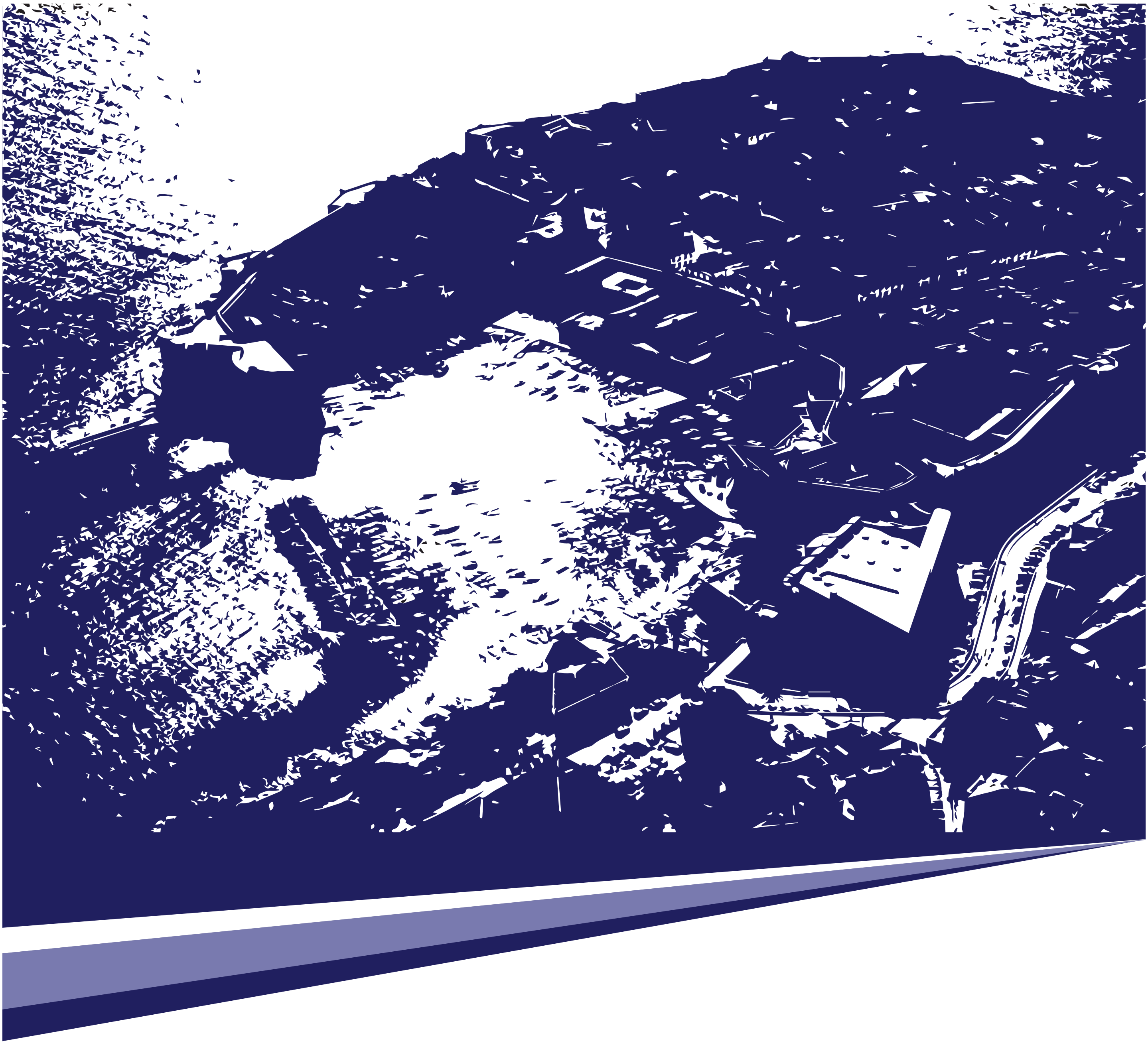

NAŠE MORE 2019

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CONTENT

ADDED RESISTANCE PARAMETRIZATIONS DUE TO WAVES IN A WEATHER SHIP ROUTING SYSTEM

Clara Borén
Department of Nautical Science and Engineering
Universitat Politècnica de Catalunya (Barcelona·TECH), Spain
E-mail: cboren@cen.upc.edu

