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A study of Ship's Mooring Method with Controllable Pitch Propeller (CPP) by Applying Generalized Minimum Variance Control

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Abstract— **The purpose of this study is to improve a mooring system with Controllable Pitch Propeller (CPP). Because of the slip of propeller, velocity response of CPP has time delay. In this study, the ship's propelling force with the CPP's angle was identified on an actual ship and delay time was observed by analyzing the data of propelling force. Then the CPP angle is controlled by using Generalized Minimum Variance Control (GMVC) to obtain better performance for the mooring system.**

I. INTRODUCTION

The mooring lines are usually used to moor a ship to a pier [1] in the soft wind. But in the case of a strong wind, ships usually leave piers and drop their anchors offshore because the strong wind may cut their mooring lines, otherwise, the ships may drift about near the piers leading to damages on their hull [2]. Therefore, the mooring line is so important that we can avoid the malign influence by the wind [1]. In order to avoid this type of undesirable consequence by a strong wing, a way to moor a ship to the pier is to use Controllable Pitch Propeller (CPP) [3]. Fig.1 shows typical shapes of CPPs: Forward (ahead), Neutral, and Backward (astern). A mechanism of CPP, which can change propeller's pitching angle to control the ship's propelling force back and forth, allows to maintain the revolution of engine by controlling the pitch angle of propellers. Fig.2 depicts a ship mooring to the pier in the strong wind. The CPP angle is set ahead when the wind blows from the ship's prow. On the contrary, CPP angle is set astern in the case of the back wind. Then the propelling force can be balanced with respect to the direction and power of the wind.

The way to keep mooring to the pier by using CPP has been popular these days because the CPP type propeller spreads out. However, the mooring with the CPP in a strong wind requires manual operation of CPP angle by a crew of the ship.

In this study, a new mooring method in the strong wind environment is proposed. The proposed method optimizes the CPP angle. Generally the CPP angle is calculated based on the real-time wind data, but the CPP propelling response has time delay. Therefore, the CPP angle is optimized by using Generalized Minimum Variance Control (GMVC) [4][5][6][7], which is a predictive control method effective to the system with time delay.

First, CPP propelling response without the wind was analyzed. Second, the wind's effect without CPP's force is measured [8]. Third, Auto-Regressive Moving Average (ARMAX) model is designed to identify the system by results of the CPP and the wind. Finally, GMVC for CPP propelling against the wind is designed.

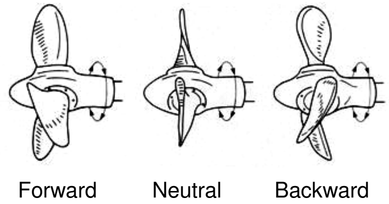

Fig. 1. Force and its direction generated by Controllable Pitch Propeller

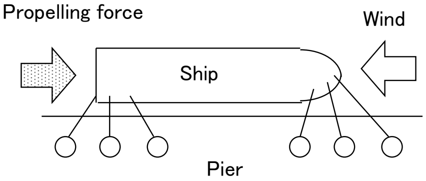

Fig. 2. A setup to moor the ship to pier in the strong wind

II. EFFECT OF CPP AND WIND

A. Wind Effect

Without any countermeasure such as mooring or anchoring, the ship is subject to drift due to the strong wind. Especially, the big-size tanker and ferry are heavily affected by such wind power. When the ship arrives at a port in the strong wind, the ship cannot be operated only by its steerage with its engine power and rudder. Therefore, the crew calls a tag boat in order to let the boat come alongside the quay safely. In general, a wind pressure is expressed [2] as

$$R = \frac{1}{2}\rho C(Acos^2\phi + Bsin^2\phi)v^2. \quad (1)$$

where R is the wind pressure$[N/m^2]$, ρ is an air density$[0.125kg/m^3]$, C is a coefficient due to a relative direct angle ϕ of the wind, v is a relative wind velocity $[m/sec]$, A and B are the suffering square $[m^2]$ with the wind. Fig.3 shows the condition of the wind pressure.

