Weather Routing Model for Ship Motions Reduction and Fuel Saving

Silvia PENNINO[a,1] and Antonio SCAMARDELLA[a]
[a] *University of Naples "Parthenope", Department of Sciences and Technology, Naples, Italy*

Abstract. When a vessel sails in a seaway, wind and current can influence the ship's speed, the comfort on board and the fuel consumption. Maritime trades are strictly dependent on the environmental conditions that the ships encounter during their sailing, safe navigation and energy efficiency are the key factors to improve the competitiveness and sustainability of ship operations. Optimization algorithms provide a significant support to the decision-making process and allow selecting the best route in sight of one or more objectives. The weather routing problem has been addressed by many authors and different approaches have been proposed. The new route optimization procedure will be developed on the shortest path algorithm in order to maximize the ship seakeeping performances and to minimize the added resistance caused by sea conditions. The optimization will be performed in accordance with two objective functions, the best routing solution is thus selected by the Dijkstra algorithm modified to take into account dynamically changing of ship's position and weather conditions. The minimization of a Seakeeping Performance Index, containing all the operability limiting criteria for induced vertical motions in rough sea, and of an Added Resistance Index, are the objectives to be achieved. The first for safe and comfortable navigation, the second for fuel saving, reducing the added resistance the engine power required to overcome the resistance and, as a result, the fuel consumptions decrease. The data of wind and swell waves are derived, for each route segment, from global-WAM (GWAM) model. Results and discussion of the proposed method will be presented for a containership ship in a test case voyage through the Pacific Ocean, for ocean-going ships the voyage and sailing time are long and the weather conditions in the sea area around the route vary widely. The code can be integrated in an On-Board Decision Support System.

Keywords. Adaptive weather routing; Seakeeping Performance Index; Route optimization; Dijkstra algorithm; Added Resistance

1. Introduction

In recent years the availability of reliable weather forecast data has improved the safety of the ship voyages, helping the operators to select suitable routes. The weather conditions, indeed, can strongly influence fuel consumption, energy efficiency, ship and human life safety, crew and passengers comfort, voyage time management. In this framework, even if the route selection is entrusted to the ship master, the adaptive weather routing optimization algorithms can provide a significant support to the decision-making process in order to select the best choice in sight of one or more

[1] Silvia Pennino, University of Naples "Parthenope", Department of Sciences and Technology, isola C4 Naples - Italy; silvia.pennino@uniparthenope.it

objectives. The weather routing problem was addressed by many authors, utilizing different approaches. Zoppoli [1], James [2], Papadakis and Perakis [3] are the pioneering works, the first generation of weather routing criteria was aimed to minimize the voyage duration and, consequently, the fuel consumption, neglecting the impact of the ship response behaviour in rough sea. Nevertheless, in the last years the voyage optimization problem was approached also considering the ship seakeeping performance. The second-generation algorithms are generally categorized into: dynamic programming, genetic algorithms and pathfinding methods. In [4], an overview of weather routing and safe ship handling approaches is presented. The most used techniques include multi-objective genetic algorithms [5-7] that stochastically solve a discretized nonlinear optimization problem. Zaccone et al. [8] developed a 3D Dynamic Programming optimization aiming to find the minimum fuel consumption voyage. The path-finding method is used also by Padhy et al. [9] and Sen et al. [10] trough the Dijkstra [11] algorithm. In [12] a modified version of Dijkstra's algorithm has been recursively applied until an optimal route is obtained assessing fuel oil consumption over alternative routes. Most of the existing weather routing optimization methods generate the optimal route from an economic point of view to minimize the fuel oil consumption, instead, in Pennino et al. [13] a new adaptive weather routing model, based on the Dijkstra shortest path algorithm, aiming to select the optimal route that maximizes the ship performances in a seaway has been presented. The reference route has fallen in the North Atlantic Sea, the effect on the optimum route assessment of both wave and combined wind/swell wave conditions have been investigated as well as the incidence of the vessel speed. The results clearly showed the possibility to achieve appreciable improvements, up to 50% of the ship seakeeping performance, without excessively increasing the route length and the voyage duration. Starting from [13] in the present paper a different oceanic route is adopted to test the algorithm and confirm the results, in addition, another objective function has been considered, namely the minimization of the added resistance, due to the speed loss, caused by sea conditions.

