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On the Fuel Saving Operation for Coastal Merchant Ships using Weather Routing

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ABSTRACT: It is well known that Weather Routing is one of the effective ship operation methods to reduce fuel consumption and many studies have been conducted to develop the effective calculation methods. However, most studies were performed focusing on the ocean going ships, and there were few studies made for coastal ships. The authors propose a minimum fuel route calculation method for coastal ships that use the precise forecasted environmental data and the propulsion performance data of the ship on actual seas. In the proposed method, we use the Dijkstra's algorithm to calculate an optimum minimum fuel route suitable for coastal ships. Simulation study was carried out to evaluate the effectiveness of the proposed method using two coastal ships. As the result of study, the authors confirmed that the proposed calculation method is effective for fuel consumption reduction and is applicable for the operation of coastal merchant ships.

1 INTRODUCTION

In the late years, the ship operation cost increased due to the raise of oil prices and the reduction of CO_2 and NO_x gas emission have become a urgent matter to protect the environment.

Up to now, various researches on the weather routing (here after WR) had been conducted and various calculation methods were developed in order to find the safest route, shortest time route, minimum fuel route. But until now WR researches are performed focusing on the operation of ocean going ships. Being mainly developed for long voyages with a wide choice of routes, WR cannot be directly applied for ships sailing on confined coastal water (Haibo 2005).

In the recent years there have been tremendous advances in weather forecasting techniques, forecast of current also greatly progressed. Taking advantages of these progresses we developed a routing method with minimum fuel consumption for coastal ships.

In this paper we present a method for calculating the minimum fuel consumption route (here after MFR) for a specified voyage time for coastal ships using precise weather forecast data and ship's performance model, the results of the simulation study with this calculation method will also be discussed.

2 CALCULATION OF MINIMUM FUEL ROUTE USING DJIKSTRA'S ALGORITHM

For calculating the minimum fuel route, Djisktra' s algorithm was used. This algorithm was developed by Edsger W. Dijkstra in 1959; it is one of the most common algorithms for solving the shortest path problem, it finds the shortest path from a single source vertex to other vertices in a graph that is weighted (non negatively weighted), directed and connected.

Setting the departure point as P_0 and the destination point as Ps, the standard route from P_0 to Ps is constructed. A set of vertex (nodes) is constructed on the perpendicular to the standard route (hereafter we call all the nodes lying on the same perpendicular from the standard route "vertex line") (Takashima 2008).

The distance between the vertex lines is a function of the ship's type and average speed and can be easily changed to accommodate the type of voyage; the distance between each vertex on a vertex line is set to 2 miles in this work but it can also be changed.

In the method, we propose the propeller revolution number is kept constant during the voyage and only the course can be controlled, which is more in accordance with the practice onboard ship where propeller revolution number is not constantly being changed but kept constant and the course is gradually adjusted.

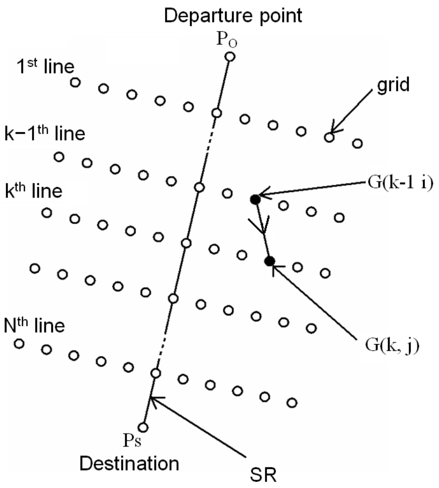

Figure 1. Grid points of DP to calculate minimum fuel route.

The propeller revolution number is determined so as to reach the destination point at the desired time of arrival. We will look for the minimum propeller revolution number that will allow us to reach the destination at the desired time of arrival, by doing so we will find the most practical minimum fuel route for the desired voyage time.

Ship's position can be described by the following equation:

$$x = f(t, x, S, C) \quad (1)$$

Where t is the time, x the position of the ship, S the speed and C the control parameter, which in our case is dependent only on rudder angle since the propeller revolution number in kept constant.