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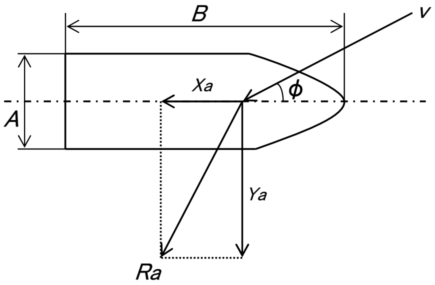

Fig. 3. Components of wind pressure

B. Response of propeller

A controlled target of this study is adjusting the propelling force by the CPP's angle change. The angle of CPP's propeller cannot change rapidly. The change of angle with a big motor takes a time for seconds. It is a delay time of the system. Furthermore, the propelling thrust has a slip because it is generated by paddling water. Therefore, the response of the ship's velocity change is slow. This study defines the response of the system.

III. EXPRESSION OF SYSTEM

The problem to control the CPP is simple because the velocity is generated due to the CPP's angle against the effect of the wind and a tidal current in the sea. In other words, this system is expressed Multi-Input Single-Output (MISO) system. In this study, the system model is expressed by Auto Regressive Moving Average (ARMAX) model.

$$\begin{aligned} A(q^{-1})y(k) \\ &= q^{-jcpp}B_{cpp}(q^{-1})u_{cpp}(k) \\ &\quad +d_{wind}(k)+d_{tidal}(k) \\ &\quad +\xi(k) \end{aligned} \tag{2}$$

$$\begin{aligned} A(q^{-1}) &= 1+a_1q^{-1}+\cdots+a_nq^{-n} \\ B_{cpp}(q^{-1}) &= b_{0cpp}+b_{1cpp}q^{-1}+\cdots+b_{mcpp}q^{-mcpp} \end{aligned} \tag{3}$$

$y(k)$ is the ship's velocity m/sec as an output signal. $u_{cpp}(k)$ is a CPP angle as an input signal. $d_{wind}(k)$ is wind's effect. $d_{tidal}(k)$ is a tidal current in the sea. q^{-1} is a time shift operator. q^{-jcpp} stands for a delay time of CPP propelling. $\xi(k)$ is a white noise with the zero mean and variance σ^2.

IV. PRELIMINARY EXPERIMENT

A. Delay time of CPP Propelling

Through the preliminary experiment, the response in the velocity against the CPP's angle change ahead or astern was measured. The data are recorded every second. The ship used for this experiment is a training ship named "Yuge Maru" (240 gross ton) which belongs to Yuge National College of Maritime. The condition for this experiment is defined as follows:,
First, regarding the CPP's effect,
(1) CPP angle is changed as 0,1,2,3,4,5 degree ahead and astern.
(2) The velocities are measured at each angle.
(3) The delay time of the response is verified.
Second, regarding the wind's effect,
(1) The initial CPP angle is 0, in other words, the initial propelling forth is 0.
(2) The ship's place is pointed on a sea map with the GPS information.
(3) The wind's effect is verified.

The experiment was done in July 2009. Fig.4 and Fig.5 show responses as the ship's velocity with each CPP angle. Fig.4 is those of ahead CPP and Fig.5 is those of astern CPP. The astern propeller with pitching angle of -1 degree generates -0.2 knots, -0.5 knots by -2 degree, -0.6 knots by -3 degree, -0.7 knots by -4 degree. This result shows that the astern CPP does not effect the propelling force more than the ahead CPP.

