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MULTI-OBJECTIVE WEATHER ROUTING OF SAILBOATS CONSIDERING WAVE RESISTANCE

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ABSTRACT

The article presents a method to determine the route of a sailing vessel with the aid of deterministic algorithms. The method assumes that the area in which the route is to be determined is limited and the basic input data comprise the wind vector and the speed characteristic of the vessel. Compared to previous works of the authors, the present article additionally takes into account the effect of sea waves with the resultant resistance increase on the vessel speed. This approach brings the proposed model closer to real behaviour of a sailing vessel. The result returned by the method is the sailing route, optimised based on the multi-criteria objective function. Along with the time criterion, this function also takes into account comfort of voyage and the number of performed turns. The developed method has been implemented as simulation application SaillingAssistance and experimentally verified.

Keywords: sailing vessels, weather routing, waves, navigation, resistance

INTRODUCTION

Although practised from very beginning of navigation, only in recent decades planning the vessel's route has been dynamically developed in terms of both applied methods, and implemented algorithms. This has led to the evolution from single criterion optimisation, which usually aimed at determining the fastest route, to modern multi-criteria approach with a set of constraints, also of dynamic nature.

The analysed problem of vessel's route planning belongs to good seamanship standards and is executed, using available methods, on all vessels, regardless of their size or propulsion type. In sea navigation, the International Convention for the Safety of Life at Sea (SOLAS) imposes a formal requirement of route planning for a conventional ship before the start of its voyage. For obvious practical reasons, the route plan refers not only to conventional ships, but to all watercraft: power-driven ships, sailing vessels, small tourist and sport yachts, and other watercraft units, including unmanned vessels. According to International Regulations for Preventing Collisions at Sea (COLREGS), the term "ship" means floating equipment of any type. Depending on the type of voyage and requirements of the ship user, various initial assumptions and tasks to be performed can be formulated, which results in different sequence of items in the voyage plan. For instance, the ship user can be a merchant ship owner, or the captain of a sailing vessel, the team of a sailing yacht taking part in a great ocean race, or the person controlling an unmanned vessel. That is why the shortest possible route is not always the only required result of the use of an optimisation method.

Criteria taken into account when vessel's route planning can also include feeling of comfort (for passenger ships, or recreation yachts), minimal stock consumption (for merchant ships), feeling of safety (for novice sailors), or finding the longest route without repetitions (for devices monitoring a given water region). What should also be taken into consideration is a very important group of criteria referring to various aspects of safety of sailing. In the optimisation task, those criteria can play a role of either objective function or constraint, and cover the issues of avoiding excessive ship rolling and accelerations [7] and other elements specific for a given navigation zone (for instance avoiding excessive rolling of a sailing yacht during recreation navigation). Due to a great variety of requirements expected by people involved in given ship navigation, its priority is selecting a vessel's route which will be optimal from the subjective point of view of its user [23].

Along with subjective requirements of the user, the route also depends on objective factors, such as the type of watercraft and navigation, and the navigation zone. These factors impose some constraints affecting the final shape of the sailing trajectory. For instance, when planning the route in ocean navigation, special attention is paid to limited visibility areas, ice-covered areas, and iceberg occurrence areas, as a result of which so- called meteorological navigation is conducted [1]. It is noteworthy that a key issue in those cases is the assistance of e-navigation systems [21, 27]. During great sailing races, in which of major importance is competition between the racing teams, the abovementioned meteorological aspects are complemented by strategic planning during the race [19] in which different weather scenarios are assumed [18]. For unmanned sailing vessels, the properly selected route may be crucial for correct execution of voyage tasks (such as monitoring, or hydrographic work), avoiding damages and, above all, reaching the assumed reception point by the vessel. For this type of vessels of high importance is to maintain sailing abilities along the entire voyage trajectory [22].