The speed of the ship at any instant is function of ship's heading and response to the external weather elements, such as wave, wind and current.

$$S = f(\theta, wave, wind, current) \quad (2)$$

Knowing the weather elements we can determine the speed of the ship, and knowing this later allows us to compute the time needed to travel from one node to another.

Let the i-th node on the k-th vertex line from P_0 be $G(k, i)$. The ship starts from $G(k, i)$ at time t_k and reaches the node $G(k\text{-}1, j)$ on the k-1-th vertex line at time $t_{k\text{-}1}$ (see fig.1 for more details).

The minimum time route from the departure point P_0 to the destination Ps is obtained by solving the following iterative equation:

$$T_{\min}(G(k,i)) = \underset{j}{Min}\{T(G(k-1,j), G(k,i)) + T_{\min}(G(k-1,j))\} \quad (3)$$

$$(k=1,2,\ldots,N+1)$$

where T_{min} $(G(k, i))$ represents the minimum passage time from the departure P_0 to the node $G(k, i)$, and $T(G(k\text{-}1, j), G(k, i))$ represents the passage time from the previous node $G(k\text{-}1, j)$ to the node $G(k, i)$.

Eq.3 means than the minimum passage time from departure point P_0 to any point $G(k, i)$ can be determined by finding the minimum of the sum of passage time from $G(k\text{-}1, j)$ to $G(k, i)$ and the minimum passage time from departure point P_0 to $G(k\text{-}1, j)$ (when k reaches N+1, $G(N+1)$ is Ps).

If the T_{min} obtained by solving (3) is not equal to the desired voyage time the propeller revolution number is changed and (3) resolved, we will gradually adjust the propeller revolution number until we get a T_{min} as close as possible to the desired voyage time.

The route thus obtained can be considered as the minimum fuel route for the specified voyage time. Here after we will refer to this route as MFR.

The MFR obtained by this method is not the true minimum fuel route from the mathematical point of view, but it can be regarded as the sub-optimal route that will allow us to reach destination at the desired time with a minimum consumption and a fixed propeller revolution number. In this method since the only control parameter is the ship's course the amount of calculation is largely reduced

3 ENVIRONMENTAL DATA

The environmental data used for carrying simulation with this calculation method are forecasted data of surface winds, waves, ocean and tidal currents, these data were used to calculate the ship's speed trough the water and over the ground. The forecast data are available for each 1 hour, extending for a period of 72 hours, the forecast data are updated 8 times a day (i.e. base time of forecast: 00,03,06,09,12,15,18,21 UTC).

3.1 *Wind and wave data*

The wind data comprises mean wind direction and mean wind speed; the wave data comprises the significant wave height, predominant wave direction and significant wave period.

For the forecast period up to 15 hours ahead the forecasted data are the result of the input of the surface winds from the mesoscale numerical forecast model of the Japan Meteorological Agency into the 3rd generation wave forecast model "WAM" of the Japan Weather Association, the data are given for grids of 2 by 2 miles .

For the forecast period from 16 to 72 hours ahead, the data are from the output of the wave forecast model of the Japan Meteorological Agency, the data are given for grids of 6 by 6 miles.

3.2 *Ocean and tidal current data*

The ocean current forecasted data are the output from the Japan Coastal Predictability Experiment operated by Frontier Research Center for Global Change; the data are given for grids of 5 by 5 miles.

The Tidal current forecasted data are from the output of the tidal calculation program developed by the National Astronomical Observatory of Japan. The data are given for grids of 2 by 2 miles. The data are given for grids of 2 by 2 miles

4 SPEED AND ENGINE PERFORMANCE IN SEAWAY

Two ships, A roll-on/roll-off container ship plying between Tokyo and Tomakomai/Kushiro in Hokkaido (north of Japan) and a cement career plying between Ube in Yamaguchi (south-east of Japan) and Tokyo were used for the simulation to investigate the effectiveness of the proposed minimum fuel route calculation method, hereafter we refer to the Ro/Ro container ship as “model ship-A” and to the cement carrier ship as “Model ship-B”. The principal characteristics of the two ships are shown in Table 1 and Table2.