2. Shortest path detection

The route optimization procedure, developed in this Section, is based on the Dijkstra algorithm, that allows to find the shortest path between two known points by minimizing a non-negative cost-function. The Dijkstra algorithm is based on solving two problems: the construction of the tree of minimum total length between n nodes and the research of the best path of minimum total cost between a start and an end node. In the current analysis two cost functions are considered: the complement to 1 of the Seakeeping Performance Index (SPI), provided by equation (1), and the Added Resistance Index (ARI), defined in equation (9). Before evaluating the ship performances in a seaway, a network of nodes, between the start and the end points of the scheduled route, needs to be provided to delineate a region that restricts the ship route. The network, which is a special form of a graph, is generated as described by Lee et al [14]. After seeking the great circle (blu line) centre point (red dot), a set of centre points (blu dots), with a chosen step distance, belonging to the rhumb-line perpendicular to the great circle. Connecting departure point and the point in the set of centre points a half great circle route is composed, similarly, connecting the point in the set of centre points and arrival point the other half great circle route is generated. After providing the network of nodes, a set of arcs, connecting two adjacent grid points, is generated, the arcs are divided into straight arcs, right arcs and left arcs, for a node inside the network, i.e. excluding the start and end node, it has possibility of going to two or three different nodes. An example of the grid network between a start and an end point is shown in Figure 1.

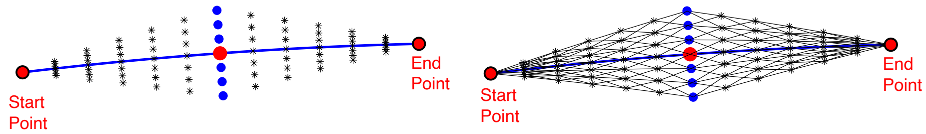


Figure 1. Network for routing

Each node contains a set of static information, such as the geographic coordinates, and a dynamic grid with the weather data, namely the significant wave height, the mean wave period and the prevailing wave direction, which are systematically updated once a new data set is available. Each segment of the optimal route corresponds to the minimum cost function among the set of possible values referenced to the calculation point, the Dijkstra algorithm is not applied statically but is updated, changing the started point, based on the time elapsed and the path already travelled by the ship.

2.1. Ship Seakeeping Index

The ship seakeeping performance are determined, according to equation (1), on the basis of five reference criteria: the amplitude of the pitch motion, rms_p is its RMS, the relative vertical acceleration at the ship forward perpendicular, rms_a is its RMS, the probability of slamming occurrence, p_{sl}, the probability of green water on deck, p_{wd}, and the Motion Sickness Incidence, MSI. The denominators, in equation (1), represent the relevant limit values. The considered criteria can be modified and adapted to the ship type and service.

$$SPI = max\left\{0; \left(1-\frac{rms_p}{rms_{p,l}}\right)\cdot\left(1-\frac{rms_a}{rms_{a,l}}\right)\cdot\left(1-\frac{p_{sl}}{p_{sl,l}}\right)\cdot\left(1-\frac{p_{wd}}{p_{wd,l}}\right)\cdot\left(1-\frac{MSI}{MSI_l}\right)\right\} \qquad (1)$$

When any seakeeping index is greater than the limit value, the SPI is null, so satisfying the non-negative condition required to apply the Dijkstra method. The limit values of the pitch amplitude and the Motion Sickness Incidence are based on the NATO STANAG 4154 criteria, while the remaining ones comply with the NORDFORSK seakeeping criteria. The RMS of the pitch motion and relative vertical acceleration are evaluated according to the equations (2) and (3), where: H_3 and H_5 are the heave and pitch motion transfer functions; S_ς is the wave spectrum, ω_e is the encounter wave frequency, $\bar{x}$ is the forward perpendicular longitudinal distance from the centre of gravity, $k$is the wave number in deep water condition and μ denotes the ship's heading with respect to the waves. The modulus of heave and pitch motion transfer functions are derived solving the heave and pitch equations, as detailed in Pennino et al. [13]. The Motion Sickness Index is determined according to the formulation developed by O'Hanlon and McCauley [15] and modified by Colwell [16], reported in equation (4), where: Φ is the standard normal cumulative distribution, while z_a and z'_T are functions of the exposure time, the RMS and the mean frequency of the ship vertical acceleration. The slamming occurrence is assessed using the equation (5) proposed by Faltinsen [17], where: $v_{cr} = 0.093\sqrt{gL}$ is the threshold velocity, C_s is the swell up coefficient, d is the ship draught at the forward perpendicular, $m_{0,r}$ and $m_{2,r}$ are the 0[th] and 2[nd] order spectral moments of the ship relative motion considering the sea surface. Finally, the probability of green water on deck is evaluated using equation (6), f_b is the freeboard at the ship forward perpendicular.

