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Design of Ship Dynamic Positioning Controller Based on Dynamic Matrix Predictive Control

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***Abstract* — This paper presents a design of ship dynamic positioning (DP) controller based on dynamic matrix predictive control (DMPC) technique. Rolling optimization and feedback correction approaches are used to design the controller. Through simulation studies and analysis of the dynamically positioned surface vessel, it can be proved that the controller can cause the ship's position and heading converge to the desired predetermined values.**

***Keywords* — dynamic positioning, dynamic matrix, feedback correction, predictive control, performance index, rolling optimization,.**

I. Introduction

The upsurge of world's inhabitants and rapid growth of the economy leads to large consumption of land resources. As a result, the problem of energy scarcities has become of more importance in today's world. Thus, developing and make use of the rich marine resources are more significant and of practical implication. With the human beings continuing to explore the deep sea, the traditional anchor mooring positioning system cannot meet the requirements of vessel positioning operation. Thus, this is the reason that the vessel dynamic positioning (DP) systems were introduced.

The DP system is an automatic control system that acts to maintain the vessel position and heading at a reference point by means of the vessel's own propulsion systems [1]. In addition, the ship DP system is a closed-loop control system of multiple inputs and multiple outputs.

The dynamic positioning system is used in a wide range of vessel types and in different marine operations such as marine construction, wreck investigation, pipe-laying and oil and gas explorations [2]. In view of that, the DP technology plays an important role in the offshore industry aimed at improving the effectiveness and safety of ocean exploitation techniques.

In the 1960s, the first DP system based on the PID control technique was introduced [3]. Consequently, a new model-based controller which is based on multi-variable optimal control and Kalman filtering techniques was employed in the design of DP control system [4]. With the advancement in control theories, many nonlinear control schemes have been developed for the DP control design so as to handle the inherent nonlinear characteristics of ships. Fossen and Grøvlen derived a globally exponentially stable nonlinear control law for DP by employing the vectorial backstepping method, where the environmental disturbances are eliminated [5]. In general, vessels controlled by dynamic positioning systems have dissimilar types of thrusters, such as azimuth thrusters, propulsion propellers with rudders, for generating forces for maintaining the vessel's desired position and heading in the horizontal plane [6 - 7]. DP systems involving different control techniques based on linear optimal and Kalman filter theories have been used in ships to overcome DP problems [4, 7].

However, the Kalman filter should in general be combined with another analytical method in practice [9]. Lee and others [10] developed a DP system based on fuzzy control theory, which was used for the control outputs, including the rudder angle, propeller thrusters, and a lateral bow thruster, to neutralize environmental forces. Tannuri and Donha developed a controller design technique for a DP system for floating production storage and offloading vessels in deep sea [11]. In 2009, Perez and Donaire proposed a control design that combined position and velocity loops in a multivariable anti-windup implementation [12]. Later, it was proven that the application of PID controllers for output feedback control, nonlinear control, or hybrid control could enhance the performance and operability of onboard dynamic positioning systems, rendering the ship appropriate for a variety of missions and environments [1].

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Without relying on ship's accurate model, robust fuzzy controller by using optimal control technique on DP ships was proposed and showed good enactment in disturbance elimination and fast response and had good robustness [13]. In order to eradicate the effects of uncertainties, backstepping control technique was applied to construct suitable virtual control law. And neural network control of DP ships was employed to solve the problem of estimate of uncertainties and unmodelled items [14]. In this context, many other studies have been conducted and proposed to enhancing the control of ship dynamic positioning system [15 – 24]. Most of the above-mentioned controllers for the DP system entail a priori information of the ship dynamics. Practically, the ship dynamics are hard to be determined since they are connected with ship's operating and environmental conditions that are constantly changing. Hence, the environmental disturbances acting on ships are always unknown and time-variant.

Inspired by the above works, this paper presents the design of dynamic positioning controller by using dynamic matrix predictive control algorithm under the condition of unknown disturbance. The dynamic matrix predictive control algorithm consists of prediction model, rolling optimization and feedback correction. One of the advantages of the proposed controller is that it belongs to the model predictive control and thus, the control law can be calculated online. In addition, the proposed controller doesn't require any a priori data of the model parameters and has the virtuous robustness against the environmental disturbances. The simulation studies are carried out on a dynamically positioned ship, and the simulation results demonstrate the efficacy of the proposed control design.

The remaining parts of the paper are organised as follows: Section 2 presents the mathematical modeling of dynamically positioned ships. Section 3 investigates the control design using DMC for the DP system. Section 4 provides the simulation studies to show the efficacy of the proposed control design. Finally, conclusions are drawn in section 5.