Overall, the vessel's route depends on: voyage priorities and tasks formulated by the user, type of watercraft unit, and water region. The contemporary literature on the subject does not offer solutions to all abovementioned aspects of the problem. Such a solution was only proposed by the authors in [24, 29], where the problem of planning the route for a sailing vessel from starting point to target point in discrete space is solved. In these works, a discrete model of vessel motion and the discrete model of navigation environment are proposed. Also, a method is described to determine the route for a given sailing vessel with given speed parameters. The method takes into account various route optimisation criteria, such as minimal voyage time, maximal feeling of comfort, or minimal number of course changes. Moreover, certain constraints are introduced, such as, for instance, navigable and unnavigable zones, or the maximal course change value. In the proposed model, the navigable zone is represented by a grid of points covering a limited area. At each point of this area, for current hydrometeorological data a temporary, local speed characteristic of the sailing vessel is determined. The present article is continuation of that research, taking into consideration the effect of waves on the vessel speed, omitted in earlier works. For this purpose, the authors propose a method which takes into account the action of waves when determining the vessel speed and, indirectly, its route. The effect of waves has the form of changes introduced to the polar speed characteristic of sailing vessel at each point of the discrete grid representing the navigable zone for given hydrometeorological conditions. All this finally results in significant modification of the shape of the navigable zone as a whole, due to changes of the dead angle of sailing vessel navigation in situation when the vessel experiences additional resistance generated on the hull by sea waves.

RESEARCH METHODS

This Section presents an overview of basic methods used in vessel's route planning (Subsection "*Route planning methods available in literature*"), and then discusses two versions of the method proposed by the authors (Subsections "*Method variant without sea wave effect*" and "*Extended method variant taking into account sea wave effect*").

ROUTE PLANNING METHODS AVAILABLE IN LITERATURE

The applicable route planning methods can be basically divided into deterministic and nondeterministic (Fig. 1.).

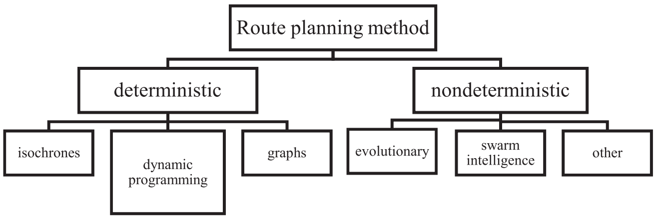


Fig. 1 Division of route planning methods

The deterministic isochrone based method was firstly presented in [5] as the manual graphic method of meteorological navigation. It was then modified and implemented in [1] and [28]. Provided that the isochrones are constant, this method can be considered deterministic. Other methods in this group, which can be found in [2, 10, 12, 13, 25], are based on dynamic programming, in which the route finding process is executed in a recursive manner. The literature also provides descriptions of deterministic graph methods, for instance those based on the modified Dijkstra algorithm [14, 16] or the A* algorithm [15].

The other group comprises nondeterministic methods, which do not guarantee repeatability of the same results for the same input data, nor obtaining the optimal solution in the strict sense. Here, evolutionary methods can be named, including evolutionary and genetic algorithms, in which the solution is iteratively improved in successive generations [23], and methods based on so-called Swarm intelligence (SI), including Ant Colony Optimisation (ACO) [11] or Particle Swarm Optimisation (PSO). Another family in the group of nondeterministic methods comprises evolutionary-probabilistic methods, discussed in [3] for instance.

Inspired by the above methods available in scientific literature, the authors propose a novel method to determine the optimal route for a sailing vessel. The proposed method can be classified as a deterministic multi-criteria graph method. In this sense it is comparable with the method presented in [10], but with a number of substantial differences, including larger number of directions of motion and the effect of sea wave action. These two aspects contribute to obtaining more realistic routes as the solution of the optimisation task executed by the algorithm of the proposed method.