$$rms_p = \sqrt{\int_0^\infty |H_5(\omega_e)|^2 S_\varsigma(\omega_e)} \tag{2}$$

$$rms_a = \sqrt{\int_0^\infty |H_3(\omega_e) - \bar{x}H_5(\omega_e) - e^{-ik\bar{x}cos\mu}|^2 \omega_e^4 S_\varsigma(\omega_e)} \tag{3}$$

$$MSI = 100\Phi(z_a)\Phi(z_T') \tag{4}$$

$$p_{sl} = e^{-\left(\frac{v_{cr}^2}{2C_S^2 m_{2,r}} + \frac{d^2}{2C_S^2 m_{0,r}}\right)} \tag{5}$$

$$p_{wd} = e^{-\frac{f_b^2}{2C_S^2 m_{0,r}}} \tag{6}$$

2.2. Added resistance

As regards the added resistance, which is a second order quantity with respect to wave height, there are several relations available for its determination. These formulae do not always produce consistent results and therefore some uncertainties exist in the determination of added resistance. This is still a matter of research. It the present work, formula given by Gerritsma and Beukelman [18], generalized by Loukakis and Sclavounos [19] for different wave headings, is used:

$$R_{aw}(\omega_e) = -\frac{k\cos\mu}{2\omega_e}\int_L \left(b_z^{2D}(x) - V\frac{da_z^{2D}(x)}{dx}\right)V_{za}^2(x)\,dx \tag{7}$$

where k is the wave number, a_z^{2D} and b_z^{2D} are the sectional added mass and damping, V is the ship speed and V_{za} is the amplitude of the relative vertical velocity between the ship and the waves. The calculation in an irregular sea is based on the superposition principle, the mean added resistance in irregular waves is obtained as follows:

$$\overline{R_{aw}} = \int_0^\infty \frac{R_{aw}(\omega_e)}{\zeta_a^2} S_\varsigma(\omega_e)d\omega_e \tag{8}$$

$$ARI = \overline{R_{aw}}/\Delta \tag{9}$$

where ζ_a is the wave amplitude and Δ the displacement in KN.

3. Input data

The reference vessel is the S175 containership, in Table 1 are listed the main dimensions. The reference route, shown in figure 2, falls in the North Pacific Ocean. The start and the end point are totally arbitrary and lightly far from the departure and arrival ports, this choice is linked to the marine traffic congestion approaching the coastline that makes hard and useless the application of adaptive routing models. The shortest path route, the great circle or orthodrome, is equal to 1739 nautical miles covered in about 5 days considering a vessel speed of 14.5 knots, corresponding to a Froude number equal to 0.18. The great circle requires to constantly change the vessel heading, while the rhumb line or loxodrome is slight longer, in the considered case is equal to 1742 nautical miles, but it allows a constant heading. The availability of daily operational weather forecast data is a key point to assess the reference scenario required in the adaptive weather routing algorithm. In this respect, different software packages, with different resolutions, domains (from regional to global) and quality, are available.

Table 1. S175 containership main dimensions.

Length between perpendiculars	175.0	m
Breadth	25.4	m
Design draught	9.5	m
Displacement	24539	t

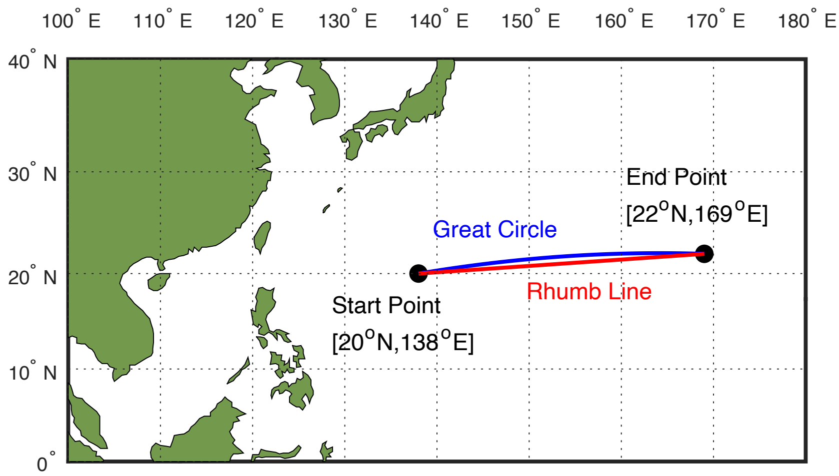


Figure 2. Great circle (blue) and rhumb line (red) between departure and arrival points

