AN AUTOMATIC DECOUPLING CONTROLLER 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 controller and corresponding designing issues. Simulation results for a Very Large Crude Carriage (VLCC) in a typical harbor maneuver are given to verify the designing of the controller. Excellent effects of the controller are showed by very good simulation results of ship motions during several 180 deg. turning maneuvers under various strong wind conditions. Robustness of the controller against parameters’ uncertainty, strong environment disturbances such as strong wind and currents is also studies and presented in this paper.

Keywords: Optimal Control, Linear control, Decoupling control, Ship dynamic, Evaluation

I. INTRODUCTION
Controlling ship motions in harbor areas is always one of the most sophisticated actions carried out by human operators. Recently the volume and size of the super tankers have considerably increased in order to meet the ever-raising demands of the marine transportation. 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, in order to keep ships’ safety, it is a very important task to construct a controller for ships’ harbor maneuvers.

To develop such controller 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. Unlike the high speed and ordinary speed maneuvers, where the mathematical models for ship have been firmly established, although in the last twenty years several studies have been carried out, there is still no established one available. The reason is that ship motions in harbor areas (usually at low speed) are very complicated, and even a simple environmental disturbance such as rather weak currents may have very strong effects on ship maneuverability.

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 (Kose, et al., 1989). The model was originally presented by K. Kose, et al., (2000) and has further been developed by Le and Kose (Le and Nguyen, 2000; Kose, 1987) 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 it is not surprising that Decoupling Control has been motivated by the needs of a wide range of applications. The highly coupled nature of ship dynamics in harbor maneuvers and high performance requirements, together with the lack of a good MIMO design procedure for the field made this study essential. Moreover, since analyses of practical control of ship show that ships’ maneuvering motions in harbors can be divided into elemental motions for practical purposes (Iwamoto, 1999), the Decoupling Control can be seen as the best choice for the control method.

Recently several studies concerning automatic control systems for ships’ harbor maneuvers have been carried out (Ogawara and Iwamoto, 1998; Berge, et al., 1998; Ohtsu, et al., 1991; Fossen, 1994; Kose, 1982) 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. Therefore, studies concerning automatic control systems for ships’ harbor maneuvers with controlling forces and moment provided from tugboats are necessary. This study applies the Decoupling Control Method (DCM) to construct a controller for large ships in harbor maneuvers through the use of tugboats. Excellent effectiveness of the controller 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. Influences of parameters’ uncertainty and environmental disturbances such as strong wind and currents are also studied.

2. THE NON-LINEAR, MULTI-TERM MATHEMATICAL MODEL

2.1 Typical patterns for harbor maneuvers of large ships

A typical pattern of harbor maneuvers for a large tanker (Iwamoto, 1999) is shown in Fig. 1. 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) so that when some troubles may happen in approach, this distance can prevent the ship from a fatal accident. The ship then turns around the false goal, her heading is adjusted parallel to the real berth, her longitudinal position is adjusted to just in front of the berth. Lastly, the ship enters the berthing maneuver by shifting laterally to the berth.

![Fig. 1 A typical pattern of approaching and berthing for large ships](image)

2.2 The non-linear, multi-term mathematical model

In this study, the MMG model (Kose, et al., 1989) is adopted to express the ship’s surge, sway, and yaw motions. The model 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:

\[ m' \left( \ddot{X} - \dot{\psi}' \dot{r}' - x_0 \dot{r}' \right) = X_0 + X_1 + X_2 + X_3 \\
\[ m' \left( \ddot{Y} + \dot{u}' \dot{r}' + x_0 \dot{u}' \right) = Y_0 + Y_1 + Y_2 + Y_3 \\
\[ I_0 \dot{\phi} + m' x_0 \left( \ddot{r}' + \dot{u}' \dot{r}' \right) = N_0 + N_1 + N_2 + N_3 \\
\]

where:
- \( u' \), \( \dot{u}' \), \( \dot{r}' \) are the ship’s surge, sway and yaw velocities, respectively and \( \ddot{u}' \), \( \dot{\psi}' \), \( \dot{r}' \) are their corresponding derivatives with respect to time;
- \( m', I_0 \) are ship mass and moment of inertia;
- \( x_0 \) is distance from mid-ship to ship’s center of gravity;
- \( X, Y, N \) terms with subscripts \( H, P, R, E \) respectively are forces in longitudinal and lateral directions and moments 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 originally presented by Kose, et al., 2000. Its form is given in the following formula:

\[ X_0 = -m' \dot{u}' - X_0' + X_0' + X_0' + X_1 + m' \dot{u}' \]
\[ X_1 = -X_1' + X_1' + X_1' + X_1' + X_2 + m' \dot{u}' \]
\[ X_2 = -X_2' + X_2' + X_2' + X_2' + X_3 + m' \dot{u}' \]
\[ X_3 = -X_3' + X_3' + X_3' + X_3' + X_4 + m' \dot{u}' \]

Here: \( U^* = \sqrt{u^2 + \dot{u}^2} \) and \( \tan \beta = (\dot{\psi}' / \dot{u}') \), \( m', m', I_0 \) are added mass and moment of inertia in the forward, transverse, and yaw directions, respectively. Non-dimensional forms of ships’ hydrodynamic coefficients are calculated using ship length (L), gravity acceleration (g), and water density (\( \rho \)) as described in (Kose, et al., 2000). All the parameters (the hydrodynamic coefficients on the left hand side of equation (2)) for a VLCC used in this study have been estimated with high accuracy (Le and Nguyen, 2000; Kose, 1987).

![Fig. 2 The coordinate system](image)

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3. APPLICATION OF THE DECOUPLING CONTROL METHODOLOGY

3.1 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:

\[ M \ddot{v} + N(v, \eta) = T \]

\[ \ddot{\eta} = J(\eta)v \]

where \( \eta = [x \ y \ \psi] \) and \( v = [u \ v \ r]^T \) are the vectors that express ship position (and Euler angle) and velocity in the horizontal plane (surge, sway, yaw), respectively. Both \( \eta \) and \( v \) are usually assumed to be measured. \( M \) is a matrix that expresses the influence of the earth-fixed reference frame \( \chi X \chi Y \chi Z \) and the body-fixed reference frame \( XYZ \) (see Fig. 2). \( T \) is a matrix that expresses control forces and moment (from tugboats, tugboats, rudders and so on), as well as the environment effects.

\[ J = \begin{bmatrix} \cos \psi & -\sin \psi & 0 \\ \sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \]

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

\[ T = \dot{a} - M_0 \dagger \eta \]

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

\[ \ddot{\eta} = J(\eta)v + J(\eta)\dot{v} \quad \text{or} \quad \dot{v} = J^{-1}(\eta)[\ddot{\eta} - J(\eta)v] \]

Denoting:

\[ M_0 = J^{-1}(\eta)MJ(\eta) \quad \text{and} \quad a_0 = J^{-1}(\eta)J(\eta)a \]

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

\[ M_0[\ddot{\eta} - a_0] = 0 \]

This equation suggests that \( \ddot{\eta} - a_0 \) should have the form of a 2nd order differential expression:

\[ \ddot{\eta} - a_0 = \ddot{\eta} + K_s \dddot{\eta} + K_p \dot{\eta} \]

where \( \ddot{\eta} = \eta - \eta_d \) and \( \eta_d \) denotes the desired vector of state variables, \( K_s \) 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 \( \lambda^2 + K_s \lambda + K_p = 0 \) for (10) should be negative.

The command acceleration should be chosen as:

\[ a_0 = \ddot{\eta} - (\dddot{\eta} + K_s \dddot{\eta} + K_p \dot{\eta}) = \ddot{\eta} - K_s \dddot{\eta} - K_p \dot{\eta} \]

3.2 Issues concerning designing of the control system

Two important issues in implementation of the Decoupling Controller are how to design the maneuvering trajectory (ship path) and how to select parameters of the control law. Denoting the steady-state reference vector of ship position by \( \eta_*, \) that is \( \eta_* = \dot{\eta}_*, \) two possible methods for computation of desired states are (Fossen, 1994):

- Using the decoupled reference models to calculate desired position:

\[ \ddot{\eta}_* + 2\zeta \omega \dot{\eta}_* + \omega^2 \eta_* = \omega^2 \eta_0 \]

