AN AUTOMATIC DECOUPLING CONTROL SYSTEM FOR SHIP HARBOR MANEUVERS AND ITS ROBUSTNESS EVALUATION

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Abstract

Presented and discussed in this paper are mathematical model used for expressing ship motions, application of Decoupling Control Methodology to construct the automatic control system and corresponding designing issues. Computer simulation results for a Very Large Crude Carriage (VLCC) in a typical harbor maneuver are given to verify the designing of the control method. Excellent effects of the automatic control system are showed by very good simulation results of ship motions during several 180 deg. turning maneuvers under various strong wind conditions. Robustness of the control system against parameters' uncertainty, strong environment disturbances such as strong wind and currents is also studies and presented in this paper.

Keywords: Nonlinear control, Decoupling control, Ship dynamic, Robustness

1 Introduction

Controlling ship motions in harbor areas is always one of the most sophisticated actions carried out by human operators. When a ship moving at a low speed approaches or leaves a berth, the ship is often in the most complicated and dangerous operation. Therefore, to keep ships' safety, it is a very important task to construct an automatic control system for ships' harbor maneuvers.

To develop such an automatic control system for large ships, several problems must be solved. Among them the most difficult is the how to lead the ships follow a desired trajectory precisely. Then a suitable mathematical model of ship maneuvering motions in harbors and a proper control method are necessary. Since ship dynamics in harbor maneuvers are fundamentally non-linear in nature, a multi-term mathematical model of ship motions should be adopted to describe a wide range of ship maneuvering motions in harbors. The model used here was based on a well-known and widely applied one, known as the MMG model that expresses surge, sway and yaw motions of ship by open-water characteristics of hull(s), propeller(s), rudder(s) individually and interaction terms among them [1]. The model was originally presented by K. Kose et al. [2] and has further been developed by Le and Kose [3], [4] recently. All the parameters (in the model) for a Very Large Crude Carriage (VLCC) have also been estimated with high accuracy, and used in this study for simulation purpose.
Besides, to automatically control such a non-linear system, a robust control methodology must be employed. Over the last three decades, the problems of achieving decoupling, or non-interaction, in MIMO control systems has been widely studied and Decoupling Control Method (DCM) has been motivated by the needs of a wide range of applications. Because of highly coupled nature of ship dynamics, high performance requirements, and possibility to divide ships' maneuvering motions in harbors into elemental motions for practical purposes [5], the DCM can be seen as the best solution for this study.

Recently several studies concerning automatic control systems for ships' harbor maneuvers have been carried out [6] - [10], however, in most of those studies, bow and stern thrusters were used as the means to provide controlling forces and moment. But in practical handling of ships, control of large ships in harbor areas, especially in berthing and de-berthing maneuvers, usually involves the use of tugboats. This study applies the DCM to construct an automatic control system for large ships in harbor maneuvers through the use of tugboats. Excellent effectiveness of the automatic control system is illustrated by simulation results of the VLCC in a typical pattern of approaching and berthing maneuvers. Moreover, not only the accuracy of the position tracking is emphasized, but the robustness of the control system is also considered carefully.

2 The mathematical model and a typical pattern of approaching and berthing for large ships

The non-linear, multi-term mathematical model

The MMG model [1] shown in formula (1) (non-dimensional form) consists of the open-water characteristics of hull(s), propeller(s) and rudder(s) individually and interaction terms among them:

$$\begin{aligned} m^*(\dot{u}^* - v^* r^* - x_G^* r^{*2}) &= X_H^* + X_P^* + X_R^* + X_E^* \\ m^*(\dot{v}^* + u^* r^* + x_G^* \dot{r}^*) &= Y_H^* + Y_P^* + Y_R^* + Y_E^* \\ I_{zz}^* \dot{r}^* + m^* x_G^* (\dot{v}^* + u^* r^*) &= N_H^* + N_P^* + N_R^* + N_E^* \end{aligned} \tag{1}$$

Here, u^*, v^*, r^* are the ship's surge, sway and yaw velocities, respectively and $\dot{u}^*, \dot{v}^*, \dot{r}^*$ are their corresponding derivatives with respect to time; m^*, I_{zz}^* are ship mass and moment of inertia; x_G^* is distance from mid-ship to the ship's center of gravity; X, Y, N terms with subscripts H, P, R, E respectively are forces in longitudinal and lateral directions and moment induced by ship hull(s), propeller(s), rudder(s) and external effects, respectively. With the aim of controlling large ships in harbors, only the forces and moment produced by hull(s) and tugboats are considered in this study.

