Advanced Route Optimization in Ship Navigation

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Abstract: It is expected that international sea transportation will continue to increase as the world population increases. The International Maritime Organization (IMO) requires preparation of ship navigation efficiency management plans, including improvement in ship cruising methods such as appropriate ship trajectory selection. Moreover, shipping companies pay careful attention to fuel consumption and environmental conservation, while striving to maintain navigation safety and punctual cargo arrival. Generally speaking, slow navigation results in energy savings, but takes longer. Ship speed is determined on the basis of such factors as customer transportation-time and cost requirements, ship officers' wages, insurance, port charges, and ship building costs. Operational methods in ship navigation are limited to output reduction and route selection. In this paper, we propose a newly developed weather routing optimization technology that monitors fuel consumption, considering on-going sea and weather condition variation, including wind, waves, and current.

1 INTRODUCTION

Weather routing is defined as selection of an optimal sea route from one point to another point by considering evaluation standards such as safety, convenience, fuel consumption, minimum voyage time considering ship conditions, and/or ability and performance using estimated weather and sea conditions. Seafarers have used wind, waves, and current in voyages since ancient times, but as a result of developments in weather forecast technology, improvements in computer performance, and establishment of physical mathematical dynamic models in ship navigation, weather routing has advanced substantially in recent times.

In 1957 R.W James tried to apply weather forcast information to ship navigation from the viewpoint of minimum voyage time using an isochrone method(James, 1965). More recently, many methods have been proposed considering not only voyage time, but also fuel consumption and CO_2 emissions.(Takashima, 2004)(Tsujimoto, 2005).

Moreover, since 2013 the International Maritime Organization (IMO) has required ships of 400 gross tonnage or more to prepare a Ship Energy Efficiency Management Plan (SEEMP). This guideline includes the weather routing method as one of the effective measures for improving voyage efficiency.

In this paper, we propose a newly developed weather routing optimization technology that treats fuel consumption considering variation of on-going sea and weather conditions such as wind, waves, and current.

2 MATERIALS AND METHODS

2.1 Mathematical Model

A mathematical model for ship navigation consists of three-dimensional independent free expressions, such as surge, sway, and yaw motion, as in differential equations that treat the dynamical relationship between inertial forces and moment and other hydrodynamic forces and moments of hull, propeller, and rudder, as well as external forces and moments. In these equations, steady forces acting on a hull owing to wind, current, and added resistance due to waves are taken into account as external forces and moments. These equations in relation to the coordinate system in Figure 1 are as follows:

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$$\left.\begin{aligned} (m + m_x)\ \dot{u} - (m + m_y)vr \\ = X_H + X_P + X_R + X_A + X_W + X_C \\ (m + m_y)\ \dot{v} + (m + m_x)ur \\ = Y_H + Y_P + Y_R + Y_A + Y_W + Y_C \\ (I_{ZZ} + J_{ZZ})\dot{r} = \\ = N_H + N_P + N_R + N_A + N_W + N_C \end{aligned}\right\} \quad (1)$$

where m is the mass of the ship, I_{ZZ} is the mass moment of inertia of the ship about the z-axis, m_x is the added mass of the ship in the x-direction, m_y is the added mass of the ship in the y-direction; J_{zz} is the added mass moment of inertia of the ship about the z-axis, u is the velocity component in the x-direction, v is the velocity component in the y-direction, r is the turning angular velocity, u, v, and r are time differentiations of u, v, and r, respectively, X_H, Y_H, and N_H are the longitudinal and lateral forces and the moment acting on the ship, respectively, X_P, Y_P, and N_P are the longitudinal and lateral forces and the moment acting on the rotatable propellers, respectively; X_R, Y_R, and N_R are the longitudinal and lateral forces and the moment acting on the rudder, respectively; X_A, Y_A, and N_A are the longitudinal and lateral wind forces and the wind moment, respectively; and X_W, Y_W, and N_W are the longitudinal and lateral wave force, respectively; and X_C, Y_C, and N_C are the longitudinal and lateral current forces and moment, respectively.
Representative expressions of forces and moments are shown in APPENDIX. Fuel oil consumption is a proportional value to shaft horse power (SHP) derived from equation (9) in the Appendix.