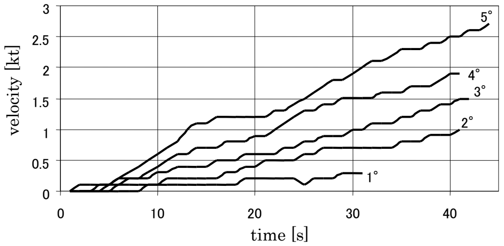

Fig. 4. Ship's velocity change with ahead CPP

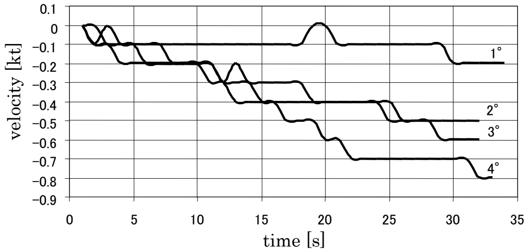

Fig. 5. Ship's velocity change with astern CPP

Fig.6 and Fig.7 show results in detail in the case of the ahead CPP angle of 3 degree. Fig.8 and Fig.9 show results of 5 degree. Fig.6 and Fig.8 confirm that the angle has been reached to the setting angle in about 10 seconds. On the other hand, Fig.7 and Fig.9 confirm that the velocity lately increases after reaching the CPP setting angle. The results confirm that the ship's propelling force has a delay in time with respect to CPP setting angle and CPP slip.

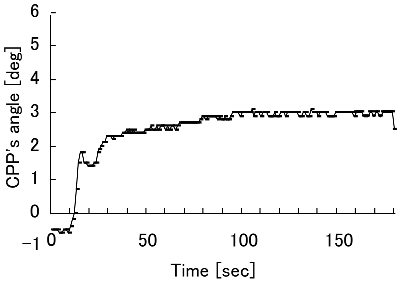

Fig. 6. Angle change of CPP (Ahead 3 degree)

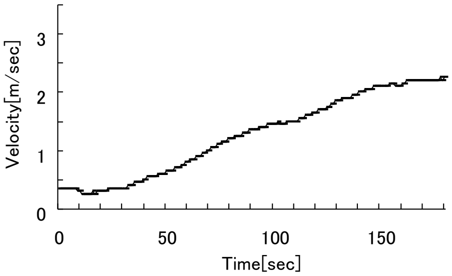

Fig. 7. Velocity responses (Ahead 3 degree)

B. Effect of Wind and Tidal current

Fig10 shows a locus of ship's drifting on East 133°15', North 34°5' without ship's propelling force. The wind velocity is 3m/sec and its direction is WSW. The wind's effect can be distinguished from the tidal current. This experiment has been done in the condition of no tidal current.

V. OFF-LINE IDENTIFICATION OF SHIP'S PROPELLING

A. Theory of off-line identification

Collecting parameters $A(q^{-1})$ and $B(q^{-1})$ of ARMAX model (2),

$$\theta = [a_1, \cdots, a_n, b_{0cpp}, \cdots b_{mcpp}]^T. \tag{4}$$

θ is defined as a parameter vector. Otherwise, a regression vector $\varphi(k)$ is,

$$\begin{aligned}\varphi(k) = & [-y(k-1), \cdots, -y(k-n), \\ & u_{cpp}(k-1), \cdots u_{cpp}(k-mcpp)]^T.\end{aligned} \tag{5}$$

The output $y(k)$ is expressed as

$$y(k) = \theta^T \varphi(k) + d_{wind}(k) + d_{tidal}(k) + \xi(k). \tag{6}$$

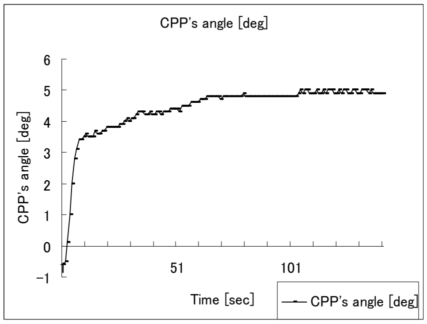

Fig. 8. Angle change of CPP (Ahead 5 degree)

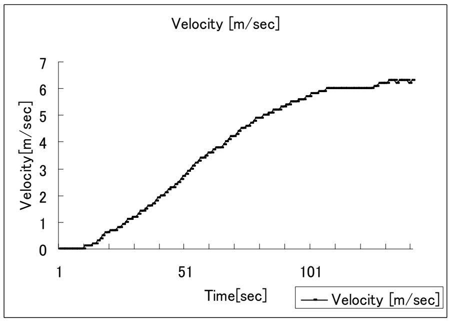

Fig. 9. Velocity responses (Ahead 5 degree)

