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Effect of Wind and Current on Course Control of a Maneuvering Vessel

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***Abstract*—The equations of motion of a maneuvering vessel under the action of wind, current, rudder and propulsion are solved by the MATLAB Runge-Kutta solver ode45. The hydrodynamic derivatives used are those presented by Clarke et al. (1982)[1]. Wind and current loads are applied to segments of the vessel via a relative velocity formulation and drag coefficients. Course control is achieved by autopilot gains derived from a first order Nomoto approximation. The intent is to provide a tool for assessing a vessel's maneuvering capabilities in terms of a simple single parameter (track deviation) under various environmental conditions. Results of simulations are presented for various wind and current scenarios. Keywords: maneuvering; course control; wind; current; track deviation**

I. Introduction

This paper reports the results of simulations of ship maneuvers in order to quantify ship behaviour in the presence of wind and current with autopilot course control. The model provides time histories of ship trajectory, orientation and velocity and we present the track deviations from a mean path as well as the minimum settling distance after a prescribed turn. The intent is to provide a tool for assessing a vessel's maneuvering capabilities in terms of a simple single parameter (track deviation) under various environmental conditions. This is different from other assessment tools in that in takes into account many conditions at once (rather than holding all but one constant, as is normally done) and reports a very simple answer which can be used for designing vessels and vessel steering systems for certain channels or ports. This can be a useful aid in defining safe procedures for port and harbour maneuvers in consultation with vessel operators.

II. General Model Description

The simulation model is based on standard maneuvering equations of motion which are solved by the Runge-Kutta solver ode45 in MATLAB[5]. The model requires the following inputs.

- *Environmental data.*

Water depth, wind speed and direction, current speed and direction

- *Ship's main particulars and data*

Beam at waterline, length at waterline, draft, block coefficient, displacement, rudder area, rudder lift coefficient, rudder time constant,projected areas exposed to wind and current, drag coefficients for wind and current, moment of inertia about vertical axis through ship's waterplane centre, location of centre of gravity relative to ship centre, propulsive forces at various settings, thruster forces

- *Maneuvering Coefficients (Hydrodynamic Derivatives)*

Hydrodynamic derivatives can be determined for a particular vessel either through model testing (PMM), sea trials, or by using CFD codes to emulate the PMM tests. For this study, we have used the coefficients presented by Clarke et al. (1982)[1] which were derived from analytical and empirical methods. These coefficients depend on hull geometry and are to be regarded as valid about a nominal operating surge speed. We note further that Clarke provides shallow water corrections to these coefficients. Verification of these corrections can be performed by CFD studies.

- *Autopilot gains*

These are proportional and derivative gains derived using a standard first order Nomoto approximation.

A. Governing Equations

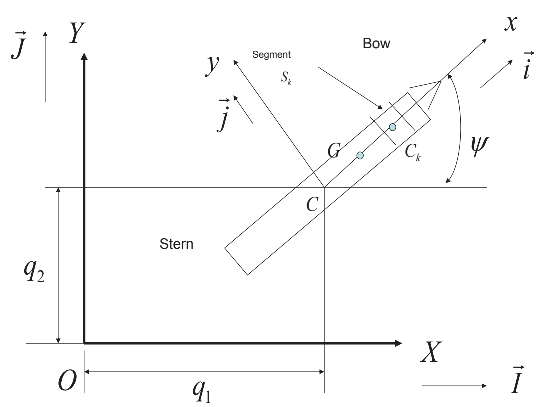


Fig. 1. Configuration

The governing equations of the maneuvering model are derived with reference to Fig. 1. We define a fixed inertial frame with origin at O and X, Y axes in the horizontal plane. The ship has a body-fixed frame B with origin at the ship's centre C. The x axis of frame B is directed along the ship's longitudinal axis as shown, and the y axis is directed towards port. Unit vectors along the x and y axes are denoted by $\overrightarrow{i}$ and $\overrightarrow{j}$ respectively. The ship's centre C has inertial coordinates (q_1, q_2). The heading angle ψ is here defined as the angle between the body-fixed x axis and the inertial X axis measured anticlockwise from the X axis, and we define $q_3 = \psi$. Let the ship centre C have velocity $\overrightarrow{v}_C$ with components u, v in the B frame,i.e.