Loïc Falevitch
Offshore and Naval Architecture Department
ENSTA Bretagne, Brest, France
E-mail: loic.falevitch@ensta-bretagne.org

Marcella Castells-Sanabra
Department of Nautical Science and Engineering
Universitat Politècnica de Catalunya (Barcelona·TECH), Spain
E-mail: mcastells@cen.upc.edu

Manel Grifoll Colls
Department of Civil and Environmental
Barcelona School of Nautical Studies (FNB)
Universitat Politècnica de Catalunya (BarcelonaTECH), Spain
E-mail: manel.grifoll@upc.edu

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Summary

This contribution compares the parametrization of the wave effect on navigation in a weather ship routing system using three different formulations. The investigation is supported by the use of a ship routing system, the SIMROUTE software, developed to obtain the optimal route and the minimum distance route through the use of pathfinding algorithms founded on high-resolution meteo-oceanographic predictions. The formulations developed by Aertssen [1], Khokhlov (suggested by Lubkovsky [17]) and Bowditch [5] have been implemented into the aforementioned software for comparing their outputs when analysing wave effect on navigation. Ship routing systems have become a key issue in recent years due to a global target focused in reducing costs and fuel emissions in Europe. In terms of time savings, the optimal ship routing analysis is investigated in a European short sea shipping system: the link between Spanish and Italian ports. As a first approach, the results show the discrepancies when using different calculation methodologies on ship routing in terms of time during energetic wave episodes. For a particular case, the rate of time savings may vary from 0.1% to more than 6% depending on the methodology applied. However, out of the three considered methods, Aertssen and Khokhlov ones give very similar results whereas Bowditch shows considerably higher values. This fact may lead to the conclusion that Bowditch approach may be too generalist to be applied to investigate the wave effect on navigation.

Keywords: Weather ship routing, wave effect on navigation, speed reduction, significant wave height

1. INTRODUCTION

Vessels speed has a pronounced effect on the fuel consumption because of the relation between the increase of speed to the exponential required propulsive power. This fact highlights the reason for being interested in lowering fuel consumption, especially when fuel prices overgrow. A major factor of competitiveness in the maritime industry is the minimization of fuel consumption and environmental protection for shipping routes. This agrees with an increase of the world tendency to reduce air emissions (energy efficiency) in the framework to mitigate the climate change effects. From the shipping industry point of view this may be achieved with an optimum route plan design. Academic research has focused the ship routing optimization through pathfinding algorithms [3, 12, 19, 21, 22, 23] which take into account the meteo-oceanographic forecasts (for example, wind, waves or currents predictions). Wave action is the major factor that affects the ship performance [13, 14, 15]. Wave field affects the ship motions decreasing the propeller thrust and adding a resistance in comparison to absence of waves. In this case, the effective speed comes by equating the propulsive forces and the resistance forces. In a still water scenario, the ship should overcome the frictional resistance because of the viscosity of the water. When the ship is sailing, the resistance increases because of the deformation of the free water surface. In this case, the added resistance is still governed by the ship hydrodynamics, but complex interactions arise between ships and both waves and currents and wind [9]. Thereafter the vessel's sailing time depends on weather conditions which are random and subject of statistical analysis. The influence of weather on ship speed can be estimated by experimental or theoretical methods. Tank tests and/or theoretical calculations are carried out to analyse the effect of waves on navigation. However, a common alternative approach is to analyse ship voyage data to predict speed loss for a given power or to find out the increase in power to maintain a particular speed. The approximate methods implemented in this study for analysing the wave effect on navigation have the advantage of relying only on key vessel characteristics such as vessel's speed in calm waters (v_0), dead weight tonnage (DWT) and vessel's length between perpendiculars (L_{BP}). These parameters serve to calculate the time saving that the vessel would attain when following the optimized route proposed by the Weather Ship Routing (WSR) software instead of following the minimum distance one under a wide range of meteorological conditions. Vessels operating on schedule often sail at designed speed and need to increase power margin up to 15 - 30% [20] to compensate for rough sea conditions in contrast to calm waters operations. The degradation of the ship performance in a seaway is accounted on the design stage for the application of a "sea margin" onto the total required engine power and a value of 15% is typically used [2]. A more accurate prediction of the added resistance with motions and ship speed loss is essential to evaluate the ship performance and environmental impact under actual weather and operating conditions. On on-going vessels, the degradation of ship performance due to hitting waves could be minimized by choosing an optimized route which would avoid high waves area as proposed in this contribution. The use of WSR can lead to the reduction of external and internal costs. On one hand, avoiding the bad weather conditions using WSR, a reduction of the fuel consumption and the mitigation of carbon emissions can be achieved. [4] introduced a calculation method into a ship routing algorithm to bring into light the impact of applying WSR on short sea shipping routes in terms of pollution mitigation using high-resolution wave numerical products. On the other hand, [11] investigates the economic benefits of using WSR on Short Sea Shipping activities, reaching the 18% of the total external costs under particular bad weather conditions in the navigation area.

