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Research paper

A Positioning Mooring System Design for Barge Ship Based on PID Control Approach

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Abstract : This paper presents some experimental results about Position Mooring (PM) system applied to the barge ship. In PM operation, the station keeping in surge, sway of vessel is provided by the mooring system. In this paper, a system, consisting of a barge vessel and mooring lines, is mathematically modeled. The position and orientation of vessel is controlled by changing the tensions in the mooring lines. The PID control strategy is applied to evaluate the efficiency of proposed system. Experimental result which corresponds to the applied control strategy is presented and discussed.

Key Words : Positioning Mooring, Barge Ship, Tension, PID

1. Introduction

In recent years, there have been increasing activities which relate to oil exploration and exploitation as well as offshore applications such that production and pipe laying (Fig. 1).

To increase the safety and efficiency of these purposes, the offshore vessel must be satisfied about station keeping operation where the position and orientation of vessel is kept in the acceptable area. The approach of station keeping is DP or PM.

The DP system exclusively uses thrusters to control the position and heading of vessel. It is really efficient for deep water operation. In contract to DP, in the PM system, the vessel's position is keep by the mooring lines.

The mooring system basically compensates for slowly-varying disturbances. In the normal weather condition, PM system is considered as the passive control system, and the tension of mooring lines should be controlled to ensure the position as well as to prevent the line breakage in the hard disturbance conditions. The PM is the most efficient for moored vessels in shallow water with reducing the operational cost and risk. Several control strategies for modeling and PM control were proposed(1~4).

In the reference [1], the PM was modeled on the basis of mooring line tension characteristic by solving the catenary equation. The LQG controller design of an automatic thruster assisted position mooring system was also studied and the line breakage compensation with feed-forward control was recommended. Aamo and Fossen(2,3) developed a finite element model (FEM) for mooring lines which suspended in water and proposed a passive controller to reduce the fuel consumption by adjusting mooring lines' stiffness.

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Nguyen and Sorensen[4)] presented the switching control strategy for thruster-assisted position mooring. Depend on the environmental and operational conditions, a supervisor control was adopted to facilitate the automatic switching for heading, damping, restoring and mean force controllers of PM system.

In this study, the vessel is considered as barge ship. It means that the thrusters are not equipped in the vessel. The station keeping operation is done by using PM system with 4 mooring lines. The tensions of mooring lines are measured through load-cells attached at wall of the basin and each winch system. Four sail winches installed on the vessel are used to make actual control forces/change of tensions by pulling or releasing the lines. The PID control strategy is applied to evaluate an efficiency of the proposed idea and control system. Especially, all results are to be made from experimental study operated on the water pool.

Fig. 1 Oil and gas drilling operation

2. Problem Statement and Modeling

2.1. vessel dynamics

The floating vessel is usually considered as low-frequency (LF) and wave frequency (WF) model. The WF model accounts the motions due to the first-order wave disturbance, where the LF model primarily considers the effect of second-order mean and slow varying wave, current and wind load. However in PM system, the effect of WF motion is quite small and can be ignored.

The 3 DOF low frequency motions in surge, sway and yaw of floating vessel are formulated as follows:

$$\begin{aligned} &\dot{\boldsymbol{\eta}} = \boldsymbol{R}(\varphi)\boldsymbol{\nu}, \\ &\boldsymbol{M}\dot{\boldsymbol{\nu}} + \boldsymbol{C}_{RB}(\boldsymbol{\nu})\boldsymbol{\nu} + \boldsymbol{C}_{A}(\boldsymbol{\nu}_r)\boldsymbol{\nu}_r \\ &\quad + \boldsymbol{D}(\boldsymbol{\nu}_r) + \boldsymbol{G}(\boldsymbol{\eta}) = \boldsymbol{\tau}_{wave2} + \boldsymbol{\tau}_{wind} + \boldsymbol{\tau}_{moor} + \boldsymbol{\tau}_{thr}, \end{aligned} \tag{1}$$

where $\eta = [x,\ y,\ \varphi]^T \in R^3$ represents inertial position (x, y) and heading angle φ in the earth fixed coordinate frame and $\nu = [u,\ v,\ r]^T \in R^3$ describes surge, sway, and yaw rate of ship motion in the body fixed coordinate frame. The rotation matrix in heading direction $R(\varphi)$ describes the kinematic equation of motion; that is

$$\boldsymbol{R}(\varphi) = \begin{bmatrix} \cos\varphi & -\sin\varphi & 0 \\ \sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix}. \tag{2}$$

The relative velocity vector considering the effect of current is defined as:

$$\boldsymbol{\nu}_r = [u - u_c,\ v - v_c,\ r]^T. \tag{3}$$

And the current components are calculated by

$$u_c = V_c\cos(\beta_c - \psi), \quad v_c = V_c\sin(\beta_c - \psi), \tag{4}$$

where V_c and β_c are the velocity and direction of surface current.