II. Dynamic Positioning Ship Kinematics Model

The position (x, y) and heading angle φ of the vessel in Earth's fixed coordinate system is given by a vector $\eta = [x, y, \varphi]^T = \mathbb{R}^{3\times1}$. The velocity of vessel on its own (body) frame is expressed in the vector as $\upsilon = [u, v, r] = \mathbb{R}^{3\times1}$, where u is the surge velocity, v is the velocity in sway direction and r is velocity in yaw direction.

The relationship between the vessel's position and speed in the vessel's coordinate system can be obtained by means of coordinate transformation [25]:

$$\dot{\eta} = J(\varphi)\upsilon \qquad (1)$$

where $J(\varphi)$, the rotation matrix between Earth-fixed frame and Body-fixed frame expressed by:

$$J(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad (2)$$

The horizontal plane motion equation of the dynamic positioning (DP) ship can be expressed as [25]:

$$\begin{aligned} m(\dot{u} - vr - x_G r^2) &= X_H + X_{env} + T_x \\ m(\dot{v} + ur + x_G \dot{r}) &= Y_H + Y_{env} + T_y \\ I_z \dot{r} + m x_G(\dot{v} + ur) &= N_H + N_{env} + T_n \end{aligned} \qquad (3)$$

where X_H, Y_H and N_H are hydrodynamics, in the direction of the ship's surge, sway and the yaw, in the horizontal movement. Applying Taylor series expansion, (3) can be deduced to:

$$\begin{aligned} &(m - X_{\dot{u}})\dot{u} - X_u u = X_{env} + T_x \\ &(m - Y_{\dot{v}})\dot{v} + (m x_G - Y_{\dot{r}})\dot{r} - Y_v v - Y_r r = Y_{env} + T_y \\ &(m x_G - N_{\dot{v}})\dot{v} + (I_z - N_{\dot{r}})\dot{r} - N_v v - N_r r = N_{env} + T_n \end{aligned} \qquad (4)$$

where, $\tau = \begin{bmatrix} T_x & T_y & T_n \end{bmatrix}^T$ is a three-dimensional column vector composed of forces and torque respectively, in the direction of the surge, sway and yaw produced by the cramping force. $\omega = \begin{bmatrix} X_{env} & Y_{env} & N_{env} \end{bmatrix}^T$ is the sea environment force produced by the wind, waves and water currents. Then equation (4) can be simplified as:

$$M\dot{v} + Dv = \tau + \omega \qquad (5)$$

The matrix M is the inertia mass given by:

$$M = \begin{bmatrix} m - X_{\dot{u}} & 0 & 0 \\ 0 & m - Y_{\dot{v}} & m x_G - Y_{\dot{r}} \\ 0 & m x_G - N_{\dot{v}} & I_z - N_{\dot{r}} \end{bmatrix} \qquad (6)$$

where, m is the mass of the ship, I_z is the moment of inertia along the $z-$ axis. The additional mass due to ship acceleration are $X_{\dot{u}} < 0$, $Y_{\dot{v}} < 0$ and $N_{\dot{r}} < 0$. Since the ship is moving on the ocean surface, it will be affected by wave drift and laminar surface friction, resulting in a damping matrix D, is defined as:

$$D = \begin{bmatrix} -X_u & 0 & 0 \\ 0 & -Y_v & -Y_r \\ 0 & -N_v & -N_r \end{bmatrix} \qquad (7)$$

III. Dynamic Matrix Predictive Control Predictive Model

This section presents the dynamic matrix predictive control algorithm in the design of ship dynamic positioning system controller. It can be comprehended that the algorithm is an online repeated finite time domain optimization algorithm with strong robustness.

The dynamic matrix predictive control algorithm consists of prediction model, rolling optimization and feedback correction. For the given controlled object, the step responses of the object are $a_i = a(iT)$ $(i = 1,2,\cdots,p)$, where T is the sampling period is and p is the prediction horizon. Thus, the object step response vector $\{a_1, a_2, ..., a_P\}$ will be applied to define the system predictive model [26]. When the sampling point is $t = k$, then the control input is $u(k)$. The time responses of the system at sampling points $t = k+1, ..., k+p$ are denoted as:

$$y_0(k+1|k), y_0(k+2|k), \cdots, y_0(k+p|k) \qquad (8)$$

which are known as the predictive initial values. When the sampling points are $t = k+1, ..., k+p-1$, then the system has control input increment of $\Delta u(k), \Delta u(k+1), \cdots, \Delta u(k+p-1)$. Hence, the output of the system at the given time is called the predicted output and is expressed as follows:

