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Advanced Navigation Route Optimization for an Oceangoing Vessel

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ABSTRACT: A new weather routing method is proposed that accounts for ship maneuvering motions, ocean currents, wind, and waves through a time domain computer simulation. The maneuvering motions are solved by differential equations of motion for every moment throughout the voyage. Moreover, the navigation route, expressed in terms of a Bézier curve, is optimized for minimum fuel consumption by the Powell method. Although the optimized route is longer than the great circle route, simulation results confirm a significant reduction in fuel consumption. This method is widely applicable to finding optimal navigation routes in other areas.

1 INTRODUCTION

An oceangoing ship is affected by external forces such as wind, ocean currents, and waves. Weather routing techniques are usually applied in cases where the magnitude of those external forces are very large and may pose a danger to ships. In addition, optimal navigation is required from an economical point of view. Although there have been many efforts to develop route optimization techniques, most cases do not take ship maneuvering dynamics into account. Recent improvements in computing performance have made it possible to carry out a large amount of computation, so it is even possible to take ship motion dynamics into consideration. In this study, a new weather routing method was developed that takes ship maneuvering motions, current, wind, and waves into account by time domain computer simulation.

An MMG-type mathematical model of ship maneuvering motions is introduced for the dynamic calculation. The model includes many variables such as sway, yaw, propeller thrust and torque, rudder force, and fuel consumption. The maneuvering motions are solved by differential equations of motion for every moment throughout the voyage. Moreover, the optimal navigation route is determined by minimizing the fuel consumption through Powell's method. In this paper, the mathematical models of the ship maneuvering navigation model are first shown. Next, methods for calculating the current, wind, and waves from the database are introduced and demonstrated. Then, several kinds of computer simulations for weather routing are shown. Finally, the applicability and future works are discussed.

2 TARGET SHIP AND ROUTE

A container ship was chosen as the subject ship of this study because it is one of the principal means of marine transportation. Moreover, container ships consume more fuel than other marine vehicles because they are run faster to accommodate tight customer schedules. The specifications of the subject ship are shown in Table 1.

Table 1. Specifications of subject container ship.

Length overall	Loa	299.85 m
Length between perpendiculars	Lpp	299.85 m
Breadth molded	Bmld	40.00 m
Depth molded	Dmld	24.30 m
Draft designed	d	14.02 m
Propeller diameter	Dp	9.52 m
Propeller pitch	Pp	7.25 m
Lateral projected area	A_{AL}	8284.25 m^2
Transverse projected area	A_{AT}	1052.18 m^2
Gross tonnage	GT	75,201 t
Service speed	Vs	25.0 kt

The intercontinental route between Yokohama, Japan, and San Francisco, USA, as shown in Figure 1, was used as the subject route in this study because it is a very important trade route for Japan and weather conditions along the route are sometimes rough.

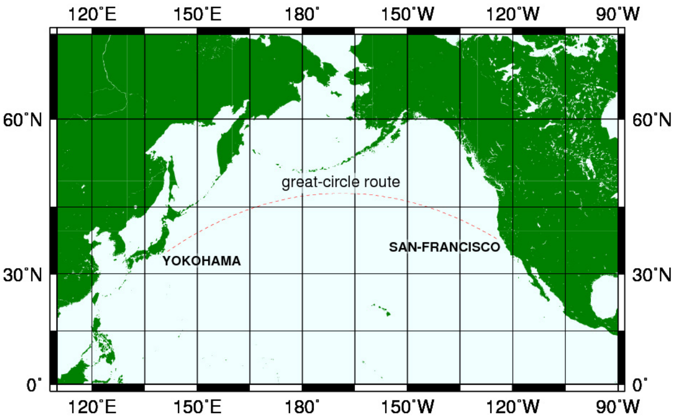

Figure 1. Subject transportation route between Yokohama and San Francisco.