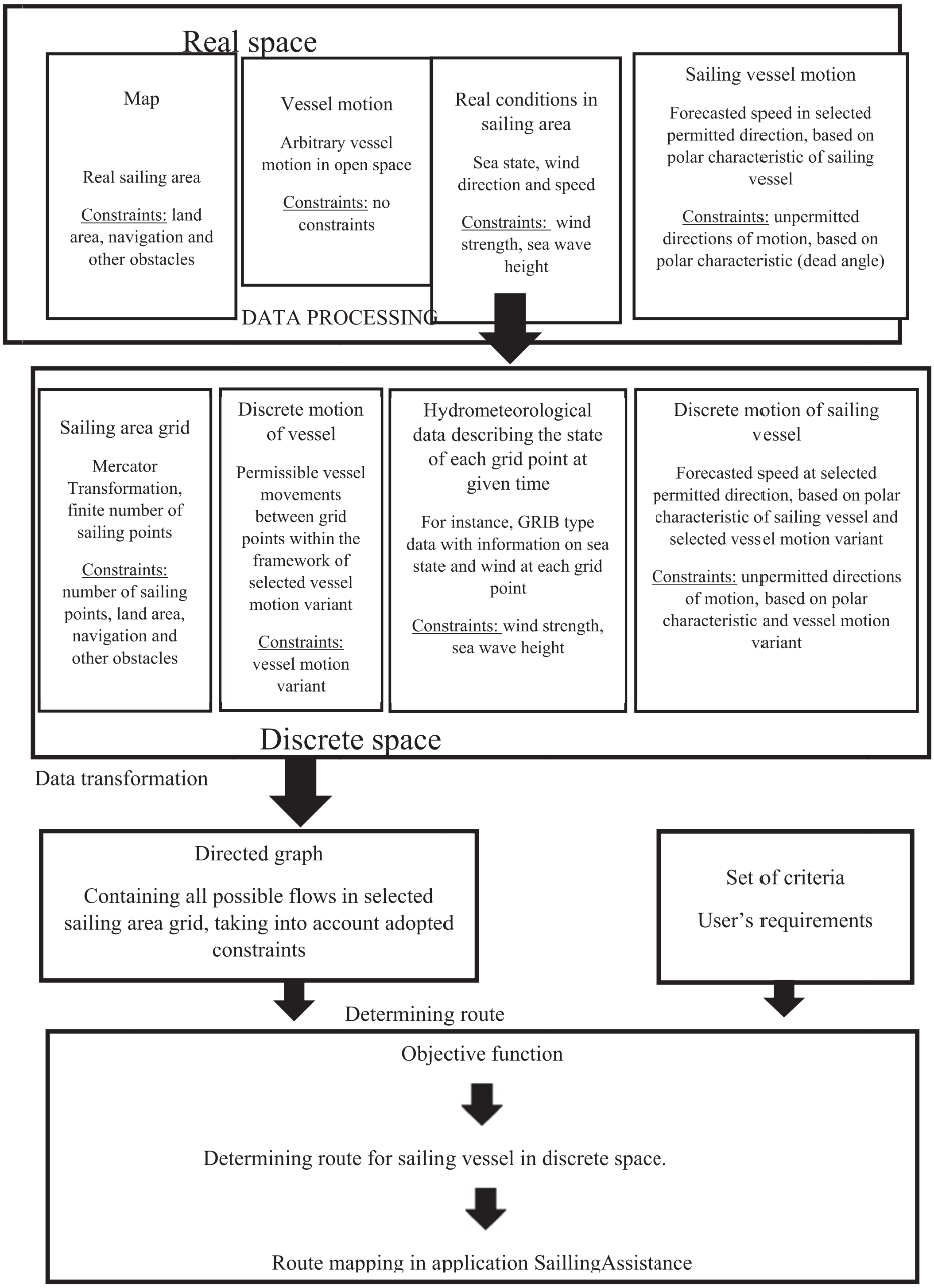


Fig. 2 Scheme of applied methodology

METHOD VARIANT WITHOUT SEA WAVE EFFECT

This method is executed in accordance with the scheme of methodology applied at subsequent research stages (Fig. 2.) The proposed discrete model of sailing vessel motion is an approximate representation of vessel motion in real space. Consequently, the real space is replaced by discrete space – a grid of points of certain resolution. This discrete space is described by the graph G(V,E), where V represents a set of graph vertices – grid points P_{ij}, i.e.

$$V = \{ P_{i,j} ; i = 1,2, \ldots , m . j = 1,2, \ldots , n\} \tag{1}$$

The set of edges E determines possibilities of passing between all vertices in the graph (points P_{ij}). The graph G(V, E) defined in the above way represents all possible routes from distinctive point A to distinctive point B.

Taking into account sailing conditions and parameters of the vessel (including its speed characteristic), the graph G(V, E) is transformed into the weighted graph +G(V, E, S) which is then used for determining the optimal route with the aid of the modified Dijkstra algorithm for the assumed optimisation criteria.

In earlier studies conducted by the authors, the optimisation problem was described with the aid of a multi-criteria objective function which should be minimised.

$$f_g = \sum_{i=1}^{m} [t_i \cdot c(\beta_i)] + \sum_{i=1}^{m-1} [t(|\alpha_{i+1} - \alpha_i|) + p(|\alpha_{i+1} - \alpha_i|)] \tag{2}$$

where:

m – number of all route segments (flows),

i – current route segment (flow)

t_i – time of flowing past *i*-th route segment

$c(\beta_i)$ – discomfort coefficient for *i*-th route segment, depending on ship rolling (value 1 means no feeling of discomfort)

(α_i) – course on i-th route segment,

$t(|\alpha_{i+1} - \alpha_i|)$ – time of course change between route segments,

$p(|\alpha_{i+1} - \alpha_i|)$ – additional coefficient of temporary discomfort, depending on curse change magnitude.

