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Route Optimization Algorithm for Minimum Fuel Consumption of Wind-assisted Ship

Zhang Yingjun, Li Yuankui and Yang Xuefeng
Navigation College of Dalian Maritime University, Dalian, China

Abstract: Wind-assisted ship is an effective way for energy-saving and emission reduction and by the using of ocean winds effectively, it is very useful for transoceanic crossings to cut down fuel costs, this study focuses on route optimization to minimize the fuel consumption of wind-assisted ships. Firstly, by the analysis of monthly means speed of ocean winds, it was found that the wind-assisted propulsive efficiency was high as auxiliary power. Secondly, the ship route was discretized to a series of waypoints which can be considered small deviations to generate a new route and the “minimum fuel consumption” was taken as optimization objective, then the optimization model was built based on ship motion equations. Thirdly, based on the simulated annealing algorithm, the optimal route searching strategy was designed and the model was solved. At last, a 76, 000 DWT wind-assisted cargo ship was taken as the experimental ship and the optimization algorithm was simulated and verified by an optimized wind-assisted route. As the simulation shows, the optimization effect is satisfactory, so the route optimization algorithm designed in this paper can be applied to the solving of path planning problem of wind-assisted ship and thus provides theoretical guidance to further study on wind-assisted projects.

Key words: Wind-assisted ship, ocean wind field, route optimization, minimum fuel consumption

INTRODUCTION

Route optimal problem belongs to the researching of weather routing in some extents and the route optimization is the key technology of weather routing (Bowditch, 2002). Ship weather routing develops an optimum track for ocean voyages based on forecasts of weather, sea conditions and a ship’s individual characteristics for a particular transit. Within specified limits of weather and sea conditions, the term optimum is used to mean maximum safety and crew comfort, minimum fuel consumption, minimum time underway, or any desired combination of these factors (Hanssen and James, 1960; Journee and Meijers, 1980; Bottner, 2007; Tsujimoto *et al*., 2009). In this study, the minimum fuel consumption is taken as optimization objection.

Research on the wind-assisted ship has a long time history which can go back to 1970s, then from the 1990s to early 2000s, the shipping industry was developing to its peak and its main goal was to travel faster and faster to carry more cargoes in limit time, which leaded to the very slow development of wind-assisted ship. But with the call for global energy-saving and emission-reduction strategies and the declining of shipping industry in the last decade, the renascence of wind-assisted ship has become one of the effective way to solve above problems. Current ship routing optimization study mainly focus on the traditional ship or sailboat (Hagiwara and Spaans, 1987), on wind-assisted ship, there is little research available.

Weather route or optimum route for traditional ship is the term that deviate ship route to avoid adverse environmental factors, which is just “avoiding” (Delitala *et al*., 2010), while wind-assisted ship is searching advantageous factors for stronger wind-assisted propulsion and the heuristic algorithm may be used here. Meanwhile, the rapid growth in knowledge on atmospheric and hydrospheric processes since the second half of the twentieth centuryCsupported largely by the dramatic improvements in computer technology-has provided meteorologists with sophisticated operational tools that facilitate increasingly accurate climate analyses and weather forecasting (Kleywegt *et al*., 2004; Engineer *et al*., 2011; Cabrera-Gamez *et al*., 2013). But the higher time or space resolutions means the bigger searching space and the exponential growth of solution size, which will lead to the traditional model and solution for ship route optimum become invalid (Lee *et al*., 2002; Christiansen *et al*., 2004). Fortunately, the intelligent optimization algorithms provide a new way to route optimum. In this paper, the optimization problem is abstracted to mathematical model and the optimal routing model for minimum fuel consumption of wind-assisted ship is built.

Corresponding Author: Zhang Yingjun, Navigation College of Dalian Maritime University, Dalian, China

ROUTE OPTIMAL MODEL

Analysis of wind speed characteristics: The wind field data used in this study provided by UCAR (University Corporation for Atmospheric Research) from SCOW (Scattermeter Climatology of Ocean Winds) dataset, which is monthly means grid data of 10 year record (September 1999-October 2009), its detailed coverage information is: 0.25×0.25°, 0.125-359.875° E and 69.875°S to 69.875°N (1440×560) Longitude/Latitude. The wind grids on land is set to-9999 to ensure the integrity of data structure (Risien and Chelton, 2008), which can be used to locate wind grids only by the using of column and row index values.