In this research, hindcast values from the National Center for Environmental Prediction (NCEP) are used with respect to wind and wave data while the five-day averaged value from the National Oceanic and Atmospheric Administration (NOAA) is determined with respect to current data. In addition, in regard to the actual navigation, the wind and wave data were updated in the calculation using the latest forecast data every three hours in the ship ocean-going navigation simulation. Figures 2, 3 and 4 indicate the wind direction and velocity, significant wave height, and five-day averaged current, respectively, on 25 December 2009.

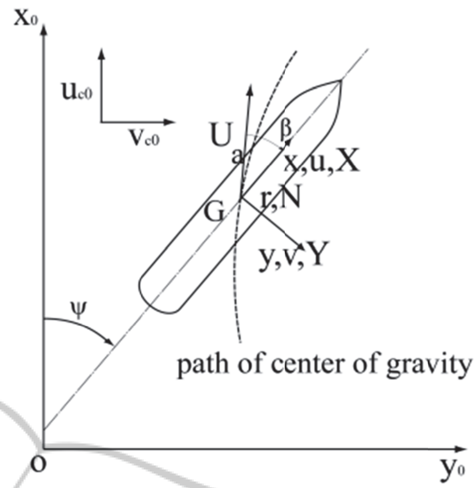

Figure 1: Coordinate system.

2.2 Route Optimization

The route optimization in this research was conducted by minimizing a cost function denoting the total fuel consumption in the navigation from departure point to destination point, calculated by solving the above-mentioned equations.

The total fuel consumption was calculated by conducting navigation from the start point to the destination point along the designated course by solving equation (1) under the start-time weather forecast. At a particular navigation time in the simulation (for example, three hours later), a course from the point corresponding to the same navigation time from the starting point to the destination was reviewed using a revised weather forecast modified from the starting one. Repeating this procedure, the weather routing problem is solved iteratively using Powell's method(Powell,1964), a conjugate gradient method that does not require calculating the derivatives of an objective function. Moreover, in this study, Mercator sailing is used for ship sailing calculations, such as distance or course. In addition, the route is expressed using a high-degree Bézier curve enabling us to generate the complex shape of the curve. The route optimized using the Powel method is replaced by finding appropriate valuables for expression of the Bézier curve. The order of the Bézier curve is defined as six based on our previous work(Ishii, 2009). This route optimization procedure is shown in Figure 2.

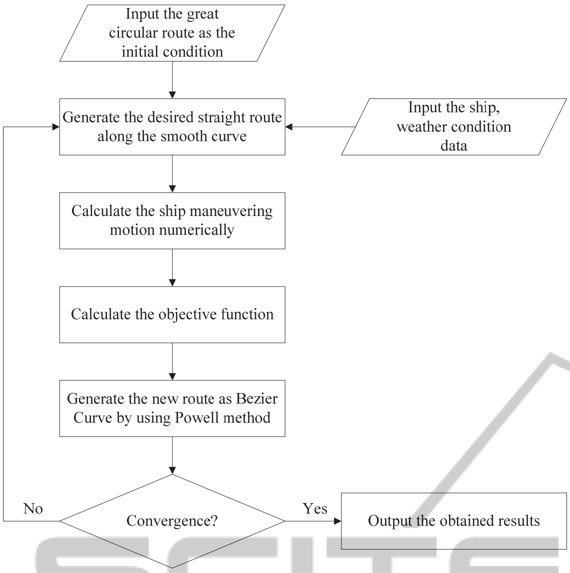

Figure 2: Flowchart of the proposed method.

First, the initial navigation route from start to end is set. Next, a navigation simulation is conducted by solving equation (1) from start to end along the first navigation route, resulting in the calculation of a cost function. Then, a new route with a smaller cost function is found using Powell's method.

3 RESULTS AND DISCUSSION

Computer simulations were carried out for the subject ship departing on 6 December 2008, eastbound from Yokohama, Japan to San-Francisco, U.S.A. to validate the efficiency of the proposed method. A great circle route between Yokohama and San Francisco was chosen for the iterative calculation's initial values, and a containership was chosen as subject ship. The principal particulars are shown in Table 1.

Table 1: Principal particulars of the subject ship.

Length	285.00 m
Breadth	40.00 m
Depth	24.30 m
Draft	14.02

An automatic rudder control algorithm was introduced in this simulation for the ship to navigate along the designated route as follows:

$$\delta^* = -C_1\Delta y - C_2\Delta\psi - C_3 r \quad (2)$$

where, δ^*, Δy, $\Delta\psi$, and r are the command rudder angle, lateral deviation from the route, deviation from the designated course, and yaw rate, respectively. In this formula, C_1, C_2, and C_3 are empirical feedback gains. The propeller revolution number was set to be constant through the simulation.

