Weather Hazard Avoidance in Modeling Safety of Motor-Driven Ship for Multicriteria Weather Routing

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ABSTRACT: Weather routing methods find the most suitable ocean's route for a vessel, taking into account changeable weather conditions and navigational constraints. In the multicriteria approach based on the evolutionary SPEA algorithm one is able to consider a few constrained criteria simultaneously. The approach applied for a ship with hybrid propulsions has already been presented by one of the authors on previous TransNav'2009. This time a motor-driven version of the solution is presented. The paper is focused especially on a proposal of ship safety measure, based on restricting the impact of weather hazards on the ship. Besides the weather conditions and navigational restraint the safety of a vessel is one of more important factors to be considered. The new approach towards a safety factor modeling is described and implemented.

1 INTRODUCTION

Weather routing methods and tools deal with a problem of finding the most suitable vessel route. During the route optimization process they take into account changeable weather conditions and navigational constraints. Such a problem is mostly considered for ocean going ships where adverse weather conditions may impact both, often contradictory, economic and security aspects of voyage. Most of recent scientific researches in weather routing focus on shortening the passage time or minimization of fuel consumption alone.

One of the first weather routing approaches was a minimum time route planning based on weather forecasted data. Proposed by R.W. James (James 1957) an isochrone method, where recursively defined time-fronts are geometrically determined, was in wide use through decades. In late seventies based on the original isochrone method the first computer aided weather routing tools were developed. Numerous improvements to the method were proposed since early eighties, with (Hagiwara 1989, Spaans 1986, Wisniewski 1991) among others. Nonetheless, even the improved method has recently been displaced by genetic algorithms.

Evolutionary approach as a natural successor of genetic approach has become popular in the last two decades and has been successfully applied to anti-collision maneuver modeling. Modern weather routing tools often utilize evolutionary algorithms (Wisniewski et al. 2005) instead of the deprecated isochrone time-fronts. Due to multiobjective nature of weather routing the multicriteria versions of evolutionary algorithms have been also recently applied to the ship routing problem (Marie et al. 2009, Szlapczynska et al. 2009)

One of the authors has already proposed a multicriteria weather routing algorithm - MEWRA (Szlapczynska et al. 2009) designed especially for a ship with hybrid propulsion. In this paper an adjusted for a motor-driven ship and revised version of the algorithm is presented. One of the key amendments is related with modeling the safety measure. Here a new measure, based on reducing the impact of weather hazards on ship is proposed. The new approach towards modeling of ship safety is based on dynamical phenomena taking place while sailing in rough sea. As the ship behavior is strongly nonlinear and difficult for exact prediction (Landrini 2006) a sort of generalization is used. The proposed method is based on the IMO Circ. 1228, concisely comprising significant hazards resulting from complex interactions of ship's hull and waves, especially following and quartering seas.

The paper is organized as follows: section 2 recalls the optimization model and key technical background of original MEWRA algorithm for a hybrid propulsion ship. Section 3 describes the amendments required to suit MEWRA to motor-driven ship model. Section 4 addresses ship stability and seakeeping performance as optimization factors. Then again in section 5 the new measure of safety for MEWRA is introduced. Finally, section 6 summarizes the material presented.

2 MULTICRITERIA WEATHER ROUTING FOR A SHIP WITH HYBRYD PROPULSION

The following subsections recall the optimization model and the general framework of the Multicriteria Evolutionary Weather Routing Algorithm - MEWRA (Szlapczynska et al. 2009) designed for a ship with hybrid propulsion.

2.1 Optimization model

A proposed set of goal functions in the weather routing optimization process is presented below:

$$f_{passage\_time}(t_r) = t_r \rightarrow \min \qquad (1)$$

$$f_{fuel\_consumption}(v_{fc}) = v_{fc} \rightarrow \min \qquad (2)$$

$$f_{voyage\_risks}(i_{safety}) = (1 - i_{safety}) \rightarrow \min \qquad (3)$$

where:

t_r – [h] passage time for given route and ship model,

v_{fc} – [t] total fuel consumption for given route and ship model,

i_{safety} – [-] safety coefficient for given route and ship model. It is defined as a value ranging [0;1], describing a level to which the route is safe to be passed. "0" depicts totally impassable route and "1" absolutely safe route.