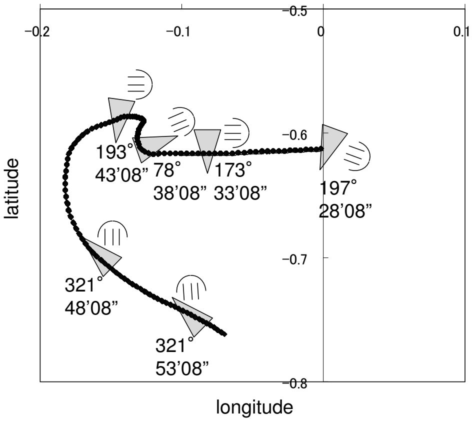

Fig. 10. A locus of ship's drift

The one step predictor without delay in the system is expressed as

$$\begin{aligned} \hat{y}(k+1) &= [1-A(q^{-1})]y(k+1) \\ &\quad +B_{cpp}(q^{-1})u_{cpp}(k) \\ &\quad +d_{wind}(k)+d_{tidal}(k) \\ &= \theta^T\varphi(k), \end{aligned} \tag{7}$$

and the system with the delay time is expressed by ARMAX model (2). Set a cost criterion to estimate parameters $J_N(\theta)$ as

$$J_N(\theta) = 1/N\Sigma_{k=1}^{N} l(k,\theta,\varepsilon(k,\theta)), \tag{8}$$

where $l(k,\theta,\varepsilon(k,\theta))$ is a scalar function to measure the value of a predictive error. The predictive error is

$$\varepsilon(k,\theta) = y(k) - \hat{y}(k \mid \theta). \tag{9}$$

Estimated values of unknown parameters are determined by

$$\hat{\theta}(N) = argmin J_N(\theta). \tag{10}$$

The noise of system is white noise, therefore the function is

$$l(k,\theta,\varepsilon(k,\theta)) = \varepsilon^2(k,\theta). \tag{11}$$

The cost criterion is expressed as

$$\begin{aligned} J_N(\theta) &= 1/N\Sigma_{k=1}^{N}\varepsilon^2(k,\theta) \\ &= 1/N\Sigma_{k=1}^{N}\{y(k)-\theta^T\varphi(k)\}^2, \end{aligned} \tag{12}$$

which is arranged to

$$J_N(\theta) = c(N) - 2\theta^T f(N) + \theta^T R(N)\theta, \tag{13}$$

where $R(N)$, $f(N)$ and $c(N)$ of (13) are

$$\begin{aligned} R(N) &= 1/N\Sigma_{k=1}^{N}\varphi(k)\varphi^T(k), \\ f(N) &= 1/N\Sigma_{k=1}^{N}y(k)\varphi^T(k), \\ c(N) &= 1/N\Sigma_{k=1}^{N}y^2(k). \end{aligned} \tag{14}$$

Differentiating J_N of (13) and set as 0,

$$R(N)\hat{\theta}(N) = f(N). \tag{15}$$

Therefore, the system parameters are estimated by an off-line least-squares method

$$\hat{\theta}(N) = R^{-1}(N)f(N). \tag{16}$$

B. Result of off-line identification for ship's propelling

This study identified the ship's propelling. The coefficients $A(q^{-1})$ and $B(q^{-1})$ of the ARMAX model are identified by calculating the navigation data with $u(k)$ as input data (setting CPP angle) and $y(k)$ as output (ship's velocity) data. The coefficients of the ARMAX model (5) for CPP's angle as the ahead 2.5 degree are identified as

$$\begin{aligned} &A(q^{-1}) = 1 - 0.6398q^{-1} - 0.3448q^{-2}, \\ &B_{cpp}(q^{-1}) = 0.0115. \end{aligned} \tag{17}$$

Table. I shows the coefficients of ARMAX model regarding CPP setting angle as 0.5∼ 5.0°.