$$\hat{y}(k+1|k), \hat{y}(k+2|k), \cdots \hat{y}(k+p|k) \qquad (9)$$

By using linear superposition principle we can see: at time $t = k$, the input $u(k)$ has an input increment of $\Delta u(k)$, Then, $k+1, k+2, \cdots, k+p$, the output increments at time $t = k$ are $a_1 \Delta u(k), a_2 \Delta u(k), \cdots, a_p \Delta u(k)$ respectively. Then in $k+1$ the predicted output for the time is:

$$\hat{y}(k+1|k) = y_0(k+1|k) + a_1 \Delta u(k) \qquad (10)$$

On the basis of the increase, when, $\Delta u(k+1)$ then $k+2, k+3, \cdots k+p$, the resulting output increments are $a_1 \Delta u(k+1)$, $a_2 \Delta u(k+1), \cdots, a_p \Delta u(k+1)$, $k+2$ Time, the forecast output is:

$$\hat{y}(k+2|k) = y_0(k+2|k) + a_1 \Delta u(k+1) + a_2 \Delta u(k) \qquad (11)$$

The predicted output at time k is as shown in equation (12):

$$\begin{bmatrix} \hat{y}(k+1|k) \\ \hat{y}(k+2|k) \\ \cdots \\ \hat{y}(k+p|k) \end{bmatrix} = \begin{bmatrix} a_1 & & & 0 \\ a_2 & a_1 & & \\ \vdots & \vdots & \ddots & \\ a_p & a_{p-1} & \cdots & a_{p-m+1} \end{bmatrix} \bullet \begin{bmatrix} \Delta u(k) \\ \Delta u(k+1) \\ \vdots \\ \Delta u(k+m-1) \end{bmatrix} + \begin{bmatrix} y_0(k+1|k) \\ y_0(k+2|k) \\ \vdots \\ y_0(k+p|k) \end{bmatrix} \qquad (12)$$

Thus, (12) is called predictive model can be written as:

$$\hat{\boldsymbol{Y}}(k) = \boldsymbol{A} \Delta \boldsymbol{U}(k) + \boldsymbol{Y}_0(k) \qquad (13)$$

where $\Delta \boldsymbol{U}(k) = [\Delta u(k), \Delta u(k+1), \ldots, \Delta u(k+m-1)]^T$ is the system input increment at time $k, k+1, \cdots k+m-1$.

Then $\boldsymbol{A} = \begin{bmatrix} a_1 & & & 0 \\ a_2 & a_1 & & \\ \vdots & \vdots & \ddots & \\ a_p & a_{p-1} & \cdots & a_{p-m+1} \end{bmatrix}$ depends entirely on the model vector of the system $\mathrm{a} = \lfloor a_1, a_2, \cdots, a_p \rfloor$, Reflecting the dynamic performance of the system, called the dynamic matrix; $U(k)$ is the control input at time k

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and
$Y_0(k) = [y_0(k+1|k), y_0(k+2|k), ..., y_0(k+p|k)]^T$
is the constant initial value of the forecast vector at for $k+1, k+2, \cdots, k+p$.
$\hat{Y}(k) = [\hat{y}(k+1|k), \hat{y}(k+2|k), ...\hat{y}(k+p|k)]^T$ is the predicted output of the vector for $k+1, k+2, \cdots, k+p$.

A. Dynamic Matrix Predictive Control Rolling Optimization

Dynamic matrix predictive control is similar to the traditional control algorithm, that is, dynamic matrix predictive control is also through the optimization of performance indicators to determine the control strategy, but in determining the control strategy optimization process, the dynamic matrix predictive control is not for the global optimal, But is optimized for the predicted time domain. It can be seen that the dynamic optimization of the dynamic matrix prediction control is not done offline, nor is it optimized in the global scope, but rather an on-line optimization. By controlling the control target and some other application conditions, the control input in the control time domain makes a certain control performance index minimum, so that the control time domain within the time control volume. The system expects output at each moment of the future $w(k+i)$ can be obtained from (14):

$$w(k+i) = a^i y_s(k) + (1-a^i) y_r \qquad (14)$$

where a is the smoothing coefficient. Thus, the performance indicator is proposed as follows:

$$J(k) = \sum_{i=1}^{i=p} q_i [w(k+i) - \hat{y}(k+i)]^2 + \sum_{j=1}^{j=m} r_j \Delta u^2 (k+j-1) \qquad (15)$$

where q_i and r_j represent the weighting coefficients for the tracking error and the control increment respectively. By taking $\boldsymbol{w}(k) = [w(k+1) \quad \cdots \quad w(k+p)]$, then (15) can be written as:

$$\boldsymbol{J}(k) = \left\| \boldsymbol{w}(k) - \hat{\boldsymbol{Y}}(k) \right\|^2 \boldsymbol{Q} + \left\| \Delta \boldsymbol{U}(k) \right\|^2 \boldsymbol{R} \qquad (16)$$

where $\boldsymbol{Q}$ and $\boldsymbol{R}$ are the error weighting matrix and control weighting matrix respectively.