Exact formulas for goal functions (1) – (3) strongly depend on the assumed ship model. Thus, the explicit formulas for a ship model with hybrid-propulsion can be found in (Szlapczynska et al. 2009).

Set of constraints in the considered optimization problem includes the following elements:

– landmasses (land, islands) on given route,
– predefined minimum acceptable level of safety coefficient for given route,
– shallow waters on given route (defined as waters too shallow for given draught of ship model),
– floating ice bergs expected on given route during assumed ship's passage,
– tropical cyclones expected on given route during assumed ship's passage.

2.2 Mutlicriteria Evolutionary Weather Routing Algorithm (MEWRA)

The Multicriteria Weather Routing Algorithm (MEWRA), presented in Figure 1, searches for an optimal route (according to goal functions (1) – (3)) for the assumed ship model. The input data for the algorithm are:

– geographical coordinates of route's origin & destination,
– weather forecasts (wind, wave and ice) for considered ocean area and time period of the voyage being planned.
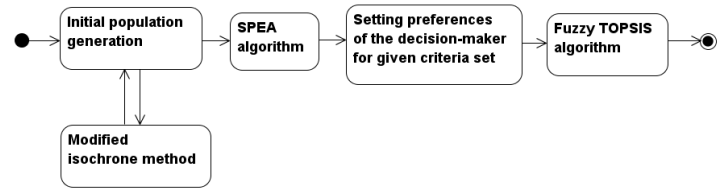

Figure 1. Multicriteria Evolutionary Weather Routing Algorithm (MEWRA)

The algorithm starts with a generation of initial population i.e. a diversified set of routes including the outermost elements of the searching space (Figure 2). The modified isochrone method (Hagiwara 1989) with extensions described in (Szlapczynska et al. 2007) is a source of single-criterion time-optimal and fuel-optimal routes. The routes are then a base for random generation of initial population. Also the original routes are included in the population.

In the next step SPEA algorithm iteratively proceeds the evolution on the initial population towards achieving Pareto-optimal set of routes. Once the evolution cannot improve on the Pareto set anymore the first optimization procedure is stopped. Then, from the set of Pareto-optimal routes (Figure 3) a single route must be selected, becoming a route recommendation.

Yet another problem might be encountered: how to decide which route should be recommended? To solve this problem decision-maker's (e.g. captain's) preferences to the given criteria set should be defined. Hence a tool for sorting the Pareto-optimal set is provided – Fuzzy TOPSIS method. First the decision-maker has to set their preferences for given criteria set. In MEWRA these preferences are expressed by means of linguistic values (Table 1) with fuzzy sets assigned accordingly. The decision-maker selects a linguistic value of the predefined set to each of optimization criteria. Then the corresponding fuzzy sets build a weight vector for the ranking method. The last step of MEWRA – Fuzzy TOPSIS – is responsible to apply given weight vector to the decision matrix built of the goal function values of the Pareto-optimal routes. The route having the

highest value of ranking automatically becomes then a route recommendation (Figure 4). Exemplary MEWRA results (Figures 2 – 4) have been obtained for hybrid propulsion ship model, Miami-Lisbon voyage on 2008-02-15 (departure time 12:00 pm) and decision-maker preferences given in Table 2.

Table 1. Linguistic values and corresponding triangular fuzzy values, utilized to express decision-maker's preferences to the criteria set

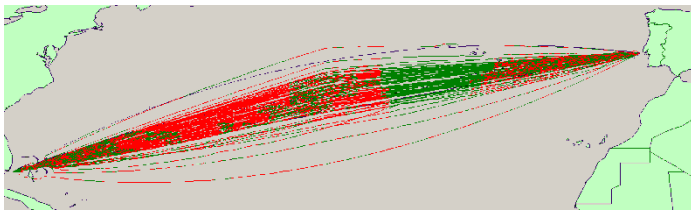| Linguistic value	Triangular fuzzy set
very important	(0.7; 1.0; 1.0)
important	(0.5; 0.7; 1.0)
quite important	(0.2; 0.5; 0.8)
less important	(0.0; 0.3; 0.5)
unimportant	(0.0; 0.0; 0.0)