Figures 3, 4, and 5 indicate the wind direction and velocity, significant wave height, and five-day averaged current prediction on 25 December 2009, respectively.

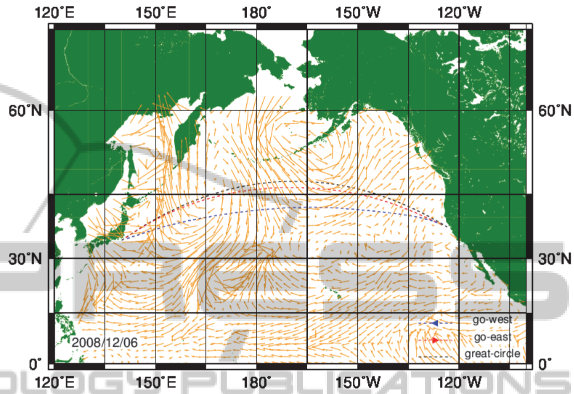

Figure 3: Wind direction and speed at departure.

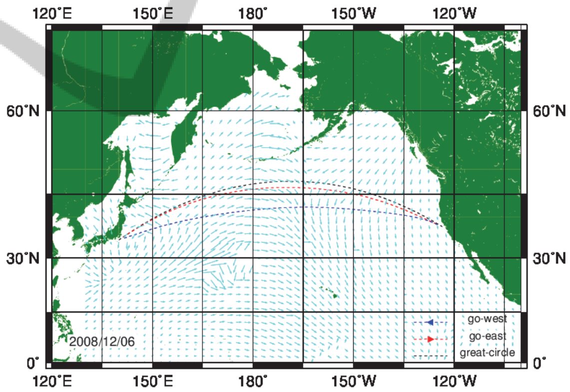

Figure 4: Significant wave height at departure.

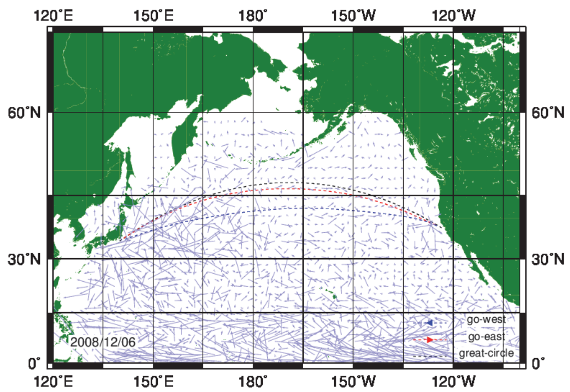

Figure 5: Predicted ocean current at departure.

The above-mentioned figures denote the predictions at the starting time. There are revised predictions at times other than the starting time, such as, for example, three hours later. Revised wave, wind and current prediction data replaced previous data in a navigation simulation from the starting point to the destination.

Figure 6 shows the simulation results after repeating this procedure, the east bound (red dotted line) and west bound (blue dotted line) optimized routes obtained using the above-mentioned method, and the great circle route (black dotted line), the initial route before the optimization.

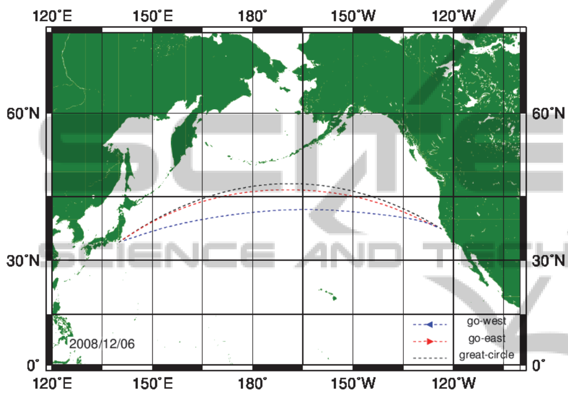

Figure 6: Great circle and optimum fuel consumption routes in the Pacific Ocean.

Both optimized routes are located south of the great circle route, providing ships with fewer wind, wave, and current effects.

