DSA-inspired assessment of autonomous ships stability during turning maneuver

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ABSTRACT

Assessing the stability of autonomous ships is challenging due to a lack of crew ensuring situational awareness, experience and good seamanship, which have contributed to safety of navigation to date. Therefore, a comprehensive approach towards evaluation of autonomous ship stability in each phase of operation is required. This problem is raised here with respect to the ship turning maneuver. A Direct Stability Assessment (DSA) inspired approach is applied. Therefore, a series of ship motion simulations are carried out to obtain the dynamic angle of heel for sample operational scenarios and numerous irregular wave realizations to enable identification of a stability failure. An up-to-date 6DoF ship dynamics model is utilized. The simulations account for both the maneuverability and stability characteristics of a vessel. A 56-m long training vessel is used as an example. The simulation results are statistically processed to elicit the maximum instantaneous angle of heel corresponding to a 5% probability of exceedance, to be compared to the assumed threshold. However, the required number of simulations ensuring the required statistical significance of the results remains an open question.

Keywords: *stability assessment, stability during turning, heel due to ship turn, ship operational stability, MASS.*

1. INTRODUCTION

A development of autonomous shipping will constitute a radical change to the maritime business and society (Goerlandt, 2020; Munim, 2019). Although such a transformation might be feasible in the nearest future, satisfying solutions to existing safety issues is a necessity for public acceptance (Thieme et al., 2018). One such safety issue that requires further study is ship stability in operation. The main challenge stems from the nature of the contemporary intact stability criteria. Any ship is examined to assess her stability at the design stage, and later reevaluated during operation to consider the actual loading conditions. Nevertheless, those checks cannot ensure safety in all operational scenarios, since the IS Code based criteria does not address all possible hazards with respect to stability failures (Francescutto, 2004; IMO, 2009). For that reason, the need for special caution, good seamanship and proper precautionary provisions are stated as the fundamental disclaimer in the IS Code. Those are experience-based skills gained by captains and deck officers with years of sea practice. The IMO MSC Circular 707 (IMO, 1995), and the extended MSC Circular 1228 (IMO, 2007), were published in order to provide a piece of advice to ship masters. However, its automated application of onboard autonomous ships is hardly feasible due to the far extent of subjective assessments of interactions needed when a ship is sailing in actual environmental conditions. Currently, the situation awareness is predominantly achieved through human cognitive processes where onboard personnel constantly detects potential dangers, assesses the situation of their own vessel, and acts accordingly (Montewka et al., 2017). Certain perceptive processes may even be unconscious, because the crew after boarding, learns the ship's responses to external forces. The origin of the forces, mainly due to wave action, is observed by the navigator and associated with the ship response. This learning process, which is carried out in a natural way, may be easy and imperceptible to humans, but it poses a great challenge to autonomous machines. Thus, maritime autonomous surface ships (MASS) are recognized as special ships to date (Utne et al., 2020; Wróbel et al., 2021).

The ENDURE project has been launched ("ENDURE, Detection, prediction, and solutions for safe operations of MASS," 2021) to address the infirmity of MASS with respect to intelligent situational awareness,. The project aims at strengthening autonomous shipping by addressing several key issues related to unmanned ship operation, including stability assessments relevant to realistic hazards in seaways.

For the sake of stability control and situation evaluation, the typical ship operation has been divided into three phases, as shown in Figure 1.

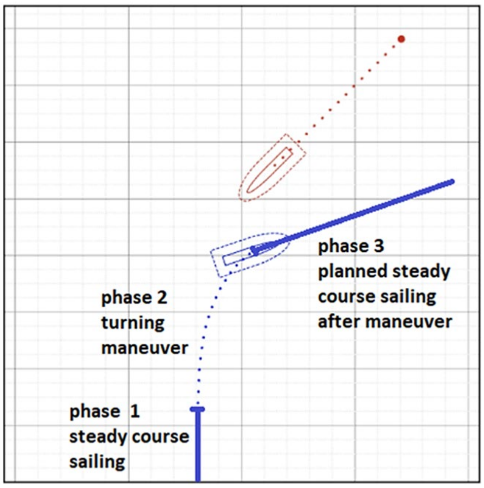

Figure 1: Distinction of sailing phases of MASS according to stability control options.