Figure 2. Initial population generated by MEWRA for Miami-Lisboa voyage on 2008-02-15 (departure time 12:00 pm)
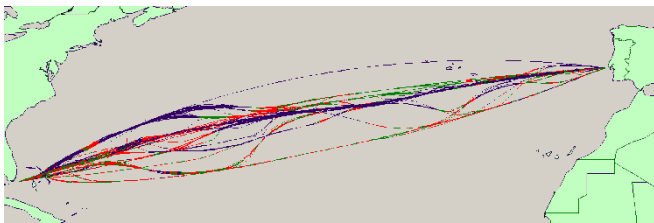

Figure 3. Pareto-optimal set of routes generated by MEWRA for Miami-Lisbon voyage on 2008-02-15 (departure time 12:00 pm)

Table 2. Linguistic values assigned by a decision-maker to the criteria set

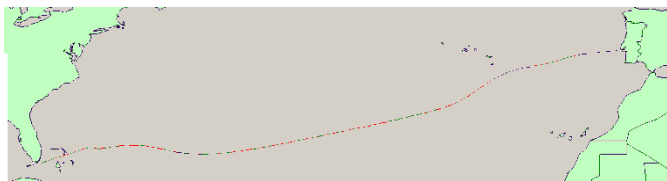| Criterion name	Linguistic value	Triangular fuzzy set
Passage time	Important	(0.5; 0.7; 1.0)
Fuel consumption	quite important	(0.2; 0.5; 0.8)
Voyage safety	very important	(0.7; 1.0; 1.0)

Figure 4. Recommended route selected by MEWRA according to the preferences given in Table 2 for Miami-Lisbon voyage on 2008-02-15 (departure time 12:00 pm)

3 MULTICRITERIA WEATHER ROUTING FOR MOTOR-DRIVEN SHIPS

MEWRA application for the motor only propulsion has been constructed based on its hybrid propulsion predecessor. The key differences between application versions for hybrid and motor driven ship model are as follows.

1 The safety coefficient i_{safety} (utilized by goal function (3) and appropriate constraints) in case of the hybrid propulsion model is based on wind speed and heading only (assuming strict correlation between wind and wave conditions). In the motor-driven model the coefficient has been redefined as a percentage part of a route that is free from disturbances caused by weather hazards. However, regions with severe wave threat are still by-passed by means of fulfilling a new constraint for restricted course sectors. More details on both these elements are given in the following sections.

2 Weather input forecasts for the motor-driven model has been enlarged by wave period and wave angle. Also MEWRA's graphical user interface (GUI) has been changed accordingly to allow displaying the new data on the screen.

3 In the hybrid propulsion case there is a possibility to use one of the three propulsion modes, namely "motor only", "sails only" or "motor & sails". The "sails only" mode for a route segment requires the engine to be temporarily switched off, which in return may significantly decrease the fuel consumption. In the motor-driven case there is only one propulsion mode i.e. "motor only", which drastically limits possible fuel savings.

4 SHIP STABILITY AND SEAKEEPING PERFORMANCE AS OPTIMIZATION FACTORS

The most straightforward attitude towards ocean voyage routing and route optimization is about to find the shortest way from a point of origin to a destination. However, getting rid of any other important aspects of navigation seems to be too simple and incomplete. Thus, a set of objectives has been implemented in the MEWRA's optimization model with voyage safety as the most important element, with the highest degree of significance as given in Table 2, of the goal function set Thus, it is required to elaborate on safety of the vessel modeling.

The desirable course of ship exploitation requires not only fast steaming of a vessel but also a lack of ship and cargo damage. The analysis of historical data regarding LOSA casualties reveals that their causes may be attributed to interacting elements pre-

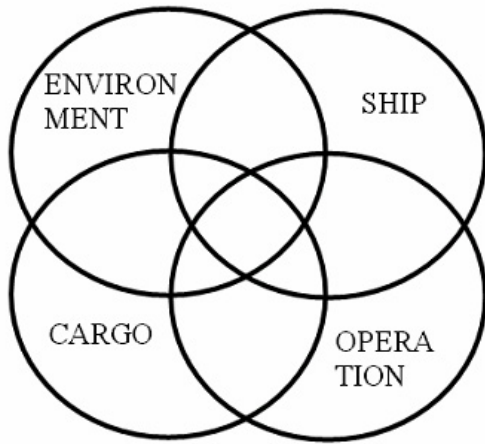sented at the Venn diagram in Figure 5 (Kobyliński 2007a).