3 WIND, WAVES, AND CURRENT ESTIMATION

Ocean surface current data from the National Oceanic and Atmospheric Administration (NOAA) of the United States Department of Commerce were used in this study. The data were five-day averages for a 1.0° × 1.0° mesh in the area between 0.5°E and 0.5°W and 59.5°N and 59.5°S. Sample data from 26 December 2008 are shown in Figure 2. The arrows show the eastbound and westbound current vectors, respectively.

The predicted data for wind and waves were derived from global prediction data by NCEP (National Center for Environmental Prediction); they include several parameters for wind wave information, such as wind direction, wind velocity, and significant wave height every 3 h; the data were updated every 6 h. The range of the data were between longitudes of 0°E and 1.25°W and latitudes of 78°N and 78°S; the mesh size was 1.25° and 1° for longitude and latitude, respectively. The target data times of the voyage simulation starting in this study were midnight on 6, 9, 22, and 25 December 2008. The current, wind, and wave data were updated every 3 h.

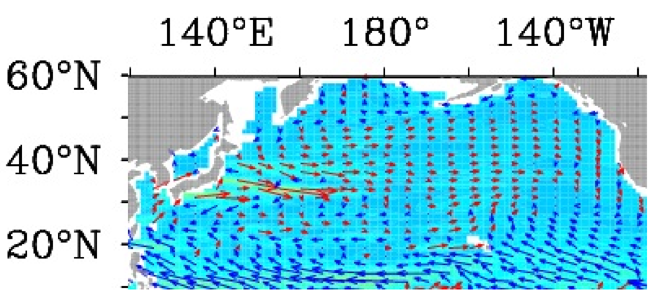

Figure 2. Sample data of ocean surface current.

4 MATHEMATICAL MODEL OF SHIP MANEUVERING

4.1 *Coordinate system and basic equations*

A body-fixed coordinate system whose origin is located at the ship center of gravity was adopted to express ship maneuvering motions (Figure 3).

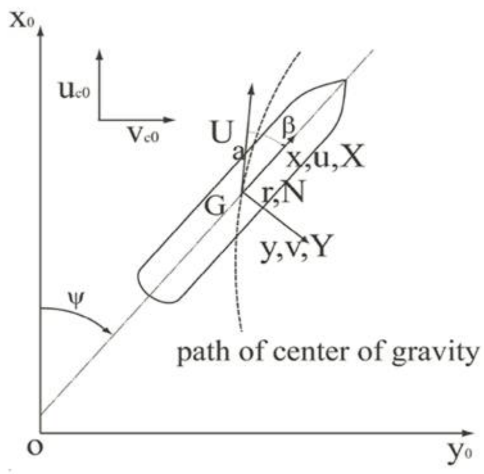

Figure 3. System coordinates in ship maneuvering motion.

Basic equations for ship maneuvering motions in the longitudinal, lateral, and yaw directions are expressed in the following equations:

$$\left.\begin{aligned}
&(m+m_x)\dot{u}-(m+m_y+X_{vr})vr\\
&-(u_{c0}\sin\psi\text{-}v_{c0}\cos\psi)(m_y-m_x+X_{vr})\\
&=X_H+X_P+X_R+X_A+R_{AW}\\
&(m+m_y)\dot{v}+(m+m_x)ur\\
&-(u_{c0}\cos\psi+v_{c0}\sin\psi)(-m_y+m_x)r\\
&=Y_H+Y_P+Y_R+Y_A\\
&(I_{zz}+J_{zz})\dot{r}=N_H+N_P+N_R+N_A
\end{aligned}\right\} \quad (1)$$

where m = mass of a ship; m_x, m_x = added masses in the x and y directions, respectively; I_{zz},J_{zz} = mass moment of inertia and added mass moment of inertia around the z axis; u,v = ship speed components in x, y coordinates; u_{C0},v_{C0} = current velocity components in x, y coordinates; r = rate of turn; ψ = yaw angle; $\dot{u}$,$\dot{v}$ = time differentiation for u,v; X_H,Y_H,N_H, X_P,Y_P,N_P, X_R,Y_R,N_R, X_A, Y_A,N_A = longitudinal force in the x direction, lateral force in the y direction, and yaw moment in the z axis acting on the hull, propeller, rudder and wind, respectively; R_{AW} = added resistance by waves; and X_{vr} = hydrodynamic derivative.