Table 1 Principal particulars of the model ship-A

Length over all	161.13 m
Length between perpendiculars	150.00 m
Breadth	24.00 m
Full load draught	6.424 m
Gross tonnage	7,323 ton
Engine type	Diesel engine x 1
Max engine power	16,920 kW
Normal engine power	14,380 kW
Sea speed	23.00 kn
Carrying capacity	50 trailers (12 m) 200 containers (12 feet)

Table 2 Principal particulars of the model ship-B

Length over all	159.7 m
Length between perpendiculars	152.5 m
Breadth	24.2 m
Full load draught	9.016 m
Gross tonnage	13,787 ton
Engine type	Diesel engine x 1
Max engine power	6,960 kW
Sea speed	13.0 kn

The speed through the water of the two ships was calculated by numerically solving the equilibrium equation between total resistance (sum of the still water resistance, the wind resistance and the added resistance due to waves) and the propeller thrust (Kano 2008). For various rpm, wind conditions and

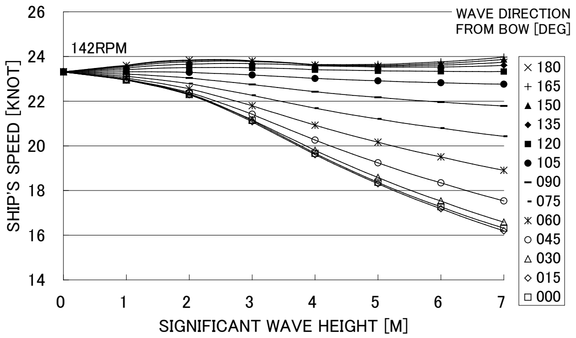

Figure 2. Speed performance curve of model ship-A at 142 RPM.

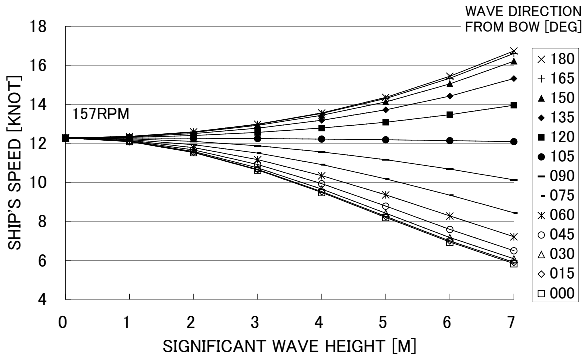

Figure 3. Speed performance curve of model ship-B at 157 RPM

wave condition we get the corresponding speed through the water. In figure 2 and 3, speed performance curve 142 rpm (for model ship-A) and 157 rpm (for model ship-B) for various wave heights and wave direction from the bow are shown. When drawing these curves, the wind speed (m/s) was taken to be four times the significant wave height (m), the wind direction was assumed to be equal to four times the square root of the significant wave height. It can be clearly seen that the speed reduction increase with the decrease of the wave direction from the bow. In the elaboration of these performance curves, operational limits due to excessive ship’s motion and accompanying dangerous phenomena are not considered when elaborating these curves.

The fuel consumption F in kg per hour of the model ship is calculated using the following equation

$$F = KP \tag{4}$$

Where K is the specific fuel consumption of the ship (for model ship-A, K=0.180 kg/kW h, for model ship-B, K=0.182 kg/kW h) and P is the engine power in BHP (kW) of the model ship.

5 RESULTS OF MFR SIMULATION

We conducted MFR simulation for the two ships (model ship-A and model ship-B) using the proposed calculation method. For demonstrating the effectiveness of the proposed calculation method, we also simulated the fuel consumption for the route usually used by the ship (hereafter UR). A suitable propeller revolution number is set, the propeller revolution number is set to be constant during the voyage, according to this and using the environmental data, speed and engine performance data, the voyage time is calculated.

If the voyage time is not close to the desired voyage time, the propeller revolution number is changed and the voyage time recalculated, the calculation will be stopped when the difference between the calculated voyage time and desired voyage time reaches ±0.1 hour. The fuel consumption thus obtained is assumed to be the UR fuel consumption.