Figure 5. Four-fold Venn diagram for ship stability system (Kobylinski 2007a)

The interaction of all four groups of conditions from Venn diagram can lead to stability accident of a vessel and perturb a voyage. To avoid such a situation a set of stability standards are worked out. The ship's loading condition of insufficient stability may induce a list, a strong heel and even a capsizing.

Vessels' stability calculation and evaluation, performed on-board nowadays, is based on the stability criteria published by the ship's classification societies. These criteria are mainly based on the A749(18) Resolution of International Maritime Organization. The resolution and their later amendments are known as the Intact Stability Code.

The ship stability criteria are to ensure the relevant level of safety against capsizing and strong heel. The capsizing is not often occurring phenomenon at the sea, although it cause considerable number of fatalities. The most significant feature influencing the capsizing rate is the size of a vessel (Krata 2007). Generally the smaller is the vessel, the bigger is the risk of capsizing. This is due to the scalability in vessel stability. It depends on the square-cubed rule; i.e. the heeling forces, which depends on water and wind impact areas, go up with the square of the dimensions, but the righting moment which depends on the displacement, goes up with the cube of the dimensions (Womack 2002).

Taking into account the square-cubed rule of ship stability and simultaneously the same stability standards for all size of vessels, the Intact Stability Code cannot be applied as a basis for safety factor estimation for the purpose of route optimization. Moreover, ISC stability standards are related to one state of weather and one state of a sea, described by the wind pressure and ships rolling amplitude, while the optimization procedure has to follow variable weather and sea conditions to be passed by a vessel on her way.

The state-of-the-art solution to the stability assessment problem is a risk based approach. The core idea of this approach is presented in Figure 6.

The risk based approach to ship stability assessment reveals a list of advantages but the simplicity comparing to proscriptive stability standards based on IS Code. It comprises a seakeeping performance of a ship and a wide range of possible weather and sea conditions, however cannot be computed relatively easy. The researches are still underway and no complete practical tool has been established yet. Furthermore, application of such an approach would be extremely time-consuming which is unacceptable for the purpose of multicriteria evolutionary weather routing algorithm described in the paper.
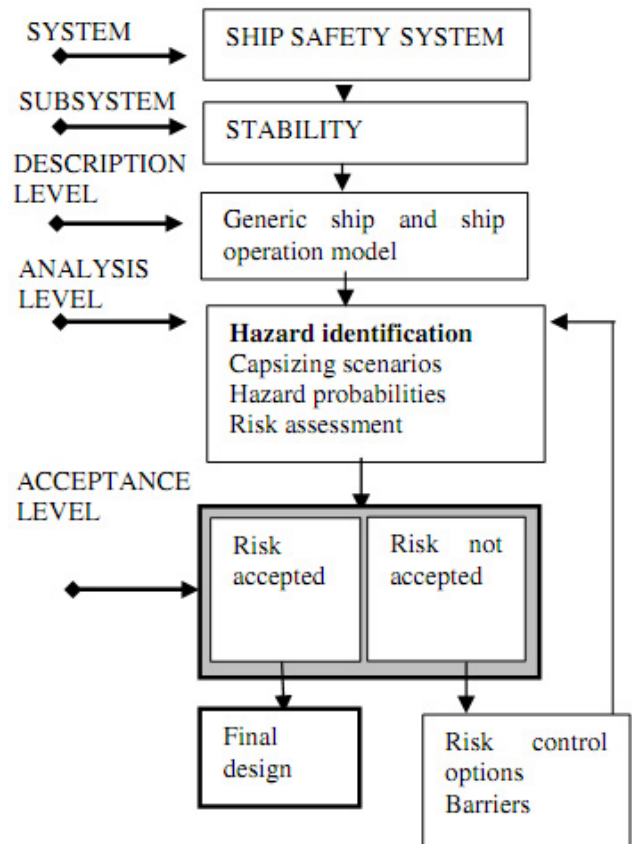

Figure 6. Block diagram of risk based approach related to ship stability (Kobylinski 2007b)

5 NEW MEASURE OF SHIP SAFETY BASED ON WEATHER HAZARD AVOIDANCE

Consideration of characteristic features of contemporary methods of ship stability assessment (described in section 4) and the main aim of the study i.e. weather routing optimization, leads to the conclusion that there is a need for new measure of ship safety. The index or coefficient of safety should comprise safety aspects related to ship stability and seakeeping performance and simultaneously it has to be reasonably applicable. Both, time of computation

and reliability of computation results need to be considered and balanced.