4.2 *Hull force*

The hull forces and moment acting on the ship were expressed by the polynomial of motion variables u, v, and r in the abovementioned basic equations for maneuvering motion based on the model test results as follows:

$$\left.\begin{aligned} X_H &= -R + \frac{1}{2}\rho L d U^2 X'_{H1} \\ Y_H &= \frac{1}{2}\rho L d U^2 Y'_H \\ N_H &= \frac{1}{2}\rho L^2 d U^2 N'_H \end{aligned}\right\} \quad (2)$$

$$\left.\begin{aligned} X'_{H1} &= X'_{vv}v'^2 + X'_{rr}r'^2 + X'_{vr}v'r' + X'_{vvvv}v'^4 \\ Y'_H &= Y'_v v' + Y'_r r' + Y'_{vvv}v'^3 + Y'_{vvr}v'^2 r' + Y'_{vrr}v'r'^2 + Y'_{rrr}r'^3 \\ N'_H &= N'_v v' + N'_r r' + N'_{vvv}v'^3 + N'_{vvr}v'^2 r' + N'_{vrr}v'r'^2 + N'_{rrr}r'^3 \end{aligned}\right\} \quad (3)$$

where R is ship resistance; X'_{H1}, Y'_H, N'_H are nondimensional forces and moments acting on a wetted hull due to swaying and yawing motions in the the *x*, *y*, and yawing directions, respectively; and $X'_{vv}, X'_{rr}, ..., N'_{rrr}$ are the hydrodynamic derivatives.

4.3 *Propeller force and fuel consumption*

In this study, the lateral force and moment due to the propeller were neglected because they were negligible under straight-going conditions in the ocean. The longitudinal propeller force is expressed as follows:

$$X_P = (1-t)T, Y_P = 0, N_P = 0 \quad (4)$$

where t is the propeller thrust reduction factor and T is propeller thrust. Moreover, the propeller thrust is expressed as follows:

$$\left.\begin{aligned} T &= \rho n^2 D_P^4 K_t \\ K_T &= c_0 + c_1 J + c_2 J^2 \\ J &= \frac{u_P}{n D_P} \end{aligned}\right\} \quad (5)$$

where n is the number of propeller revolutions; K_T is the propeller thrust coefficient; J is the advance coefficient; c_0, c_1, c_2 are the propeller characteristics coefficients; and u_P is the propeller inflow velocity.

The propeller torque Q is expressed as follows:

$$\left.\begin{aligned} Q &= \rho n^2 D_P^5 K_Q \\ K_Q &= d_0 + d_1 J + d_2 J^2 \end{aligned}\right\} \quad (6)$$

where K_Q is the propeller torque coefficient; and d_0, d_1, d_2 are the propeller open characteristics coefficients.

Then, the main engine power is calculated as follows:

$$\left.\begin{aligned} BHP &= DHP / \eta_t \\ DHP &= 2\pi n Q \end{aligned}\right\} \quad (7)$$

where BHP represents the brake horsepower of the main engine, DHP is the delivered horsepower, and η_t is the transmission efficiency.

Finally, the fuel oil consumption per unit time ΔFOC is calculated by the equation below:

$$\Delta FOC = BHP \times FOCR \quad (8)$$

where $FOCR$ is the fuel oil consumption rate.

Then, the total fuel oil consumption during the voyage FOC is expressed as follows:

$$FOC = \int \Delta FOC dt \quad (9)$$

where $FOCR$ is the fuel oil consumption rate.

