Przemysław Krata  
Gdynia Maritime University, Faculty of Navigation, Poland

Jakub Montewka  
Gdynia Maritime University, Faculty of Navigation, Poland  
Finnish Geospatial Research Institute, Dept. of Navigation and Positioning, Masala, Finland

Tomasz Hinz  
Waterborne Transport Innovation Foundation, Łapino, Poland

TOWARDS THE ASSESSMENT OF CRITICAL AREA IN A COLLISION ENCOUNTR ACCOUNTING FOR STABILITY CONDITIONS OF A SHIP

Abstract: The rules of road, called COLREGS provide guidelines for navigators onboard ships involved in collision encounter at navigable waters. Specific roles for stand-on and give-a-way vessels are assigned, depending on the phase of the encounter. In this paper we extend further our earlier work on the definition of the boundaries for the third phase of the encounter. The latter is referred to as critical area for an escape maneuver of a stand-on ship, in the situation where the give-way vessel does not take an action. This area is determined with the use of a state-of-the-art, six degree-of-freedom hydrodynamic model of ship motion. Series of simulations are conducted for a specific type of encountering ships applying various rudder angles to perform collision evasive maneuvers. Varying rudder angles reflect the fact, that hard-to-side command cannot always be executed, due to stability conditions of a ship. As a result we obtained a set of areas of various size, depending on the rudder angle used to perform evasive action for the predefined ship loading conditions related to her transverse stability characteristics. These demarcate the boundaries of the third phase of encounter for the stand-on ship, where other ships on collision courses must not enter. Otherwise a collision cannot be avoided by an action of one ship alone or the ship would have to turn too vigorously causing actual stability-related threat.

Keywords: collision risk, maritime traffic safety, ship domain, ship stability, ship list
1. INTRODUCTION

The COLREG convention assigns specific roles for stand-on and give-a-way ships, which depend on the phase of the encounter; see (IMO, 2003). The convention specifies three such phases, where the obligation of the stand-on ship changes from keeping her course and speed, when in the area of “collision avoidance by the give-a-way-ship”, through the permission to take an action while in the area of “action for stand-on ship”, to the collision evasive action, when in the area of “escape action”. However the boundaries between these three phases are not clearly defined in the COLREGS. It is understandable, since they depend on numerous factors, both endogenous (e.g. ship characteristics, her maneuverability, maximum applicable rudder angle), and exogenous (e.g. type of encounter, weather conditions). Exemplary boundaries for a specific encounter are depicted in Figure 1.

The amount of existing research on this topic is very limited. However, the available materials are very promising. The studies of (Colley, Curtis and Stockel, 1983; Hilgert, 1990; Hilgert & Baldauf, 1997, Łukaszewicz, 2007) have lead to the development of simple formula allowing for the coarse assessment of those boundaries. The model by (Curtis, 1986) determines the safe distance for overtaking for a very large crude carrier. In the paper of (Zhang et al., 2012) a minimum distance for escape action is calculated for one encounter scenario. The major limitation of the above studies is low number of encounter scenarios and significant simplification in ship motion modelling. In our earlier work presented in (Krata & Montewka, 2015) we show the applicability of advanced ship motion model and wide set of simulation to the assessment of a critical area around the stand-on ship. However the main limitations of our earlier work, likewise the other existing studies, is the adoption of maximum rudder angle for the collision evasive manoeuvre. This obviously leads to the smallest turning radius for an escape action, however may lead to the development of significant roll angle. This in turn may lead to ship capsizing, if the stability conditions of that ship are poor, see for example a recent case of Hoegh Osaka, (MAIB, 2016).

Ship stability remains one of the crucial issues related to safety of navigation. The most serious and spectacular type of the stability failure is ship capsizing. However the excessive heel incidents are actually also dangerous and they can be costly causing the potential loss of cargo. Despite the significance of ship stability issues, its not appreciated sufficiently while planning ship maneuvers, especially in collision avoidance. In case of passenger ships and container vessels the stability rules introduce the maximum allowed heel angle due to ship turning, however the other types of ships are not considered. As a result, the officers of the watch performing anti-collision maneuvers are not fully aware of the expected heel angle. In general, ship stability is usually found as an independent question separated from the navigational process which approach seems to be counterproductive in terms of safety and efficiency of shipping.