For wind-assisted ship, when the wind speed is higher, the propulsion effect is stronger but from navigation safety aspect, although the wind resisting capacity of modern ships are more than force seven (13.9-17.9 m sec^{-1}) but the high speed wind may bring the strong currents and rough seas which will make trouble to ship maneuvering. So, when the wind speeds are nearly 9 m sec^{-1}, it is the ideal condition for wind-assisted ship to use as auxiliary power. As seen in Fig. 1, the speed statistics curves for ocean wind grids in May, June, September and December are plotted, the ocean winds with speed 7-10 m sec^{-1} are mostly up to 50% of the total ocean wind grids and the wind speeds and directions of winds in one relatively large sea area have little differences (Li *et al*., 2010), which brings great advantage to provide wind-assisted propulsion.

Minimum fuel consumption route design: The main idea of wind-assisted ship route optimization is that the ship looks for "better winds" by moderate deviation if condition permits, such as shipping date, limited navigation areas. By this way, the total voyage distance is added but the fuel consumption is reduced because of the increasing of wind-assisted propulsion. Figure 2 shows the different wind-assisted propulsions according to different wind speeds and angles on the condition of fixed ship speed, the source data is from literature (Ren, 2012). The curves present similar normal distribution characters when the wind angles are changing form 0-180° and the peak values are gained nearly 110°. As the wind speed is rising, the wind-assisted propulsions become stronger and stronger and present severer changing with different wind angles. Thus, as auxiliary power for wind-assisted ships, ocean winds with different speeds and angles have great differences in wind-assisted propulsions, so the route for traditional ship is no longer suit for wind-assisted ship and further has excellent optimized space to improve wind utilization to reduce emissions and save energy and improve shipping efficiency finally.

For ships, when equipped with wind-assisted propulsions, the ocean winds can provide additional thrusts, not just speed-loss effect and ship power source is increased: main engine and ocean wind. So, the wind-assisted ship sails in a combination thrust of engine and winds (Ren, 2012). When changes the waypoints, the voyage distances and courses and the navigation area change followed, so the ocean winds are different. The changing of ship speed, course and ocean winds will directly influence the effects of ocean winds on wind-assisted ships. Figure 2 shows the different wind-assisted thrust presses in different wind speeds and angles and Fig. 3 shows the ship resistances in different wind velocities and ship speeds. Cost function is used to estimate how these differences will influence the shipping efficiency or benefits.

For different optimization objective, the cost functions are different. In this study, the research goal is that, on the condition of guaranteeing the shipping date with fixed ship speed, to rise the wind-assisted propulsion and reduce main engine output and ultimately, to cut down fuel consumption mostly.