By making the performance index (16) the minimum, we can obtain a set of estimated control increments $\Delta \boldsymbol{U}(k)$ to solve the optimal value problem so that the upper performance index for minimum control incremental matrix is reached:

$$\Delta \boldsymbol{U}(k) = (\boldsymbol{A}^T \boldsymbol{Q} \boldsymbol{A} + \boldsymbol{R})^{-1} \boldsymbol{A}^T \boldsymbol{Q} [\boldsymbol{w}(k) - \boldsymbol{Y}_0(k)] \qquad (17)$$

Thus the initial control increment is used as the input of the controlled system, the control increment at the previous time is:

$$\Delta u(k) = c \Delta \boldsymbol{U}(k) \qquad (18)$$

where $c = [1 \quad 0 \quad \cdots \quad 0]^T_{1xp}$, and the control increment at the current time is:

$$u(k) = u(k-1) + \Delta u(k) \qquad (19)$$

B. Dynamic Matrix Predictive Control Feedback Correction

Due to external disturbances and other factors, (19) can be obtained depending on the control force applied to the controlled system, $k+1$ is the actual output of the system and the predicted output may not be equal, thus constituting to the prediction error as:

$$e(k+1) = y_r(k+1) - \hat{y}(k+1|k) \qquad (20)$$

By the above-mentioned weighting error, the estimated value is:

$$\tilde{\boldsymbol{Y}}_p(k) = \hat{\boldsymbol{Y}}(k) + \boldsymbol{h} e(k+1) \qquad (21)$$

where
$\tilde{\boldsymbol{Y}}_P(k) = [\tilde{y}(k+1|k), \tilde{y}(k+2|k), ..., \tilde{y}(k+p|k)]^T$
is the correction error of the system to predict the output, $\boldsymbol{h}$ is the error correction vector. Thus;

$$\begin{aligned} y_0(k+2|k+1) &= \tilde{y}(k+2|k) \\ y_0(k+3|k+1) &= \tilde{y}(k+3|\mathrm{k}) \\ &\vdots \\ y_0(k+p|k+1) &= \tilde{y}(k+p|k) \end{aligned} \qquad (22)$$

For k all the time, $k+p+1$ is the predicted value at time is corrected $k+p$.

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The corrected value of the time is:

$$\tilde{y}(k+p+1|k) \approx \tilde{y}(k+p|k) \quad (23)$$

then;

$$y_0(k+p+1|k+1) = \tilde{y}(k+p+1|k) \quad (24)$$

where

$y_0(k+2|k+1), y_0(k+3|k+1), \cdots, y_0(k+p+1|k+1)$

Recalling the initial prediction vector $Y_0(k+1)$ at time $k+1$, then

$$Y_0(k+1) = \begin{bmatrix} y_0(k+2|k+1) \\ y_0(k+3|k+1) \\ \vdots \\ y_0(k+p+1|k+1) \end{bmatrix} \quad (25)$$

which is:

$$Y_0(k+1) = S\tilde{Y}_P(k) \quad (26)$$

where $S = \begin{bmatrix} 0 & 1 & 0 \\ & \ddots & \ddots & 1 \\ 0 & 0 & 1 \end{bmatrix}$. There is $k+1$ time prediction of the initial value, according to the above process for the next round of optimization calculations, that is $\Delta u(k+1)$.

C. Establishment of Ship Dynamic Matrix Prediction Model

From (1) and (2) we can notice that when the yaw angle of the ship is small enough, we have the following [27]:

$$\mathbf{R}(\psi) \cong \mathbf{I} \quad (27)$$

Therefore, using (1) and (15) the ship state space model can be written as:

$$\begin{aligned} \dot{\boldsymbol{X}} &= \boldsymbol{AX} + \boldsymbol{B}(\tau + \omega) \\ \boldsymbol{Y} &= \boldsymbol{CX} \end{aligned} \quad (28)$$

where, $\boldsymbol{X} = \begin{bmatrix} \boldsymbol{\eta}^T & \boldsymbol{v}^T \end{bmatrix}$, $\boldsymbol{A} = \begin{bmatrix} \boldsymbol{0}_{3\times3} & \boldsymbol{I}_{3\times3} \\ \boldsymbol{0}_{3\times3} & -\boldsymbol{M}^{-1}\boldsymbol{D} \end{bmatrix}$, $\boldsymbol{B} = \begin{bmatrix} \boldsymbol{0}_{3\times3} \\ \boldsymbol{M}^{-1} \end{bmatrix}$, $\boldsymbol{C} = \begin{bmatrix} \boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} \end{bmatrix}$, Y for the ship's position and heading.