The article is structured into the following sections: after the introduction (Section 1), the case study is presented in Section 2, then, the Methodology (Section 3) includes the description of the three calculation methodologies implemented into the software that will provide an optimized route in function of the ocean-meteorological conditions in short distances. The results are presented in Section 4 including the discussion (Section 5) of the assessment of the calculation methodologies to be evaluated with the proposed WSR software. Finally, the conclusions and future developments are underlined in the last section (Section 6).

2. CASE STUDY

The implementation of the optimal weather ship routing case-study using the three existing methods is investigated in a European short sea shipping system: the link between Spanish and Italian ports. The main particulars of the case-study vessel, required for the analysis, are given in Table 1.

Table 1 Case-study vessel particulars

v_0 = 16 knots	L_{BP} = 225 m	DWT = 8000 tons

Three different routes between Spain and Italy are considered in this case study, namely: (1) Barcelona and Porto Vesme route; (2) Málaga and Ajaccio route and (3) Melilla and Ajaccio route. Moreover, a wide range of different weather conditions (from calm weather to waves height up to 8 meters) during the period from November 2018 to June 2019 is also considered. Then, five different cases have been analysed applying the three methodologies (see Table 2).

Table 2 Case-study scenarios

Case No.	Wave height	Route	Date	Design speed (knots)
1	Negligible	Barcelona – Porto Vesme	12/06/2019	16.1
2	8 m	Barcelona – Porto Vesme	09/01/2019	16.1
3	5 to 8 m	Málaga – Ajaccio	23/01/2019	16.1
4	Negligible	Melilla – Ajaccio	25/11/2018	16.1
5	negligible to 8m	Melilla – Ajaccio	02/02/2019	24*

*Due to the high significant wave height, at 16.1 knots the vessel's speed would have been null

The wave predictions used are provided by Puertos del Estado and AEMET (Spanish Meteorological Agency) giving wave field forecasts and variables as significant wave height (Hs), wave direction and wave period twice a day for the Western Mediterranean Sea.