EXTENDED METHOD VARIANT TAKING INTO ACCOUNT SEA WAVE EFFECT

In this variant, sailing conditions are described by the wind vector and, optionally, by wave parameters. The action of these waves can be neglected or taken into account to assess their effect on final result of vessel's route optimisation. Taking into account the sea wave effect as a component of sailing conditions leads to the appearance of new constraints concerning the sailing area. These constraints result from the wave spectrum which affects the vessel motion vector, especially when the vessel course is opposite to the wave approach direction (windward course). It is noteworthy that the polar speed characteristic VPP which is only available on a sailing vessel is determined for calm water, using, for instance, the typical application MaxSurf VPP 30.

In the article, the speed characteristic of the sailing vessel is assessed for a given wave spectrum. To obtain the polar speed characteristic taking into account waves, a model was developed which is executed by the procedure named VppCorr for the purpose of the performed research.

The procedure VppCorr is implementation of the model adopted to determine speed changes of the sailing vessel caused by the presence of waves. When the vessel sails on rough sea, an additional force bearing the name of added resistance is generated on its hull. This added resistance can be determined. In the reported experiments, it was calculated using the code MaxSurf Motion 30. However, a key input variable to this code is the vessel speed, which also depends on the added resistance (i.e. on the final result of modelling with the aid of MaxSurf Motion). That is why an iterative approach was applied to determine the magnitude of total resistance of the vessel sailing on rough sea, which is described further in the article.

Introducing certain technical data of a sailing vessel to the application Bentley MaxSurf VPP we get the following output data: (1) vessel speed diagram, which depends on wind speed (in knots) and wind attack angle (in degrees); (2) hull resistance R_{hull} at given vessel speed V_s. The calculations are performed for calm water and meet the conditions of IMS VPP standards of ORC 31. The hull resistance R_{hull} is determined using the method Delft II [4, 17]. Moreover, an assumption is made that the sail propeller generating the effective thrust $Thrust_{calm}$ on calm water is equivalent to hull resistance R_{hull} . Here, the effective propeller thrust is understood as the thrust deducted by losses resulting from propeller/hull cooperation. In the analysis, the term of effective thrust can be replaced by total efficiency, used in screw propeller analyses and defined by the ratio of effective towing power to power delivered by the engine. This way, total efficiency takes into account hull efficiency, including thrust deduction factor and wake coefficient, efficiency of isolated propeller, rotating efficiency, and shafting efficiency. However, for sail propulsion the term of total efficiency is not well grounded in the literature, that is why the approach based on balance of forces (term: "effective propeller thrust") is applied instead of energy related approach which makes use of efficiency terms. The effective propeller thrust takes into account factors which affect total efficiency on a sailing vessel.

Based on the grid of results obtained using the application Maxsurf VPP, the diagram of vessel speed Vs is approximated by the fifth-order polynomial taking into account wind speed Vw and wind direction angle βTW with respect to the vessel.

$$V_s = \sum_{i=1}^{5} p_i \, V_w^i \beta_{TW}^{5-i} \tag{3}$$

where:

p_i –coefficients of polynomial

The above diagram-to-polynomial transformation, being in fact construction of a meta-model, is shown in Fig. 3. Here, the surface on the diagram is described by the fifth-order polynomial, while black points represent data calculated by the application Maxsurf VPP.

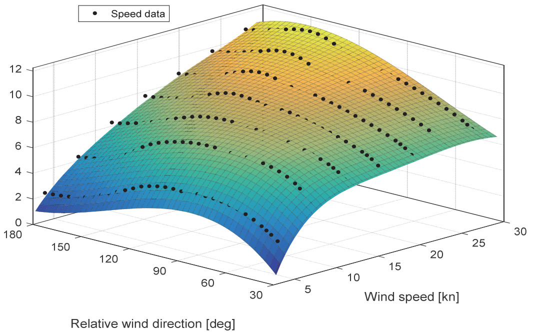


Fig. 3 Surface visualisation of VPP calm water speed meta-model using fifth-order polynomial. Points represent data from application Maxsurf VPP