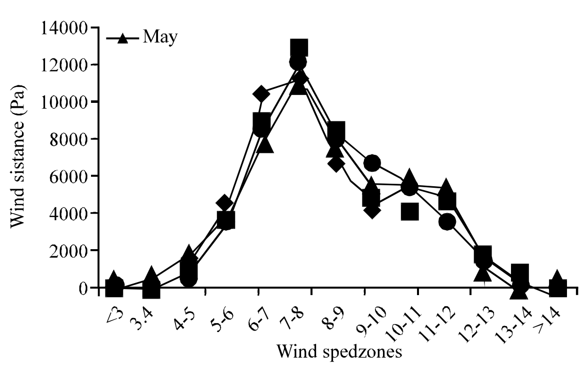

Fig. 1: Statistics curves of monthly means speed

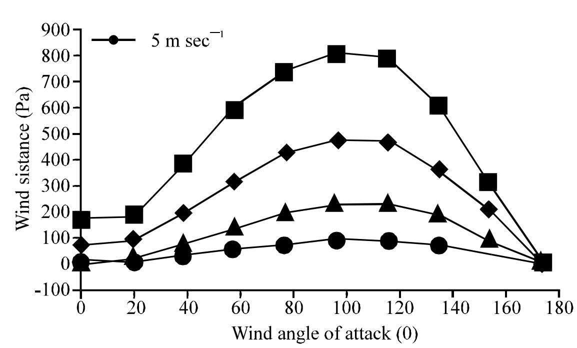

Fig. 2: Wind-assisted thrust press curves

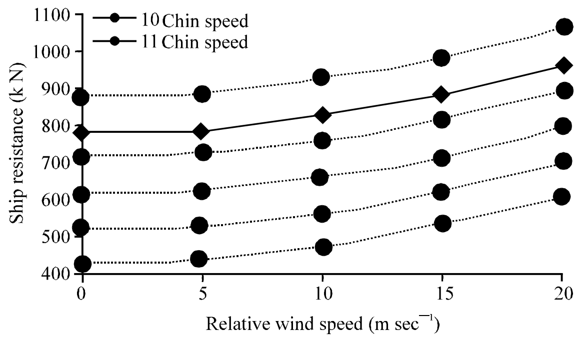

Fig. 3: Resistances curves of wind-assisted ship

Cost function: When ship sails in fixed speed, according to Newton's First Law, the following equation is got:

$$R = T_e + T_w \quad (1)$$

where, R is the ship resistance, T_e is the engine thrust, T_w is the wind-assisted thrust.

The ship resistances includes calm water resistance, rough sea resistance and air resistance (also called wind resistance). In this study, rough sea resistance is ignored to simply calculation and only calm water resistance and air resistance is considered. By consulting the previous researches, the ship resistance R is an increasing value of ship speed V_s and relative wind speed V_w, as the Fig. 3 has shown, the source data is from literature (Ren, 2012).

The wind-assisted propulsion T_w is determined by the performance of wind-assisted equipment, ship course, wind speed and angle. In this study, ship speed is fixed to a certain value to guarantee the shipping date, so the improvement of T_w is improved only by doing some deviations which will change the relative wind speeds and angles according to the different ship courses and navigation sea areas. When experimental ship sails full load with speed of 13.6 kn (7 m sec^{-1}), the simulation of wind-assisted propulsion press curves for various relative wind angles and speeds are plotted in Error! Reference source not found.

Wind-assisted propulsion T_w can be calculated with Eq. 2:

$$T_w = \eta_w, P_w, S_w \quad (2)$$

η_w = Coefficient of wind-assisted propulsion efficiency, generally assigned with 0.5
P_w = Wind-assisted propulsion press as shows in Fig. 2
S_w = Pressure area of wind on wind-assisted equipment

So, in order to get stronger wind-assisted propulsion, the ship course should be changed to adjust relative wind angles and speed and make the wind-assisted propulsion presses close to its peaks.

Work needed in whole voyage is defined as W_R, while work provided by ocean wind is W_w, the formula for them is listed:

$$\begin{cases} W_R = \sum_{i=1}^{N-1} R_i, S_i \\ W_w = \sum_{i=1}^{N-1} (T_w)_i, S_i \end{cases} \quad (3)$$

So, the work provided by main engine in the whole voyage is:

$$W_e = W_R - W_w = \sum_{i=1}^{N-1} \left(R_i - (T_w)_i\right), S_i \quad (4)$$

The total fuel consumption in the whole voyage is proportional to the work provide by main engine, so the cost function for minimum fuel consumption can be described as:

$$\begin{cases} f = \sum_{i=1}^{N-1} \left(R_i - (T_w)_i\right), S_i \\ t \le SD \end{cases} \quad (5)$$

where, $t \le SD$ is the constraint condition, which means the voyage time t is subject to fixed shipping date. N is the number of waypoints, S_t is the distance of rhumb line between each two succession waypoints, the total distance of the voyage is:

$$S = \sum_{i=1}^{N-1} S_i$$

ALGORITHM DESIGN

This algorithm refers to calculation for ship courses, distances and wind grids extracted in rhumb lines. Based on above analysis for ship motion and objective function, the algorithm for wind-assisted route optimization will solve by the using of intelligence algorithm.

