference, bearing in mind that it has never been adopted with a regulatory status. The results with respect to the transient angle of heel and the corresponding ratio of '*c*' coefficients, are shown in Figures 7 and 8.

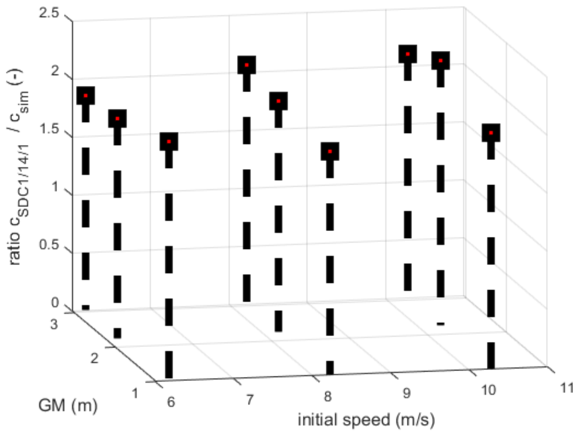


**Figure 7: Coefficients ratio $c_{SDC1/14/1}$ (according to the proposal submitted for SDC 1/14/1) over $c_{sim}$ (simulations-based) accounting for the dynamic angle of heel for the ship A within the considered range of *GM* and initial speed.**

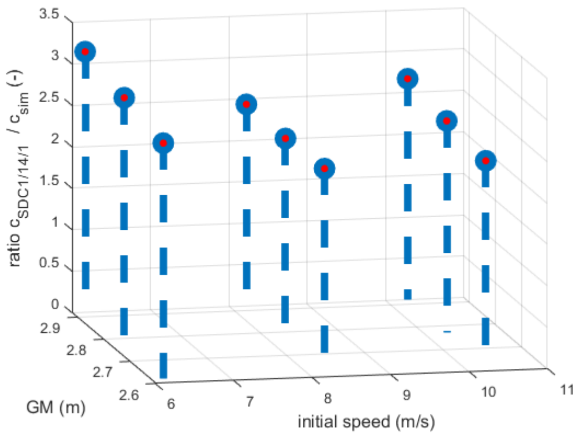


**Figure 8: Coefficients ratio $c_{SDC1/14/1}$ (according to the proposal submitted for SDC 1/14/1) over $c_{sim}$ (simulations-based) accounting for the dynamic angle of heel for the ship B within the considered range of *GM* and initial speed.**

## 4. DISCUSSION

The obtained results reveal the conservatism of the current regulatory approach. The formula provided by the 2008 IS Code overestimates the heeling moment due to the ship turn. In case of the ship B this overestimation is larger than in case of the ship A in all considered cases. The quantitative data are summarized in Table 4.

**Table 4: Stastistical description of the obtained coefficients ratios.**

| Ship | Ratio | Mean value | Standard deviation |
|---|---|---|---|
| A | $c_{IMO} / c_{sim}$ | 1.23 | 0.19 |
| A | $c_{PRS} / c_{sim}$ | 2.48 | 0.12 |
| A | $c_{SDC1/14/1} / c_{sim}$ | 2.03 | 0.13 |
| B | $c_{IMO} / c_{sim}$ | 1.88 | 0.23 |
| B | $c_{PRS} / c_{sim}$ | 3.75 | 0.44 |
| B | $c_{SDC1/14/1} / c_{sim}$ | 2.66 | 0.31 |

Having the results collected we ought to consider what feature of the ships is examined with the use of the regulations. It is not purely stability characteristics, rather it is the relation between several factors. The elevation of the center of gravity (*KG*), which influences the metacentric height and the *GZ* curve, is one such feature. The ship speed appears crucial as well, especially since the speed is squared in the regulatory formula, which makes the outcome sensitive to this variable. The reduction of speed in the steady state turn of the ship is assumed in the simplified formulas and computed in the time domain in the course of numerical simulations of the ship motion. The ship speed reduction is massive for such a rapid turn as considered in this study, as seen in Figure 2 for a sample case. Therefore, the simulation software should be carefully validated with respect to proper modeling of the thrust-resistance balance.

The limitation of this study is the very low number of considered ships. Considering the range of initial speed values and the range of *KG* values, we carried out 18 simulations of both ships. Furthermore, the regulatory formula applicable to inland vessels has been applied to two large seagoing passenger ships. It has been done for the sake of comparison, though the massive differences of the ships hull forms make the calculations capable to reveal the tendency, but they cannot justify any criticism of the inland shipping rules. At the present stage of the research, the findings cannot be generalized.

## 5. CONCLUSION

This paper describes the initial study on evaluation of the stability criteria limiting the angle of heel due to the ship turn. The obtained results show significant discrepancies between the analyzed versions of the formula for the heeling moment calculation, specifically the '*c*' coefficient present in that formula. The contemporary regulations appear to be conservative, which is not exceptional in terms of regulatory purpose. As long as the ship is able to meet the existing criterion, conducting numerical simulations in calm sea conditions appears not justified in the light of this research. However, the approach based on ship motion simulations is capable to comprise effects induced by waves, which may be a significant step forward in case of special ships or exceptional cargo shipments. As the considered simplified formulas perform not accurately, the simulation-based approach might be found helpful in ambiguous cases with high valued cargo engaged. This may open a discussion on a potential extension of the Second Generation Intact Stability Criteria by a sixth stability failure mode to be applied on supplementary basis in well-founded cases. Possibly, such simulations could be also restricted to Operational Guidance applicable occasionally when economically justified.

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