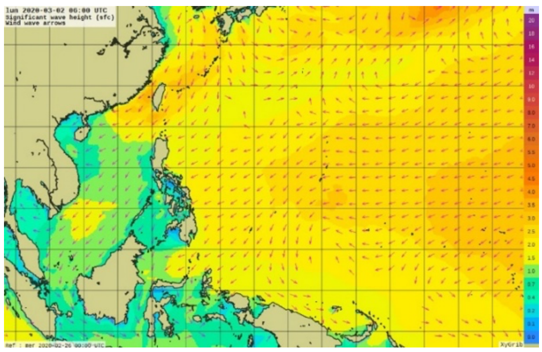
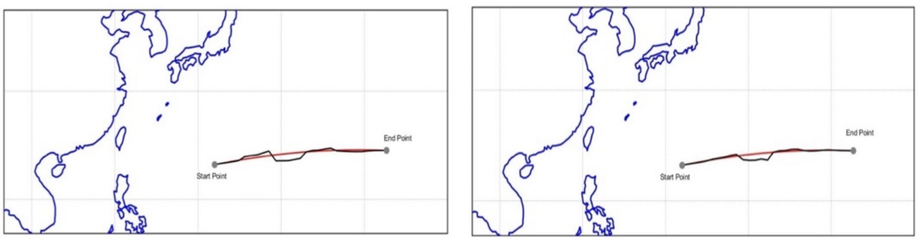


Figure 3. Significant wave height and wind wave arrows form GyGrib

Nowadays the meteorological community generally follows the standardization established by the World Meteorological Organization (WMO), delivering all information in a self-descripting GRIB (GRIdded Binary) format, so making the reading of the input data very easy [20]. In the current analysis, these data are obtained by the third-generation Global Wave Model (GWAM). The GRIB files were downloaded for the period from 22nd up to 26th February 2020, with 0.25° x 0.25° grid spacing 3-hour forecast interval and two observation periods equal to 1 and 5 days, respectively. An example of wave height, geometric mean between swell and wind wave significant heights, and wind wave directions in the period and zone analyzed in this work is shown in figure 3.

4. Case study

In the route optimization procedure two types of GRIB files are embodied: the former, referenced as “Case 1”, is a 5-day forecast GRIB file, ranging from 22 up to 26 February 2020, the latter, referenced as “Case 2”, is a 1-day GRIB file, updated daily in the same reference period, according to the effective position of the ship during the voyage. In this respect, Figures 4a–b display the optimal routes optimizing the seakeeping performances and Figures 5a–b show the optimal routes minimizing the added resistance. In all cases, the great circle route is highlighted in red and the optimum route in black, the grey circles represent the starting and the ending points. Besides, table 2 and 3 provides the difference, Δ_c, between the great circle and optimum route, together with the percentage variation, Δ_{SPI}, of the Seakeeping Performance Index (SPI), and, Δ_{ARI}, of the Added Resistance Index (ARI), as regards the values corresponding to the great circle. All calculations were performed based on Froude number equal to 0.18 and using a JONSWAP spectrum. Based on the current results using the SPI as objective function the percentage increase of the route length ranges from 2.7% up to 4.5%, while the SPI increase is much higher and ranges from 42% up to 58%. On the other hand, using the ARI as objective function the increase on length is lesser but also the improvement of the encountered added resistance is low. The employment of 5-day and 1-day GRIB files play a fundamental role in the assessment of the optimum route, the update frequency of the weather conditions is a key point and it should be as high as possible. In figure 6 and table 4 the incidence on the optimum route detection of each seakeeping index is investigated; based on the current results, the Motion Sickness Incidence seems to be the most sensitive parameters. The sensitivity analysis highlights that the optimum route varies according to the seakeeping parameter embodied, this outcome suggest that the adaptive weather routing model shall be specialized on a case-by-case depending on which parameters need to be improved.