Therefore, in this paper we extend our earlier work on the definition of the boundaries for the third phase of the encounter, referred to as critical area for an escape maneuver of a stand-on ship, by accounting for various rudder commands used to execute the collision avoidance maneuver. In our approach the rudder commands are the direct reflection of the stability condition of a ship. The critical area is determined with the use of a state-of-the-art six-degree-of-freedom hydrodynamic model of ship motion, allowing for evaluation of trajectories along with the associated roll angle. Series of simulations are conducted for a
specific type of encountering ships (mid-size RoPax), wide set of encounter scenarios, applying five rudder commands to perform collision evasive maneuvers.

As a result we obtained a set of areas of various size, depending on the rudder command used to perform evasive action. These demarcate the boundaries of the third phase of encounter for the stand-on ship, where the other ships on collision courses must not enter. Otherwise a collision cannot be avoided by an action of one ship alone.

The remainder of the paper is organized as follows: Section 2 elaborates on the methodology to assess the critical area. Section 3 presents the obtained results, whereas Section 4 discusses the findings and concludes the paper.

Fig.1. Decision ranges and actions boundaries for a sample situation with stand-on ship A meeting a give-way ship B at 16kt with no change of compass bearing to port side, (Hilgert & Baldauf, 1997)

2. ASSESSMENT OF CRITICAL AREA

The critical area (CA) is understood here as the area around a ship, which is required to perform in a safe manner collision evasive manoeuvre. Its dimension and shape is determined mainly by the maneuvering characteristics of the ship, relative speed of two encountering ships and their relative spatial orientation. Obviously more room is needed to evade a collision where the other ship is approaching from the traverse, than when she is coming from the bow shoulder. In the first substantial course alteration is required, whereas in the second case just a few degrees of course change may suffice. However, for a ship with poor stability, even a moderate rudder angle may lead to severe consequences. The recent case of m/s Hoegh Osaka, which developed a list of 40 degrees to starboard when negotiating a turn with an initial rudder command of 10 degrees to port (which was far from hard-to-port) and speed of 12 knots, clearly demonstrates that the stability conditions of a ship determine the available pools of maneuvers to evade an accident, (MAIB, 2016). Furthermore, if an applied rudder command does not correspond with the actual stability conditions, it may lead to the development of another accident like ship capsizing or heavy
listing resulting in cargo damage. Some ships are more prone to this type of accident than the others, like car carriers, RoPax or container ships, due to their construction and how the cargo is loaded and stowed. Therefore it is of utmost importance for a ship crew to understand the maneuvering limitations of their ship, which in turn determine the required area for a safe and successful collision, escape action.

In order to determine the CA for a given ship, a number of encounter scenarios (ES) need to be evaluated. For each ES the shortest, safe distance between own ship and the other ship on collision course is determined. That is called critical distance (CD), and is understood as a distance between a stand-on ship and the other ship on collision course, at which the stand-on ship is able to escape from the collision encounter by her own maneuvers only. The graphical representation of CD is depicted in Figure 2. The most important factors affecting the CD are: the angle of courses intersection in an encounter (alpha), the relative bearing from a stand-on ship to another (beta), the maneuverability of a ship which is related to the ship type and size as well applied rudder angle (manoev, rudder). A combination of all these factors yields a specific encounter scenario (ES_i) for two ships, for which a single value of CD_i is determined. These relations can be expressed as follows:

\[ CD = f(ES) \]  
\[ ES = [ES_1, ES_i, ..., ES_n] \]  
\[ ES_i = [alpha_i, beta_i, manoev_i, rudder_i] \]