4.4 *Rudder force*

The rudder forces and moment are expressed as follows:

$$\left.\begin{aligned} X_R &= -(1-t_R)F_N \sin\delta \\ Y_R &= -(1+a_H)F_N \cos\delta \\ N_R &= -(x_R + a_H x_H)F_N \cos\delta \end{aligned}\right\} \quad (10)$$

where X_R, Y_R, N_R are nondimensional forces and moments on the rudder in the *x*, *y*, and yaw directions, respectively; F_N = rudder normal force; δ = rudder angle; t_R, a_H, x_H = interaction coefficients between the hull and rudder; and x_R = coordinate of rudder position. The abovementioned rudder normal force is expressed as follows:

$$F_N = \frac{1}{2}\rho A_R U_R^2 f_\alpha \sin(\delta_e) \quad (11)$$

where A_R is the rudder area; U_R is the rudder inflow velocity; f_α is the rudder normal force coefficient; and δ_e is the effective rudder angle. For the value of f_α, the following empirical formula is used:

$$f_\alpha = \frac{6.13\lambda}{2.25+\lambda} \quad (12)$$

where λ is the aspect ratio of the rudder as expressed by $f_\alpha = b/h$.

On the other hand, the rudder inflow velocity U_R is expressed by

$$U_R = \sqrt{u_R^2 + v_R^2} \quad (13)$$

where u_R and v_R are the velocity components in the *x* and *y* directions, respectively. Here, u_R is expressed by the following equation as a function related to propeller thrust:

$$u_R = \varepsilon u_P \sqrt{1 + 8\frac{\kappa K_T}{\pi J^2}} \quad (14)$$

where ε and κ are empirical or experimental coefficients for the propeller flow acceleration; u_P is the propeller inflow velocity, and is expressed as $u_P = (1-w)u$ by the use of the wake fraction coefficient w; and K_T and J are the thrust coefficient and advance constant explained above, respectively. Moreover, v_R is expressed as follows:

$$v_R \quad = -\gamma\left(v + l'_R L_{PP} r\right) \tag{15}$$

where γ and l'_R are empirical factors, v is the lateral velocity component, and r is the rate of turn. The effective rudder angle δ_e is expressed as follows:

$$\delta_e \quad = \delta - v_R / u_R \tag{16}$$

where v_R and u_R is the longitudinal and lateral rudder inflow velocity components.

4.5 *Rudder control*

An automatic rudder control algorithm was introduced to perform ship maneuvering simulations during the voyage for the ship passing through designated points and courses as follows:

$$\delta_{\square\square} = -\tilde{c}_0 \Delta y - \tilde{c}_1 \Delta \psi - \tilde{c}_2 r \tag{17}$$

where $\tilde{c}_0, \tilde{c}_1, \tilde{c}_2$ are control coefficients; Δy is the deviation from the designated route, $\Delta \psi$ is the deviation from the designated heading angle, and r is the rate of turn.

4.6 *Wind force and moment*

The forces and moment by wind are expressed as follows:

$$\left.\begin{aligned} X_A &= \frac{1}{2}\rho_A V_A{}^2 A_T C_{XA}(\theta_A) \\ Y_A &= \frac{1}{2}\rho_A V_A{}^2 A_L C_{YA}(\theta_A) \\ N_A &= \frac{1}{2}\rho_A V_A{}^2 A_T C_{NA}(\theta_A) \end{aligned}\right\} \tag{18}$$

where X_A, Y_A, N_A are nondimensional forces and represent the moment due to wind in the *x*, *y*, and yaw directions, respectively; ρ_H is the density of air; V_A is the relative wind velocity; A_T is the transverse projected area; A_L is the lateral projected area; θ_A is the relative wind direction; and C_{XA}, C_{YA}, C_{NA} are the wind force and moment coefficients in the *x*, *y*, and yaw directions, respectively.