Integral design: The flowchart of algorithm implementation is shown in Fig. 4, the route is broken up to series of joint rhumb lines by waypoints. Then the courses and distances of each rhumb line are calculated and wind speeds and angles around ship route are also obtained here, based on them the wind-assisted propulsions and resistances are derived using Eq. 1 and 2. At last, as the fixed ship speed, the total distance S is key constraint condition for limited voyage time and optimization objective:

$$E = f\,(T_w, R, S) \qquad (6)$$

can be defined and estimated. Simulated annealing is used here by adjusting algorithm parameter to make the searching results converge fast. In Error! Reference source not found., T is the variable of temperature in simulated annealing and T_f is final temperature which is also called stopping criterion of the algorithm.

Simulated annealing for route optimization: Simulated Annealing (SA) is motivated by an analogy to annealing in solids, it simulated the cooling of material in a heat bath which is the process known as annealing. If you heat a solid past melting point and then cool it, the structural properties of the solid depend on the rate of cooling (Dowsland and Thompson, 2012). If the liquid is cooled slowly enough, large crystals will be formed. However, if the liquid is cooled quickly (quenched) the crystals will contain imperfections. Metropolis's algorithm simulated the material as a system of particles. The algorithm simulates the cooling process by gradually lowering the temperature of the system until it converges to a steady, frozen state.

To make the algorithm converge to global optimal value, the parameters of simulated annealing may satisfy the following conditions:

- **The initial temperature:** T_0 is hot enough to allow a move to almost any neighborhood states
- **Iterations:** At each temperature are many enough, which are also called Markov chains L_k, so that the system stabilizes at that temperature
- **Final temperate:** T_f is suitably low
- **Temperature decrement:** Is slow enough an alternative is geometric decrement, $T_{i+1} = \alpha T_i$ $(0 \le \alpha < 1)$ which will be used in this research

Experience has shown that the above conditions can't be satisfied simultaneously, so in practice, the parameters may be assigned after analysis of solution space and other actual factors. In the experiment, takes the parameters as:

$$T_0 = 1000,\ \alpha = 0.9,\ T_f = 10,\ L_k = 2000$$

The simulated annealing for wind-assisted ship route optimal is described as following:

- Take the great circle between departure and destination points as initial route which also called initial solution x_0 in algorithm. Calculate the voyage distance and time of the great circle and the number of waypoints can be obtained, then the initial solution can be defined as $x_0 = \{P_0, P_1, P_2, \ldots, P_N\}$, where P (Lat, Lan) is one waypoint
- Let $T = T_0$ as the initial temperature and the initial objection function value $E\,(x_0) = f\,(T_{w0}, R_0, S_0)$
- Make cooling list $T_{i+1} = \alpha T_i$, let current temperature T is equal to the next value in cooling list
- Choose a random n, where $0<n<N$ and generate two small n-dimensional changing vectors Lat_Lat_delta and Lon_delta, where Lat_delta∊[-1, 1], Lon_delta∊[-1, 1]. Randomly selecte n points from waypoints set $\{P_0, P_1, P_2, \ldots, P_N\}$ of solution x_i and change them with Lat_delta and Lon_delta to generate a new solution x_j. Then the objection function value $E\,(x_j)$ can be calculated
- Calculate the objective function difference between x_j and x_i: $\Delta E = E\,(x_j)-E\,(x_i)$. If $\Delta E<0$, solution x_j is accepted to optimal solution and regarded as current solution to take place of x_i, else the x_j is regarded as current solution with the probability of $\exp\,(-\Delta E/T_i)$. Where, T_j is current temperature
- At each temperature T_i, step 4 and 5 are iterated L_k times
- Judge whether T is lesser than T_f, yes to terminate the algorithm, while no to goto step (3)

Accepting of a worse solution, which is also coincidence with principle of ship route optimization. In one searching procedure, when a new solution x_j is generated from x_i and its cost function value $E\,(x_j)>E\,(x_i)$, traditionally, it must be abandoned but when the solution x_k is generated from x_j and its cost function value even lesser than value of $E\,(x_i)$, which means $E\,(x_k)<E\,(x_i)< E\,(x_j)$. This illustrates that the solution x_k is better than x_i and when we abandon x_j directly, the x_k will be missed. So, without accepting the worse solution, the rout optimization algorithm will be failure to find the actual best solution called global optimum, instead a pseudo best solution called local optimum will obtained finally.