The limitation of ISC-based approach is its disregard of size of a vessel and consideration of only one hydrometeorological conditions. Correspondingly the limitation of risk based approach towards ship stability is a lack of fully practical computational tools and a long time of processing. A sort of a trade-off between these two methods may be the new approach based on weather hazard avoidance.

The proposal of a new measure of ship safety or just a method for safety index calculation is derived form the *Revised guidance to the master for avoiding dangerous situation in adverse weather and sea conditions*, published by the International Maritime Organization as MSC Circular 1228. The relatively up to date publication (in comparison to dr. Rahola's findings from 1939 being the foundation of IS Code) comprises a set of remarks and advices regarding avoidance of following dangerous dynamical phenomena at sea (IMO 2007):

− surf-riding and broaching-to;
− reduction of intact ship stability when riding a wave crest amidships;
− synchronous rolling motion;
− parametric roll motions.

According to the IMO Circ. 1228 some combinations of wave length and wave height under certain operation conditions may lead to dangerous situations for ships complying with the IS Code. As the sensitivity of a ship to dangerous phenomena depends on the actual stability parameters, hull geometry, ship size and ship speed, the vulnerability to dangerous responses, including capsizing, and its probability of occurrence in a particular sea state may differ for each ship (IMO 2007). In addition the wave encounter period and the wave length and height depend on actual hydrometeorological conditions. These features are strictly advantageous for the purpose of weather routing applications and as a consequence they are desirable for safety index calculation in the course of route optimization.

The dangerous surf-riding zone cay be obtained from a graph presented in IMO Circ. 1228 which is shown in Figure 7. The symbol *V* denotes velocity of a vessel in knots and *L* – ship's length between perpendiculars.
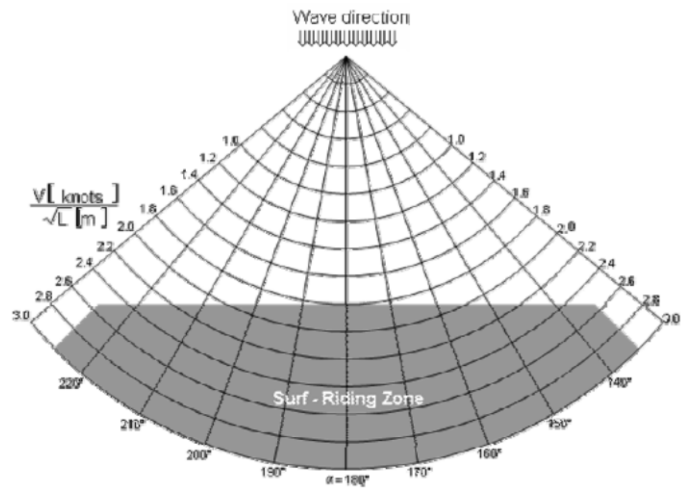

Figure 7. Dangerous zone of surf-riding in following or quartering seas (IMO 2007)

It is found out that ship surf-riding and broaching-to may occur when:

− the angle of encounter α is in the range 135°<α<225°;
− and the ship speed is higher than $(1.8 \cdot L) \cdot \cos(180 - \alpha)$ (knots).

To avoid surf riding, and possible broaching the ship velocity should be taken outside the dangerous region reported in Figure 7 (IMO 2007). The alternation of the speed, the course or both is advised.

The next group of dangerous dynamic phenomena taken into account in IMO guidance 1228 is related to resonance gain of rolling motion. This may occur due to nonlinearity of ship response in resonance conditions, i.e. when the encounter wave frequency is similar to first or second harmonic frequency of natural roll motion of a ship (Landrini 2006).