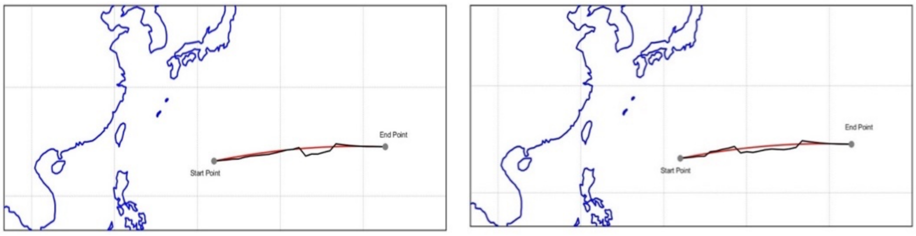


(a) (b)

Figure 4. Minimum distance (great circle) and optimal route detection (SPI): (a) Case 1; (b) Case 2.

Table 2. Results of optimal route detection using SPI

Case	GRIB file update	Δ_c (nm)	Δ_c (%)	Δ_{SPI} (%)
1	5-day	77.8	4.5	42.5
2	1-day	47.6	2.7	58.3

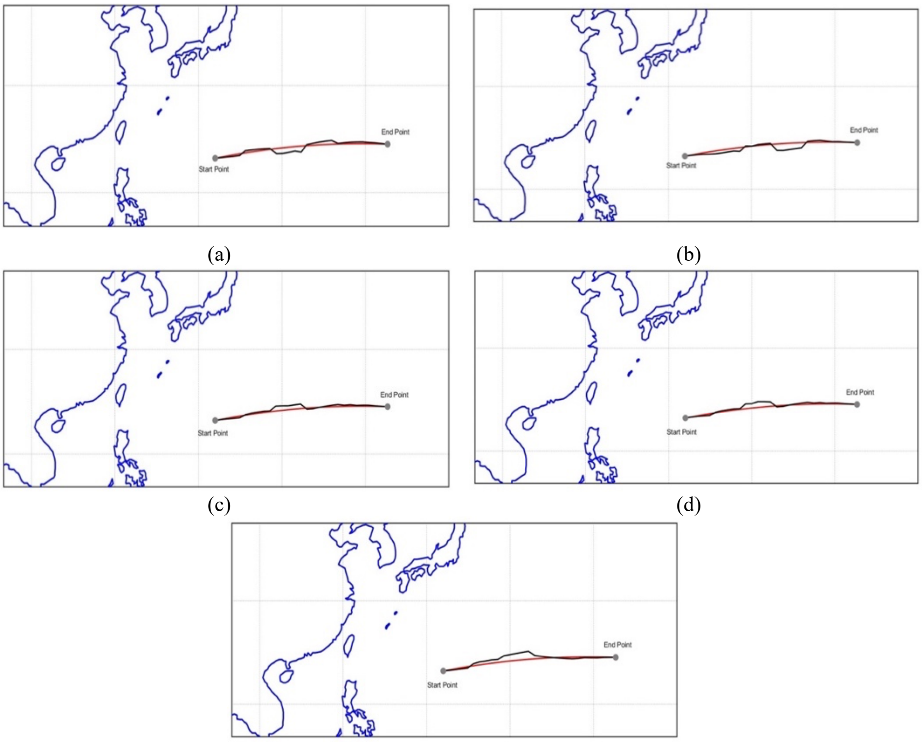


(a) (b)

Figure 5. Minimum distance (great circle) and optimal route detection (ARI): (a) Case 1; (b) Case 2.

Table 3. Results of optimal route detection using ARI

Case	GRIB file update	Δ_c□(nm)	Δ_c□(%)	Δ_{ARI} (%)
1	5-day	64.4	3.7	2.3
2	1-day	61.5	3.5	2.3



(a) (b) (c) (d) (e)

Figure 6. Sensitivity analysis (a) RMS of pitch amplitude; (b) RMS of vertical acceleration; (c) Slamming probability; (d) Water on deck probability; (e) MSI

Table 4. Sensitivity analysis, 1-day

Seakeeping parameter	Δ_c□(nm)	Δ_c□(%)	Δ_{SPI} (%)
RMS of pitch amplitude	59.0	3.4	19.1
RMS of vertical acceleration	66.3	3.8	26.4
Slamming probability	33.5	1.9	7.4
Water on deck probability	34.8	2.0	3.3
Motion Sickness Incidence	29.3	1.7	34.7