$$\overrightarrow{v}_C = u\overrightarrow{i} + v\overrightarrow{j} \tag{1}$$

The angular velocity of the ship is

$$\overrightarrow{\omega} = r\overrightarrow{k}$$

where $r = \dot{\psi}$ and $\overrightarrow{k} = \overrightarrow{i} \times \overrightarrow{j}$ is the vertical unit vector. Differentiation with respect to time t is denoted by overdots. The centre of mass of the ship is denoted by G and is assumed to lie on the longitudinal axis with x coordinate x_G,i.e. $\overrightarrow{CG} = x_G\overrightarrow{i}$. The velocity and acceleration of G are

$$\overrightarrow{v}_G = u\overrightarrow{i} + (v + rx_G)\overrightarrow{j}$$

$$\overrightarrow{a}_G = \left(\dot{u} - vr - r^2 x_G\right)\overrightarrow{i} + \left(ur + \dot{v} + \dot{r}x_G\right)\overrightarrow{j} \tag{2}$$

and the angular acceleration of the ship is

$$\overrightarrow{\alpha} = \dot{r}\overrightarrow{k} \tag{3}$$

Let the sum of all forces and moments acting on the ship (from all sources) be equivalent to a force $\overrightarrow{F}$ at C together with a couple $\overrightarrow{N}$. Let $\overrightarrow{F} = X\overrightarrow{i} + Y\overrightarrow{j}$ and $\overrightarrow{CG} = x_G\overrightarrow{i}$. The equations of motion are

$$m_0\left(\dot{u} - vr - r^2 x_G\right) = X \tag{4}$$

$$m_0\left(ur + \dot{v} + \dot{r}x_G\right) = Y \tag{5}$$

$$I_{Cz}\dot{r} + m_0 x_G\left(ur + \dot{v}\right) = N \tag{6}$$

where m_0 is the mass of the ship and I_{Cz} is the moment of inertia of the ship about the vertical axis through C. These are the same equations presented by Clarke et al. (1982)[1].

B. MMG Model

This is a modular model of the external force components (X, Y) and couple N . These are written as (Yoshimura,1985)

$$\begin{aligned} X &= X_H + X_P + X_R \\ Y &= Y_H + Y_R \\ N &= N_H + N_R \end{aligned}$$

where the subscripts H, P, R refer to the hull,propeller and rudder respectively. We wish to add force and moment components due to current ,wind and thrusters using subscripts C,W and T respectively, so that

$$\begin{aligned} X &= X_H + X_P + X_R + X_C + X_W \\ Y &= Y_H + Y_R + Y_C + Y_W + Y_T \\ N &= N_H + N_R + N_C + N_W + N_T \end{aligned} \tag{7}$$

C. Forces on Hull in Calm Water

Following Triantafyllou and Hover (2003)[2], we express the hydrodynamic forces on the hull as perturbations about a steady forward speed u_0. These are written in the usual form as

$$\begin{aligned} X_H &= (u - u_0)\, X_u + \dot{u}X_{\dot{u}} \\ Y_H &= vY_v + rY_r + \dot{v}Y_{\dot{v}} + \dot{r}Y_{\dot{r}} \\ N_H &= vN_v + rN_r + \dot{v}N_{\dot{v}} + \dot{r}N_{\dot{r}} \end{aligned}$$

where the hydrodynamic derivatives

$$X_u,\ X_{\dot{u}},\ Y_v,\ Y_{\dot{v}},\ Y_r,\ Y_{\dot{r}},\ N_v,\ N_{\dot{v}},\ N_r,\ N_{\dot{r}}$$

are given by Clarke et al.(1982)[1].