The hull resistance on calm water is approximated by the fifth-order polynomial depending on the vessel speed Vs. As the forces are in balance during vessel motion with constant speed, at the present stage this resistance is equated with effective propeller thrust force Thrustcalm.

$$Thrust_{calm} = \sum_{i=1}^{5} p_i V_s^i \qquad (4)$$

where:
p_i – coefficients of polynomial

Then, making use of the method based on widely used strip theory, described in [20] and applied in the application MaxSurf Motion, the added hull resistance resulting from sea waves is calculated. Here, an assumption is made that the total hull resistance is given by the formula:

$$R_T = R_{hull} + \Delta R \qquad (5)$$

The additional resistance ΔR obtained from MaxSurf Motion is approximated by the third-order polynomial, depending on wind speed V_w and wind direction angle β_{TW} with respect to the vessel.

$$\Delta R = \sum_{i=1}^{3} p_i V_w^i \beta_{TW}^{3-i} \qquad (6)$$

The quality of modelling can be assessed based on the visualisation in Fig. 4, which shows the convergence between the polynomial surface and points representing the results obtained from the application.

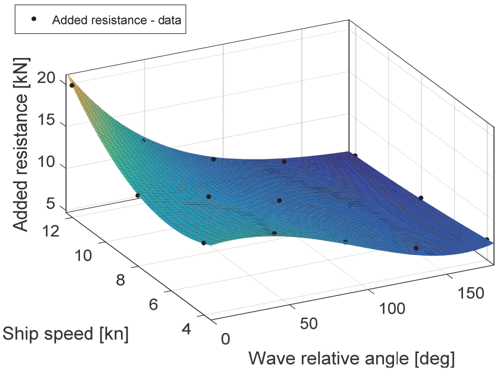


Fig. 4 Visualisation of added resistance meta-model (third-order polynomial)

In the next step, the balance of forces is calculated, from which the effective propeller thrust $Thrust_{corr}$ deducted by the added resistance ΔR is obtained according to the formula:

$$Thrust_{corr} = Thrust_{calm} - \Delta R \qquad (7)$$

Then, for the corrected propeller thrust $Thrust_{corr}$ new vessel speed V_{scorr} is read from the initial VPP, i.e. for calm water. This relation is described in polynomial form:

$$V_{scorr} = \frac{\sum_{i=0}^{3} p_{i+1} Thrust_{corr}^{i}}{\sum_{i=0}^{3} q_{i+1} Thrust_{corr}^{i}} \qquad (8)$$

As the final step, the added resistance ΔR_{corr} is recalculated using the corrected speed V_{scorr}. Then, the propeller thrust $Thrust_{calm}$ is deducted by new added resistance ΔR_{corr} and the corrected speed V_{scorr} is calculated. As a result of this iterative procedure, the speed V_s of the sailing vessel is determined for specific wave spectrum.

RESULTS

The developed method was implemented in the application SailingAssistance, which was used in numerical experiments comparing the method variants taking into account and neglecting the effect of sea waves. In both variants, the same starting and final positions were assumed. The algorithm searching for the optimal route minimises the objective function (Equation 2).

All these routes were determined for a sailing vessel characterised by technical parameters given in Table 1.

Tab. 1 Technical data of sailing vessel used in experiments

Name of parameter	Value	Unit
Displacement	6,531	t
Volume (displaced)	6,372	m^3
Draft Amidships	2,475	m
Immersed depth	3,054	m
WL Length	10,636	m
Beam max extents on WL	2,866	m

Wetted Area	29,911	m^2
Max sect. area	1,213	m^2
Waterplane Area	21,243	m^2
Foresails		
I	16.605	m
J	4.489	m
LP	7,602	m
SPL	4.871	m
SL	16.002	m
SMW	8.778	m
Mainsail		
P	14.783	m
E	4.203	m
MGU	1.554	m
MGM	2.743	m
BAS	2.102	m
Mast		
MDT1	0.116	m
MDL1	0.213	m
MDT2	0.116	m
MDL2	0.152	m
HBI	1.126	m
TL	2.262	m

where:

I - height from the sheer line to the top of the foretriangle,
J - distance from the headstay base to the front of the mast,
LP - jib clew to the luff taken perpendicular to the luff,
SPL - spinnaker pole length,
SL - spinnaker luff length,
SMW - spinnaker maximum width,
P - mainsail luff length from lower to upper band on the mast,
E - mainsail foot length from the mast to the boom band,
MGU/MGM - upper and middle girth dimensions of the mainsail,
BAS - height of the lower mainsail luff band above the sheer line,
MDT 1/MDL 1 - athwartships measurement and fore and aft dimension of the mast near the deck (below any taper),
MDT 2/MDL 2 - the same measurements as above taken at the upper mainsail band. If there is no mast taper, the upper and lower dimensions will match and the TL will be zero,
HBI - freeboard at the base of the mast,
TL - taper length of the mast.