Where the subscript \( n \) denotes the number of anticipated ES, and \( i \) stands for a given encounter. The \( n \) depends mostly on the discretization level adopted for the relative bearing and crossing angle, as well as on the number of ship types and rudder commands analyzed. In the experiments described here one ship type is considered (RoPax), thus the maneuverability of the ships is considered constant, and will be omitted in the further description of ES. However five rudders commands (rudder) are considered, 12 relative bearings (beta) and 17 crossing angles (alpha), as presented in Table 1. Thus, the number of all analyzed encounter scenarios is 1020. For all these ESs a set of CDs is obtained. Based on that set the CA is defined as an envelope joining the vortices of all CDs. This is performed for all the computed ES for one side of own ship, as depicted in Figure 2 and the values for another side are drawn by symmetry.

\[ CA = \{CD(\beta)|\beta \in (-120^\circ, 120^\circ)\} \]

The existing differences in trajectories for port and starboard rudder command, stemming from the interaction between hull and propeller, we consider negligible for our purpose. Thus the trajectories are considered symmetrical for both sides.

Table 1

<table>
<thead>
<tr>
<th>Ship type</th>
<th>Relative bearing [deg]</th>
<th>Crossing angle [deg]</th>
<th>Rudder command [deg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RoPax</td>
<td>10-120 with 10° increment</td>
<td>10-170 with 10° increment</td>
<td>5,10,15,20,30</td>
</tr>
</tbody>
</table>
Towards the assessment of critical area in a collision encounter accounting for stability...

2.1. MATHEMATICAL FORMULATION OF THE CONCEPT

A mathematical formulation of the concept analyzed here is based on the tempo-spatial relation between encountering ships’ trajectories. The trajectory of each vessel is computed with the use of a state-of-the-art six degree-of-freedom hydrodynamic model, described in details in (Matusiak 2011, 2013). The trajectories of both vessels are described by the following formula (5), discretized in time, (Krata & Montewka, 2015):

\[ \text{Trajectory}_A: (X_A, Y_A, T); \text{Trajectory}_B: (X_B, Y_B, T); T = \{t_0, t_1, \ldots, t_n\}, \]

where: \( X, Y \) – vessel position co-ordinates in a local two-dimensional reference system, in meters; \( t_i \) – consecutive time steps in seconds, from the initial moment of the manoeuvre \( t_0 \) to the last moment \( t_n \), where the encounter situation is solved. Subsequently, these trajectories are inputted to an algorithm determining the critical distance, as presented in Figure 3. The CD is determined for selected ships encountering at the collision courses, according to the formula, (Krata & Montewka, 2015):

\[ CD(t_0) = |(X_A, Y_A, t_0) - (X_B, Y_B, t_0)| \Leftrightarrow \exists! \ t \in T: |(X_A, Y_A, t) - (X_A, Y_A, t)| = \max(\text{ShipBreadth}(A, B)) \]

where: \( \text{ShipBreadth} \) denotes the breadth of an encountering ship. Two ships are considered escaping safely from the collision encounter, if a minimum distance between their corresponding contours is not less than the breadth of a larger ship. The reverse iterative algorithm adopted to estimate the CD is described in the following section.
2.2. ASSESSMENT OF CRITICAL DISTANCE

In order to calculate the CD for a given ES, an iterative algorithm is used, as depicted in Figure 3. The basic assumption is that the two ships collide at a time instant \( t_i \). The aim of the algorithm is to find such an initial distance between two encountering ships on collision courses, that if a give-way vessel is not reacting, meaning she keeps her speed and course, the stand-on ship is able to safely escape from that situation by her own manoeuvres with her rudder. Five rudder commands are considered, as presented in Table 1, resulting in five different trajectories of ship A. Also an assumption is made, that once the rudder command is given, it is kept during the whole encounter until the collision situation has been cleared. This is considered reasonable, since it allows for the shortest time for escape action and tighter turning circle resulting in smaller CA.