D. Forces on Rudder

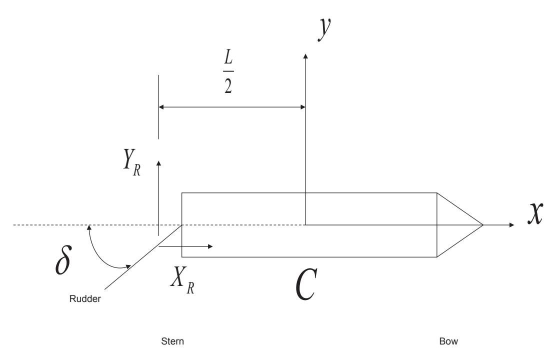


Fig. 2. Rudder Forces

The net force on the rudder is written as $X_R\overrightarrow{i} + Y_R\overrightarrow{j}$ as shown in Fig. 2. Assuming that X_R passes through C approximately, this is equivalent to a force $X_R\overrightarrow{i} + Y_R\overrightarrow{j}$ at C with a couple $N_R\overrightarrow{k} \equiv Y_R\left(\frac{L}{2}\right)\left(-\overrightarrow{k}\right)$, where L is the length of the ship at the waterline. That is, $N_R = -Y_R\left(\frac{L}{2}\right)$. Assume that the rudder force and moment are functions of the rudder angle $\delta(t)$ only and not $\dot{\delta}$ (Papoulias,[3]). We can then write

$$\begin{aligned} X_R(\delta) &= \simeq 0 \\ Y_R(\delta) &= Y_\delta \delta \\ N_R(\delta) &= N_\delta \delta \end{aligned}$$

where $Y_\delta = \left(\frac{\partial Y_R}{\partial \delta}\right)_{\delta=0}$ and $N_\delta = \left(\frac{\partial N_R}{\partial \delta}\right)_{\delta=0}$. Since $N_R = -Y_R\left(\frac{L}{2}\right)$ we have

$$N_\delta = \left(\frac{\partial N_R}{\partial \delta}\right)_{\delta=0} = \frac{\partial}{\partial \delta}\left(\frac{-Y_R L}{2}\right)_{\delta=0} = -\frac{L}{2}Y_\delta \tag{8}$$

E. Forces due to Current and Wind

In order to model the distributed current and wind forces on the ship, we divide the hull into n transverse segments $S_k \quad (k = 1, \ldots, n)$ as illustrated in Fig. 1. The centre of segment S_k is C_k and we let $\overrightarrow{CC}_k = d_k \overrightarrow{i}$ $(k = 1, \ldots, n)$. The velocity of C_k is

$$\overrightarrow{v}_{C_k} = u\overrightarrow{i} + (v + rd_k)\overrightarrow{j}$$

The current and wind velocities are specified in inertial coordinates (OXY frame) as

$$\overrightarrow{v}_{\text{current}} = v_1^{\text{c}}\overrightarrow{I} + v_2^{\text{c}}\overrightarrow{J} \quad ; \quad \overrightarrow{v}_{\text{wind}} = v_1^{\text{w}}\overrightarrow{I} + v_2^{\text{w}}\overrightarrow{J}$$

Their components in the body-fixed frame Cxy are given by

$$\begin{pmatrix} v_x^{\text{c}} \\ v_y^{\text{c}} \end{pmatrix} = [C]\begin{pmatrix} v_1^{\text{c}} \\ v_2^{\text{c}} \end{pmatrix}$$

$$\begin{pmatrix} v_x^{\text{w}} \\ v_y^{\text{w}} \end{pmatrix} = [C]\begin{pmatrix} v_1^{\text{w}} \\ v_2^{\text{w}} \end{pmatrix}$$

where matrix $[C]$ is given by

$$[C] = \begin{pmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{pmatrix} \tag{9}$$