The stability of the autonomous ship needs to be evaluated in each of the distinguished phases with the use of feasible means. Thus, measurements may be applied only in the first phase during its execution, while the second and third phases are at the planning stage if the ship steams ahead with steady course. The leading safety factors are intended to be applied as presented in Table 1.

Table 1: Stability control concept applicable for MASS.

Phase of MASS operation	Stability assessment	Stability failure detection
Phase 1: Actual steady course sailing	Operational guidance based on 2nd level SGISC	Onboard measurements for threshold violations
Phase 2: Turning maneuver	DSA-inspired simulations of ship motions	None at the planning stage. Onboard measurements for threshold violations during actual turning.
Phase 3 Planned steady course sailing	Operational guidance based on 2nd level SGISC	None

The main issue raised in this paper comprises a potential stability failure resulting from the ship turning. Following the International Code on Intact Stability regulations, passenger vessels need to satisfy the criterion designed to prevent excessive heeling during rapid course alterations, while cargo vessels do not (IMO, 2009). One may consider the stability requirement as related only to passengers and possible panic due to an excessive heel. However, the incidents record shows that occasionally insufficient stability may manifest during turning, 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).

If a MASS would be examined according to this criterion, and the estimated angle of heel in turn appears lower than the adopted threshold set to 10 degrees, the static calculations considered in the criterion may not capture the actual dynamic ship response during hard turns in a real sea state. A preliminary study, presented during the STAB&S2021 conference, revealed significant discrepancies between static and dynamic approaches (Hinz et al., 2021). However, that research particularly addressed the problems inherent with limiting the stability assessment to the static criterion analysis.

Considering the limitations mentioned above, one may conclude that there does not currently exist a straightforward way to ensure the safety of a MASS with respect to her stability. Therefore, further investigations on predicting the angle of heel during turning have been initiated. The dynamic angle of heel during turns is analyzed using a method inspired by the Direct Stability Assessment (DSA) approach originated from the Second Generation Intact Stability Criteria (SGISC) (IMO, 2020). None of the failure modes covered by the SGISC directly covers ship turning, although numerical simulations and statistical measures of failure rates comprise the core of the DSA (Belenky et al., 2011; Peters et al., 2011).

Some difficulties emerge in interpreting the obtained data, and subsequently drawing conclusions for ship safety. The time of simulations is well defined in the DSA in case of steady course sailing, though this needs to be replaced by the number of repetitions of the ship turning maneuver. Moreover, it is not obvious whether the same value of the maximum instantaneous angle of heel should be adopted as the definition of the stability failure during turning as it is set in the SGISC, since the ship rolling is asymmetric.

The main objective of this paper is to initiate a debate addressing the most prospective approaches to simulations-based ship stability assessments during rapid course alteration of MASS. This might contribute to the potential future extension of the SGISC to address stability failure during ship turning.

2. SIMULATION METHODOLOGY

The research questions raised in this study relate to any autonomous ship. However, we use one ship to demonstrate sample calculations and methodology. In the ongoing ENDURE research project, in which we assess the safety of MASS during turning maneuvers, we use training vessels as demonstrators. One of which, the *Horyzont II*, is utilized here. The main particulars are:

- length overall 56.34 m;
- length between perpendiculars 48.37 m;
- breadth 11.36 m;
- draft 5.33 m;
- speed 12 knots;
- main engine power 1280 kW.

The general view and the 3D model of the ship are shown in Figure 2. The ship is typically manned, however, for the purpose of testing and demonstrating the solutions for MASS, she will emulate an automated machine with extra watch provided by humans for safety.

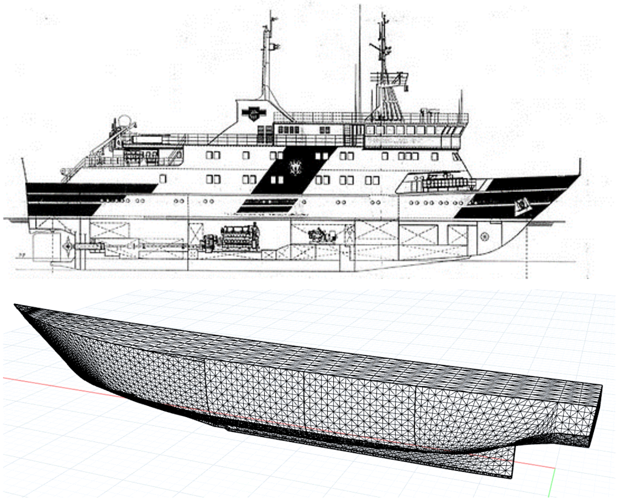

Figure 2: Training vessel *Horyzont II* used as the solution demonstrator; general view and the 3D hull model visualization.