The forces and moment induced by ship hull(s) in low speed motions are described by a multi-terms mathematical model [2], its form is given in formula (2).

$$\begin{aligned}
X_H^* &= -m_x^* \dot{u}^* + X_{uu}^* u^{*2} + X_{vv}^* v^{*2} + (X_{vr}^* + m_y^*) v^* r^* + \\
&\quad X_{|v|vr}^* |v^*| v^* r^* / U^* + X_{vvu}^* v^{*2} u^* / U^* + X_{|v|u}^* |v^*| u^* \\
Y_H^* &= -m_y^* \dot{v}^* + Y_v^* v^* + Y_{|v|v}^* |v^*| v^* + Y_r^* r^* + \\
&\quad (Y_{ur}^* - m_x^*) u^* r^* + Y_{rrr}^* r^{*3} + Y_{vvru}^* v^{*2} r^* u^* / U^{*2} \\
N_H^* &= -J_{zz}^* \dot{r}^* + (Y_v^* v^* + Y_{|v|v}^* |v^*| v^*)(L_2^* + L_3^* b) + \\
&\quad N_r^* r^* + N_{uur}^* u^{*2} r^* + N_{rrr}^* r^{*3} + N_{vvru}^* v^{*2} r^* u^* / U^{*2} + \\
&\quad N_{|v|vr}^* |v^*| v^* r^* + N_{uvr}^* u^* v^* r^*
\end{aligned} \tag{2}$$

, here: $U^* = \sqrt{u^{*2} + v^{*2}}$ and $\tan b = -(v^* / u^*)$, m_x^*, m_y^*, J_{zz}^* are added mass and moment of inertia in the forward, transverse, and yaw directions, respectively.

Figure 2 shows the coordinate systems used in this study. All the terms in the above mathematical model are expressed in the ship-fixed coordinate system XYZ with the origin at the center of symmetry of the hull, and the Earth-fixed coordinate system is $X_0Y_0Z_0$.

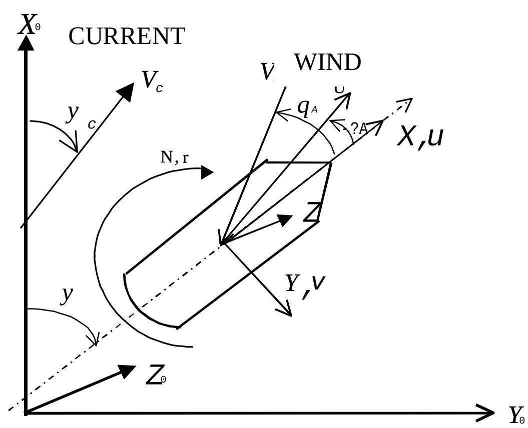

Figure 1. The coordinate system

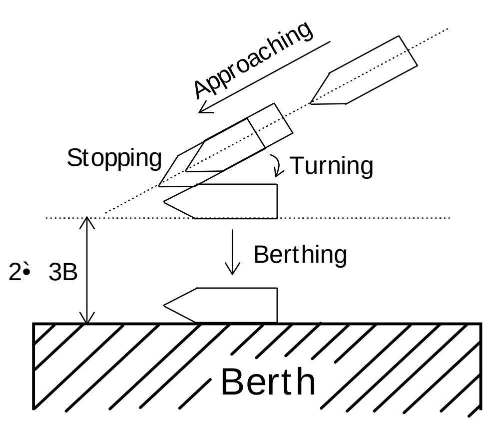

Figure 2. A typical pattern of approaching and berthing for large ships.

Typical patterns for harbor maneuvers of large ships

A typical pattern of harbor maneuvers for a large tanker [5] is shown in Fig. 2. The ship firstly enters the approaching maneuver, stops at some point located in front of a berth (this position is called as a “false goal”). There is enough safety distance between the false goal and the real berth (about 2-3 B, where B is the ship breadth molded [5]). The ship then turns around the false goal, her heading is adjusted parallel to the real berth, her longitudinal position is also adjusted to the just in front of the berth. Lastly, the ship enters the berthing maneuver by shifting laterally to the berth.