For flow in the axial direction (unit vector $\overrightarrow{i}$), we denote the wetted surface area by A_{CA} with associated friction coefficient C_{DA}^{c}[1]. The projected surface area for wind flow in the axial direction is denoted by A_{WA} with associated drag coefficient C_{DA}^{w}. The densities of seawater and air are denoted by ρ, ρ_{air} respectively. Current and wind forces in the x direction (axial) are then

$$\begin{aligned} X_C &= \tfrac{1}{2}\rho A_{CA} C_{DA}^{\text{c}} \left|v_x^{\text{c}} - u\right| \left(v_x^{\text{c}} - u\right) \\ X_W &= \tfrac{1}{2}\rho_{\text{air}} A_{WA} C_{DA}^{\text{w}} \left|v_x^{\text{w}} - u\right| \left(v_x^{\text{w}} - u\right) \end{aligned}$$

The areas of segment S_k exposed to current and wind flow in the beam direction $\left(\text{unit vector } \overrightarrow{j}\right)$ are denoted by $A_k^{\text{c}}, A_k^{\text{w}}$ with associated normal drag coefficients $C_{DN}^{\text{c}}, C_{DN}^{\text{w}}$ respectively. Considering the flow velocities relative to the ship segment S_k, we write the forces on S_k due to current and wind as

$$\overrightarrow{F}^{\text{c}/S_k} = \gamma^{\text{c}/S_k}\overrightarrow{j} \;;\; \overrightarrow{F}^{\text{w}/S_k} = \gamma^{\text{w}/S_k}\overrightarrow{j}$$

where

$$\begin{aligned} \gamma^{\text{c}/S_k} &= \tfrac{1}{2}\rho A_k^{\text{c}} C_{DN}^{\text{c}} \left|v_y^{\text{c}} - v - rd_k\right| \left(v_y^{\text{c}} - v - rd_k\right) \\ \gamma^{\text{w}/S_k} &= \tfrac{1}{2}\rho_{\text{air}} A_k^{\text{w}} C_{DN}^{\text{w}} \left|v_y^{\text{w}} - v - rd_k\right| \left(v_y^{\text{w}} - v - rd_k\right) \end{aligned}$$

The y direction current and wind forces are therefore equivalent to forces $Y_C\overrightarrow{j}$ and $Y_W\ \overrightarrow{j}$ at point C with couples $N_C\overrightarrow{k}$, $N_W\overrightarrow{k}$ where

$$\begin{aligned} Y_C &= \textstyle\sum_{k=1}^{n} \gamma^{\text{c}/S_k} \qquad N_C = \sum_{k=1}^{n} d_k \gamma^{\text{c}/S_k} \\ Y_W &= \textstyle\sum_{k=1}^{n} \gamma^{\text{w}/S_k} \qquad N_W = \sum_{k=1}^{n} d_k \gamma^{\text{w}/S_k} \end{aligned}$$

F. Thruster Forces

Forces applied by all thrusters can be expressed as a force $Y_T\overrightarrow{j}$ at C and a couple $N_T\overrightarrow{k}$.

[1]Note that for the remainder of this discussion, superscripts 'c' and 'w' refer to 'current' and 'wind', respectively.

G. Rudder Model

Rudder dynamics is described by the equation

$$T_R\dot{\delta} + \delta = \delta_D \tag{10}$$

where T_R is the rudder time constant, $\delta(t)$ is the rudder angle and δ_D is the rudder angle demanded by the autopilot. The autopilot is a P-D type with gains selected using a Nomoto first order approximation.

H. Autopilot

The simulated autopilot system implemented here was chosen for its ease of use and its consistency. Since a vessel's steering dynamics are a function of its forward speed, proportional and derivative gains were chosen such that the steering dynamics of the closed-loop autopilot control remained the same as the open-loop dynamics of the ship (at a nominal forward speed). Reference headings were continuously fed into the controller by attempting to steer the vessel through a set of arbitrarily chosen way-points along a desired course. The first-order Nomoto approximation of the steering dynamics and the rudder demand equation were used to derive a second order differential equation for heading angle. The autopilot gains were then chosen from a specified overshoot and settling time. Due to the nature of the changing reference heading set-point and integral control's need for sufficient build-up and settling time, no integral control was used in this controller.