The algorithm initiates its calculations from an instant where two ships already collide - at time \( t_i \) - meaning that their corresponding trajectories have at least one common point. From this time, the reverse iterative algorithm is applied, which uses a backward calculation method in the space domain. At each iteration, the ships’ contours are plotted every second along their predefined trajectories. If two corresponding contours along the trajectories have at least one common point, indicating that they collided in a given time instance, the algorithm increases the initial distance between these two ships at time instant \( t_0 \) by a constant value (0.1 of the average length of ships involved), and the trajectories are redrawn. The new trajectories begin in the new initial positions of the ships. These are obtained by moving ship B away from ship A along the line of a given relative bearing. For the simplicity of calculations it is assumed that ship A always holds her initial position \((0,0)\) at \( t_0 \), while ship B is displaced along the line. The iterations are performed until the initial position of ship B results in such layout of both trajectories that the contours of the ships along the predefined trajectories have no overlaps at any time instant for a given relative bearing. In such a situation, the initial positions at time \( t_0 \) of both vessels are recorded and the distance between the ships is calculated and stored. This distance is called crossing distance for a given relative bearing. Then, for each relative bearing (labelled as beta in Figure 1), the crossing distances for 17 crossing angles are estimated (labelled as alpha in Figure 1). To calculate the critical distance for a given beta, the maximum value of those 17 records is taken. Then the procedure is repeated for all 12 relative bearings, yielding 12 values of the critical distances for one side of a ship. The values for another side are drawn by symmetry. As a result a set of CDs is obtained, based on that one CA is determined for a given trajectory of ship B (making evasive action). Then the experiment is repeated for the remaining rudder commands, yielding different trajectories of ship B. This results in the development of a set of CA for all rudder angles considered.

In the case study presented here, we analyzed only one ship type, which is a RoPax, proceeding with an initial speed of 16 knots. The particulars of the ships are listed in Table 2.

The main particulars of the analysed ships

<table>
<thead>
<tr>
<th>Ship type</th>
<th>Overall length [m]</th>
<th>Breadth [m]</th>
<th>Draught [m]</th>
<th>Cb [-]</th>
<th>Speed [kn]</th>
</tr>
</thead>
<tbody>
<tr>
<td>RoPax</td>
<td>158.0</td>
<td>25.0</td>
<td>6.2</td>
<td>0.571</td>
<td>16</td>
</tr>
</tbody>
</table>
2.3. SHIP STABILITY AND MOTION MODELLING

The accident of car carrier Hoegh Osaka in January 2015 demonstrates the direct link between the ship stability and the allowable set of maneuvering patterns. Unfortunately the awareness of the existence of the above among the ship crews is very often at low level.

When planning and conducting collision evasive maneuvers on board large ship (car carrier, RoPax, container carrier) two contradictory objectives need to be considered, namely the effectiveness of the evasive action and avoidance of an excessive heel. One may tend to set up ship rudder hard achieving the smallest possible turning circle and another one may focus on gentle rudder settings ensuring small angle of ship’s heel while the trade off seems to be the most reasonable solution.

In the study presented here we aim to find the rational balance between the ship turning circle and her transverse heel limitations. Ship motion resulting from her stability and ship maneuverability are simulated with the use of a nonlinear hybrid hydrodynamic model, see (Matusiak 2011, 2013).

Fig. 3. An algorithm evaluating critical distance, (Krata & Montewka, 2015)
3. RESULTS

The history of ship’s angle of heel in each considered case is assessed in terms of breaching the predefined – arbitrary chosen - critical angle of heel. The intention of this paper is not to provide detailed specification of that angle, which requires further studies. The trajectory of the ship becomes the input to the algorithm shown in Figure 3 enabling the critical distance and critical area determination. This is done for the given set of rudder commands \{5, 10, 15, 20, 30°\} and for a sea wave height of 1.5 meter, which for a given RoPax can be considered mild. The results of the critical area modeling are shown in Figure 5, where a surface describing the critical areas for the five rudder commands is depicted. For the sake of ship safety, the rudder settings causing the excessive angle of heel during the collision evasive maneuvers shall be rejected. In the considered case the heel angle larger than 20 degrees is considered excessive, and there are two rudder commands that produce such heel for the given ship: 20 degrees and 30 degrees. Therefore, the two corresponding critical areas, despite their smallest dimension (~6 lengths of the ship), should not be taken into account by the officer of the watch while planning the collision escape maneuver, due to risk of own ship cargo damage or ship capsize. The results presented here should not be considered complete. They point to the direction, where relevant studies coupling the stability issues with maneuvering patterns need to be carried out. Moreover, the results presented, despite promising, hold only for specific parameters of encounter between a specific ship type. At this stage of the research, the obtained results by no means can be generalized nor transferred to any other case.
4. CONCLUSIONS