The probability of accepting a worse move is a function of both the temperature of the system and the difference in the cost function. It can be appreciated that as the temperature of the system decreases the probability of accepting a worse move is decreased. When the

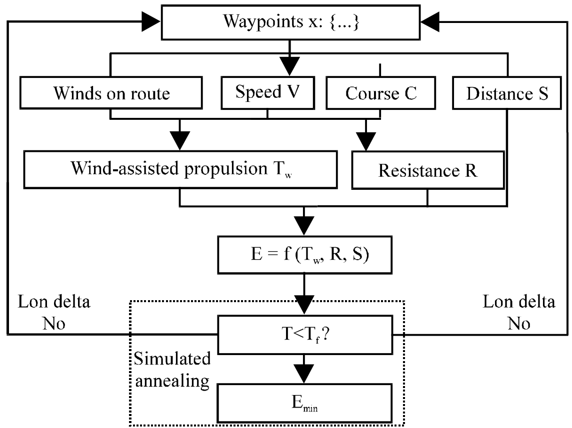

Fig. 4: Flowchart of algorithm implementation

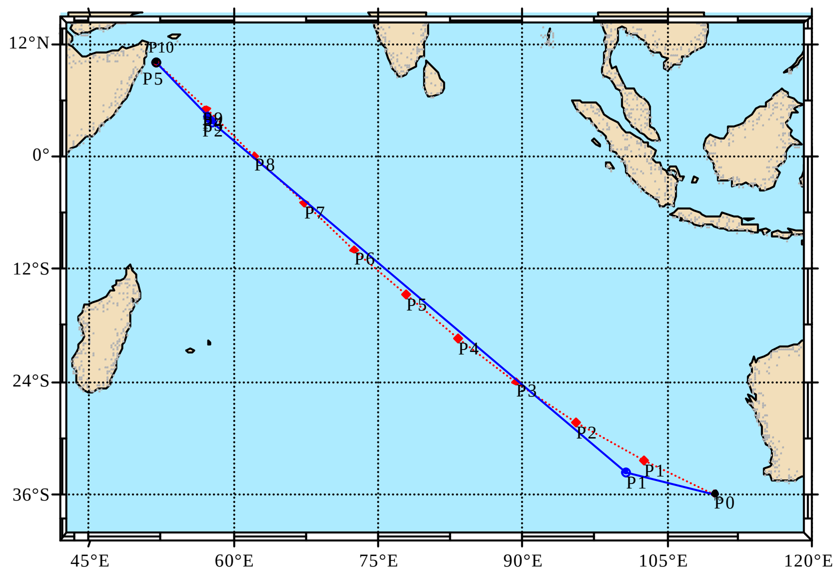

Fig. 5: Simulation of optimal route of wind-assisted ship

temperature of system is high, the algorithm can search big solution space to avoid plunging into a local optimal solution, then when temperature is low, the algorithm can search in small solution space. By this way, the wide scope searching is achieved as temperature is high and the global optimum solution can be found in a small space when temperature is low. This is the same as gradually moving to a frozen state in physical annealing. Also note, that if the temperature is zero then only better moves will be accepted which effectively makes simulated annealing act like hill climbing.

SIMULATION AND NUMERICAL RESULTS

A 76, 000 DWT wind-assisted cargo ship was taken as the experimental ship and monthly mean wind data of June as experimental data. In the experiment, the optimal route is calculated form departure point (36°S, 110°E) to the destination point (10°N, 52°E) and the initial route is the great circle between them. Take the "minimum fuel consumption" as optimization objective, the algorithm is programmed with Matlab, the result is plotted in Fig. 5. The red dotted line is initial route, while blue solid line is optimal for minimum fuel consumption route of wind-assisted ship in June.