3 Application of the decoupling control methodology

Decoupling control methodology applied to the non-linear model of ship in harbor maneuvers

System of equations (1) and (2) can be rewritten in the following form of non-linear equation system:

$$M\dot{n} + N(n, h) = T \tag{3}$$

$$\dot{h} = J(h) n \tag{4}$$

, where $h = [x\ y\ y]^T$ and $n = [u\ v\ r]^T$ are the vectors that express ship position (and Euler angle) and velocity in the horizontal plane (surge, sway, yaw), respectively. Both h and n are usually assumed to be measured. M, N, T are matrices expressing influence of inertia, damping part, and control forces and moment as well as environment effects, respectively; J is transformation matrix that expresses the relationship between the $X_0Y_0Z_0$ and XYZ coordinate systems (see Fig. 1).

$$J = \begin{bmatrix} \cos y & -\sin y & 0 \\ \sin y & \cos y & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{5}$$

Equation (3) suggests a non-linear solution q_n (in the body-fixed reference frame) that satisfies:

$$T = Mq_n + N(n, h) \tag{6}$$

Taking differentiation of both sides of the equation (4) with respect to time yields:

$$\ddot{h} = J(h)\dot{n} + \dot{J}(h) n \quad \text{or} \quad \dot{n} = J^{-1}(h)[\ddot{h} - \dot{J}(h) n] \tag{7}$$

Denoting:

$$M_h = J^{-T}(h) M J^{-1}(h) \text{ and } a_h = \dot{J}(h) n + J(h) a_n \tag{8}$$

, and using equations (3) and (6) with notation (8), the following result is derived:

$$M_h[\ddot{h} - a_h] = 0 \tag{9}$$

This equation suggests that $\ddot{h} - a_h$ should have the form of a 2nd order differential expression:

$$\ddot{h} - a_h = \ddot{\tilde{h}} + K_d \dot{\tilde{h}} + K_p \tilde{h} \tag{10}$$

, where $\tilde{h} = h - h_d$ and h_d denotes the desired vector of state variables, K_d and K_p are two positive definite matrices. In order to keep the error dynamics of the control system stable, the real part of solutions of the characteristic equation $S^2 + K_d S + K_p = 0$ for (10) should be negative.

The commanded acceleration should be chosen as:

$$a_h = \ddot{h} - (\ddot{\tilde{h}} + K_d\dot{\tilde{h}} + K_p\tilde{h}) = \ddot{h}_d - K_d\dot{\tilde{h}} - K_p\tilde{h} \qquad (11)$$

4 Compute simulation results and robustness of the control system

Simulation results of a typical harbor maneuver

Applying the above described method, a position and attitude tracking controller was designed for the VLCC [4], [11]. To illustrate the application, let examine ship motions in a simple harbor trajectory similar to the typical pattern of approaching and berthing maneuvers described Fig. 2, with position and heading (x, y, Psy) of marked points in the ship trajectory given as:

- Starting position: (1000m, 900m, -145deg.),
- False goal: (0m, 150m, -180deg.),
- Real berth: (0m, 0m, -180deg.).

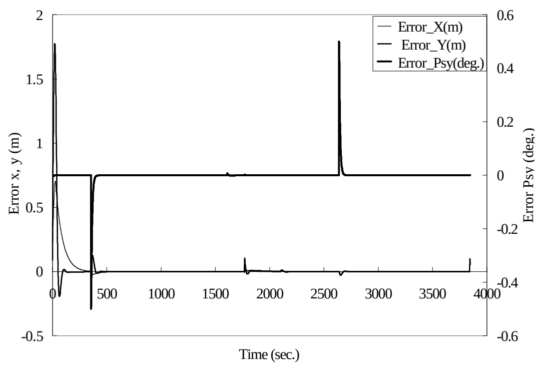

Figure 3. Tracking errors of the controller during a typical pattern of approaching and berthing

Figure 3 shows tracking errors (deviations from the designed trajectory) of the controller. Except for some small periods when the ship entered new manoeuvres, the tracking errors are considerably small and the final errors were limited to the allowable values for harbour manoeuvres (of the order of decimetre level).

Robustness of the control system again parameters' uncertainty

Since in de-berthing process ships often have to turn 180deg. in a very limited space, it is important to study the turning ability of the ship in this manoeuvre. Denoting the largest distance from initial mid-ship position to any point in the ship during ship manoeuvring by $R_{\max}$, the minimum required diameter (non-dimensional) of the basin's space for that manoeuvre is given by:

$$D_{\min} = 2R_{\max} / L \qquad (12)$$

, where L is the ship length. The smaller the value of D_{min} is achieved, the better the controller is.

Suppose that M and N respectively are the true values of added mass and moment, and damping coefficients in the formula (3) while M_e and N_e are the corresponding estimated values of M and N.

Defining the relative values:

$$m = M_e / M \text{ and } n = N_e / N \qquad (13)$$

, then the relations between the values of m, n and the corresponding values of D_{min} show the influence of the coefficients' mismatch on the performance of the automatic control system.