Suppose P, M and T are the prediction time domain, control time domain and sampling period respectively. In this section let as define $Y = \eta$, $U = \tau$.

The model vector consisting of the sampled values of the system when the surge control force and torque are the unit step signals: τ_1, As the unit step signal, the model vector of the ship state space model in response to the sampled values are: $\boldsymbol{a}_{11}$, $\boldsymbol{a}_{12}$ and $\boldsymbol{a}_{13}$; The Sway control force and torque τ_2 model vector of the ship state space model in response to the sampled value is: $\boldsymbol{a}_{21}$, $\boldsymbol{a}_{22}$ and $\boldsymbol{a}_{23}$; the yaw moment τ_3 for the unit step signal, the model vector of the ship state space model in response to the sampled values is: $\boldsymbol{a}_{31}$, $\boldsymbol{a}_{32}$ and $\boldsymbol{a}_{33}$; where $\boldsymbol{a}_{ij} = \begin{bmatrix} a_{ij1} & a_{ij2} & \cdots & a_{ijp} \end{bmatrix}, (i, j = 1,2,3)$ which can be obtained for each model vector corresponding to the dynamic matrix:

$$\boldsymbol{A}_{ij} = \begin{bmatrix} a_{ij1} & & & 0 \\ a_{ij2} & a_{ij1} & & \\ \vdots & \vdots & & \\ a_{ij,p} & a_{ij,p-1} & \cdots & a_{ij,p-m+1} \end{bmatrix}_{p\times m} \quad (29)$$

From (29) we obtain the following:

$$\boldsymbol{A} = \begin{bmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} & \boldsymbol{A}_{13} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} & \boldsymbol{A}_{23} \\ \boldsymbol{A}_{31} & \boldsymbol{A}_{32} & \boldsymbol{A}_{33} \end{bmatrix} \quad (30)$$

Taking $Y(k) = \begin{bmatrix} Y_1(k) & Y_2(k) & Y_3(k) \end{bmatrix}^T$ for ship position and yaw angle from $t = k$ to $t = p$ prediction output vector is:

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$$\boldsymbol{Y}_l(k) = [y_l(k+1|k) \quad y_l(k+2|k) \quad y_l(k+3|k) \quad \cdots \quad y_l(k+p|k)]_{1\times p}^T \quad (l=1,2,3) \tag{31}$$

where $\boldsymbol{Y}_l(k)$ for ship position and yaw angle from $t=k$ to $t=p$ prediction output vector is:

$Y_0(k) = [Y_{10}(k) \quad Y_{20}(k) \quad Y_{30}(k)]^T$ for ship position and yaw angle from $t=k$ to $t=p$ prediction output vector is:

$$\boldsymbol{Y}_{l0}(k) = [y_{l0}(k+1|k) \quad y_{l0}(k+2|k) \quad y_{l0}(k+3|k) \quad \cdots \quad y_{l0}(k+p|k)]_{1\times p}^T \tag{32}$$

Taking $\Delta U(k) = [\Delta U_1(k) \quad \Delta U_2(k) \quad \Delta U_3(k)]^T$ for the ship in the control of the time domain where m vector that controls incremental predictions is:

$$\Delta \boldsymbol{U}_l(k) = [\Delta u_l(k) \quad \Delta u_l(k+1) \quad \cdots \quad \Delta u_l(k+m-1)]_{1\times m}^T \tag{33}$$

where $\Delta \boldsymbol{U}_l(k)$ is the control moment and torque increments. Thus, the ship's prediction model is:

$$\begin{bmatrix} \boldsymbol{Y}_1(\mathrm{k}) \\ \boldsymbol{Y}_2(k) \\ \boldsymbol{Y}_3(k) \end{bmatrix} = \begin{bmatrix} \boldsymbol{Y}_{10}(k) \\ \boldsymbol{Y}_{20}(k) \\ \boldsymbol{Y}_{30}(k) \end{bmatrix} + \begin{bmatrix} \boldsymbol{A}_{11} & \boldsymbol{A}_{12} & \boldsymbol{A}_{13} \\ \boldsymbol{A}_{21} & \boldsymbol{A}_{22} & \boldsymbol{A}_{23} \\ \boldsymbol{A}_{31} & \boldsymbol{A}_{32} & \boldsymbol{A}_{33} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{U}_1(k) \\ \Delta\boldsymbol{U}_2(k) \\ \Delta\boldsymbol{U}_3(k) \end{bmatrix} \tag{34}$$

which can be written as:

$$\boldsymbol{Y}(\mathrm{k}) = \boldsymbol{Y}_0(k) + \boldsymbol{A}\Delta\boldsymbol{U}(k) \tag{35}$$