Because of the characteristics of the intelligence algorithm, generally the solution it found is just extremely close to but not the theoretical optimum value. In practice, the algorithm is executed several times and the best result is chosen as optimum value. Through several experiments, it is found that the obtained routes are not identical and have some difference. But from aspect of the route trends

Table 1: Waypoints, courses, distances list of optimal route

	P0	P1	P2	P3	P4	P5
Lat (°)	-36.0	-33.8	3.7	3.9	4.3	10.0
Lon (°)	110.0	100.7	57.8	57.6	57.3	52.0
Course (°)	286.4	312.7	320.8	318.2	317.6	/
Dis (nmile)	/	475.2	3317.3	15.8	29.7	467.3

Table 2: Simulation result list

	S (nmile)	t (h)	W_R (J)	W_w (J)	W_e (J)	W_e/W_R (%)
Great circle	4282.9	314.918	$6.3983*10^{12}$	$0.4932*10^{12}$	$5.9051*10^{12}$	92.29
Optimum	4305.3	316.569	$6.4738*10^{12}$	$1.2308*10^{12}$	$5.2431*10^{12}$	80.99
Comparison	+0.524%	+1.65 h	1.1804000%	149.5621000%	-11.2117000%	-11.30

and waypoints distribution, there has little dissimilarity between them. So, it can be concluded that the algorithm has better convergence to global optimum value, the simulated optimal route is well and very close to actual best route.

Respectively, the geographic coordinates of waypoints, courses and distances of optimal route are listed in Table 1. Combining with Fig. 5, it is found that some waypoints can be canceled or merged, such as P2 and P3 have nearly identical geographic coordinates, or P3 and P4 have nearly identical courses, so the P3 and P4 can be canceled if necessary, by this way, the number of ship turning is reduced and seaman's workload is lessened.

Table 2 shows the performances of the initial and optimum route, the comparison values are also listed. Compared to the great circle, for optimum route, the voyage distance adds by 0.52% with adding additional voyage time 99 MIN and the total work consumption rises by 1.18%, while the work provided by wind-assisted propulsion adds by 149.56%, which leads to the cutting of work provided by main engine by 11.21% and reducing of main engine contribution by 11.3%.

From above analysis, it concluded that the fuel consumption is cutting by 11.2% when wind-assisted ship sail on optimum route. In this study, fixed ship speed is the precondition for route optimization and the deviation of the shortest path means adding of voyage distance, so the voyage time is added. But as the result has shown in Table 2 the initial voyage time is 314.9 h, while the optimization voyage time is 316.6 hours, the time added is less than 100 min. So the algorithm described in this study has good optimization effect and can be used on wind-assisted ship.

CONCLUSIONS

As an effective way to energy-saving and emission-reduction for shipping industry, wind-assisted ship is very useful to cut down fuel consumption and improve shipping efficiency and now is very important to help shipping companies to tide over shipping economic recession. The route for wind-assisted ship is different to traditional ship and should be redesigned, this research focuses on this problem and attempts to design a competent algorithm to find the least fuel consumption route.

Firstly, the characteristics of ocean wind speeds and directions are analyzed on the basis of monthly means grid data of 10 year record from UCAR. It can be found that the wind speed is very suit for wind-assisted ships as auxiliary power. Then, wind-assisted thrust presses in different wind speeds and angles are got from full-scale measurements and wind-assisted ship resistances in different wind velocities and ship speeds are obtained from model experiments in the wind tunnel and towing tank. By doing these, the optimization model for wind-assisted ship is established. At last, the algorithm for minimum fuel consumption route of wind-assisted ship using simulated annealing is introduced and programmed using Matlab and a reasonable result is obtained.

As the result shows, on the conditions of adding voyage time by 0.52% (less than 100 min), the work provides by wind-assisted propulsion increases up to 149.6%, which can cut down fuel consumption by 11.2%. So, the algorithm designed here can be applied to the solving of wind-assisted ship route optimization and thus provides theoretical guidance to further study on wind-assisted projects.

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