Proposal of New-Generation Route Optimization Technique for an Oceangoing Vessel

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***Abstract*-The present paper proposes a new-generation route optimization technique for an oceangoing vessel. Although many studies for route optimization have been conducted, most have implicitly considered ship dynamics. The recent advances of computing performance, however, enable us to calculate ship motion dynamics. In the proposed method, numerical simulation is used to compute the objective function necessary for a route optimization model as a minimum time problem. To examine the robustness of the method, calculation results on a container linear on a trans-Pacific route as a test case are demonstrated. It is concluded that by using a Bézier curve, only a few control variables are needed to generate the optimum route. This technique is now formulated as a minimum time problem, but it could be applicable for various extended problems.**

Keywords: weather routing;ship dynamics; Bézier curve

I. Introduction

At any time throughout its voyage, an oceangoing ship can experience weather disturbances, which could alter the time schedule. Difficult weather conditions lead directly to a large energy loss, which also adversely affects the time schedule. Moreover, if a ship encounters storm events during her voyage, marine accidents are possible. Therefore, to avoid large energy loss and marine accidents while adhering to the voyage schedule, the route optimization technique called weather routing is generally applied for scheduling problems of real voyages.

Weather routing enables us to make the schedule and the route before the departure or during the voyage, and then weather forecasts and propulsion characteristics are taken into account. Recent advances of weather forecasting have been making weather routing more reliable, so that this method may play an increasingly important role in shipping service.

So far, considerable research on weather routing has been conducted. For example, Takashima et al. [1] showed that 5.7% of fuel consumption could be saved by utilizing their method, and fuel consumption is more sensitive to the selection of waypoints compared with control of the propeller revolution number. Tsujimoto & Tanizawa developed the weather adapting navigation system (WAN) [2], which enables a ship to decrease fuel consumption, and they showed that 26.1% of fuel consumption could be saved on average. In addition, they concluded that although daily renewals of weather forecasts improve total fuel consumption, the saving of fuel is generally predictable before the departure.

These studies show that the focus has primarily been on the energy loss during voyages. However, considering the recent concern with environmental protection and safeguards to prevent marine traffic accidents, objectives other than fuel consumption should be taken into account. For example, it is well known that the C11 class container ship, after encountering parametric rolling in the North Pacific Ocean, was weather-routed [3], so that the methods based only on economics were insufficient to avoid an accident. Therefore, our goal is to construct a new-generation route optimization technique in which ship dynamics and future potential risks of an individual ship can be taken into account. In this paper, as a first step, we introduce the weather routing method, which aims to reduce total navigation time by using a Bézier curve for route expression. This paper is structured as follows: after a short explanation of the mathematical model used here, the proposed novel route optimization technique is presented. Then the feasibility of the methodology is demonstrated by test calculations.

II. Mathematical Model

The mathematical model describing the ship motion is a 3-DOF (degrees-of-freedom) surge-sway-yaw maneuvering motion model. In this model, steady forces acting on the hull due to current, wind and waves are taken into account. However, time-varying forces induced by waves are ignored because it was proved by using perturbation analysis that the values resulting from waves of high frequency are a higher order than those of low frequency [4].

First, the coordinate systems are defined, as shown in Figure 1:

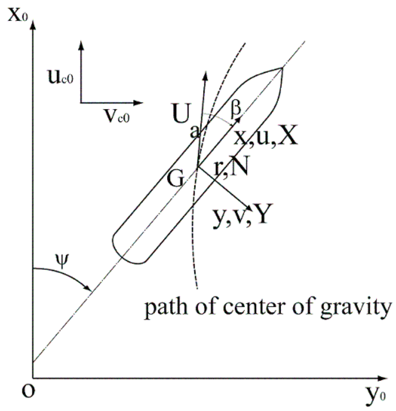

Figure 1. Coordinate systems.