- Using ship kinematics to calculate desired position and attitude:

\[ \dot{v}_d + \lambda \dot{v}_d + J^T(\eta)_d \lambda = J^T(\eta)_d \lambda \eta_0 \]

where \( v_d \) is the desired velocity, \( r_d \) is a slowly varying command input, \( \alpha > 0 \) and \( \lambda > 0. \)

The first method may result in unrealistic maneuvers of the ship since the ship dynamics have been neglected while computing the desired maneuvering trajectory. Although this problem is considered in the second method, the desired velocities do not well express ship motions in harbor maneuvers as described in 2.1. Desired velocities calculated by formula (13) will change gradually, but do not contain "no-speed-change" process as observed in many practical cases (Yamamoto, 1999). In this study, the 2nd method is modified as follow:

+ In each elemental maneuver, after reaching maximum values, ship velocities will be kept constant until the beginning of the speed-decreasing process.

+ In processes of increasing or decreasing ship speed, the desired velocities will be calculated by (13).

The beginning of the speed-decreasing process can be calculated based on the simplified mathematical model of the adopted model. For example, the forward moving motion can be simplified by following formula:

\[ (m + m_r)v = T - Ku \]

where \( T \) is force produced by tugboats in longitudinal direction, \( K = -\lambda \) (see formula (2)). Denoting:

\[ A = (m + m_r)/K \quad \text{and} \quad B = \sqrt{1/T}/K \]

the distance traveled by the ship in longitudinal direction with the initial velocity \( V_v \) is given by:

\[ x = -(A/2) \ln(1 + V_v / B) \]

If the remaining distance (to a designated position) reaches this value, the ship surge should be decreased. Similar results can be obtained for ship sway and yaw.

Value of \( \lambda \) is chosen to satisfy the following condition:

\[ \Lambda \geq \tau \]

where \( \tau \) is the (matrix) time constants of the ship.

Moreover, to ensure the limit of ship velocity \( V_v \), let \( \eta_{sw} \) be the ship position corresponding to the \( V_v \), then \( \eta \) should satisfy the following condition:
\[
\left| \mathbf{\Omega} \right| = \sqrt{\left( \mathbf{\Omega}_{1} \right) \mathbf{\Omega}_{1} + \left( \mathbf{\Omega}_{2} \right) \mathbf{\Omega}_{2} + \left( \mathbf{\Omega}_{3} \right) \mathbf{\Omega}_{3}}
\] (19)

The maximum values of ship's desired velocities should be also designed so that the ship will be kept in the track precisely. In practice, safety of the maneuvering trajectory should also be checked before being utilized.

In order to keep error dynamics of the controller stable, real part of solutions of characteristic equation for (10) should be negative. Values of parameters \( K_p \) and \( K_d \) can be chosen based on required accuracies of the tracking controller.

4. COMPUTER SIMULATION RESULTS AND EFFECTIVENESS OF THE CONTROL SYSTEM

4.1 Simulation results of a typical harbor maneuver

Applying the above described method, a position and attitude tracking controller was designed for the VLCC with the desired position and velocities calculated by formulas (13) and (14). In this study, a control system was constructed applying method presented in Section Three, and several computer simulations of various harbor maneuvers have been carried out for the VLCC with the desired position and velocities calculated by the modified method. Three tugs were used as the means to produce the control forces and moment. Of them, one tug was used for controlling ship longitudinal motion; two tugs were used for controlling ship lateral and turning motion.

To illustrate the application, let examine ship motions in a simple harbor trajectory similar to the typical pattern of approaching and berthing maneuvers described in 2.1. That kind of typical pattern helps to reduce the numbers of freedom should be controlled, so that the control action can be carried out easier. Simulation of this typical pattern was carried out with position and heading (\( x, y, \text{Psi} \)) 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](image)

Fig. 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).

4.2 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 maneuver. Denoting the largest distance from initial mid-ship position to any point in the ship during ship maneuvering by \( R_{\text{min}} \), the minimum required diameter (non-dimensional) of the basin's space for that maneuver is given by:

\[
D_{\text{av}}=2R_{\text{min}}/L
\]

(20)

where \( L \) is the ship length. The smaller the value of \( D_{\text{av}} \) is achieved, the better the controller is.