Wind force characteristics such as C_{XA}, C_{YA}, C_{NA} were calculated by using Fujiwara's (Fujiwara 2001) method, as shown in the following figure.

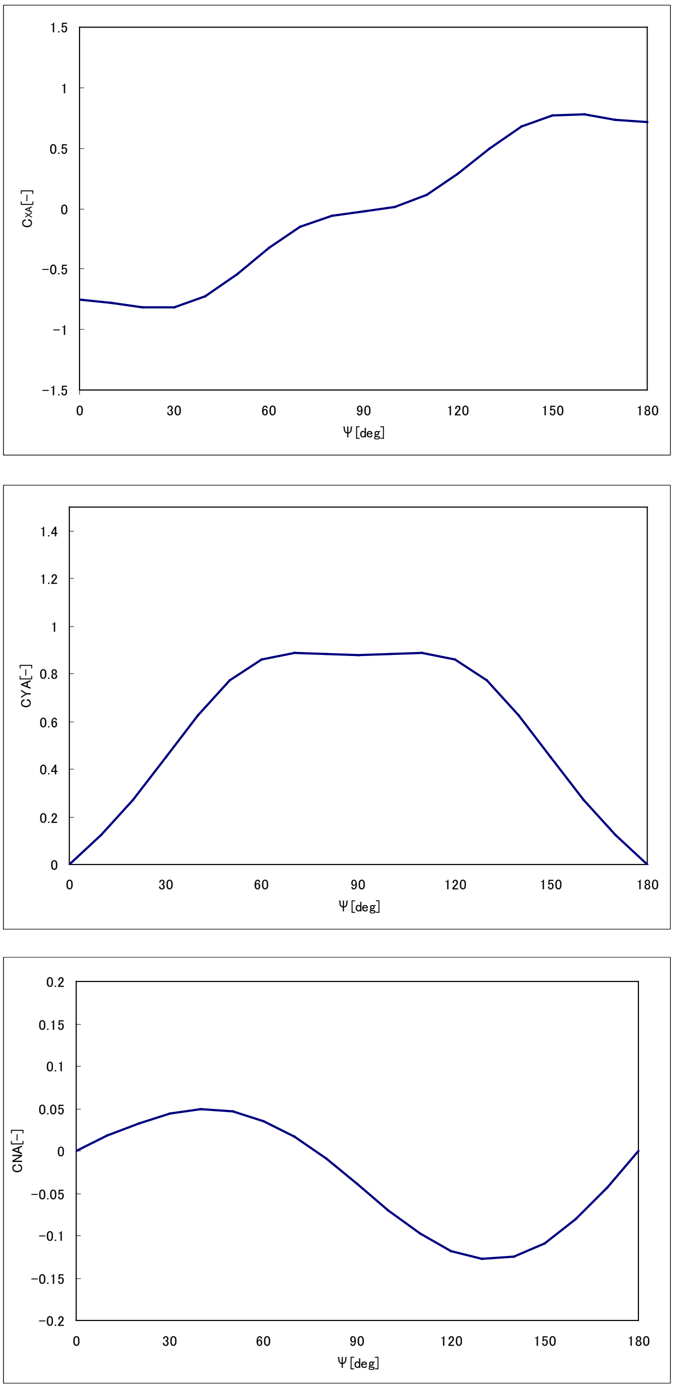

Figure 4. Wind force and moment characteristics obtained by Fujiwara's method.