$M \in R^{3x3}$ is the low-frequency system inertia matrix including added mass, $C_{RB}(\nu) \in R^{3x3}$ and $C_A(\nu_r) \in R^{3x3}$ are the skew-symmetric Coriolis and centripetal matrices of the rigid body and added mass. $D(\nu_r) \in R^3$ is the damping vector, which is a function of the relative velocity ν_r.

The restoring vector $G(\eta) \in R^3$, caused by the buoyancy and gravitation just affected by heave, roll and pitch motion, is neglected in horizontal motion. In station keeping application, where the velocity of ship is assumed small, $C_{RB}(\nu)\nu + C_A(\nu_r)\nu_r$ can be ignored and $D(\nu_r)$ is assumed to be constant. τ_{wave2}, τ_{wind}, τ_{moor} and τ_{thr} are second-order wave disturbance, wind, mooring and thruster vectors, respectively.

2.2 multi-cable mooring system

The mooring line attached at one end to the vessel via a winch system and the other end is fixed to the sea-floor by anchor. Commonly, the mooring line is subjected to three types of excitation: large amplitude LF motion, medium amplitude WF motion and small amplitude very high frequency vortex-induced vibration[5]. In the PM system design, it is simplified by considering the influence due to LF motion. Thus the model for the generalized mooring force is

$$\boldsymbol{\tau}_{moor} = -\boldsymbol{R}(\varphi)\boldsymbol{g}_{mo}(\boldsymbol{\eta}) - \boldsymbol{d}_{mo}(\boldsymbol{v}). \tag{5}$$

Where d_{mo} is the additional damping and g_{mo} is the Earth-fixed restoring force due to the mooring system. The Earth-fixed restoring force is a combination of tensions produced from the mooring lines. It can be given by the following expression

$$\boldsymbol{g}_{mo} = \boldsymbol{T}(\alpha)\boldsymbol{H}, \tag{6}$$

where $T(\alpha) \in R^{3\times N}$ is the mooring line configuration matrix and N is the number of mooring lines. Then it can be defined as

$$\boldsymbol{T}(\alpha) = \begin{bmatrix} \cos\alpha_1 & \dots & \cos\alpha_N \\ \sin\alpha_1 & \dots & \sin\alpha_N \\ x_1\sin\alpha_1 - y_1\cos\alpha_1 & \dots & x_N\sin\alpha_N - y_N\cos\alpha_N \end{bmatrix}, \tag{7}$$

where x_i, y_i, and α_i are moment arms and angle between mooring line and x axis of vessel as shown in Fig. 2. The horizontal force produced from each mooring line is the function of the horizontal distance between the top point and the anchor point of the line and the line length. Several marine software packages that solve the nonlinear horizontal force of mooring line are readily available.

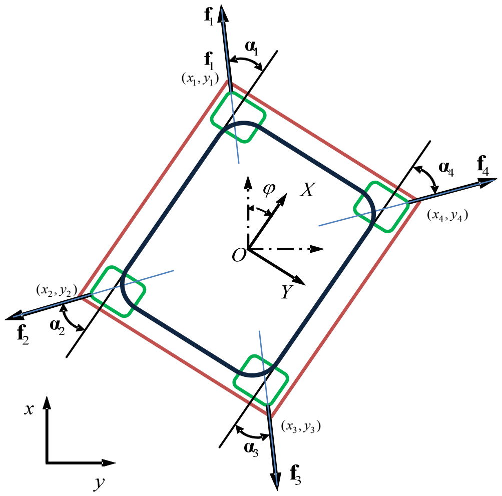

Fig. 2 Mooring line configuration in vessel control system

3. Controller Design and Experiment

3.1 controller design and experimental setup

In this paper the author apply PID control approach to the position keeping experiment. And experiment results are to be shown. For this, the experimental set-up is illustrated in Fig. 3, and the schematic diagram for experimental is shown in Fig. 4. As illustrated in the figures, the control system (NI CompactRio) is placed on the vessel and works by itself.