Then, the mathematical model, which is primarily based on the maneuvering motion model, are described for the ship's fixed coordinate system, as follows (see Section VI "Nomenclature" for an explanation of the variables):

$$\begin{aligned}&(m+m_x)\dot{u}-(m+m_y+X_w)vr\\&-(u_{c0}\sin\psi-v_{c0}\cos\psi)(m_y-m_x+X_w)\\&=X_H+X_P+X_R+X_A+X_W\end{aligned} \quad (1)$$

$$\begin{aligned}&(m+m_y)\dot{v}-(m+m_x)ur\\&-(u_{c0}\cos\psi-v_{c0}\sin\psi)(-m_y+m_x)\\&=Y_H+Y_P+Y_R+Y_A+Y_W\end{aligned} \quad (2)$$

$$(I_{zz}+J_{zz})\dot{r}=N_H+N_P+N_R+N_A+N_W \quad (3)$$

The forces and moment acting on the hull are estimated by empirical method, as follows:

$$X_H=-R+\frac{\rho}{2}LdU_c^{\,2}\left(X'_{rr}r'^2+X'_{vv}v'^2+X'_{vr}v'r'\right) \quad (4)$$

$$Y_H=\frac{\rho}{2}LdU_c^{\,2}\left(Y'_v v'+Y'_r r'\right) \quad (5)$$

$$N_H=\frac{\rho}{2}LdU_c^{\,2}\left(N'_v v'+N'_r r'\right) \quad (6)$$

The Propeller thrust X_P is estimated as follows:

$$X_P=(1-t)\rho n^2D^4K_T(J) \quad (7a)$$
$$K_T(J)=a_0+a_1J+a_2J^2 \quad (7b)$$
$$J=u(1-w)/nD \quad (7c)$$

where each a_i is chosen on the basis of a polynomial fit of the thrust coefficient. Additionally, Y_P and N_P are considered to be zero in this paper.

$$X_R=-(1-t_R)F_N\sin\delta \quad (8a)$$
$$Y_R=-(1+a_H)F_N\cos\delta \quad (8b)$$
$$N_R=-(x_R+a_Hx_H)F_N\cos\delta \quad (8c)$$

The wind forces and moment coefficients are obtained by using the Fujiwara's method as follows:

$$\begin{cases}X_A=\frac{1}{2}\rho_AV_A^2A_TC_{XA}(\theta_A)\\Y_A=\frac{1}{2}\rho_AV_A^2A_TC_{YA}(\theta_A)\\N_A=\frac{1}{2}\rho_AV_A^2A_TC_{NA}(\theta_A)\end{cases} \quad (9)$$

The wind forces and moment coefficients are obtained by using Fujiwara's method [5], but a detailed explanation is omitted for the sake of brevity. The second-order steady force due to wave can be estimated by the method [6] which is derived by simplifying Fujii & Takahashi's method [7].

A ship is navigated by following the route joining two waypoints, and deviation from the route is corrected by ship udder control. Here, waypoints are generated on the Bézier curve connecting the departure and arrival points. The reason why a Bézier curve is chosen is that only a relatively few variables are needed to represent the complex shape of the ship route. A detailed explanation for the actual control of the variables concerning the Bézier curve is presented in the following section. In this research, ship rudder control is carried out by proportional, integral and differential (PID) control.

In this research, forecast values from the National Center for Environmental Prediction (NCEP) are used for wind and wave data, while 5-day averaged values from the National Oceanic and Atmospheric Administration (NOAA) are used as current data. Figures 2, 3 and 4 indicate the wind direction and velocity, significant wave height and 5-day averaged current, respectively, on 25 December 2008.