The proposed method to be used for the autonomous ship stability evaluation at seaways, comprises two main steps. First, a set of numerical simulations are performed and processed. Then, the safety-critical variables are determined and stored in a database, which is available in real time (a lookup table) to the onboard voyage management or decision support system.

Numerical simulations are performed on a 6DoF ship motion model using the LaiDyn software (Matusiak, 2002). LaiDyn has been developed as a 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. The maneuvering nonlinear sub-model including hull loads, rudder loads and propulsion action, crucial for our research, 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 radiation and diffraction forces are calculated by linear approximation using the convolution integral approach for fluid memory effects (Matusiak, 2017) The performance of the method to cope with maneuvering in irregular waves was validated by model tests conducted at Aalto University (Matusiak, 2003; Matusiak and Stigler, 2012).

The LaiDyn code allows for simulation of the ship motion under wave excitation and simultaneous propulsion and steering loads. An example of the numerical simulation time series is shown in Figure 3. The results also indicate the time and location of two events: 1) rudder order, at which the rudder begins to actuate, and 2) rudder execution, at which the rudder has reached its maximum angle. This will be the tool used as an intermediate step in our proposed method. The outcome obtained for every presumed scenario varies to some degree depending on the irregular wave realization and other random variables.

Once the ship data and the simulation approach are established, the turning scenario considered in this study needs to be set. From the ship safety perspective such scenario should reflect the challenging though realistic maneuver, which would be similar to weather criterion also accounting for a rare situation yet the challenging one. Therefore, only the rapid course alteration shall be examined, not the routing maneuvers utilizing a gentle rudder action. Thus, the 35 degrees rudder is considered. The second question refers to the range of the ship heading alteration that should be considered. Typically, even the so called last chance maneuver applied when the collision evasive action is way too late, consists in a change of heading not more than about 90 degrees to starboard. This would found justification in AIS data collected in real operation (Mestl et al., 2016). However, occasionally this alteration needs to be larger due to the traffic or bathymetry constraints. Furthermore, very rarely ships have to perform a full loop 360 degrees to port as the only feasible collision avoidance maneuver under specific conditions. Taking all the options into account we decided to utilize simulations outcomes for the full loop.