3. METHODOLOGY

This paper focuses on the assessment of three different methodologies in order to validate their appropriateness and accuracy for simulating wave effect on navigation in regular waves and various wave headings. The applied methodology consists on implementing these three existing methods into a ship weather routing system (WRS) named SIMROUTE. The pathfinding algorithms configured in this WRS are the A* Algorithm [6] and Dijkstra Algorithm [8]. Nevertheless, the one used in this contribution is A* due to computational time reduction [7]. This algorithm is applied at gridded scheme where each gridpoint (node) is connected to a set of vicinity points, as described in [10]. To each connection (edge) a weight related with the distance is assigned. The great circle (orthodromic) track is used for the spherical coordinates of the grid nodes. A* searches among all possible paths to the solution (goal) for the one that incurs the smallest cost (least distance travelled, shortest time, etc.), and among these paths it first considers the ones that appear to lead most quickly to the solution. A* is formulated in terms of weighted mesh: starting from a specific node of the mesh, it constructs a tree of paths starting from that node, expanding paths one step at a time, until one of its paths ends at the predetermined goal node. At each iteration of its main loop, A* algorithm needs to determine which of its partial paths to expand into one or more longer paths. It does so based on an estimate of the cost (total weight) still to go to the goal node. Specifically, A* selects the path that minimizes the total cost function $f(n)$:

$$f(n) = g(n) + h(n) \qquad \text{Equation 1}$$

Where:
n is the last node on the path
$g(n)$ is the cost of the path from the start node to n
$h(n)$ is a heuristic that estimates the cost of the cheapest path from n to the goal.

For the algorithm, to find the actual shortest path, the heuristic function must be admissible, meaning that it never overestimates the actual cost to get to the nearest goal node. In this case, the heuristic function is the minimum distance between origin and destination.

Before showing the results, this section presents a cursory look into the three methods implemented on the weather routing software in order to compare and find the discrepancies when using different calculation methodologies on ship routing in terms of time during energetic wave episodes. All the cases have been tested trough the algorithm and for each single case, the period of time, from the initial node to the ending node is calculated by SIMROUTE algorithm. The wave scripts (wave height and direction) have been taken from Puertos del Estado website and they have been introduced into the file.

3.1 Bowditch method

The first method implemented into the weather routing system to analyse the vessel speed reduction due to wave effect is the one proposed by Bowditch [5]. The final speed is computed in function of the non-wave affected speed (v_0) plus a reduction in function of the wave parameters:

$$v(H,\theta) = v_0 - f(\theta) * H^2 \qquad \text{Equation 2}$$

Where,
v_0 is the vessel initial speed without wave effect
H is the significant wave height
f is a parameter in function of the relative ship wave direction (see Table 3)
θ is the angle between the vessel's heading and the wave direction

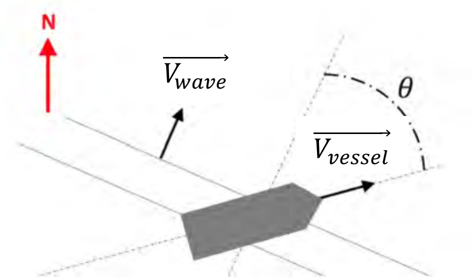


Figure 1 Definition of angle θ

Looking at Equation 2, one can see that the f coefficient has a significant impact on the speed of the vessel. The speed varies depending upon the wave height as well as the wave direction. Then, the Bowditch formula fits in the algorithm and it subtracts the speed of the vessel with the resistance of the wave in terms of height and direction. The values of f coefficient are shown in Table 3.

Table 3 Values of f coefficient

Ship-wave relative direction	Wave direction	f (in kn/ft^2)
0º≤ θ ≤45º	Following seas	0.0083
45º< θ <135º	Beam seas	0.0165
135º≤ θ ≤225º	Head seas	0.0248
225º< θ <270º	Beam seas	0.0165
270º≤ θ ≤360º	Following seas	0.0083

3.2 Aertssen method

The second methodology implemented into the WSR is Aertssen's formula [1]. Unlike Bowditch formula, this one also takes into account the ship's dimensions, in particular, the ship's length [18]. For approximating the speed reduction, Aertssen proposes the following equation:

$$v = v_0 - \left(\frac{m}{L_{BP}} + n\right)\frac{v_0}{100}$$ Equation 3

Where,
v_0 is vessel's design speed in knots and in calm waters
L_{BP} is vessel's length between perpendiculars
m and n are empirical coefficients defined in Table 4.