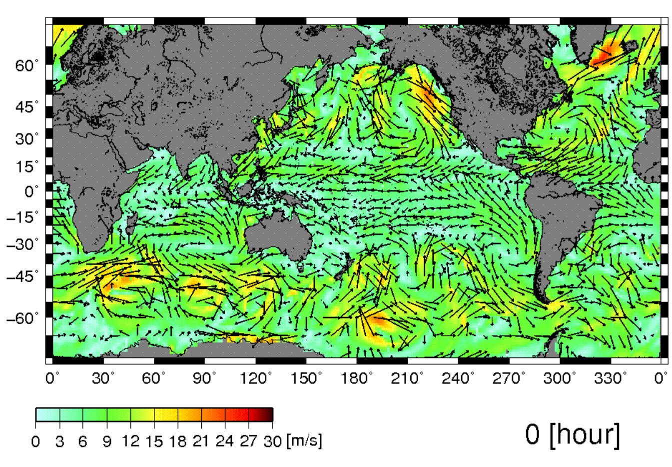

Figure 2. Forecast data of the wind direction and velocity on 25 December 2008

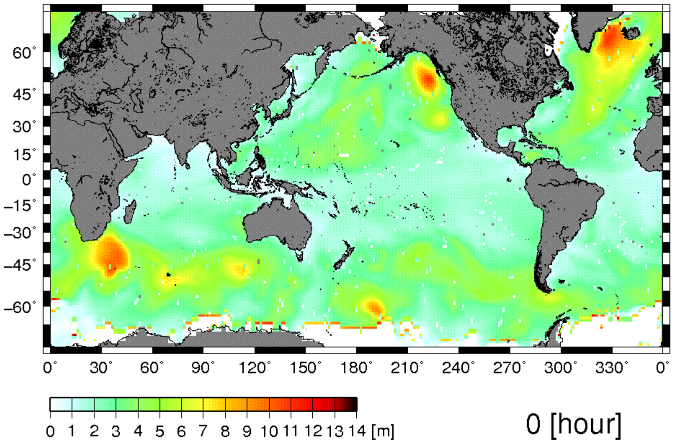

Figure 3. Forecast data of the significant wave height on 25 December 2008

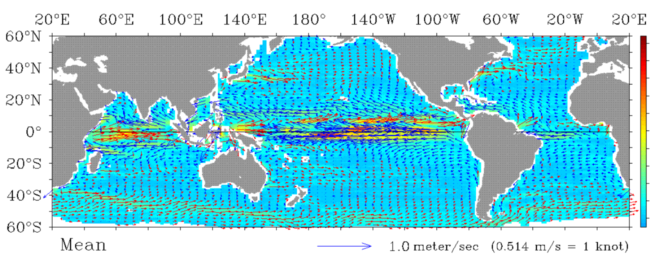

Figure 4. 5-days averaged current data around 25 December 2008

III. Route Optimization

The route optimization problem in this research is to minimize the performance index; $J = time(R)$ subject to the differential constraints, i.e. state differential equations (1)-(3). Here, $time(R)$ denotes the navigation time taken for some voyage route R, and it is calculated by numerical simulation of the ship manoeuvring motion, as mentioned above. This equation implies that weather routing is formulated as a minimum time problem, so that the solution technique for the nonlinear programming problem is applicable. In this research, the weather routing problem is iteratively solved with Powell's method [8], which is a conjugate gradient methods and does not require calculating the derivatives of the objective function as shown in Figure5. Moreover, in this study, Mercator sailing is utilized for the calculation of ship sailing, such as the distance or course.

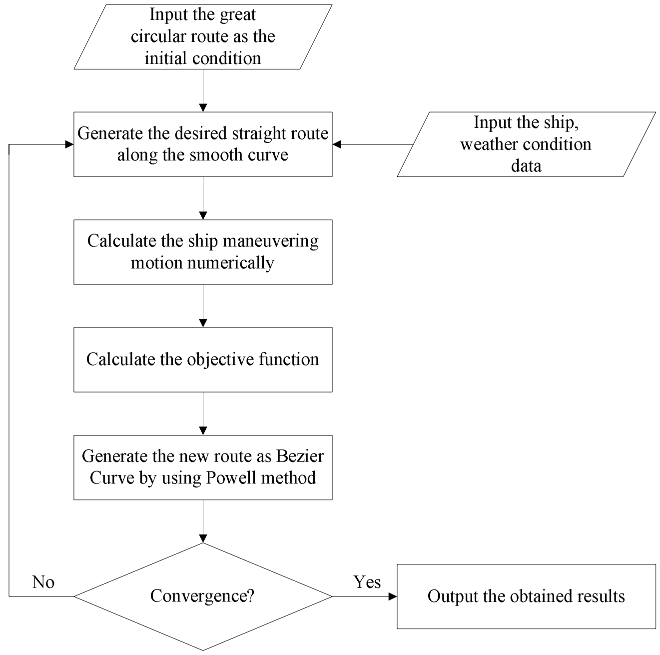

Figure 5. Flowchart of the proposed method

IV. Test Calculation

A. Traffic condition

To validate the efficiency of the proposed method, test calculations are carried out for the subject ship eastbound from Yokohama (34.30N, 140.00E) to San Francisco (37.42N, 124.30W). In this study, the great circle route is chosen as initial values for the iterative calculation. Figure 6 indicates the route connecting Yokohama and San Francisco.

The reason why the container ship is chosen as the subject ship is that the shipping service by container ships needs to be on time because the loading schedule at the container yard is arranged to the minute in advance. Principal particulars of the subject ship and are indicated in Table 1, respectively.