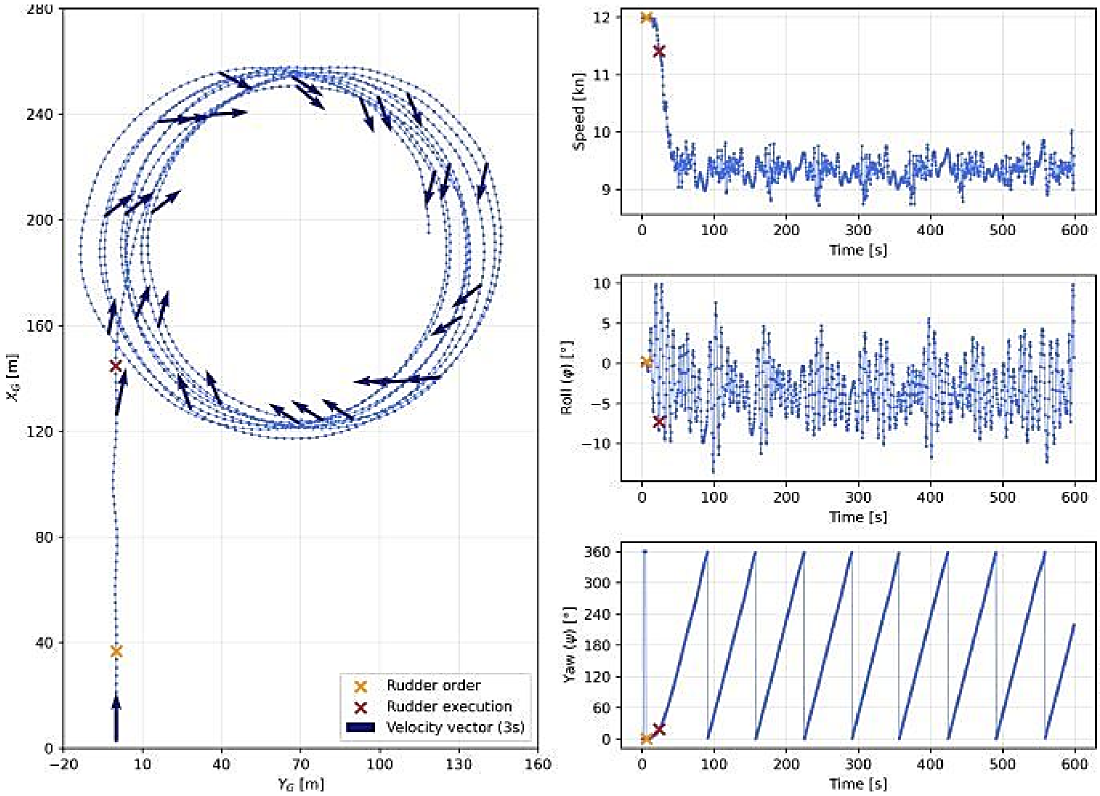

Figure 3: Representative outcome of the numerical simulation performed using LaiDyn code.

The second step of the proposed method consists of the postprocessing for stability evaluations. Our way of reasoning here, is clearly inspired by the Direct Stability Assessment (DSA) alike the Second Generation Intact Stability Criteria framework (SGISC).

For the sake of simplicity at the method development stage the stability governing variable is assumed to be the maximum angle of roll or, in other words, the maximum instantaneous angle of heel that the ship reaches during her considered turning maneuver. The lateral acceleration, being the second indicator of a stability failure in the SGISC, is out of scope. However, it will be included once the complete procedure for stability evaluation is finalized.

The DSA approach within SGISC requires simulations to last a certain duration (3 hours) to evaluate whether the failure frequency of the considered stability failure exceeds the threshold (IMO, 2020). However, all the considered phenomena are examined under stationary conditions, i.e., steady course sailing with the wave parameters fixed for the entire simulation, reflecting the assumed sea conditions. This type of analysis does not cover the potential stability failure mode resulting from transient response during ship turning for several reasons. First, the angle of wave approach varies throughout a turning maneuver. Secondly, once the rudder is set to a certain angle, the resistance rises, causing a reduction in speed. Furthermore, the subsequent sideslip and resulting change in angle of attack further increases the resistance. Since the transient response during the initial phase of a hard turn is the most critical, only the first part of the simulation result for each maneuver should be taken into account. Any long-lasting simulation, similar to what is shown in Figure 3, cannot be effectively used for stability evaluation, as seen by the speed and roll response subplots in Figure 3. The unrealistic prolonged simulation would primarily provide data that is representative of the ship in the steady turning phase, with the steady speed significantly lower than the initial one. This does not accurately reflect the conditions that the ship experiences during the execution of the evasive maneuver.

Taking all the outlined circumstances into account, the proposed method requires multiple shorter simulations performed for each maneuvering scenario, differing by the wave realization while key sea state parameters such as significant wave height (*Hs*), zero-crossing period (*Tz*), direction of wave propagation (μ), and wave spectrum (*S*) are kept constant. An open question is the number of simulations that should be carried out to effectively capture the maximum instantaneous angle of heel with the required level of confidence.

3. RESULTS

Ship motion simulations were performed for the considered ship in one typical loading condition, for one pair of *Hs* and *Tz*, and for 48 different wave realizations (using JONSWAP spectrum). Some sample results of ship trajectory and roll response are shown in Figure 4. The analyzed simulations have been restricted to the first 100 seconds, which corresponds to the estimated time of the ship heading alteration about 360 degrees (as shown in Figure 3), for the reason discussed in the previous section.