Table 4 Values *of m and n Aertssen coefficients depending on the wave characteristics (BN= Beaufort number, H_s=significant wave height, W_{speed}=wind speed) [20]*

		α	Head sea (150º-180º)		Bow sea (60º-150º)		Beam sea (30º-60º)		Following sea (0º-30º)	
BN	H_s	W_{speed}	m	n	m	n	m	n	m	n
5	2.5	17-21	900	2	700	2	350	1	100	0
6	4.0	22-27	1300	6	1000	5	500	3	200	1
7	5.5	28-33	2100	11	1400	8	700	5	400	2
8	7.5	34-40	3600	18	2300	12	1000	7	700	3

Source: own (data taken from [20])

The columns of the table contain estimated values of m and n coefficients for waves hitting a vessel at a particular angle. α is an angle off bow with respect to vessel's heading direction measured in degrees. The α parameter is derived by transformation of the mean wave direction (θ) estimate, defined as the mean of all the individual wave directions measured in degrees in a counterclockwise direction from the North [18].

3.3 Khokhlov method

Khokhlov formula (4) is suggested by Lubkovsky [17]. This method takes into account the height and direction of the waves and also the ship's dimensions, in particular, the deadweight of the ship. According to [18], the standard error for this formula does not exceed 0.5 knots. Khokhlov method calculates speed reduction as follows:

$$v = v_0 - (0.745 * H_s - 0.245 * \alpha * H_s) * (1.0 - 1.35 * 10^{-6} * D * v_0)$$ Equation 4

Where:
v is vessel speed in knots with the wave effect
v_0 is the vessel initial speed in knots without wave effect
α is the angle of waves off-bow in radians
D is vessel's deadweight (DWT) in tons
H_s is the significant wave height in meters

Khokhlov method is applicable for vessels with a deadweight range from 4.000 to 20.000 DWT including supply vessels, and design speeds in between 9 and 20 knots.

4. RESULTS

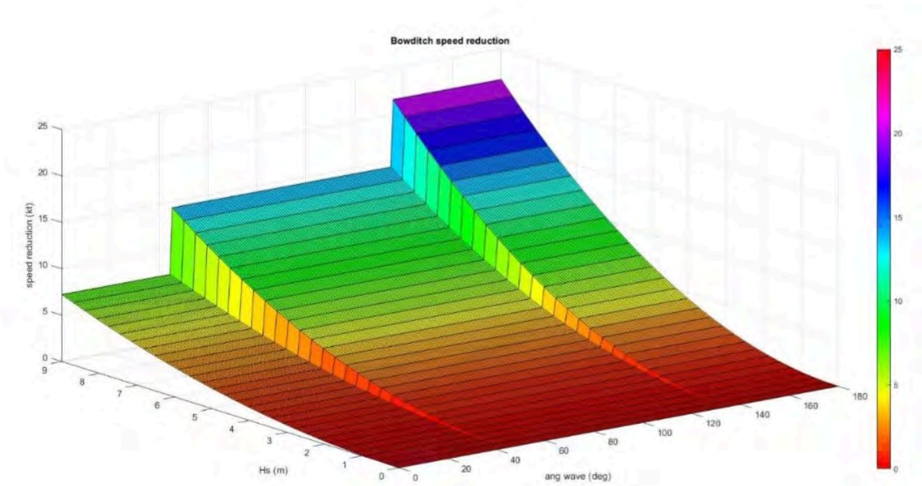
The results of this research have been obtained by implementing the three different speed loss calculation methodologies into the WSR in a particular case-study routes. The influence of wave height and wave hitting angle on the speed reduction has been compared among the three aforementioned formulations. In this section, the results of applying the three after mentioned methods are presented and intercompared.