The simulation has been conducted for the condition shown as follows.

Model ship-A

- Route: From Kushiro to Tokyo (South bound)
- Term of simulation: November 2008
- Departure time: at 15:00(UTC) on each day
- desired voyage time: 26 hours

Model ship-B

- Route: From Ube to Tokyo (East bound)
- Term of simulation: November 2008
- Departure time: at 15:00(UTC) on each day
- desired voyage time: 29 hours

5.1 *Comparison of fuel consumption in MFR and UR*

For achieving a good comparison between the MFR and UR fuel consumption it would be better to use weather data with as small error as possible. For achieving this, we use only the first three hour forecast data of each weather forecast report, hereafter we refer to this data as Analyzed Wx and to the original data as Forecast Wx.

Using the Analyzed Wx, we simulated MFR and UR fuel consumption for 1 month (November 2008). The results for ship model-A and ship model-B are shown in figure 4 and 5 respectively.

The O marked curve shows MFR fuel consumption, the △ marked curve shows the UR fuel consumption and the bar graph represents the saving of fuel between the two routes.

For both model ships, there is an evident fuel saving between MFR and UR; for model ship-A the average saving is 2.4%, the largest is 6.9%; for model ships-B the average saving is 18.4% and the largest saving amount is 22.1%.

The MFR routes obtained are shown on figure 6 for ship model-A and figure 7 for ship model-B, we can notice that the MFR tends to be farther from the coast line than the UR.

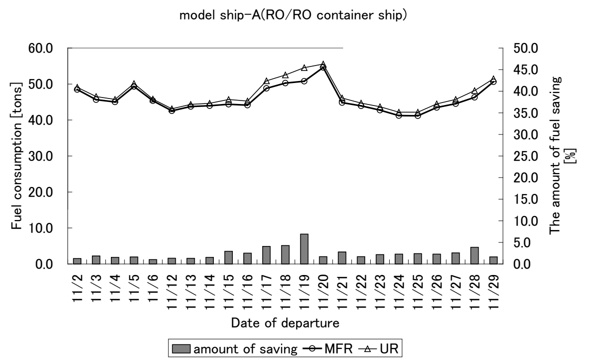

Figure 4. Fuel consumption and fuel saving amount for model ship-A.

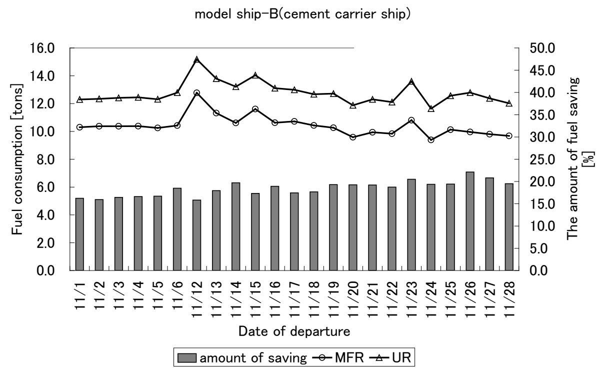

Figure 5. Fuel consumption and fuel saving amount for model ship-B.

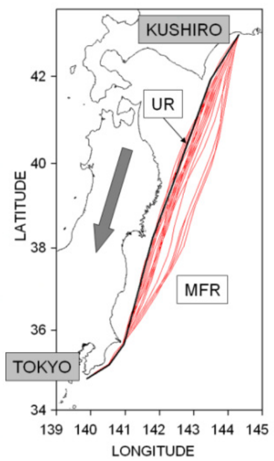

Figure 6. Comparison between MFR ad UR for November 2008 for model ship-A.

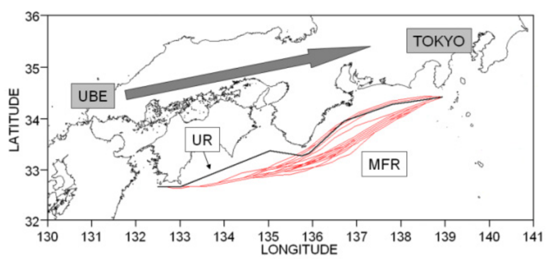

Figure 7. Comparison between MFR ad UR for November 2008 for model ship-B.