Fuel oil consumption (FOC), voyage distance, and voyage time are shown in Figures 7, 8 and 9. Fuel oil consumption for the optimized routes are 2.0 tons and 24.9 tons less than the great circle route

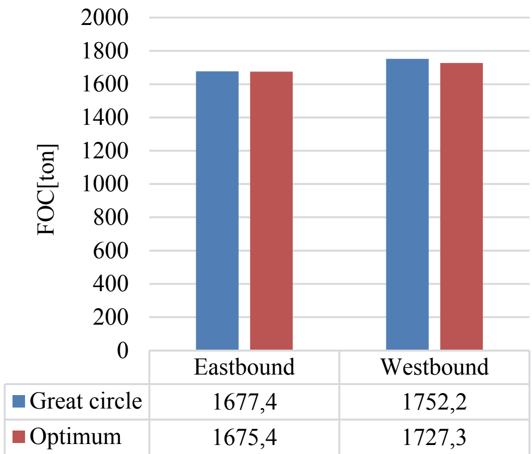

Figure 7: FOC comparison with eastbound and westbound routes.

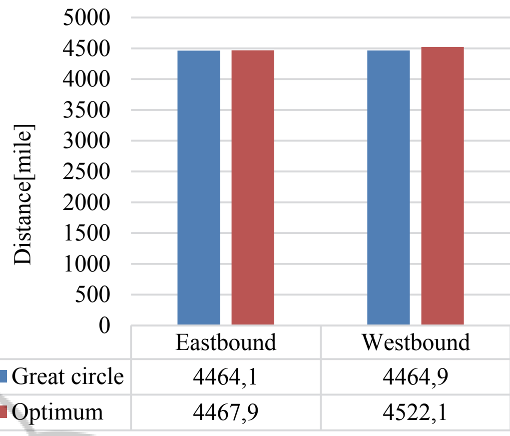

Figure 8: Distance comparison with eastbound and westbound routes.

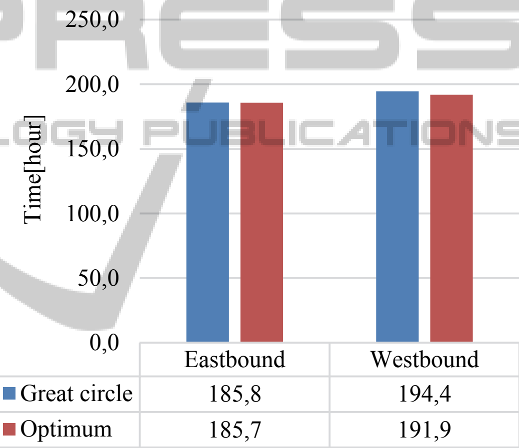

Figure 9: Time comparison with eastbound and westbound routes.

for the eastbound and westbound, respectively, and travelling times are 0.1 hours and 2.3 hours shorter than for the great circle, although distances are 3.8 miles and 57.2 miles longer than the great circle. Thus, the optimized routes provide FOC savings and travelling time reduction, although with increased travelling distance.

4 CONCLUSIONS

An advanced new weather routing method for ship navigation was proposed as a fuel oil consumption minimization problem. The designated path is expressed as a curve generated by a six-degree Bézier curve, and the optimal route was calculated by solving a cost function minimization using Powell's method. We found it possible to apply this method to the selection of an energy saving ship navigation route in limited simulations.

Moreover, it is expected to develop and install a new ship voyage on board instrument which provides optimal ship navigation routes with help of concurrent forecast of wind, wave and current through, for example, satellite data communication by applying this method.

On the other hand, there may exist a more optimal path than this use of Powell's method provides, because the answer depends on the initial conditions for the calculation. More work is required to verify its applicability to determining actual optimal routes.

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REFERENCES

Ishii, E., Kobayashi, E., 2010. *Proposal of new-generation route optimization technique for an oceangoing vessel*, Proceedings of OCEANS IEEE 2010, May 24-27, Sydney.

James R. W., 1965. Application of wave forecasts to marine navigation, U. S. Navy Hydrographic Office, Washington, D.C..