4.7 *Added resistance due to waves*

The added resistance due to waves was estimated by following simple reliable equations (Sasaki 2008) because the significant wave height in most of the navigated sea area was expected to be less than 3 m:

$$\left.\begin{aligned} R_{AW} &= C_1 \frac{1}{2}\rho g\left(1 + C_2 F_{nB}^{0.8}\right) H_W^2 B B_{fcp}^2 \\ F_{nB} &= \frac{V_S}{(gB)^{0.5}} \\ B_{fcp}^2 &= \frac{1}{\left(1 + 2\left(1 - C_{pf}\right)C_{pf}\right)^2} \end{aligned}\right\} \tag{19}$$

where R_{AW} = added resistance due to waves; ρ = density of seawater; g = gravity acceleration; F_{nB} = Froude number by breadth of the ship; H_W = significant wave height; B = breadth of the ship; B_{fcp} = bluntness coefficient; V_S = ship speed; C_{pf} = fore part of the prismatic coefficient. Moreover, the abovementioned coefficients C_1, C_2 are expressed as follows:

$$C_1 = 0.46 \tag{20}$$

$$C_2 = 2.0 \text{, when } B_{fcp} > 0.3 \tag{21}$$

$$C_2 = 2.0 + 60(0.3 + B_{fxp}) \text{, when } B_{fcp} \leq 0.3 \tag{22}$$

5 OPTIMAL METHOD

Although there are several methods such as the gradient method, which uses first-order differentiation of a function, or the Newton method, which uses second-order differentiation, they require procedures for differentiation. However, the gradient could not be obtained analytically in some complex subjects such as route optimization in this study. Therefore, Powell's method, which does not use gradients, was used in this study. Moreover, the following cost function was used in this study:

$$J = FOC \tag{23}$$

The value FOC is the integrated fuel consumption during a voyage route as defined by a Bézier curve, which is an 'N - 1'th order curve defined by 'N' control points.

In the optimal procedure using Powell's method, some variables are changed through iterative calculations until convergence. Therefore, the route should be expressed by several variables.

Although there are several methods to express a curve with several variables such as a trigonometric function and multi-degree polynomials, the Bézier curve was chosen because it can be used to create a smooth curve suitable for navigation route expression. A flowchart of this optimal calculation is shown in Figure 6. Calculations were repeated automatically until the results were confirmed to converge.

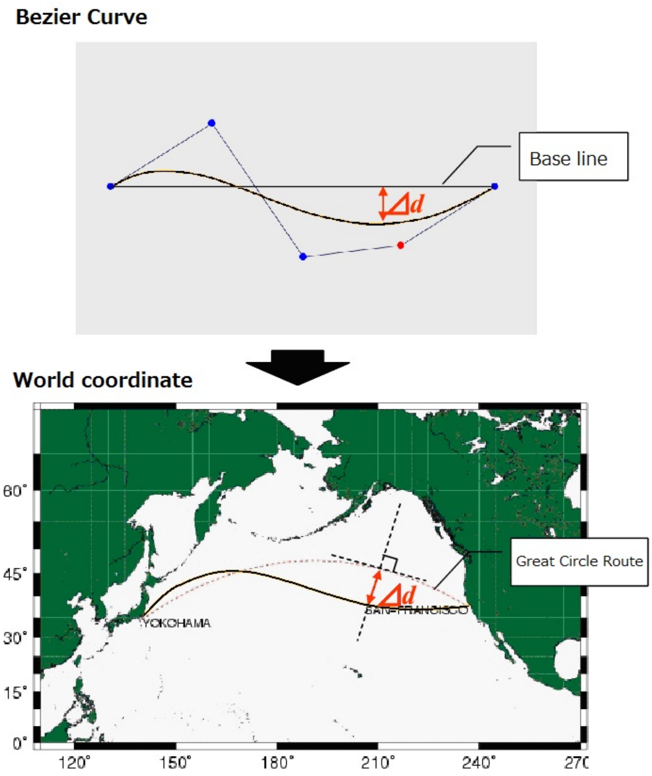

Figure 5. Bézier curve treatment for the expression of an oceangoing route. (temporary figure)