Figure 8 and 9 show the sea current data for the voyages with the largest amount of fuel saving. We can notice that the MFR avoids regions with opposite current and takes advantage of the regions where current flows in the same direction as the ship's route. We also compared the difference between the speed over ground and speed through the water for the MFR and the UR, for the MFR, nearly all along the voyage the speed over ground is higher that speed through the water, which demonstrates that the MFR is the route that takes advantage of the ocean and that for the Japanese coasts, the ocean current has a large influence on fuel saving.

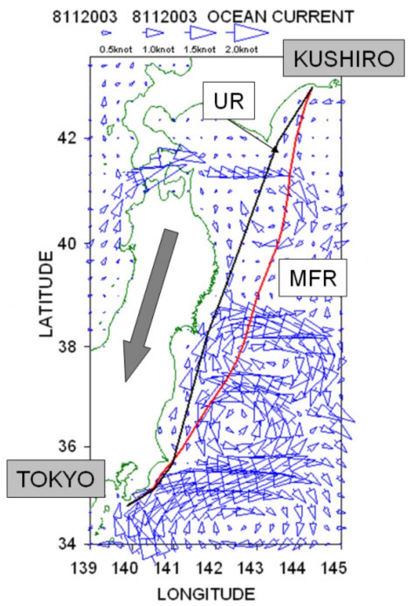

Figure 8. Ocean current data for 20/12/2008.

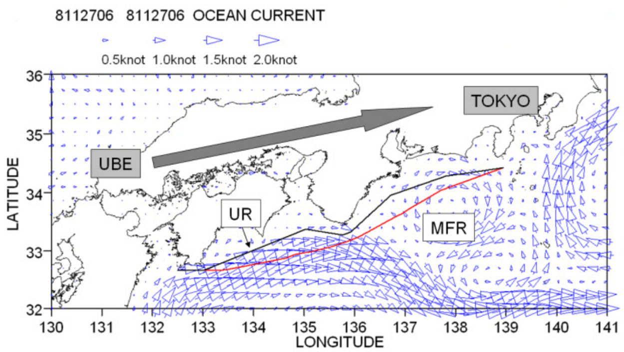

Figure 9. Ocean current data for 27/12/2008.

5.2 *Recalculation of MFR using updated environmental forecast*

Practically using Analyzed Wx for the calculation is impossible; In fact there is a time lag of about 9 hours between the forecast and its publication, so at any time only the forecast Wx data is available, the Analyzed Wx data will not be available until the time lag has passed, which means it can not be really used for calculation.

Using the latest available Forecast Wx data, we calculated the MFR for model ship-A, the departure time is 17/12/2008 at 15:00 UTC from Kushiro in Hokkaido to off Tokyo.

Hereafter we call the MFR obtained using the Forecast Wx data as MFR-F and the MFR obtained using Analyzed Wx data as MFR-A.

We can notice from figure 10 that shows both routes, that the MFR-F tends be farer from the coast than the MFR-A and this due to the error in the forecast; we checked the accuracy of weather forecast data and found that the Forecast Wx wind data tends to be smaller than the Analyzed Wx wind data.

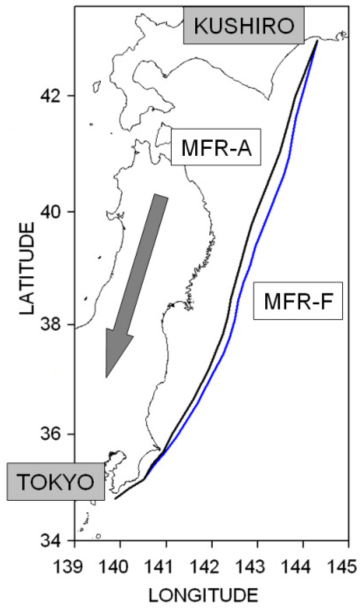

Figure 10. Comparison between MFR obtained using only Analyzed Wx data and using Forecast Wx data

To palliate the error on the route generated this error on the forecast, we use rerouting; rerouting consists on recalculating a new route from the present position to the destination point every time there is a change in the weather data, the ship starts from the departure point and sails on the MFR calculated using the available Forecast Wx data, when a new weather forecast is available the MFR is recalculated from the actual position of the ship to the destination point using the newly available data.