In this paper, we extended a concept of critical area for a ship involved in a collision encounter, where a stand-on ship must take the collision evasive action, since the give-way vessel does not fulfill her obligations. The case study presented involves a mid-size RoPax ship, meeting the same ship in a crossing type of collision encounter. To determine the critical area we use six-degree-of-freedom ship motion model, which is evaluated for over 1000 ship-ship encounter scenarios. As a result the critical area around the stand-on ship is obtained. Since the stability conditions of a ship may not allow for the use of high rudder angles to perform collision evasive action, which is a common assumption in the literature, we determined the critical areas for a set of different rudder commands. The critical areas that are obtained for different rudder commands delineate the area required for safe, collision escape maneuvers by stand-on ship only, not posing additional risks of ship capsizing or cargo loss due to violent turn.

The integration of stability characteristics with maneuvering patterns presented here generates an added value in terms of new type of information. The availability of such information may improve the awareness of bridge crew and provide guidelines in planning the last chance collision evasive maneuvers, not posing additional risk of ship capsizing or cargo loss due to excessive heel. The obtained results are promising, however the presented concept shall be further developed and other ship types should be included (different maneuvering characteristics). Also other types of encounter namely head-on and overtaking should be evaluated.

The proposed concept, when in mature state, could be implemented on board ships, as a simple yet useful tool increasing the awareness of navigators with respect to the required maneuvering space to perform safe, evasive action.
References


OKREŚLENIE OBSZARU KRYTYCZNEGO W SYTUACJI KOLIZYJNEJ NA MORZU Z UWZGLĘDNIENIEM WŁYWU STATECZNOŚCI STATKU

Streszczenie: Prawda prawa drogi dla statków nawigujących na morzu wynikająca z konwencji COLREGS określają wzajemne obowiązki statków. W szczególności w sytuacji przecinania się kursów statków idących na zderzenie przypisywane są im obowiązki związane z ustawieniem drogi oraz z utrzymaniem kursu i prędkości. Obowiązki te są jednak uzależnione od fazy spotkania. W artykule rozwinięte zostały wcześniejsze prace dotyczące określania krytycznego obszaru związanego z trzecią fazą spotkania, gdy statek uprzednio zobowiązany do utrzymania kursu i prędkości jest już zobligowany do podjęcia własnego manewru z powodu nie wykonania swego obowiązku przez statek zobowiązany do utrzymania drogi. Kształt obszaru krytycznego wynika zarówno z rozmiarów statków, ich właściwości manewrowych, ale także z parametrów statecznościowych, co stanowi nowość w stosunku do dotychczasowego ujęcia zagadnienia. Wykorzystano zaawansowany hybrydowy model hydrodynamiczny określający w toku licznych symulacji ruch statku w sześciu stopniach swobody dla manewru antykolizyjnego wykonanego przy różnych wychyleniach steru. Nie zawsze bowiem wyłożenie steru na burtę jest dopuszczalne z punktu widzenia stateczności i wywoływanej przechyli. W rezultacie wyznaczono granice obszaru krytycznego dla pełnego zakresu wychylen steru. Niedopuszczalne jest zблиżenie powodujące wejście statku w obszar krytycznych, gdyż niemożliwe stanie się wówczas uniknięcie zderzenia własnym manewrem bądź przekroczenia zostanie krytyczna wartość kąta przechyli, co jest niebezpieczne dla statku, pasażerów i przewożonego ładunku.

Słowa kluczowe: ryzyko kolizji, bezpieczeństwo ruchu morskiego, domena statku, stateczność statku, przechył

Acknowledgments

The Merenkulun säätiö – the Maritime Foundation - from Helsinki is thanked for the travel grant.

Przemysław Krata, Jakub Montewka, Tomasz Hinz