The period of encounter T_E can be calculated by the formula:

$$T_E = \frac{3 \cdot T_W^2}{3 \cdot T_W + V \cdot \cos(\alpha)} \quad [s] \tag{4}$$

where:

T_W − [s] wave period,

V – [knots] ship's speed,

α − [deg] angle of encounter (angle between keel direction and wave direction).

The prevention against a synchronous rolling motion consists in avoiding such combinations of ship speed and course which result in the encounter wave period T_E nearly equal to the natural rolling period of ship T_R.

For avoiding parametric rolling in following, quartering, head, bow or beam seas the course and speed of the ship should be selected in a way to avoid conditions for which the encounter period is

close to the ship roll period ($T_E \approx T_R$) or the encounter period is close to one half of the ship roll period ($T_E \approx 0.5\ T_R$) (IMO 2007).

Another dangerous zone presented in IMO 1228 guidance is established for high wave attack and a list of phenomena related to sailing in following and quartering rough sea. This dangerous zone is presented in Figure 8.
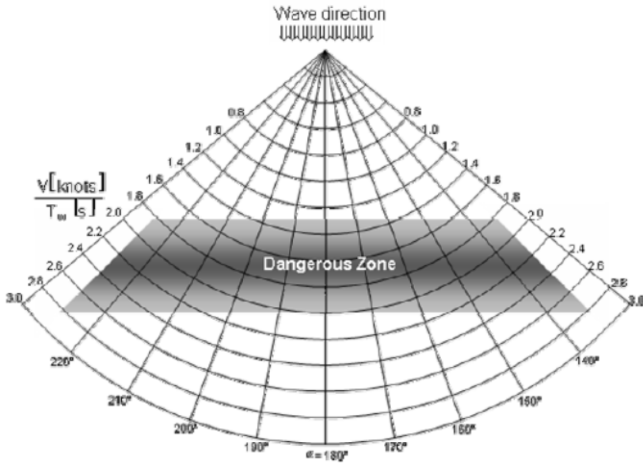

Figure 8. Dangerous zone of successive high wave attack in following and quartering seas (IMO 2007)

A ship master is advised to avoid entering dangerous zone indicated in Figure 8 when:

– the average wave length is larger than 0.8 ship's length between perpendiculars;
– and the significant wave height is larger than 0.04 ship's length;

and at the same time some indices of dangerous behavior of the ship can be seen (IMO 2007). In case of actual velocity vector violating the dangerous zone, the ship speed should be reduced or the ship course should be changed to prevent successive attack of high waves, which could induce the danger due to the reduction of intact ship stability, synchronous rolling motions, parametric rolling motions or combination of various phenomena (IMO 2007).

The core idea of new safety index calculation with regard to weather hazard avoidance is to include all the restrictions described in IMO *Revised guidance to the master for avoiding dangerous situation in adverse weather and sea conditions*. For the purpose of practical application of new concept, the appropriate software was developed. All the restrictions resulting from the guidance are computed and presented in the form of polar plots.

The polar plots presenting dangerous configurations of speed and course of a vessel need to be computed for every single ship and even for every loading conditions of a ship. The length of a ship is a variable and furthermore, the hull beam, draft and the metacentric height influences her natural rolling period. Thus, for a given ship in actual loading con-

ditions a set of polar plots should be prepared and used.

The use of such polar plot presenting zones to be avoided is quite simple. The only condition is to keep the velocity vector away from the restricted zone. For the sake of presentation an exemplary case was computed and plotted. The characteristics of a ship taken into consideration are following:

– length between perpendiculars 180 m;
– beam 30 m;
– draft 11 m;
– metacentric height 1.9 m.

The fully developed ocean wave system was considered.