Figure 11 shows the simulation of the MFR obtained using forecasted data updated every three hours. The rerouting points are shown with O marks, the rerouting has been done 9 times in this voyage.

We also calculated the difference on arrival between the MFR-A and the MFR-F calculated on each rerouting. If the ship arrives ahead of the desired time the error is deemed positive and it arrives late the error is negative.

Figure 12 shows the error on arrival time with regards to the number of rerouting calculation, without any rerouting the error on arrival time is around +28 minutes, with one rerouting recalculation the error decreases to +9 minutes and with a maximum number of recalculation the error is around +3 minutes.

Using rerouting calculation the error on arrival time can be reduced to an acceptable value.

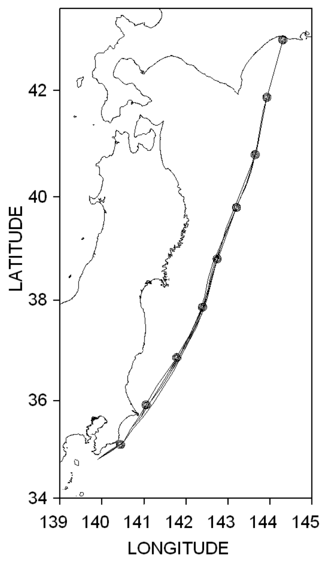

Figure 11. MFR obtained using Forecast Wx data with recalculation every 3 hours

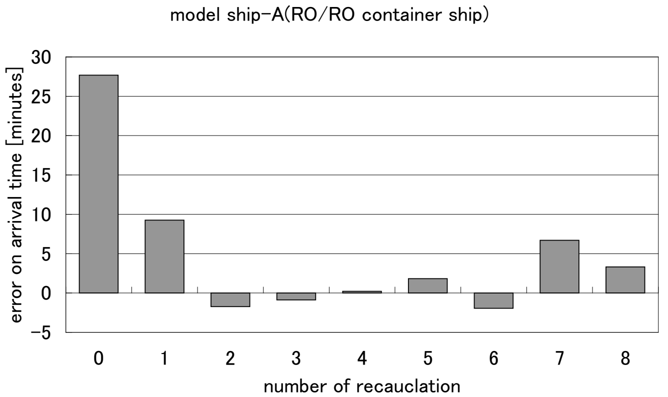

Figure 12. Error of arrival time with regards to the number of recalculation

6 CONCLUSIONS

In this paper, a method for achieving energy saving for coastal merchant ships using weather routing was proposed. An optimization method based on Dijkstra's algorithm using weather forecast data was proposed. Two ships, one is a RO/RO container ship plying between Kushiro in north Japan and Tokyo, another is a cement carrier plying between Ube in west Japan and Tokyo were taken as models, the speed and engine performances in waves of both ships were determined, simulations were also conducted.

The results of one month simulation shows that the MFR obtained using the proposed calculation method allows to save a large amount of fuel, the average saving for two model ships is 2.4% and 18.4 %, the maximum saving is 6.9% and 22.1% respectively.

There is a strong oceanic current along the Japanese coast, the proposed MFR calculation method, takes advantage of this current and achieves a good energy saving.

Recalculation of the MFR based on the updated weather forecast data during the voyage allows to reduce the effect of the forecast error.

For the further development of this research, a concept of risk of delay will be introduced to the calculation algorithm, using the information on the accuracy of wind/wave forecast, the possible error on the arrival time is determined and a minimum fuel route arriving at the destination point with a specific probability of the risk of delay can be calculated.

This study was done as a part of the "Research and Development of Environment-Harmonized Operation Planning Support System for coastal ships" by New Energy and Industrial Technology Development Organization (NEDO).

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