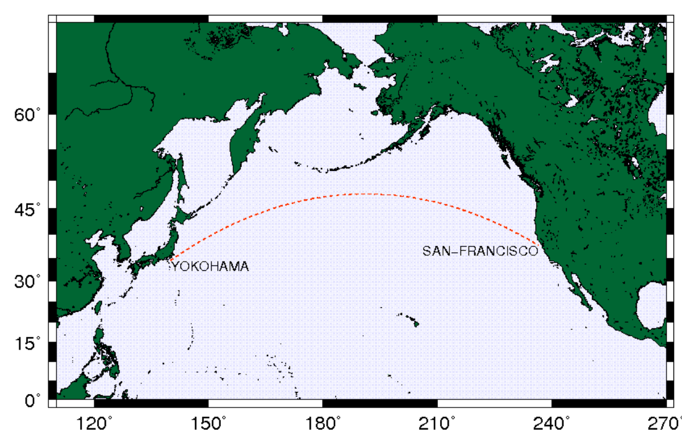

Figure 6 Great circle route connecting Yokohama and San Francisco.

TABLE I
PRINCIPAL PARTICULARS OF THE SUBJECT SHIP

Length: Lpp	285.00 m
Breadth: B	40.00 m
Depth: D	24.30 m
Draught: d	14.02 m
Propeller diameter: Dp	9.52 m
Transverse projected area: AT	1052.18 m2
Lateral projected area: AL	8284.25 m2
Block coefficient: Cb	0.6

B. Calculation Results

A Bézier curve of high degree generates a complex curve shape, but increasing the degree of the Bézier curve increases the computational time and cost, so it is desirable to find the most appropriate order of Bézier curve. Therefore, in this section, we show the comparative results between Bézier curves of different degrees. Figure 7 shows the obtained optimum voyage routes for degrees 2, 4, 6 and 8 of Bézier curves. Here, the subject ship departing at Japan on 25 December 2008 is eastbound.

In Figure 7, we notice that all the optimum solutions take a relatively southern voyage route in comparison with the great circle route utilized as the initial condition for the optimization. Figures 8-11 indicate the current speed in surge, wave speed, significant wave height and ship speed for the optimized voyage routes for the Bézier curves having degrees 2, 4, 6 and 8, respectively. The routes in these figures are for a ship departing on 25 December 2008.

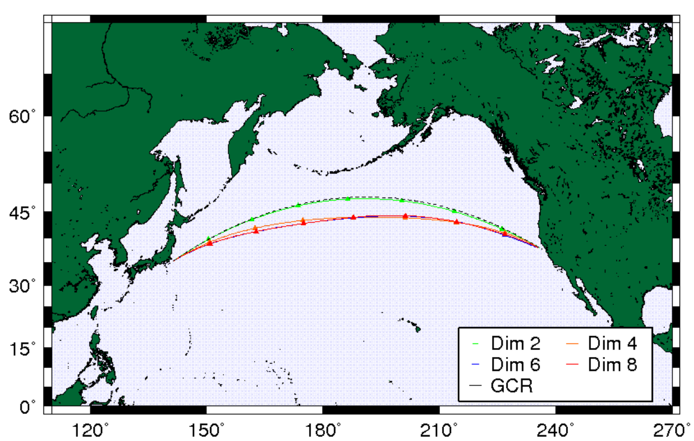

Figure 7 Obtained optimum route for Bézier curves having degrees 2, 4, 6 ,8 and the great circle route utilized as the initial condition for the optimization.

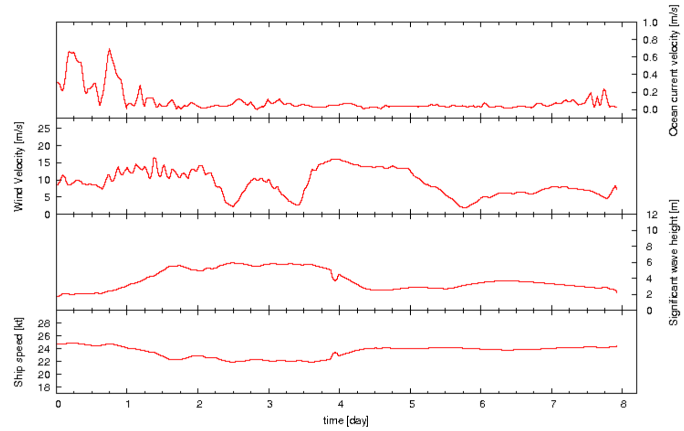

Figure 8. Ocean current velocity in surge, wind velocity, significant wave height and ship speed for the optimized voyage route for the Bézier curve of degree 2.