4.1. Speed loss prediction

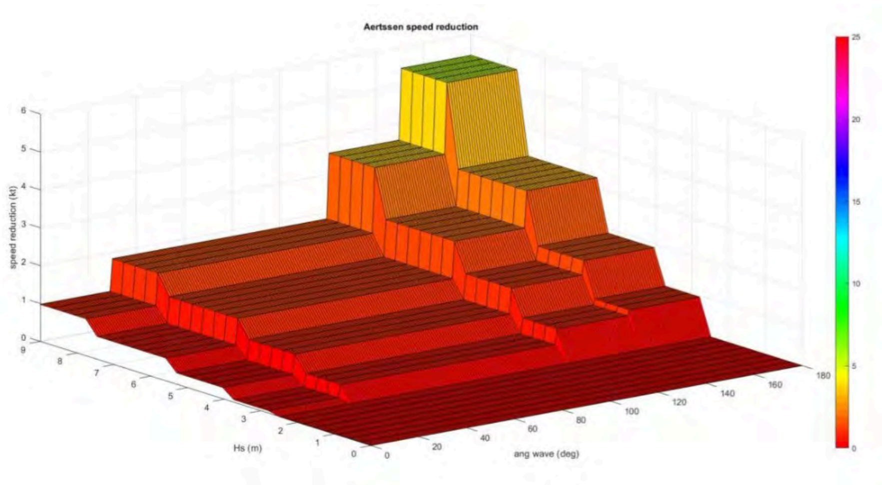
The speed loss is predicted by the proposed methodologies when the vessel faces a wide range of regular waves heights and under different wave direction conditions assuming design speed. These results will be discussed separately in section 5.

In the numerical simulations, a right-handed coordinate system x, y, z is adopted, as shown in Graphs 1, 2 and 3, where the translational displacements in the x, y and z directions are, respectively, significant wave height in meters (Hs), speed reduction in knots (v) and the ship's heading angle with respect to the incident waves in degrees (θ). For following seas, the angle θ equals 0° and for beam seas the angle equals 90°. The colour bar located at the right hand of the graphs shows the vessel's speed reduction into a range between 0 and 25 knots.

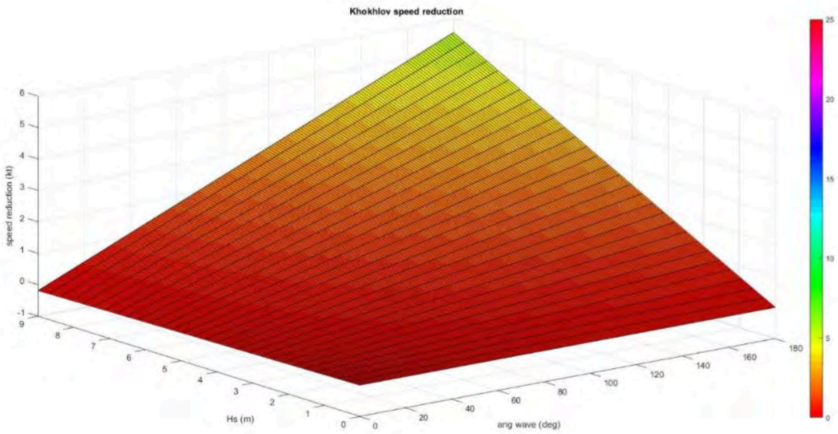
Following graphs show the speed reduction when wave height and hitting angle vary applying Bowditch method (Graph 1), Aertssen method (Graph 2) and finally, Khokhlov method (Graph 3):



Graph 1 Speed reduction related to wave height and hitting angle variation based on Bowditch formulation



Graph 2 Speed reduction related to wave height and hitting angle variation based on Aertssen formulation