Rolling optimization design of dynamic matrix predictive control for ship dynamic positioning

Let $W(k) = [W_1(k) \quad W_2(k) \quad W_3(k)]^T$ be the vector of ship's reference position and the heading of the desired value, which;

$$\boldsymbol{W}_l(k) = [w_l(k+1) \quad w_l(k+2) \quad \cdots \quad w_l(k+p)]_{1\times p}^T \tag{36}$$

where $\boldsymbol{W}_l(k)$ the vector of vessel's desired position and the bow angle, where:

$$w_l(k+i) = \alpha_l^i y_{sl}(k) + (1-\alpha_l^i) y_{rl} \quad i=1,2\cdots p \tag{37}$$

where α_l is the smoothing factor for the ship's desired position and yaw angle, y_{rl} is the desired ship's position and yaw angle, $y_{sl}(k)$ stands for ship's actual output position and yaw angle. Thus;

$$\boldsymbol{J}(k) = (\boldsymbol{W}(k) - \boldsymbol{Y}(k))^T \boldsymbol{Q}(\boldsymbol{W}(k) - \boldsymbol{Y}(k)) + \Delta\boldsymbol{U}^T(k)\boldsymbol{R}\Delta\boldsymbol{U}\ (k) \tag{38}$$

where $\boldsymbol{Q}$ and $\boldsymbol{R}$ are the error matrix of the system and the control weighting matrix respectively. From (38) we obtain so the minimum performance of the control index increment as:

$$\frac{\partial \boldsymbol{J}(k)}{\partial \Delta\boldsymbol{U}(k)} = 0 \tag{39}$$

$$\Delta\boldsymbol{U}^*(k) = (\boldsymbol{A}^T\boldsymbol{Q}\boldsymbol{A} + \boldsymbol{R})^{-1}\boldsymbol{A}^T\boldsymbol{Q}(\boldsymbol{W}(\mathrm{k}) - \boldsymbol{Y}_0(k)) \tag{40}$$

Taking the control force and control torque increments, the control output $U(k)$ is:

$$\boldsymbol{U}(k) = \boldsymbol{U}(k-1) + \Delta\boldsymbol{U}_3^*(k) \tag{41}$$

where $\Delta U_3^*(k)$ is the control increment, taking $\boldsymbol{D} = \begin{bmatrix} d_1 & 0 & 0 \\ 0 & d_2 & 0 \\ 0 & 0 & d_3 \end{bmatrix}$, $\boldsymbol{d}_l = [1 \quad 0 \quad 0 \quad \cdots]_{1\times m}$, thus

$$\Delta\boldsymbol{U}^*{}_3(k) = \boldsymbol{D}(\boldsymbol{A}^T\boldsymbol{Q}\boldsymbol{A} + \boldsymbol{R})^{-1}\boldsymbol{A}^T\boldsymbol{Q}(\boldsymbol{W}(\mathrm{k}) - \boldsymbol{Y}_0(k)) \tag{42}$$

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D. Feedback correction design of dynamic matrix predictive control for ship dynamic positioning

Taking the predictive output vector as $\boldsymbol{Y}(\mathrm{k})$ in $k+1$, the predicted values of the position and the heading angle are: $y_1(k+1|k)$, $y_2(k+1|k)$ and $y_3(k+1|k)$. After the control force and torque obtained by the formula (41) are applied to the ship system at time $k+1$, the vector of the actual position of the ship and the heading angle output are: $y_{s1}(k+1)$, $y_{s2}(k+1)$ and $y_{s3}(k+1)$. Due to the influence of ocean disturbance and other disturbance factors, there will be some error between the predicted value and the real output value. The vector composed of the above error is:

$$\boldsymbol{e}(k+1)=\begin{bmatrix} y_{s1}(k+1)-y_1(k+1) \\ y_{s2}(k+1)-y_2(k+1) \\ y_{s3}(k+1)-y_3(k+1) \end{bmatrix} \tag{43}$$