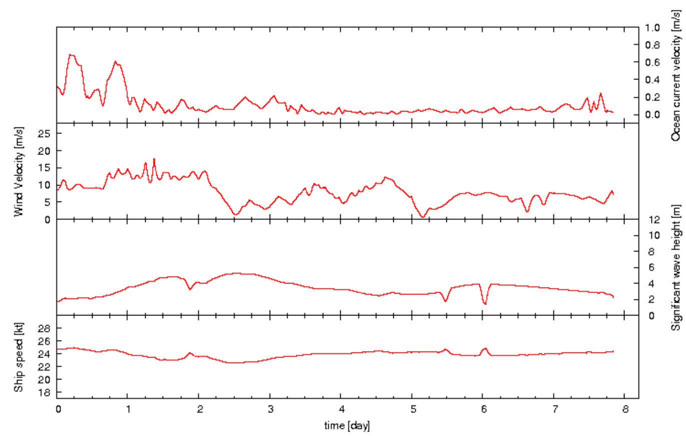

Figure 9. Ocean current velocity in surge, wind velocity, significant wave height and ship speed for the optimized voyage route for the Bézier curve of degree 4.

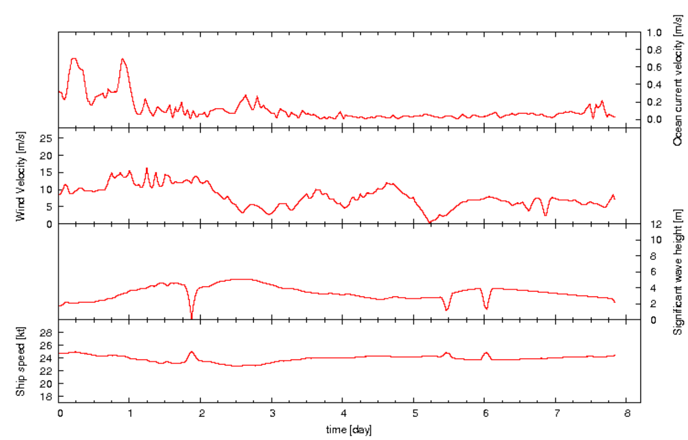

Figure 10. Ocean current velocity in surge, wind velocity, significant wave height and ship speed for the optimized voyage route for the Bézier curve of degree 6.

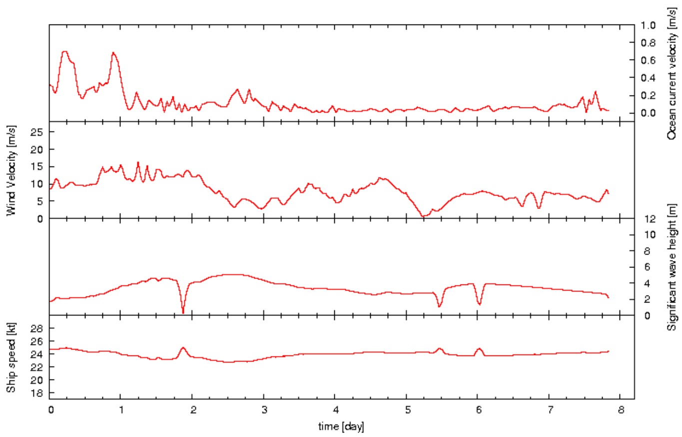

Figure 11. Ocean current velocity in surge, wind velocity, significant wave height and ship speed for the optimized voyage route for the Bézier curve of degree 8.

In these figures, we notice that the voyage route for the Bézier curve of degree 2 is the most influenced by the weather conditions because the Bézier curve of degree 2 cannot generate a complex shape of curves, and so the ship cannot avoid rough seas. In contrast, the results from the Bézier curves of degrees 6 and 8 show a similar tendency, but the speed variation is smaller on average than the curve of degrees 2 and 4.

Figures 12 and 13 show the dependency of time and the reduced time from the great circle route, respectively, on the degree of Bézier curve. In these figures, the results for the different departing dates are indicated. It is understood that, generally speaking, the larger degree of Bézier curve realizes the larger reduction of time. However, as stated above, we cannot find a large difference between the curves having degree 6 and 8 for the case of departure on 25 December 2008. In contrast, for the departure on 6 December 2008 or 22 December 2008, the reduction of time is not as large in comparison with the departure on 25 December 2008. Although the Bézier curve having degree 2 is seen to be sufficient for these two cases, it may be contingent only on the weather condition. In general, considering the computational efficiency, the route optimization using the curve having degree 6 is sufficient and recommended for practical operation.