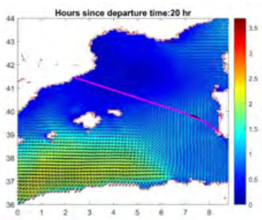
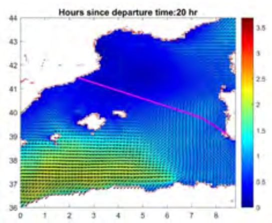
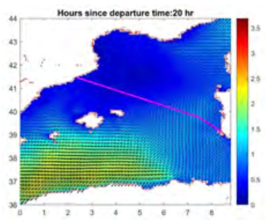
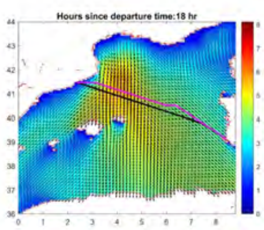
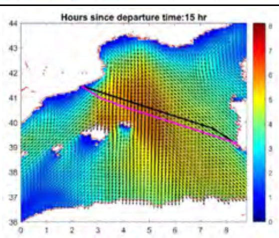
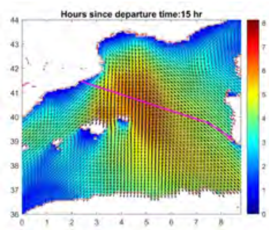
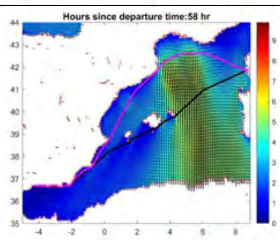
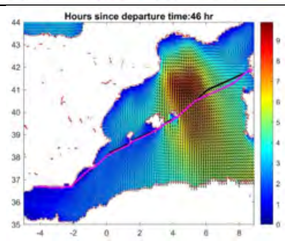
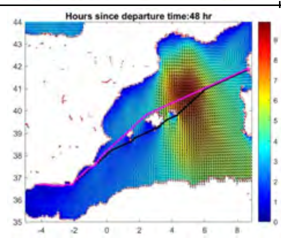


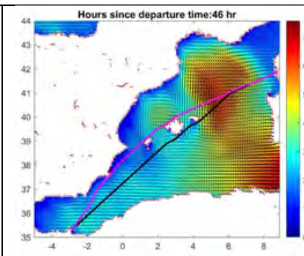
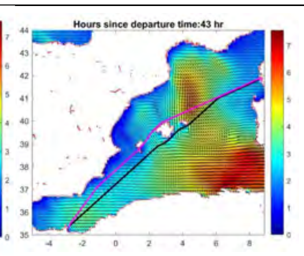
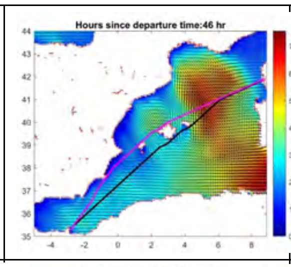
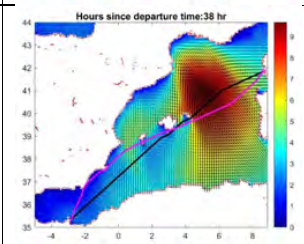
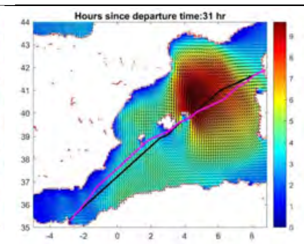
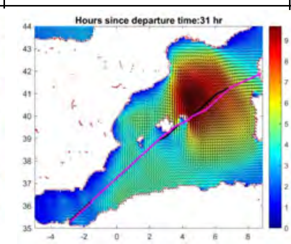
Graph 3 Speed reduction related to wave height and hitting angle variation based on Khokhlov formulation

4.2. Case-study routes results

Figure 2 shows the results of the five cases analysed where the minimum distance route is shown in black and the optimized routed proposed by the software is shown in magenta. The last column of Figure 2 shows the time saved in each case when applying Bowditch (B), Aertssen (A) or Khokhlov (K) formulation.