Powell, M.J.D., 1964. An efficient method for finding the minimum of a function of several variables without calculating derivatives, *The Computer Journal, vol.7, no.2, pp. 155-162.*

Takashima, K. Hagiwara, H., Shoji, R., 2004. Fuel saving by weather routing–simulation using actual voyage data of the container ship, *The Journal of Japan Institute of Navigation, vol. 111, pp. 259-266.*

Tsujimoto, M., Tanizawa, K., 2005. Development of a weather adaptive navigation system - influence of weather forecast, *Journal of the Japan Society of Naval Architects and Ocean Engineers, vol.2, pp.75-83.*

APPENDIX

$$\left.\begin{aligned} X_H &= -R + \frac{1}{2}\rho L d U^2 X_H' \\ Y_H &= \frac{1}{2}\rho L D U^2 Y_H' \\ N_H &= \frac{1}{2}\rho L^2 d U^2 N_H' \end{aligned}\right\} \quad (3)$$

$$\left.\begin{gathered} X_H = \\ X_{vv}' v'^2 + X_{rr}' r'^2 + X_{vr}' v' r' + X_{vvv}' v'^4 \\ Y_H' = \\ Y_v' v' + Y_r' r' + Y_{vvv}' V'^3 \\ + Y_{vvr}' v'^2 r' + Y_{vrr}' v' r'^2 + Y_{rrr}' r'^3 \\ N_H' = \\ N_v' v' + N_r' r' + N_{vvv}' v'^3 \\ + N_{vvr}' v'^2 r' + N_{vrr}' v' r'^2 + N_{rrr}' r'^3 \end{gathered}\right\} \quad (4)$$

where

L, d	:	Length and depth of the ship
U	:	Speed of the ship($= \sqrt{u^2 + v^2}$)
y	:	Density of sea water
R	:	Ship resistance

$$\left.\begin{aligned} X_P &= (1 - t)T \\ T &= \rho {n_P}^2 {D_P}^4 K_T \\ Y_P &= 0 \\ N_P &= 0 \end{aligned}\right\} \quad (5)$$

where

X_P, Y_P, N_P	:	Forces and moment due to propeller
$(1 - t)$	:	Thrust deduction factor
T	:	Thrust force by propeller
n_P	:	Revolution of propeller
D_P	:	Diameter of propeller
K_T	:	Coefficient of thrust force
J	:	Propeller advance constant
u_P	:	Inflow velocity to propeller

$$\left.\begin{aligned} K_T &= C_0 + C_1 J + C_2 J^2 \\ J &= \frac{u_P}{n_P D_P} \end{aligned}\right\} \quad (6)$$

$$K_Q = D_0 + D_1 J + D_2 J^2 \quad (7)$$

where

K_Q	:	Coefficient of Torque
$D_0, D_1. D_2$	:	1.1.1.1 Coefficient from the propeller characteristic curve

$$Q_P = K_Q \rho {n_p}^2 {D_p}^5 \quad (8)$$

where

Q_P	:	Propeller torque
ρ	:	Density of sea water

$$\mathrm{SHP} = \frac{2\pi n_p Q_p}{\eta_t} \quad (9)$$

$$= \frac{2\pi\rho D_P{}^5}{\eta_t}\left(D_0 n_p{}^3 + \frac{D_1 u_p}{D_p} n_P{}^2 + \frac{D_2 u_P{}^2}{D_P{}^2} n_p\right)$$

where

SHP	:	Shaft horse power
η_t	:	Transfer efficient

$$\left.\begin{aligned} X_A &= \frac{1}{2}\rho_A V_A{}^2 A_T C_{XA}(\theta_A) \\ Y_A &= \frac{1}{2}\rho_A V_A{}^2 A_L C_{YA}(\theta_A) \\ N_A &= \frac{1}{2}\rho_A V_A{}^2 A_T C_{NA}(\theta_A) \end{aligned}\right\} \quad (10)$$

where

X_A, Y_A, N_A	:	Wind forces and moment
ρ_A	:	Density of air
θ_A	:	Relative wind direction
V_A	:	Relative wind speed [m/s]
A_T	:	Transverse projected area
A_L	:	Lateral projected area
C_{XA}, C_{YA}, C_{NA}	:	Wind force coefficients

$$R_{aw} = C_1 \cdot 0.5\rho g\left(1 + C_2 F_{n_B}{}^{0.8}\right) H_w{}^2 B \cdot B_{fcp}{}^2 \quad (11)$$

where

L	:	Length between perpendiculars
B	:	Breadth of the ship
ρ	:	Density of sea water
g	:	Gravitation
F_{n_B}	:	Froude number
B_{fcp}	:	Bluntness coefficient
C_{pf}	:	Prismatic coefficient
R_{aw}	:	Additional resistance due to waves
H_w	:	Significant wave height
V_S	:	Speed of ship