During the tests, the same sailing conditions were assumed for all routes. The wind speed in the sailing area ranged from 9 m/s to 12 m/s, and its direction was: NE – E. The wave spectrum assumed for these conditions is given in Table 2

Tab. 2 Wave spectrum during performed tests

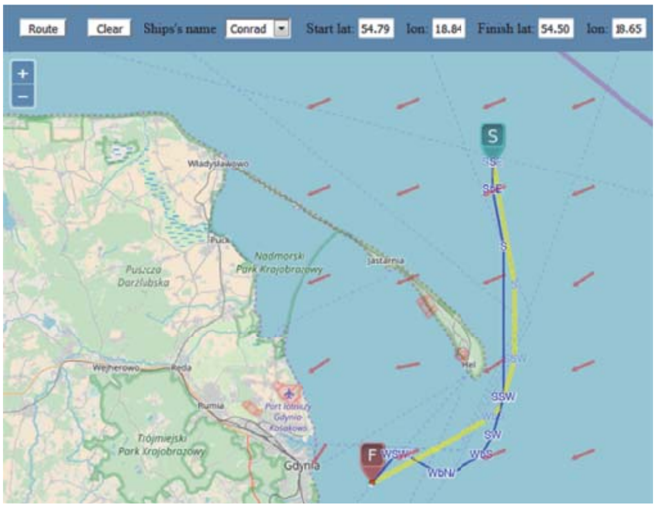
Spectrum Type	Char. height [m]	Modal period [s]	Average period [s]	Zero crossing period [s]
DNV	1,23	5,797	4,991	4,724

Routes 1 and 3, marked blue in Fig. 5 and Fig. 6, neglect the effect of sea waves, while routes 2 and 4, marked yellow, take it into account. They are characterised by numerical results given in Table 3.

Tab. 3 Comparison of method variants. Results obtained from simulation application SaillingAssitance

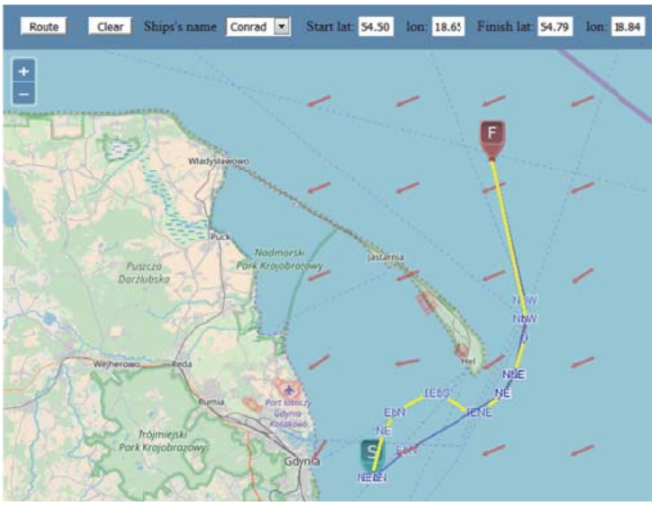
Route	1	2	3	4
Takes into account sea waves	No	Yes	No	Yes
Initial position "S"	54.79° N 018. 84° E	54.79 ° N 018. 84° E	54.50° N 018.65° E	54.79° N 018. 84° E
Final position "F"	54.50° N 018.65° E	54.50° N 018.65° E	54.50° N 018.65° E	54.79° N 018.84° E
Total length of route [Nm]	23.5	24.1	21.7	26.7
Time of route passing [min]	128	124	142	223
No of course changes	7	8	5	10

The obtained results of the research allow us to assess the extent to which taking into account sea waves (routes 2 and 4 in Table 3), as compared to planning which neglects this effect (routes 1 and 3 in Table 3), affects the planned route when determining it with the aid of the developed method. In the light of Fig. 5 and Fig. 6 it should be concluded that this effect is significant. The tests were performed for a sailing vessel of about 10 m in total length. Simultaneously, relatively strong wind was assumed, of about 5B, and corresponding high wave. For such a small watercraft unit, especially when it sails by the wind in the assumed conditions, the observed time of voyage along the examined route is extended by more than half when taking into account sea waves – routes 3 and 4. On the other hand, when the ship sails downwind the additional required time is shorter when taking into account sea waves – routes 1 and 2. An attempt to explain this result may refer to the trochoidal theory of waves and circular motion of water particles described by it. A vessel with relatively shallow draught increases its speed over the seabed when sailing with local surface current generated by waves, and decreases when sailing against the waves. Of some importance is also the generation of a large local water uplift at vessel's bow when it crosses successive wave crests.