In order to obtain a more accurate prediction at the next moment, it is necessary to correct the current predicted value p according to the error vector obtained by the equation (43). Then, the vector-corrected prediction of the ship's position and the heading angle prediction value at the next moment the vector is:

$$\hat{\boldsymbol{Y}}(k)=\boldsymbol{Y}(k)+\boldsymbol{He}(k+1) \tag{44}$$

where $\boldsymbol{H}$ stands for the error correction matrix. Using the corrected prediction vector $\hat{\boldsymbol{Y}}(k)$ to find the initial vector of the ship position and the heading angle through the shift matrix $k+1$ we have:

$$\boldsymbol{Y}_0(\mathrm{k}+1)=\boldsymbol{S}_0\hat{\boldsymbol{Y}}(k) \tag{45}$$

where,

$$\boldsymbol{S}_0=\begin{bmatrix} \boldsymbol{S} & & 0 \\ & \ddots & \\ 0 & & \boldsymbol{S} \end{bmatrix},$$

$$\mathbf{S}=\begin{bmatrix} 0 & 1 & & & \\ & \ddots & \ddots & & \\ & & & 1 & \\ & & & 0 & 1 \\ & & & 0 & 1 \end{bmatrix}.$$

from (45) we can obtain the next moment of the predicted output initial value, and according to the above process repeated online optimization calculation, as shown in Figure 1:

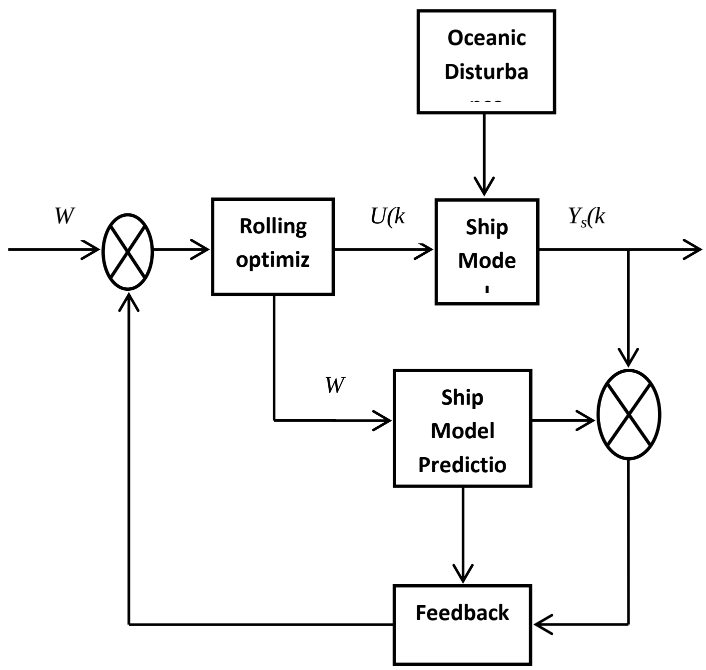

Fig. 1: The block diagram of ship dynamic positioning dynamic matrix predictive controller

IV. Simulation Study

E. Page Numbers, Headers and Footers

In order to verify the validity of the proposed controller, this section carries out a simulation study with a supply vessel. The kinetic parameters of the ship are [28]:

$$M = \begin{bmatrix} 2.642\times10^{7} & 0 & 0 \\ 0 & 3.346\times10^{7} & 1.492\times10^{7} \\ 0 & 1.492\times10^{7} & 6.521\times10^{10} \end{bmatrix}$$

$$M = \begin{bmatrix} 2.2204\times10^{4} & 0 & 0 \\ 0 & 2.2204\times10^{4} & -1.7746\times10^{6} \\ 0 & -1.7746\times10^{6} & 7.1506\times10^{8} \end{bmatrix}$$

The initial position of the ship is (0m, 0m), the heading angle is 0 °, the desired position is (20m, 20m), and the expected heading angle is 0°. The ocean simulation environmental disturbances are set as: the wave height is 3m, the wind speed is 8m/s, the flow rate is 0.5m/s. The simulation results are as follows:

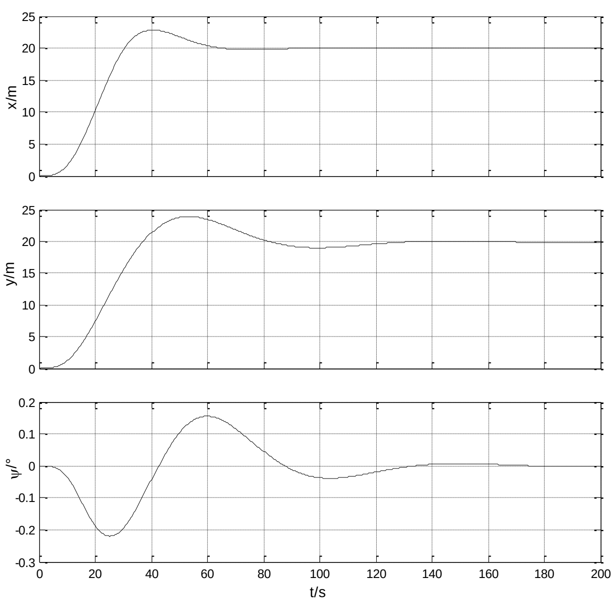

Fig. 2: The duration curve of ship's x, y direction position and heading Angle ψ

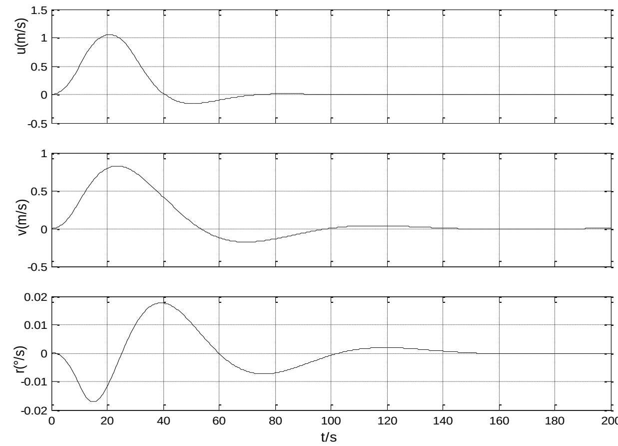

Fig. 3: The duration curve of speed in ship's surge, sway and yaw

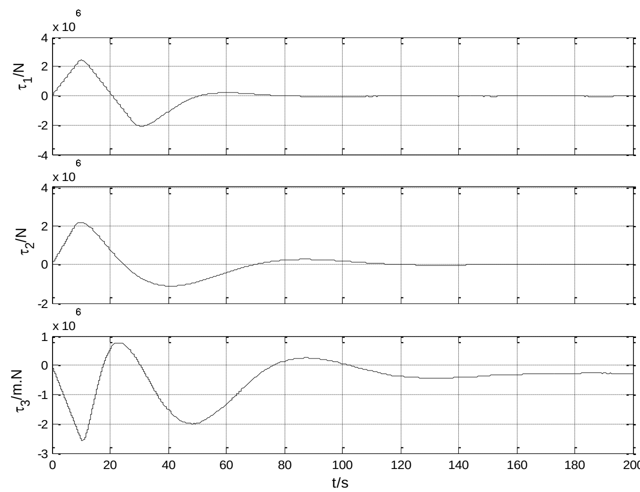

Fig. 4: The duration curve of force and torque in ship's surge, sway and yaw

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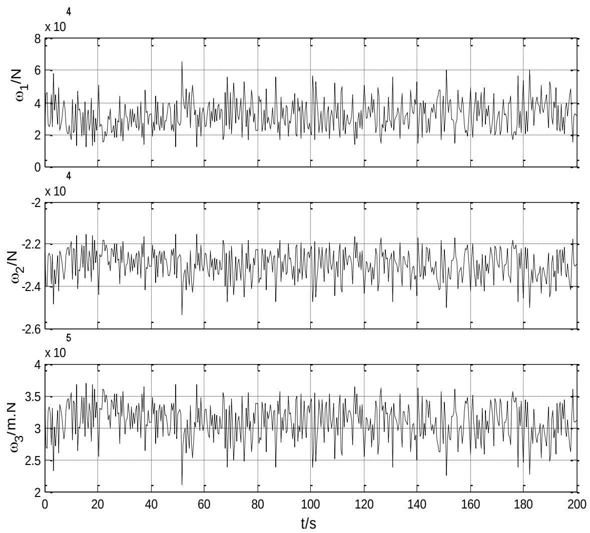

Fig. 5: The duration curve of disturbing force and torque in ship's surge, sway and yaw

It can be seen from Figure 2 that the ship dynamic positioning system controller based on the dynamic matrix predictive control design can overcome the influence of marine disturbance factors, which makes the ship tend to the desired position and bow angle. As can be seen from Figure 3, the ship reaches the desired position and the heading angle, the surge and the sway speed is 0m/s, and the yaw speed is 00/s, indicating that the ship will remain at the desired position and anticipated yaw angle. From Figure 4 shows that the control force and torque output is smooth and feasible. The validity of the designed controller is verified by the MATLAB simulation.

V. CONCLUSION

Based on the model predictive control theory, this paper studied the dynamic matrix predictive control algorithm and introduces the three components of dynamic matrix predictive control. In this paper, the dynamic matrix predictive control algorithm was introduced into the design of the ship dynamic positioning controller. The design of the ship prediction model, the rolling optimization design and the feedback correction design of the ship dynamic positioning controller are described in detail.

In the marine disturbance environment established verifies the validity of the designed controller. The feedback correction is used in the process of controller design.

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