III. Trajectory Simulation

The generalised coordinates are q_1, q_2, q_3 as defined in Fig. 1 and we use the kinematic relations

$$\begin{aligned} \dot{q}_1 &= u\cos q_3 - v\sin q_3 \\ \dot{q}_2 &= u\sin q_3 + v\cos q_3 \\ \dot{q}_3 &= r \end{aligned} \tag{11}$$

The equations of motion are re-written in dimensionless form by defining the following dimensionless quantities

$$\begin{aligned} q_1' &= \frac{q_1}{L};\; q_2' = \frac{q_2}{L};\;\; q_3' = q_3 \\ u' &= \frac{u}{u_0};\; v' = \frac{v}{u_0};\; r' = \frac{rL}{u_0};\; t' = \frac{tu_0}{L} \end{aligned}$$

Defining the 3×1 vector $\{w\} = (u'\ v'\ r')^T$ where the superscript T indicates the transpose, we can write the equations of motion in the form

$$[A]\left\{\dot{w}\right\} = \{f\} \tag{12}$$

Define the 7×1 vector $\{z\} = (q_1'\ q_2'\ q_3'\ u'\ v'\ r'\ \delta)^T$. We then have

$$\left\{\dot{z}\right\} = \begin{pmatrix} \left\{\dot{q}'\right\} \\ \left\{\dot{w}\right\} \\ \dot{\delta} \end{pmatrix} \tag{13}$$

where the 3×1 vector $\left\{\dot{q}'\right\}$ is found from (11), the 3×1 vector $\left\{\dot{w}\right\}$ is found from the solution of (12) and $\dot{\delta}$ is given by (10). Equation (13) is solved by the MATLAB Runge-Kutta solver ”ode45”.

IV. Simulation Results

Simulations for several wind and current conditions were performed for a ship of length 194 m, breadth 26.7 m, draft 5.5 m in water depth 50 m. The ship is required to execute a 60 degree turn with 500 m radius from an initial speed of 21 knots. The objective was to quantify the track deviations from a mean path as well as the minimum distance requred to settle to a steady state speed after completing the turn. Fig. 3 illustrates a typical trajectory.

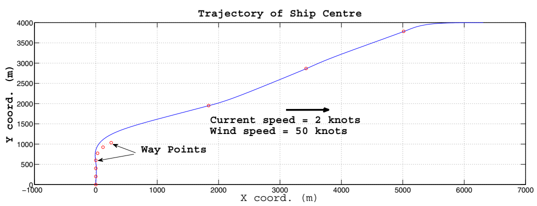


Fig. 3. Typical Trajectory

In the following polar plots, the radial lines represent the directions of wind and current vectors measured anticlockwise from the positive x axis. The plots indicate the maximum track deviations and minimum settling distance in metres for each wind or current direction.