Figure 2 Results of the case-study routes analysed. The optimal route is plotted in magenta and the minimum distance route is plotted in black. The color bar represents the Hs (in meters) and the black arrows the propagation direction of the waves

Case no.	Bowditch (B)	Aertssen (A)	Khokhlov (K)	Time saving (%)
1				B. 0.03% A. 0.00% K. 0.00%
2				B. 0.60% A. 0.21% K. 0.00%
3				B. 3.14% A. 0.41% K. 0.15%

4				B. 2.46% A. 0.79% K. 0.96%
5				B. 6.58% A.1.12% K. 0.09%

In order to find statistical data derived from running the simulation under different routes where the vessel faced diverse weather conditions, a deeper analysis of 10 vessels' trips with different routes and duration was carried out. The mean time saving percentage when applying Bowditch, Aertssen or Khokhlov formulation is observed in Table 5.

Table 5 Mean time saving percentage

Speed reduction formulation	Time Saving
Bowditch	3.11%
Aertssen	0.65%
Khokhlov	0.29%

5. DISCUSSION

Graphs 1, 2 and 3 show the reduction of speed as function of wave characteristics, the significant wave height and the angle between the vessel's heading and the wave direction. Moreover, Aertssen and Khoklov also include some vessel's particulars as a parameter to be included in the formula. As expected, all methods analysed show the same tend, being the speed reduction of the vessel higher when the significant wave height is higher and the hitting angle comes from 180 degrees. As deducted from above graphs, Aertssen and Khokhlov formula give a similar result of a maximum speed loss of 5.5 knots whereas Bowditch formula attains almost a speed reduction of about 20 knots and reveals that Bowditch method overestimates the speed reduction.

As summarized in Figure 2, if weather conditions are adverse, the time saving increases when choosing the optimized route. Nevertheless, the results differ when applying one formulation or the other. Once again, Aertseen and Khokhlov give similar results and lower values compared with Bowditch formula.

Based on comparison results of the ship speed loss due to waves considering several sea conditions for ship operation, the capability of the developed approach to predict the ship speed loss in realistic sea conditions is unlike depending on the formulation applied. From the estimated results of the ship speed loss due to waves, at low wave height, the output optimum route is the same, however at higher wave heights, which means that the sea condition is getting more severe, the optimum route obtained from applying Bowditch method differs considerably from the other two methods considered. On the one hand, the cases analysed show that when applying Aertssen and Khokhlov formula to the algorithm A*, the results are very similar although Aertssen's time doubles Khokhlov's. However, Bowditch reduction is much more significant than the other two; by almost four times (see Table 5). The reason for this important difference is that routes calculated using Bowditch formulation avoid the zones where the vessel would face higher waves. However, Aertssen method does not consider the vessel's load and the vessel's speed loss is linked to wave height intervals instead of a concrete wave height, fact that can lead to overestimation of speed loss.

6. CONCLUSION

The parametrization of the wave effect on navigation in a weather ship routing system using different formulations, based on the inclusion of the added resistance due to the waves, evidences the relevance of wave effects on navigation and, in particular, the results reveal the influence of ship particulars and wave characteristics. The implementation of Aertssen, Khokhlov and Bowditch formulation shows discrepancies in terms of time during energetic wave episodes, being essential to use the appropriate method in each situation to obtain more realistic results. The case-study shows the rate of time savings may vary from 0.1% to more than 6% depending on the methodology applied. However, out of the three considered methods, Aertssen and Khokhlov ones give very similar results whereas Bowditch shows considerably higher values. This fact may lead to the conclusion that Bowditch approach may be too generalist to be applied to investigate the wave effect on navigation. All statements above point out in one direction, Khokhlov formulation seems to be the most realistic one because it considers the whole range of conditions avoiding an intervallic behaviour of the results. Nevertheless, Aertssen formulation would be a good choice when the L_{BP} data is available. A more accurate prediction of the added resistance with motions and ship speed loss is essential to evaluate the ship performance and environmental impact under actual weather and operating conditions.

For the sake of obtaining realistic results, further research could be carried out considering other methods for obtaining speed loss due to wave effect such as Townsin-Kwon formulae [20], which would possibly approach the results of one of the selected methodologies, facilitating the choice of the most realistic one. Kwon [16] proposed an easy approximate method to predict the involuntary speed loss in irregular waves and wind, taking into account the power output.

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