TABLE I

COEFFICIENTS OF ARMAX MODEL REGARDING CPP PROPELLING

CPP [deg]	a_1	a_2	b_0	Arrival Velocity [m/s]
0.5	−1.95	0.9506	0.00045	0.38
1.0	−1.95	0.9506	0.00046	0.75
1.5	−1.95	0.9506	0.00046	1.13
2.0	−1.95	0.9506	0.00046	1.51
2.5	−0.6398	−0.3448	0.0115	1.88
3.0	−0.6398	−0.3448	0.012	2.26
3.5	−0.6398	−0.3448	0.011	2.47
4.0	−0.7493	−0.2284	0.015	2.67
4.5	−0.7493	−0.2284	0.014	2.88
5.0	−0.7493	−0.2284	0.0144	3.08

VI. GENERALIZED MINIMUM VARIANCE CONTROL

The CPP response has time delay. Predictive Control method is effective to the delay time system. Therefore, in this study, Generalized Minimum Variance Control (GMVC), which is one of the predictive control methods, is modified. The structure of GMVC is simple. This section explains the control law. GMVC controller is derived by minimizing a cost function.

$$J = E\{h(k+j)^2\} \tag{18}$$

where $h(k+j)$ stands for a generalized output

$$\begin{aligned} &h(k+jcpp) \\ &\quad = P(q^{-1})y(k+jcpp) - R(q^{-1})w(k+jcpp), \\ &\quad +S(q^{-1})\Delta u_{cpp}(k) \\ &\qquad P(q^{-1}) = 1 + p_1q^{-1} + \cdots + p_{n_p}q^{-n_p}, \\ &\qquad R(q^{-1}) = r_0 + r_1q^{-1} + \cdots + r_{n_r}q^{-n_r}, \\ &\qquad S(q^{-1}) = s_0 + s_1q^{-1} + \cdots + s_{n_s}q^{-n_s}, \end{aligned} \tag{19}$$

where $w(k)$ is a reference signal. The polynomials $P(q^{-1})$, $R(q^{-1})$, $S(q^{-1})$ are the weights of the cost function. The GMVC law is derived by minimizing the variance of the cost function $J = E\{h(k+jcpp)^2\}$. However, $y(k+jcpp)$ in the generalized output (19) must be predicted, because it cannot be observed at the present time k. In the following, the unique solutions $E(q^{-1})$ and $F(q^{-1})$ are derived with a Diophantine equation

$$\begin{aligned} &P(q^{-1}) = E(q^{-1})A(q^{-1})\Delta + q^{-jcpp}F(q^{-1}), \\ &\quad E(q^{-1}) = 1 + e_1q^{-1} + \cdots + e_{jcpp-1}q^{-(jcpp-1)}, \\ &\quad F(q^{-1}) = f_0 + f_1q^{-1} + \cdots + f_hq^{-h}. \end{aligned} \tag{20}$$

The Δ of Eqn. (19) and Eqn. (20) is set to satisfy the servo system against the reference signal change and the load disturbance. $P(q^{-1})y(k+jcpp)$ of the Eqn. (19) is calculated by applying the Diophantine Eqn.(20)

$$\begin{aligned}
&P(q^{-1})y(k+jcpp)\\
&\quad = E(q^{-1})B_{cpp}(q^{-1})\Delta u_{cpp}(k)+F(q^{-1})y(k)\\
&\quad +\Delta E(q^{-1})W_c d_{wind}(k+jcpp)+\Delta E(q^{-1})d_{tidal}(k+jcpp)\\
&\quad +\Delta E(q^{-1})\xi(k+jcpp). \qquad (21)
\end{aligned}$$

$$W_c = \frac{1}{645} \qquad (22)$$

Substituting the Eqn. (22) to the generalized output (19), the cost function is

$$\begin{aligned}
J \;=\; & \mathbf{E}[\{E(q^{-1})B_{cpp}(q^{-1})\Delta u_{cpp}(k)+F(q^{-1})y(k)\\
& +\Delta E(q^{-1})W_c d_{wind}(k+jcpp)\\
& +\Delta E(q^{-1})d_{tidal}(k+jcpp)\\
& -R(q^{-1})w(k+jcpp)\\
& +S(q^{-1})\Delta u_{cpp}(k)\\
& +\Delta E(q^{-1})\xi(k+jcpp)\}^2]. \qquad (23)
\end{aligned}$$

The cost function includes a generalized predictive output $\hat{h}(k+jcpp \mid k)$, which contains data from the past time to the present time except for the noise.