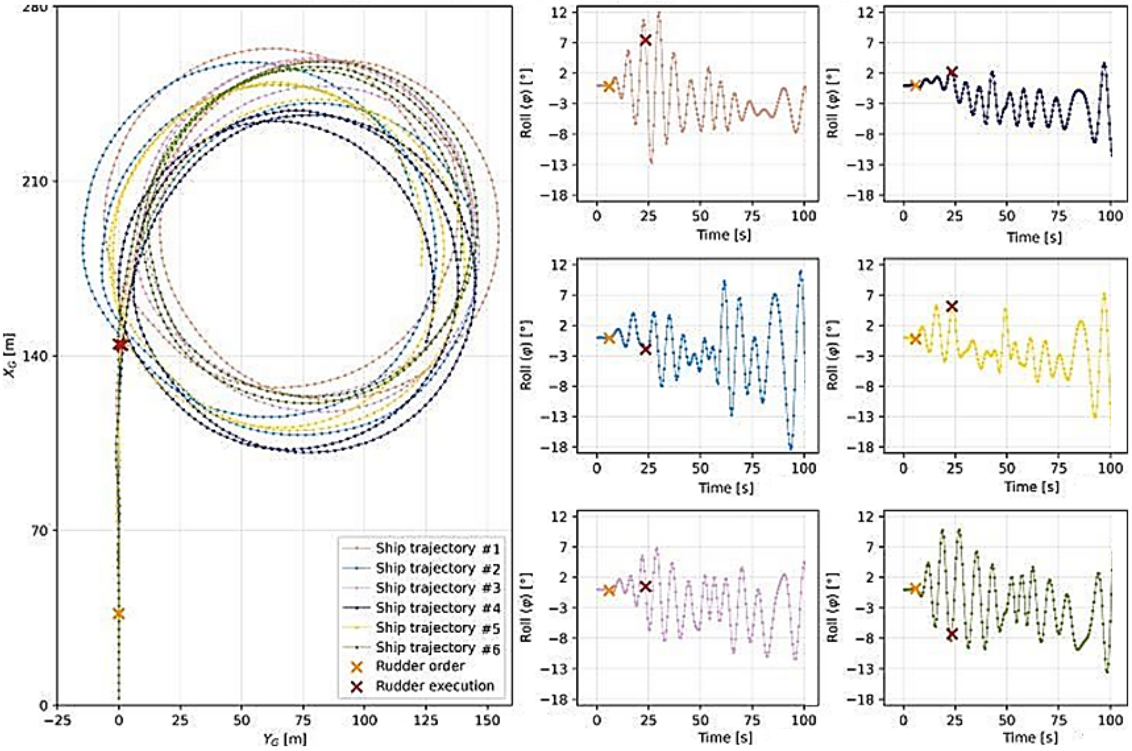

Figure 4: Simulated trajectories and roll histories for sample wave realizations (shown 6 out of 48 carried out in this study).

The simulation results are the first step of the method inspired by DSA. The next step should consist of statistical postprocessing leading to determination of an indicator to be compared to the assumed threshold that limits the maximum instantaneous angle of heel.

Data collected from all performed simulations are presented as a histogram in Figure 5. Then, the probability density distribution is fitted to the obtained data. In the considered case, the best achieved fit appeared to be the Weibull distribution with mean value equal to 14.9 deg and variance of 5.9 deg.

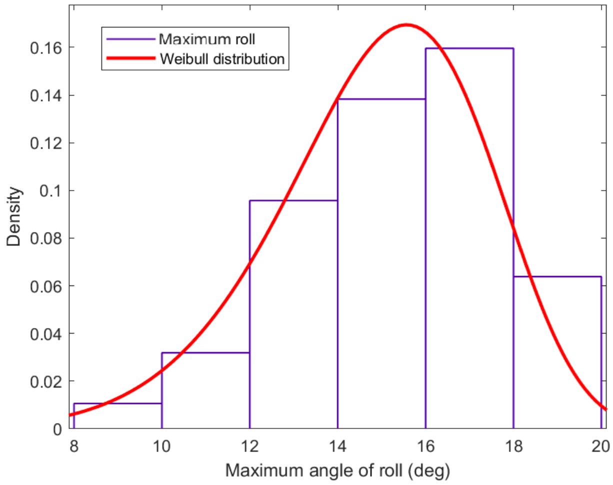

Figure 5: Histogram of the maximum instantaneous angle of roll in the considered scenario.

Once having the distribution fitted, at least when the best feasible fitting for the available data set is carried out, the probability plot was prepared as shown in Figure 6. Using this plot and applying the assumed probability level of exceedance set to 5%, we obtain a critical value of 18.4 deg, which needs to be compared to the standard in the relevant criterion.