Ships's name: Conrad
Start lat: 54.79
lon: 18.84
Finish lat: 54.50
lon: 18.65

Fig. 5 . Route 1 (marked blue) neglects sea waves, while route 2 (marked yellow) takes into account the sea state.



Ships's name: Conrad
Start lat: 54.50
lon: 18.65
Finish lat: 54.79
lon: 18.84

Fig. 6. Route 3 (marked blue) neglects sea waves, while route 4 (marked yellow) takes into account the sea state.

It is also noteworthy in Fig. 5 and Fig. 6 that the sailing vessel routes which take into account sea waves coincide with those neglecting this effect only at starting and final positions.

DISCUSSION

The presented method to determine the optimal route for a sailing vessel takes into account an important aspect, which is the change of polar speed characteristic generated by the wave field in the area of navigation. The performed research has revealed unmistakably that ignoring the effect of waves leads to determining routes which significantly differ from optimal, with respect to both time, and the aggregated cost criterion represented by the objective function. This conclusion is essential from the point of view of a typical method to determine and present to the user the speed characteristic in the form of a diagram in which this speed depends only on the wind speed and the sailing vessel course with respect to the wind. This approach can be misleading, especially for inexperienced sailors who intuitively may think that the sea waves decelerate, to some extent, the sailing vessel, but the assumed target can still be successfully reached when sailing along a similar route as that for light wave field, with smaller speed being the only difference. The truth is, however, that neglecting sea waves may lead to determining the route which will be much more difficult or – in an extreme case – impossible for practical execution.

CONCLUSIONS

The results of the performed research have revealed that far-reaching modification of the speed characteristic in the rough water region not only extends the time of voyage but also, above all, may require another route planning, as the sailing vessel has much greater dead angle in heavy waves. This observation is of high importance from the practical point of view. In particular, the assumed target point, for instance the port of refuge, may be hardly available by the vessel after worsening of hydrometeorological conditions, especially when the vessel sails upwind. If the captain makes an attempt to sail in close hauled point of sail, the increased dead angle resulting from the modified polar speed characteristic can even make reaching the target impossible, which will lead to hazardous navigation situation. In those circumstances, the use of the method proposed in the article will allow the captain to plan a feasible route, which may be related, for instance, with choosing another port of refuge. Even if that port is situated farther than the initial option, real possibility to reach it is undoubtedly much safer for the vessel and its crew than failing to reach a closer target, but situated in the unfavourable sector from the point of view of upwind course.

In the presented method, one selected wave spectrum was considered which was specific for the adopted meteorological conditions. A planned direction of further method development assumes taking into account mixed wave structures comprising wave systems of different height and frequency. Another significant direction is including the stability related vessel motion dynamics on waves to the optimisation algorithm. The vessel motion on waves can provoke dangerous phenomena, such as resonance rolling, or so-called broaching. In particular, resonance amplification of ship rolling is the effect which significantly affects the safety of navigation [9]. Most recent works on vessel's route optimisation already take into account dynamic conditions of resonance avoidance [6]. However, those works do not refer to sailing vessels and do not analyse their specificity of rolling damping, which significantly differs from that of power-driven ships. Neglecting this phenomenon may lead to annihilation of optimisation results, as rapid increase of rolling amplitude is in contrast to objective function criteria concerning the comfort of navigation. Further method development will also include extending the range of phenomena which are modelled and taken into account in optimisation, with particular attention focused on nonlinearities in the description of ship stability characteristics, as, according to recent literature on the subject, these nonlinearities are essential for determining the configuration of ship course and speed to avoid dangerous dynamic phenomena [26, 8]. The results of past research, along with observation of possibilities to introduce new objective functions and constraints to the developed method, indicate that the planned development directions will bring the route optimisation results closer to real conditions of sailing.

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