The dangerous zone where an exemplary ship is exposed to surf-riding is plotted in Figure 9.
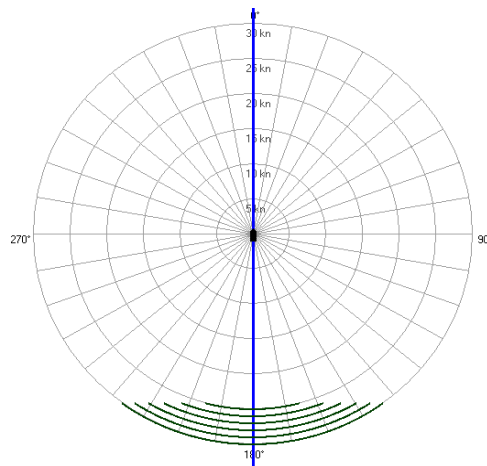

Figure 9. Surf-riding zone (exemplary case)

Then, the zones describing ship course / speed configuration where she is likely to experience synchronous roll motion or parametric rolling are shown in Figure 10.
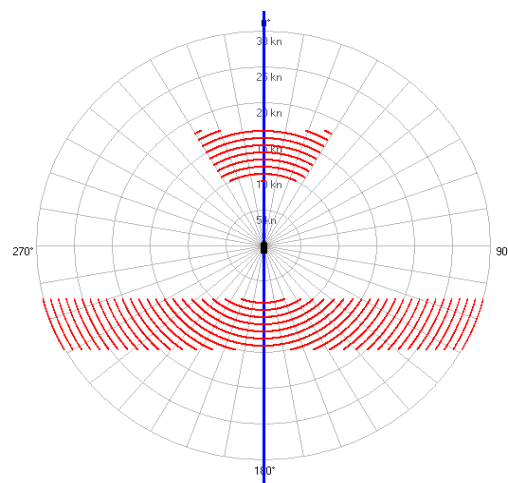

Figure 10. Synchronous rolling and parametric rolling zones (exemplary case)

The last dangerous zone is related to conditions comprising high wave action and phenomena asso-

ciated with such waves in following and quartering seas. The polar plot of this zone is computed for an exemplary case and shown in Figure 11.
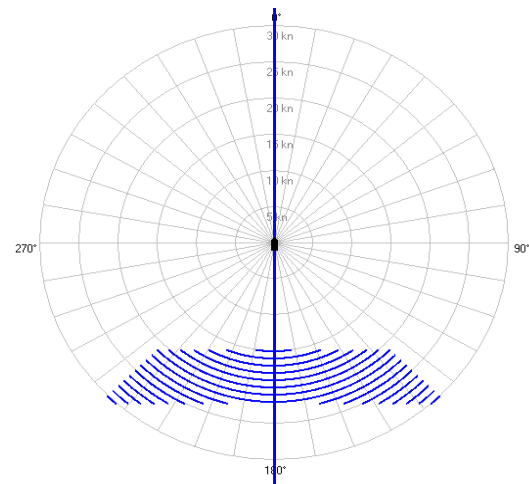

Figure 11. High wave attack zone (exemplary case)

All the results of computation of dangerous zones can be plotted together as one graph. Some of the zones may overlap for a number of conditions. The cumulative graph computed and plotted for exemplary ship characteristics is shown in Figure 12.

The core idea of the proposed new ship safety index calculation is based on the cumulative graph comprising all dangerous zones described in IMO Circ. 1228. The safety index SI is defined by the following formulas:

$$SI = \frac{A_S}{A_T} \ [-] \tag{5}$$

$$A_S = A_T - A_D \tag{6}$$

where:

A_T – total area of ship maximum speed circle,

A_S – area of non dangerous zone inside ship maximum speed circle,

A_D – area of all dangerous zones included in ship maximum speed circle.

The total area of ship maximum speed circle depicts just all possible speeds and courses of a ship. It depends on ship's hull and propulsion characteristics and does not take into account any potential danger. Thus, this total area is determined by maximum speed of a vessel.

The area of all dangerous zones (exemplary shown in Figure 12) depicts restricted configuration of ship speed and course with regard to adverse weather. The greater dangerous area is the more constraints faces a vessel.