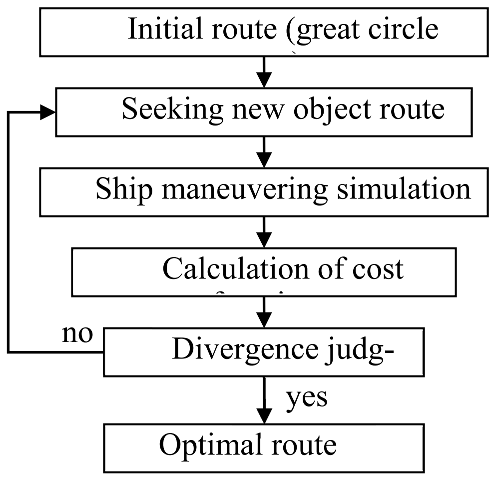

Figure 6. Flowchart of optimal calculation

6 RESULTS OF SIMULATION

The optimized westbound and eastbound routes for a voyage on 9 December 2008 using this method and the initial condition of the great circle route, i.e., minimum distance, for optimal calculation are shown in Figure 7.

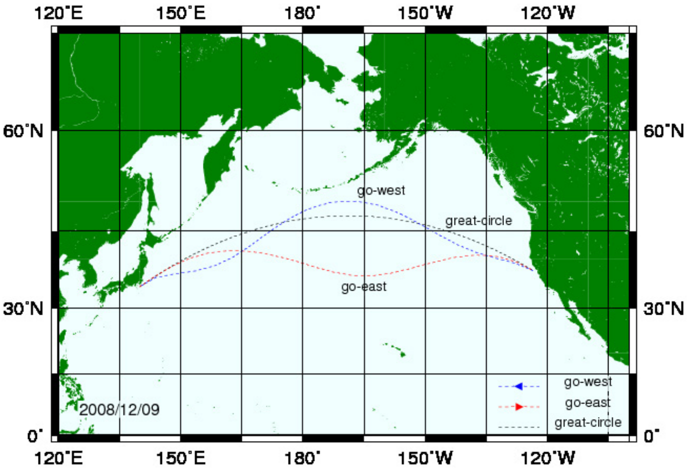

Figure 7. Optimized transportation routes between Yokohama San Francisco.

Moreover, the fuel consumption, voyage distance, and voyage time of the initial optimized routes are shown in Figures 8–10.

Although the voyage distance of the optimized route was sometimes over 200 hundred miles larger than the original great circle route, as shown in Figure 9, the fuel consumption for the optimized route was 10–50 tons less than that of the great circle route. On the other hand, the travelling times of the original and optimized routes were almost the same, as shown in Figure 10. Thus, the optimal route was concluded to be more economical. Moreover, by comparing the westbound and eastbound legs of the great circle route, the fuel consumptions of the two were found to be slightly different. This suggests that fuel consumption is affected by weather conditions such as wind and waves.

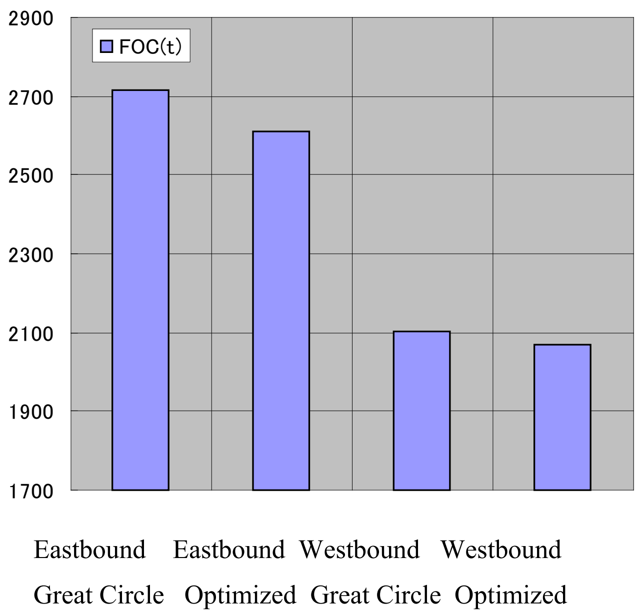

Figure 8. Comparison of fuel consumption between great circle and optimized routes.