$$J \;=\; \mathbf{E}[\{\hat{h}(k+jcpp \mid k)+\Delta E(q^{-1})\xi(k+jcpp)\}^2], \qquad (24)$$

where

$$\begin{aligned}
&\hat{h}(k+jcpp \mid k)\\
&\quad = E(q^{-1})B_{cpp}(q^{-1})\Delta u_{cpp}(k)+F(q^{-1})y(k)\\
&\quad\quad +\Delta E(q^{-1})W_c d_{wind}(k+jcpp)\\
&\quad\quad +\Delta E(q^{-1})d_{tidal}(k+jcpp)\\
&\quad\quad -R(q^{-1})w(k+jcpp)+S(q^{-1})\Delta u_{cpp}(k), \quad (25)
\end{aligned}$$

The control law is derived by minimizing $\hat{h}(k+jcpp \mid k)$, that is,

$$\begin{aligned}
&\{E(q^{-1})B_{cpp}(q^{-1})+S(q^{-1})\}\Delta u_{cpp}(k)\\
&\quad = R(q^{-1})w(k+jcpp)-F(q^{-1})y(k)\\
&\quad\quad -\Delta E(q^{-1})\{W_c d_{wind}(k+jcpp)+d_{tidal}(k+jcpp)\}, \qquad (26)
\end{aligned}$$

Fig. 11 shows the block diagram of the closed loop system with GMVC.

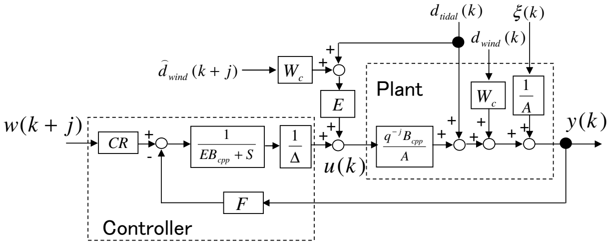

Fig. 11. Block diagram of closed loop system with proposed GMVC

VII. SIMULATION RESULTS

A. Time responses of CPP with GMVC

This section shows time responses of the velocity against the CPP's angle, which is controlled by GMVC. The simulation models are besed on the identified coefficients regarding CPP's angle of 2.5 degree as bellow.

$$\begin{aligned}
A(q^{-1}) &= 1-0.6398q^{-1}-0.3448q^{-2},\\
B_{cpp}(q^{-1}) &= 0.0115. \qquad (27)
\end{aligned}$$

The system has a delay time for 10 seconds. The sampling period is 1 second. The wind's predicted velocity is calculated with

$$\hat{d}_{wind}(k+10) \;=\; n_0 d(k)+n_1 d(k-1). \qquad (28)$$

This paper shows simulations with GMVC. The reference signal is set to 0 m/sec as the ship's velocity. "0m/sec" is stopping by the pier. In other words, the mooring line is not loaded.

Fig. 12 Shows ship's drifting velocity in the case of the strong wind (12m-22m/sec, 100 seconds periodical) from the ship's front. The solid line is the ship's velocity (m/sec). The dashed line is CPP's angle(°).

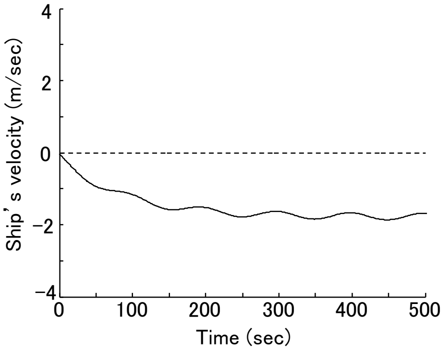

Fig. 12. Ship's velocity with wind (17m/sec)

Fig. 12 shows that the ship's velocity reaches 1.8(m/sec) with CPP's angle as 0 degree. The ship's drifting velocity 1.8(m/sec) effects to 6 (kN) regarding the mooring line's load.

Therefore, this study restrain the ship's drifting velocity by controlling CPP's angle.