However, the vessel motions are captured by the CCD camera which is attached on the celling. The image data obtained by camera is transferred to host onshore computer, and vessel motions are calculated by using vector code correlation technique in real time$^{6\sim7)}$. Then the calculated position and heading angle are sent to a real time control system CompactRio placed on the vessel.

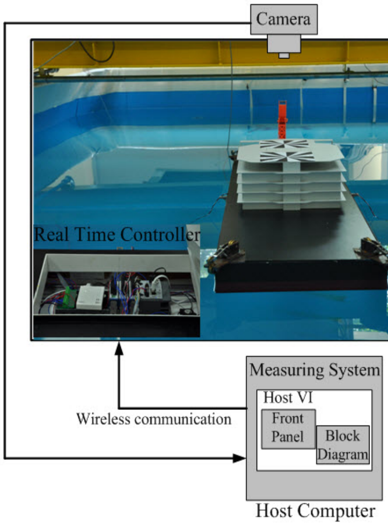

Fig. 3 Photo of the experiment system setup

Also, the information including vessel motions and all sensing signals are transferred to the monitoring system (Host Computer) by wireless network. The process and technique for experiment are precisely illustrated in Fig. 4 and Fig. 5 as described in previous. Where, the vessel comprises the barge ship and mooring lines. Especially, the barge ship has a mass m=18.5[kg], length, L=1.3[m] and breath, B=0.4[m]. And 4 mooring lines are properly interconnected between the vessel through sail winches and the wall of basin. Also, the load-cells to measure the cable tension are placed on the cable. Where the submerged mass (Balancing Weight in Fig. 4) are suspended between the two end points of cable to illustrate the passive control property of PM system which provides the restoring, damping and mean control forces to compensate the load variation due to wind, wave and current. Here, the weight of each mass is 0.2[kg].

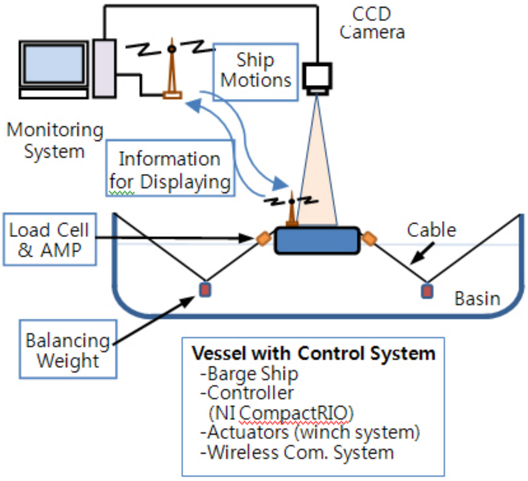

Fig. 4 Schematic diagram of experimental set-up

3.2 experiment results

The inertia and damping matrices of barge ship, M and D, are calculated by hydrodynamic software package and experiment as:

$$\boldsymbol{M}=\begin{bmatrix} 20.2[\mathrm{kg}] & 0 & 0 \\ 0 & 28.2[\mathrm{kg}] & 0.5[\mathrm{kg}\times\mathrm{m}^2] \\ 0 & 0.5[\mathrm{kg}] & 3.0[\mathrm{kg}\times\mathrm{m}^2] \end{bmatrix}, \qquad (8)$$

$$\boldsymbol{D}=\mathrm{diag}\{1.6[\mathrm{kg/s}],\ 8.0[\mathrm{kg/s}],\ 1.2[\mathrm{kg.m^2/s}]\}.$$

The mooring lines configuration are described as

$$(x_1,y_1)=(-0.65,0.2),\ (x_2,y_2)=(0.65,0.2),$$
$$(x_3,y_3)=(0.65,-0.2),\ (x_4,y_4)=(-0.65,-0.2). \qquad (9)$$