However, this standard does not exist yet, since the stability failure mode due to excessive turning maneuver is not covered by SGISC. The lack of that number does not affect the idea of assessing the angle of heel, and we suggest that this threshold may be elaborated later or adopted from another stability failure mode.

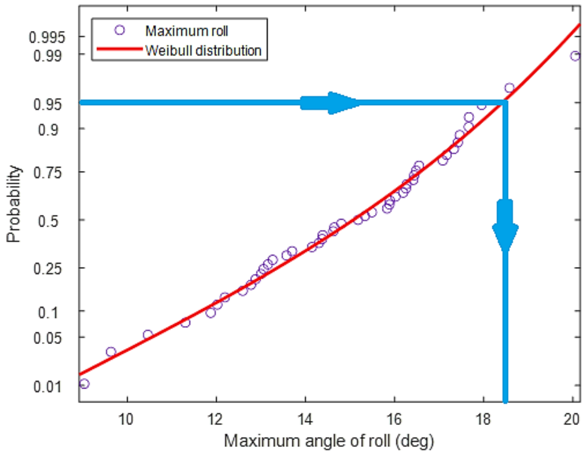

Figure 6: Probability plot of the maximum instantaneous angle of heel in the considered scenario.

As the histogram with the corresponding distribution (Figure 5) are based on merely 48 data points, the distribution fitting may be found imperfect to some degree, especially for the largest recorded roll amplitudes. However, the resultant probability plot (Figure 6) reveals a good agreement to data up to the adopted probability threshold 95%, while the remaining 5% of extreme values do not significantly influence the obtained result in terms of the critical value determined for the considered case as 18.4 degrees.

4. DISCUSSION

The key point of this research is to discuss two main aspects of the outlined method. First, whether the approach to the simulation-based data, as proposed here, may be considered valid and effective. Second, how to determine the minimum number of simulations of ship turning maneuvers, to achieve sufficient statistical significance and proof of evidence.

The proposed approach is inspired by the DSA; however, there is a key deviation in regard to the time of simulation. The DSA procedure requires a simulation to last three hours due to the nonstationary conditions inherently present in the considered phenomenon. Instead, we propose to carry out a large number of relatively short simulations in order to generate sufficient statistics. This number of simulations, while still unfinalized, should correspond to the range of possible wave encounter scenarios during the ship course alteration, instead of simulation time. Small vessels turn relatively quickly, whereas large ships need more time for their course alteration. For this reason, a requirement for the number of repetitions seems to be more appropriate than a requirement of total simulation time. Therefore, the minimum required number of sample simulations needs to be addressed.

Furthermore, as the simulation time of a single scenario should relate to the time to execute (and complete) a turning maneuver, the maneuver under consideration should be clearly defined. However, from the practical point of view it is not a trivial problem. Typically, the turn to starboard by 30-60 degrees is the most common scenario for the last chance collision evasive maneuver. Though, occasionally the situation may require turn by 90 degrees or even the full 360 degrees loop, which is taught as a part of standard training of officers. Therefore, the proposed approach might be a matter for further discussion.

5. CONCLUSION

This paper describes a direct stability assessment (DSA) inspired approach to the autonomous ship stability assessment. The motivation of the research is to eliminate the need for human perception, experience, and subjective evaluation of sea conditions during operation of MASS through a better understanding of ship stability and behavior during turning maneuvers. Therefore, satisfying the contemporary stability criteria, not comprising turning maneuver to date, may be insufficient, signifying that a method comprising the crucial dynamic phenomena with sufficient coverage, must be applied. We contend that ship stability is essential for consideration in collision avoidance algorithms. If so, an insufficient stability in a considered loading condition may prevent rapid collision evasive maneuvers, which means, from the practical point of view, that the ship control system (a virtual captain) should undertake an earlier action that require smaller rudder settings. Such action to be undertaken in ample time involves the situation awareness with respect to both the collision-related trajectory requirements and stability-related heel prediction. Both need to be provided in advance to the 'virtual captain' algorithm. The exact number describing how much time up front the closest point of ships' approach would be sufficient is not definitely established yet and this is the subject of another ongoing research. However, the time to the ship domain violation could be utilized as an indicator. This paper presents our first approach to the problem related to autonomous ships stability assessment during turning, and some sample results are shown. We hope that this will open the discussion on how to address this problem, which is expected during the ISSW2022.

6. ACKNOWLEDGEMENTS

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