Fig. 13 and Fig. 14 show effectiveness of CPP's angle control with GMVC. Fig. 13 is time responses of CPP's angle. Fig. 14 is time responses of the ship's velocity. In each figure, the control weights are set as $Q=0$, $Q=0.5$, $Q=30$. The response of $Q=0.5$ as the solid line shows that the velocity varies within 0.2 (m/sec). The result of $Q=0$ as the dashed line shows that the velocity stays around zero. However, CPP's angle in $Q=0$ reaches 20.7 degree which can not be practically used. The response of $Q=30$ as the chain line shows that the velocity is varied within 0.7 (m/sec).

Therefore, GMVC with $Q = 0.5$ as the continuous line is most effective for the CPP's control system to regulate ship's velocity. Furthermore, the wavy line in Fig. 13 and Fig. 14 are responses of non-servo GMVC as

$$\begin{aligned}&\{E(q^{-1})B_{cpp}(q^{-1})+S(q^{-1})\}\Delta u_{cpp}(k)\\&\quad=R(q^{-1})w(k+jcpp)-F(q^{-1})y(k)\\&\qquad-E(q^{-1})\{W_c d_{wind}(k+jcpp)+d_{tidal}(k+jcpp).\}\end{aligned} \tag{29}$$

The dot line of Fig. 14 shows that the offset remain without servo system regarding the wind's term and the tidal's term of GMVC law.

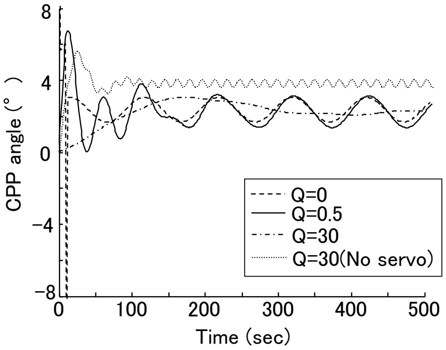

Fig. 13. CPP control with GMVC

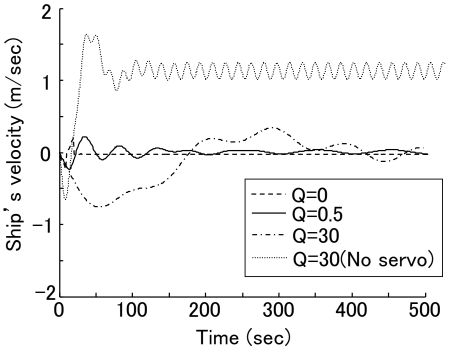

Fig. 14. Velocity with GMVC

Fig. 15 shows the comparison of the PID controller and the proposed GMVC servo. The dashed line shows velocity change by the PID controller with gains of Kd =2.5874, Kp =0.2526 and Ki =0.0247. The solid line shows velocity change by the GMVC controller with $Q = 0.5$. Fig. 15 indicates that the proposed GMVC controller shows better performance for the ship's velocity change than the PID controller.

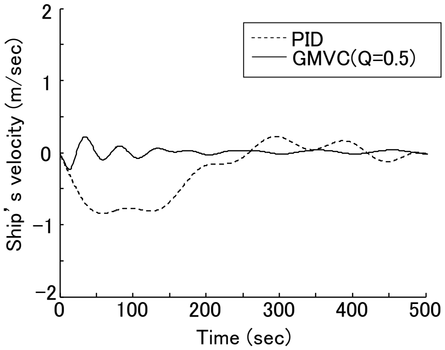

Fig. 15. Velocity with PID and GMVC

VIII. CONCLUSIONS

A. Conclusions

Through preliminary experiment, the CPP's response on the actual ship is identified. The CPP system has time delay to reach the CPP's setting angle because of the slip of propeller. By expressing the CPP's propelling system as the ARMAX model, the CPP propelling controller is designed by applying GMVC to optimize the CPP angle. Simulation study show that the proposed GMVC controller in the mooring system model improves the system performance, and confirm that the GMVC system applied to the CPP controller saves more input energy by tracking the faster reference signal than PID controller.

B. Future Works

The simulation results will be verified with this CPP's controller with GMVC on the actual ship at the sea.

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