To study the controller's robustness to uncertainty of parameters, influences of mismatch of the estimated coefficients are considered. Suppose that \( M \) and \( N \) respectively are the true values of added mass and moment, and damping coefficients in the formula (3) while \( M'_c \) and \( N'_c \) are the corresponding estimated values of \( M \) and \( N \).

Defining the relative values:

\[
m = \frac{M_c}{M} \quad \text{and} \quad n = \frac{N_c}{N}
\]

(21)

then the relations between the values of \( m, n \) and the corresponding values of \( D_{\text{av}} \) show the influence of the coefficients mismatch on the performance of the controller.

![Figure 4](image)

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

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 \( D_{\text{av}} = 1.07 \) when \( n = 4.0 \) is little bit larger compared to other values of \( D_{\text{av}} \), (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.

4.3 Robustness of the controller 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. Forces and moments generated by the wind are given by:

\[
\begin{align*}
X' &= (1/2) \rho A \omega (\theta) A V^2 \\
Y' &= (1/2) \rho A \omega (\theta) A V^2 \\
N' &= (1/2) \rho A \omega (\theta) A V^2
\end{align*}
\]

(Eq. 22)

Here, \(\rho\) is air density; \(A, A\) are transverse and longitudinal projected areas, respectively; \(\theta\) is relative wind direction; \(V'\) is relative wind speed and \(C, C, C\) are forces and moment coefficients in \(X, Y, N\) directions, respectively. Relative direction of wind \(V'\) in the ship-fixed coordinate system is defined as in Fig. 2, relation between relative wind direction and forces and moment coefficients \(C, C, C\) are shown in Fig. 5. The wind and current direction was considered for each 30 deg. in the range from -180 deg. to 180 deg. Simulations were carried out for several types of wind and current velocities with 5 values of \(m\) and \(n\): 0.25, 0.5, 1.0, 2.0, and 4.0.

Fig. 5 Relation between relative wind direction and forces and moment

Fig. 6 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 \(D_{aw}\) varies with the change of the wind direction, value of \(D_{aw}\) 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 \(N_r \leq N\) (or \(n \leq 1\)), value of \(D_{aw}\) is as small as the in the situation of no mismatch, no environmental disturbances. But if \(N_r > N\) (or \(n > 1\)), values of \(D_{aw}\) are a bit bigger than the corresponding value of \(D_{aw}\) when there is no mismatch occurred.

However, even in this case values of \(D_{aw}\) are smaller than
1.2 and that shows excellent effect of the controller on canceling influence of the wind since the value 1.3 is considered as desired value for advanced controllers.

Overall simulation results of influences of the 1m/s current and coefficients' mismatch on the 180 deg. turning maneuver are given in Fig. 7. This figure shows that the current has very strong effect on control results. Although the effect of current varies with the change of current direction as well as mismatch coefficients $m$ and $n$, the values of $D_{\infty}$ for two cases: $m = 0.25$ and $n = 0.25$ are extremely larger than values of $D_{\infty}$ for other cases. The above two results mean that: in general the effect of strong wind is not significant, while as the effect of current is very strong. However, it is not out of expectation since in harbour manoeuvres ship speed is very slow.

5. CONCLUSIONS AND FUTURE WORKS

The Decoupling Control Methodology has been applied to design a controller using a non-linear model of ship harbor manoeuvres. The control method helps to reduce the complexity of the ship control system. Excellent simulation results of a typical pattern of approaching and berthing manoeuvres using the control system show that the controller can very well deal with the non-linear dynamics of ship motions in harbor manoeuvres. The Decoupling Controller also produces extremely robustness in canceling influences of the parameter uncertainty and the environmental disturbances such as strong wind, however effect of the current is still strong, especially when large mismatch of the estimated parameters occurred.

Therefore, some further research can be pointed out as follows: more effective methods to deal with the influence of strong current in harbor (for example methods for prediction current effects) are necessary. Moreover, the influence of the other external effects such as shallow water conditions should also be considered. 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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