Simulation results of these relations are shown in Fig. 4, for 5 values of m and n: 0.25, 0.5, 1.0, 2.0, and 4.0. m = 1.0 means that there is no coefficients' mismatch on added mass and moment. Similar thing does for damping coefficients. For the cases of added mass and moment coefficients' mismatch, it is clear that the coefficients' mismatch has almost no influence on the control results. For damping coefficients' case, although the value D_{min} = 1.07 when n = 4.0 is little bit larger compared to other values of D_{min} (about 1.01), the influence of coefficients mismatch is not significant. In other words, the controller can well compensate influence of the uncertainty of model's coefficients.

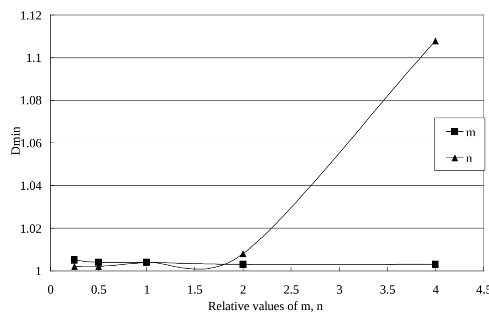

Figure 4. Influence of the coefficients' mismatch on the control results during 180 deg. turning

Robustness of the automatic control system again environmental disturbances

To study the ability of the controller in dealing with influence of environmental disturbances, several simulations of the VLCC's motions in the 180 deg. turning maneuver under various wind conditions were carried out. Simulations were carried out with the wind direction varied each 30deg. in the range from –180deg. to 180deg., while wind velocities varied with 5 values of m and n: 0.25, 0.5, 1.0, 2.0, and 4.0. Fig. 5 gives overall results of influences of the 15 m/s wind and coefficients' mismatch on the 180 deg. turning. In the case of added mass and moment coefficients' mismatch, although the value of D_{min} varies with the change of the wind direction, value of D_{min} is only a little different from the corresponding value where no mismatch has occurred (m = 1 and n = 1). In the case of damping coefficients' mismatch, results are quite different. If $N_e \le N$ (or $n \le 1$), value of D_{min} is as small as the in the situation of no mismatch, no environmental disturbances. But if $N_e > N$ (or $n > 1$), values of D_{min} are a bit larger than the corresponding value of D_{min} when there is no mismatch occurred. However, even in this case values of D_{min} are smaller than 1.2 and that shows excellent effect of the controller on cancelling the influence of the wind since the value 1.3 is considered as desired value for advanced controllers.

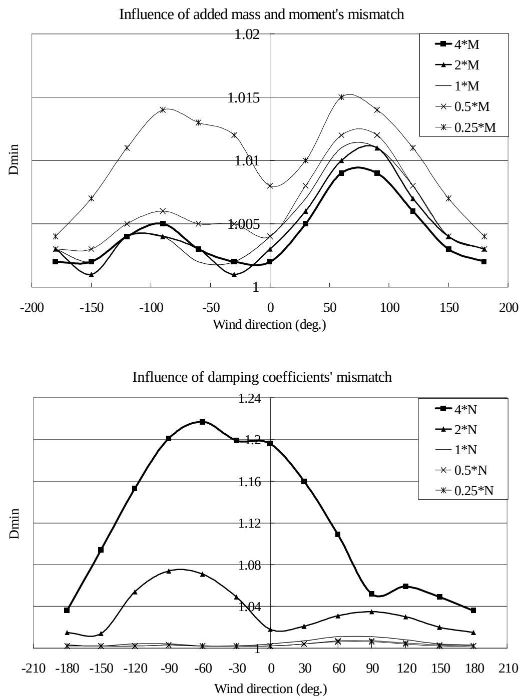

Figure 5. Influences of coefficients' mismatch and 15m/s strong wind on the control results during the 180 deg. turning manoeuvre.

5 Conclusions and future works

The Decoupling Control Methodology has been applied to design an automatic control system using a non-linear model of ship harbor maneuvers. The control method helps to reduce the complicity of the ship control system. Excellent simulation results of a typical pattern of approaching and berthing maneuvers using the control system show that the automatic control system can very well deal with the non-linear dynamics of ship motions in harbor maneuvers. The Decoupling Controller also produces extremely robustness in canceling influences of the parameter uncertainty and the environmental disturbances such as strong wind.

Some future works can be pointed out as follows: more effective methods to deal with the influence of strong current and shallow water conditions in harbour are necessary. Another possible future work is to study the use of tugboats in practice, including an optimal method for allocation of required control forces and moment to the tugboats.

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