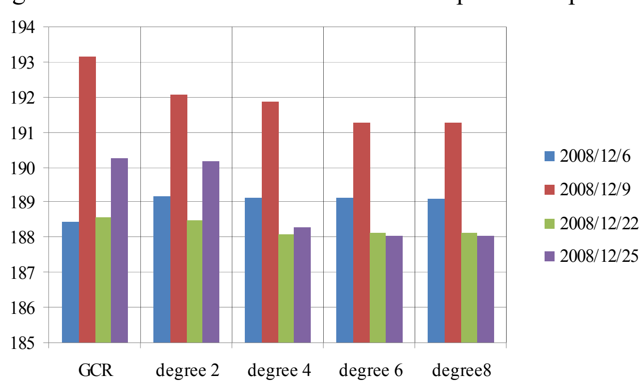

Figure 12 The dependency of the time for the different departure dates on the degree of Bézier curve.

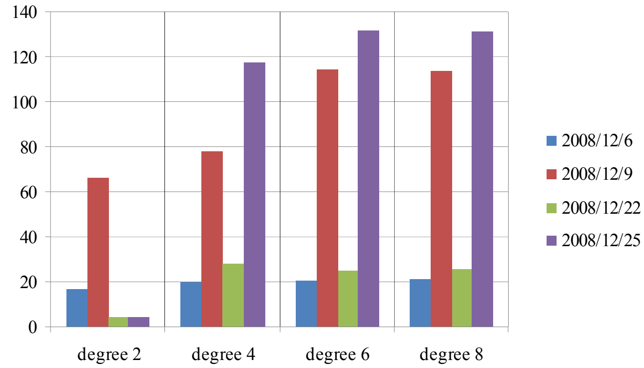

Figure 13 The dependency of reduced time from the great circle route for different departure dates on the degree of Bézier curve.

V. Concluding Remarks

In this paper, a weather routing method is formulated as a minimum time problem, and a test calculation is carried out for validation. As a result, it is shown that by using Bézier curves, relatively few control variables are needed to generate the optimum navigation route. Furthermore, a comparative study for various Bézier curves of different degrees is conducted, and it is concluded that the curve of degree 6 has the best computational efficiency for route optimization. This technique is now formulated as a minimum time problem, but it could be applicable for various extended problems in the future. Improvement of the mathematical model used here, e.g., an improved model that takes into account the heave, pitch and roll, is strongly recommended for practical purposes.

VI. Nomenclature

A_L : Lateral projected area
A_T : Transverse projected area
C_{XA}, C_{YA}, C_{NA} : Wind force coefficients for each direction
d : Ship draught
F_N : Rudder normal force
I_{zz} : Moment of inertia in yaw
J_{zz} : Added moment of inertia in yaw
L : Ship length
m : Ship mass
m_x : Added mass in surge
m_y : Added mass in sway
N_A : Yaw moment induced by wind moment
N_H : Yaw moment acting on the ship hull in calm water
N_P : Yaw moment induced by the propeller
N_R : Yaw moment induced by the rudder
N_W : 2nd-order steady moment induced by waves in yaw
N'_r N'_v : Hydrodynamic derivatives in yaw direction
r : Yaw rate
r' : Nondimensional rate of turn
R : Longitudinal hull resistance

t_R, a_H, x_H : Interaction coefficients with respect to rudder

u : surge velocity

U_c : Relative surge velocity to ocean current

u_{C0} : current velocity in x_0 direction

v : sway velocity

v' : Nondimensional sway velocity

v_{C0} : current velocity in y_0 direction

X_A : Surge force induced by wind

X_H : Surge force acting on the ship hull in calm water

X_P : Surge force induced by propeller

X_R : Surge force induced by rudder

x_R : x coordinate of rudder position

X_W : 2nd-order steady force induced by waves in surge

$X'_{rr}, X'_{vv}, X'_{vr}$: Hydrodynamic derivatives in longitudinal direction

Y_A : Sway force induced by wind

Y_H : Sway force acting on the ship hull in calm water

Y_P : Sway force induced by propeller

Y_R : Sway force induced by rudder

Y_W : 2nd-order steady force induced by waves in sway

Y'_r, Y'_v : Hydrodynamic derivatives in sway direction

θ_A : Relative heading angle to wind direction

ρ : Sea water density

ρ_A : Air density

ψ : Heading angle from x_0 direction

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