5. Conclusions

The Dijkstra shortest path algorithm was applied to detect the optimum route, considering two non-negative cost function, to maximize the ship performances in a seaway and reduce the added resistance in waves. The results clearly show that the ship seakeeping performances can be highly improved, without significantly increasing the voyage length and, consequently, the fuel consumptions. However, when the objective function is the added resistance reduction increasing distance travelled might have a greater impact on fuel consumption than the added resistance reduction and the consequent decrease in speed loss. The overall conclusion is that weather routing is certainly applicable to ensure safety of cargo and crew and to avoid rough weather but not to reduce the fuel consumption, and consequently the emissions, with the same results. Anyway, the current results are encouraging for further research activities, devoted to including additional seakeeping criteria in the adaptive weather routing algorithm, to improve the added resistance calculation model, to introduce the emission assessment, to compare these simulated results with real conditions so as to develop a support, integrated on board, for the On-Board Decision System.

References

[1] Zoppoli R Minimum-Time Routing as an n-Stage Decision Process. J. Appl. Meteorol. 1972, 11, 429–435.

[2] James RW. Application of Wave Forecasts to Marine Navigation. U. S. Naval Oceanographic Office SP-1. 1957.

[3] Papadakis NA, Perakis AN. Deterministic Minimal Time Vessel Routing. Oper. Res. 1990, 38, 426–438.

[4] Perera LP, Soares CG. Weather routing and safe ship handling in the future of shipping. Ocean Eng. 2017, 130, 684–695.

[5] Maki A, Akimoto Y, Nagata Y, Kobayashi S, Kobayashi E, Shiotani S, Ohsawa T, Umeda N. A new weather-routing system that accounts for ship stability based on a real-coded genetic algorithm. J. Mar. Sci. Technol. 2011, 16, 311–322.

[6] Vettor R, Soares CG. Development of a ship weather routing system. Ocean Eng. 2016, 123, 1–14.

[7] Szłapczyńska J, Smierzchalski R. Multicriteria optimisation in weather routing. Saf. Sea Transp., 2009, 3, 393.

[8] Zaccone R, Ottaviani E, Figari M, Altosole M. Ship voyage optimization for safe and energy-efficient navigation: A dynamic programming approach. Ocean Eng. 2018, 153, 215–224.

[9] Padhy CP, Sen D, Bhaskaran P.K. Application of wave model for weather routing of ships in the North Indian Ocean. Nat. Hazards 2007, 44, 373–385.

[10] Sen D, Padhy CP. An approach for development of a ship routing algorithm for application in the North Indian Ocean region. App. Ocean Research, vol. 50, pag. 173 – 191. March 2015.

[11] Dijkstra EW. A note on two problems in connexion with graphs. Numer. Math. 1959, 1, 269–271.

[12] Gkerekos C, Lazakis I. A novel, data-driven heuristic framework for vessel weather routing. Ocean Eng. 2020, 197, 106887.

[13] Pennino S, Gaglione S, Innac A, Piscopo V, Scamardella A. Development of a new ship adaptive weather routing model based on seakeeping analysis and optimization. J. of Mar. Science and Engineering, vol. 8, 2020.

[14] Lee H, Kong G, Kim S, Kim C, Lee J. Optimum Ship Routing and Its Implementation on the Web. In Computer Vision; Springer Science and Business Media LLC, Berlin, Germany. 2002; Volume 2402, pp. 125–136.

[15] O'Hanlon JF, McCauley ME. Motion sickness as a function of the frequency and acceleration of vertical of vertical sinusoidal motion. Aerosp. Med. 1974, 45, 366–369.

[16] Colwell JL. Human Factors in The Naval Environment: A review of Motion Sickness and Biodynamic Problems; National Defence Technical Memorandum 89/220; Defence Centre de Research Establishment Atlantic, Dartmouth, Nova Scotia, Canada. 1989.

[17] Faltinsen OM. Sea loads on Ships and Offshore Structures; Cambridge University Press, United Kingdom. 1990.

[18] Gerritsma J, Beukelman W. Analysis of the resistance increase in waves of a fast cargo ship. International Shipbuilding Progress 19, 285–293, 1972.

[19] Loukakis T, Sclavounos P. Some extensions of the classical approach to strip theory of ship motions, including the calculation of mean added forces and moments. J. of Ship Research 22, 1–19, 1978.

[20] WMO. Introduction to GRIB Edition 1 and GRIB Edition 2. Available online at: https://www.wmo.int/pages/prog/www/WMOCodes/Guides/GRIB/Introduction_GRIB1-GRIB2.pdf (accessed on 18.11.2020).