The PID controller used in this study has following structure:

$$\boldsymbol{\tau}_{cmoorPID} = \boldsymbol{R}^T(\varphi)(\boldsymbol{K}_p(\boldsymbol{\eta} - \boldsymbol{\eta}_d) + \boldsymbol{K}_i \int_0^t (\boldsymbol{\eta} - \boldsymbol{\eta}_d)) \quad (10)$$

The integral term is used to eliminate the steady-state error between the desired position and actual position of vessel. K_p and K_i are provided as:

$$\boldsymbol{K}_P = \begin{bmatrix} 15.15 & 0 & 0 \\ 0 & 21.15 & 0.375 \\ 0 & 0.375 & 2.25 \end{bmatrix}, \quad (11)$$

$$\boldsymbol{K}_I = \begin{bmatrix} 0.454 & 0 & 0 \\ 0 & 0.634 & 0.011 \\ 0 & 0.011 & 0.067 \end{bmatrix}. \quad (12)$$

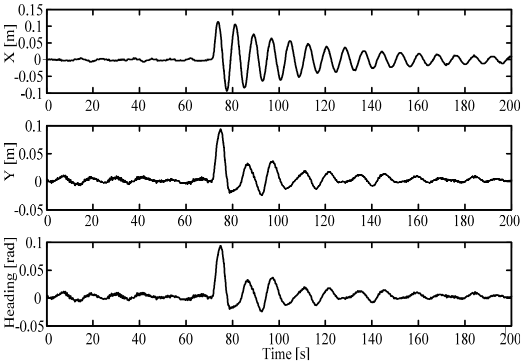

Fig. 5 Ship motions in wave disturbance without control

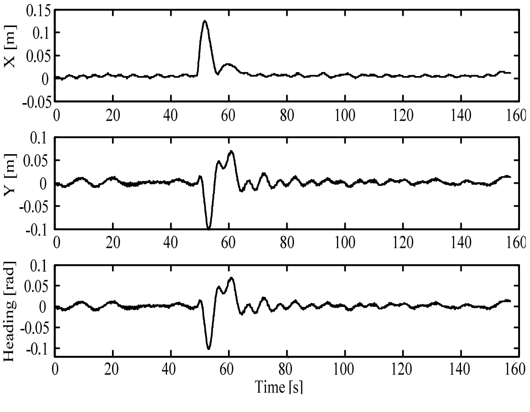

Fig. 6 Station keeping experiment in wave disturbance by using PID control

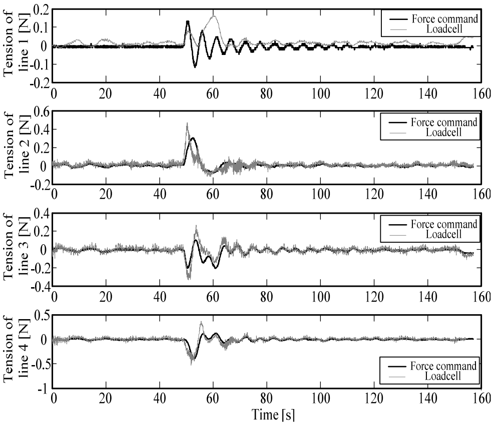

Fig. 7 Comparison between commanded forces produced from PID controller and actual tension lines

Figs. 5-7 show the performance of the controlled and uncontrolled cases. Fig. 5 shows the position keeping performance of uncontrolled case with wave disturbance. However, Fig. 5 illustrates when the hard disturbance condition is considered, the good performance of ship cannot be maintained. In this case, the ship is continuously oscillated for long time. In contract to the non-activated control given in Fig. 5, good control performance can be preserved from normal to hard disturbance condition in the case of PID control as shown in Fig. 6. The winches system change the tension of mooring lines to make the barge ship return to initial position after affection of environmental loads. The comparison between the commanded tension and actual tension of each mooring line is shown in Fig. 7. With controlling the winch by pulling and releasing each line, the tension of mooring line can follow the commanded tension made from controller. In the PID case, the smoother change of commanded tension is shown.

4. Conclusion

In this paper, as the first tries, the authors build up a mooring system model for barge ship. The system comprises a barge ship, mooring lines and winches. The mathematical system model is considered as low frequency model which means primarily the effect of second-order and slow varying wave, current and wind loads. Several experiment results by using PID control strategy is presented and discussed. The good performance of controlled system gives the motivation to improve and develop this system in the future study.

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