The area of non dangerous zone represents allowed configurations of ship velocity vector which are found as safe in terms of IMO Circ. 1228. This area reflects the potential possibility of course and speed choice and alternation or in other words a kind of freedom in safe maneuvering.
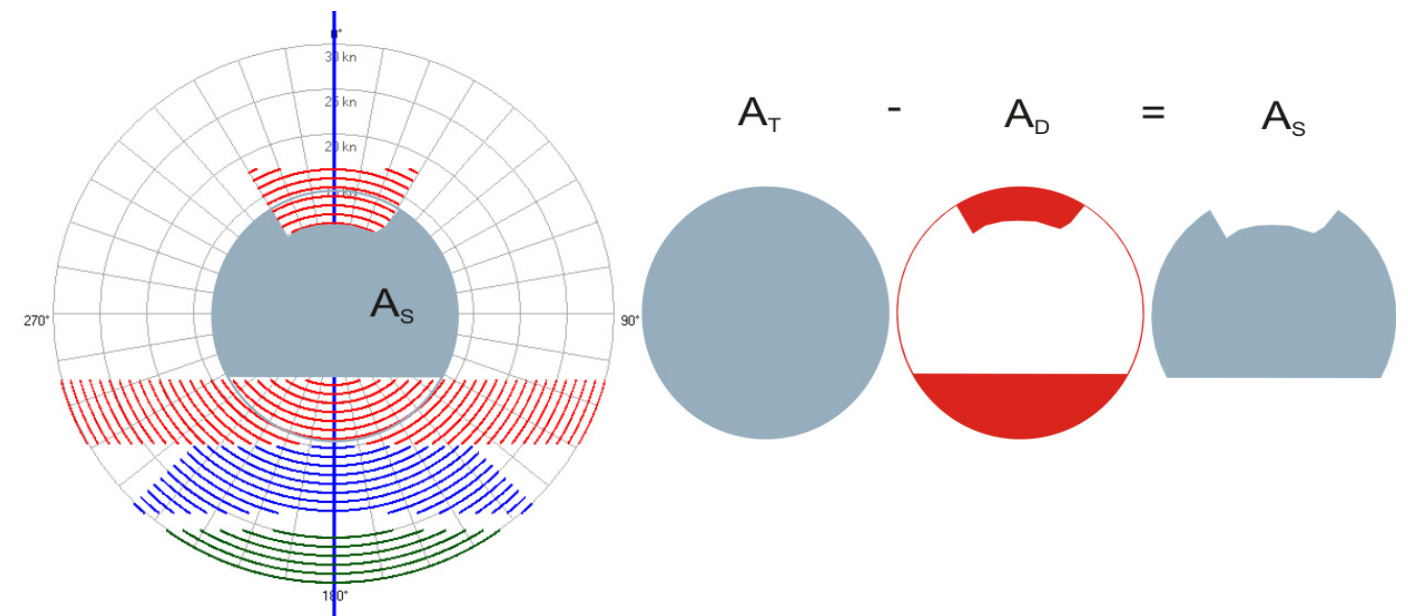

Figure 12. Cumulative graph presenting dangerous zones according to IMO Circ. 1228 (exemplary case)

77

The safety index *SI* defined by the formula (5) varies from 0 to 1. The value *SI*=0 expresses a lack of safe choice of vessel speed and course. The value *SI*=1 stands for a complete absence of any restrictions, which is typical for good weather conditions. The safety index based on weather hazard avoidance can be apply as an element of optimization process according to the formula (3) i.e. one of the goal functions in multicriteria weather routing process.

According to the procedure described in the paper it is clearly apparent that the safety index is not a fixed value for the entire voyage of a vessel, even for one type of the vessel and fixed lading conditions (however unchanging loading conditions are rather impossible to maintain in long term due to fuel consumption and ballasting). The shape of dangerous zones depends on wave characteristics therefore all the defined zones needs to be updated consequently after every reception of up to date weather forecast. It needs to be emphasized that weather routing and described weather routing optimization tool are designed for planning purposes. Thus, the processing has to be performed prior encountering adverse weather conditions.

6 SUMMARY

The multicriteria evolutionary weather routing algorithm (MEWRA) presented in the paper offers a constrained, three element goal function route optimization. Especially for a motor-driven ship the rough sea impact on ship must be taken into account when safety of people and cargo on board are in stake. Thus the authors have proposed a brand new safety measure that becomes an element of the goal function set in the optimization process.

The new safety index refers to dynamical phenomena taking place in rough sea conditions which advantages this approach among contemporary ones. The consideration of dynamical behavior of a vessel instead an application only Intact Stability Code based requirement is a significant step forward. The

authors believe that the MEWRA solution together with the safety index can be successfully applied to a motor-driven ship route planning and optimization.

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