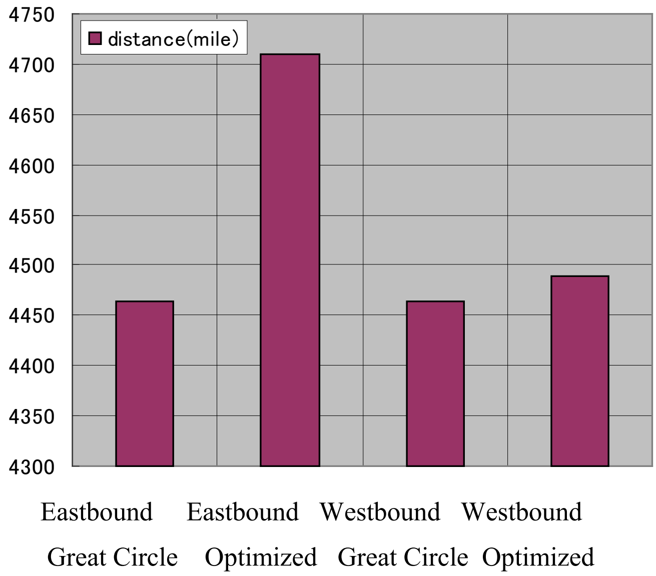

Figure 9. Comparison of voyage distance between great circle and optimized routes.

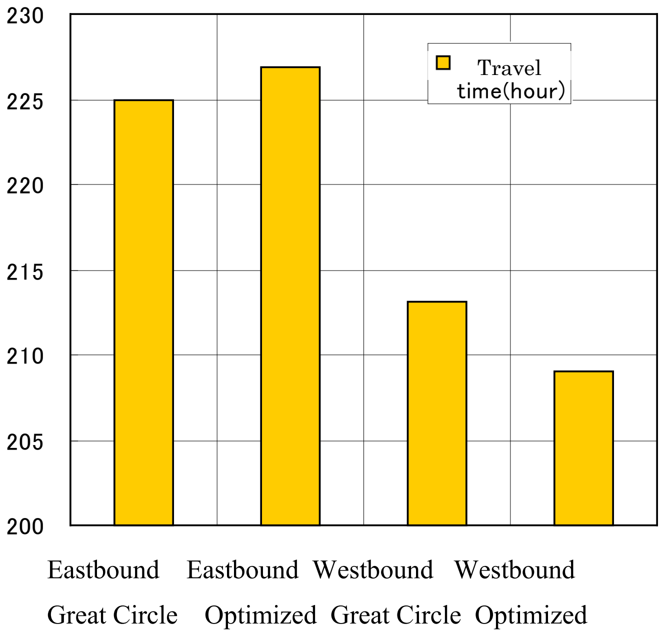

Figure 10. Comparison of voyage time between great circle and optimized routes. (to be changed, temporary figure)

7 CONCLUSIONS

In this study, advanced weather routing using a optimized method to minimize fuel consumption was demonstrated. The target ship of this study was a large container ship that traverses the Pacific Ocean between Yokohama and San Francisco. The route was expressed in term of a Bézier curve, and Powell's method (Fletcher and Powell 1963) was introduced to optimize the route. The results of this study can be summarized as follows:

1 A new weather routing method is proposed that uses an optimized Powell's method. This optimal

method can be applied to seeking an optimal navigating route.

2 Moreover, the route was expressed by a Bézier curve. The method was shown to be widely applicable to expressing a voyage route.
3 Through computer simulations, a significant reduction in fuel consumption was obtained by tracking the optimized route, even though the distance was longer than that for the great circle route.
4 This method is widely applicable to seeking optimal navigation routes in other areas.

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