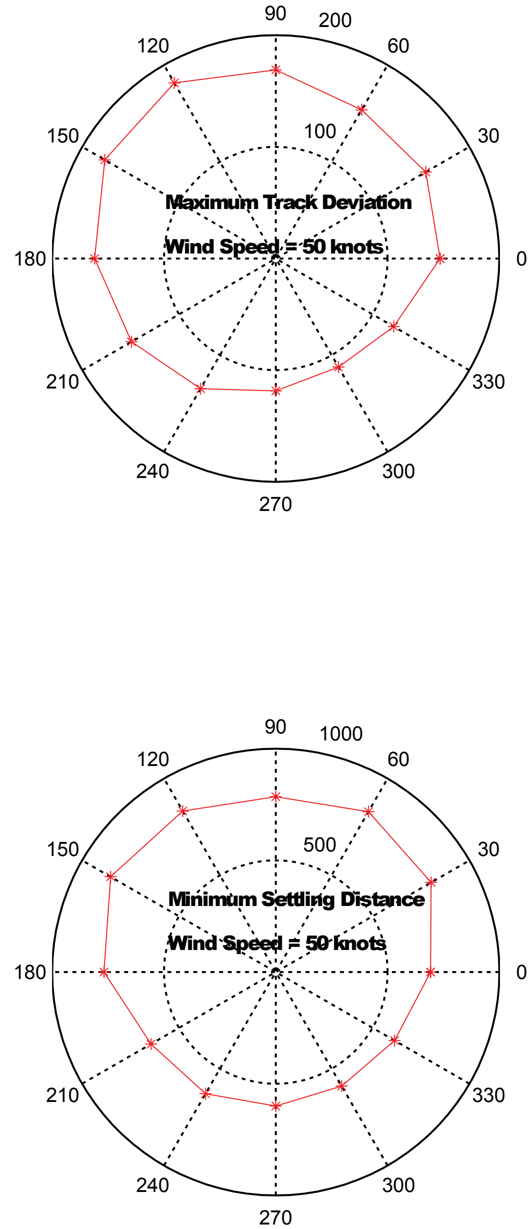
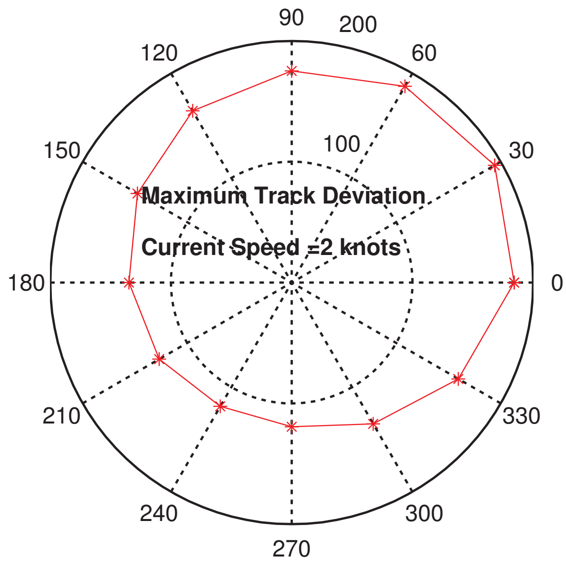


Fig. 4. Wind Speed = 50 knots



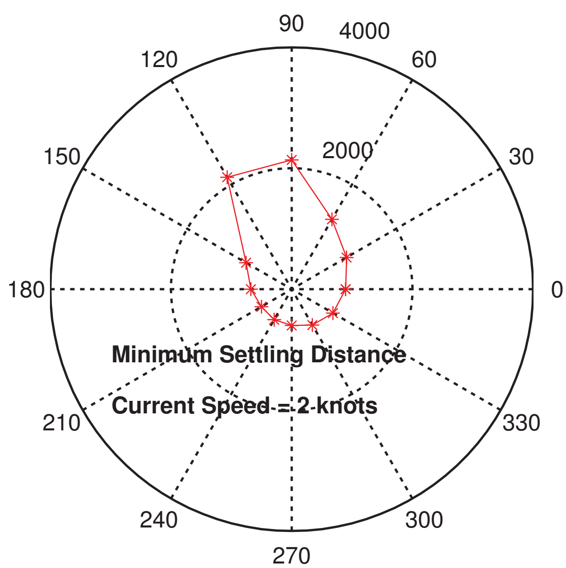


Fig. 5. Current Speed = 2 knots

V. Conclusions

We have presented the results of simulations of a maneuvering vessel under the action of wind, current, rudder and propulsion . The hydrodynamic derivatives used are those found in the literature [1] and it is recommended that these parameters be obtained for a particular vessel by model testing in conjunction with CFD studies. The wind and current loads are automatically applied at the instantaneous position and orientation of the vessel. Course control is achieved by autopilot gains derived from a first order Nomoto approximation. The track deviations from a mean path as well as the minimum settling distance after a prescribed turn are presented in an easily readable polar plot format. This provides an assessment tool that takes into account many conditions at once (rather than holding all but one constant, as is normally done) and reports a very simple answer which can be used for designing vessels and vessel steering systems for certain channels or ports. This can be used as an aid in defining safe procedures for port and harbour maneuvers in consultation with vessel operators.

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