IOP Conf. Series: Journal of Physics: Conf. Series **855** (2017) 012044 doi:10.1088/1742-6596/855/1/012044

Rudder-roll stabilization using fgs-pid controller for sigma-e warship

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ABSTRACT. The aim of rudder-roll stabilization (RSS) is controlling ship heading and reducing roll motion simultaneously using one actuator, rudder. In this paper, RSS using FGS-PID for SIGMA-e warship was performed, both in normal and disturbed sea conditions. The fuzzy system for determining PID controller are constructed from SIGMA-e linear mathematical model. The wave disturbances are generated based on the WMO. The results show that FGS-PID has superior performance compared to conventional PID controller in heading control and roll damping. It means that the proposed control method can encounter the environmental changes.

1. Introduction

Ship Integrated Geometric Modularity Approach (SIGMA)-extended, or called SIGMA-e, is a warship designed by Indonesian Research and Technology Consortium in 2012. Some developments of the ship from the original SIGMA class warship are dimension, war reliability, and maneuverability [1]. One of the components of the development is ship automatic steering, or called autopilot.

The aim of rudder-roll stabilization (RSS) are controlling ship heading and reducing roll motion simultaneously using one actuator, i.e. rudder. It is in accordance with the autopilot objective: controlling heading without increasing roll motion. Excessive roll motion is a serious issue for a warship, especially in weapon operation, launching and recovery system, aircraft landing, and sonar operation [2]. Some researches were analyzed this technic [3]-[9]. As the result, roll reduction can be achieved to 50-70%, depends on ship dynamics [10].

Conventional RSS commonly works based on PID or LQR controller with constant parameters [11]. Those controllers give well damping performance for particular condition. However, in bad weather conditions or when the ship speed is changed, the autopilot system with fix parameters does not work well [3].

Recently, the tendency of combining some methods by exploiting individual advantages for achieving better controller is increasing (12-14). Fuzzy Gain Scheduling (FGS-PID) [15] is a nonlinear

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controller that utilize fuzzy rules to determine PID controller parameters. Fuzzy system will tune the parameters automatically, based on error signal and its derivative. Some studies, [8], [16] and [17], show the utilization of fuzzy system for control in container ship, oil tanker, and multirole naval vessel, respectively.

In this paper, FGS-PID application for RSS in a SIGMA-e warship was performed. First, mathematical model of the ship was derived from common ship mathematical model, regarding to SIGMA-e specification. Then, FGS-PID for the ship was designed. Finally, we discus about the performance of the proposed controller in several weather conditions, compared with conventional PID controller.

2. RRS control design

2.1 SIGMA-e modeling

Ship has six degrees of freedom (DOF) in motion, consists of translation motion (position) in three directions: surge, sway, and heave; and rotation motion (orientation) in three axes: roll, pitch, and yaw – see Figure 1.

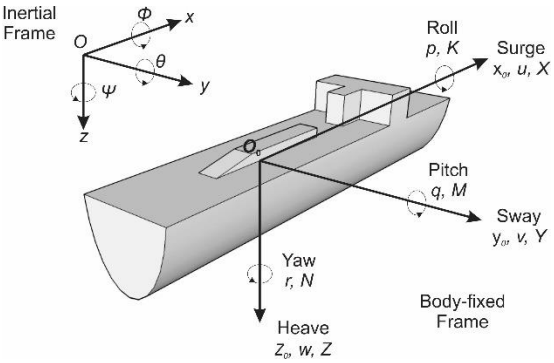


Figure 1. Standard notation and sign conventions for ship motion description based on SNAME standard [18].

Nonlinear marine vessel has the general state space form [19]:

$$\dot{x} = H^{-1} f(x, \delta) \tag{1}$$

where δ is the rudder angle,

$$x = \begin{bmatrix} u & v & p & r & \phi & \psi \end{bmatrix}^T \tag{2}$$

$$H = \begin{bmatrix} (m - X_{\dot{u}}) & 0 & 0 & 0 & 0 & 0 \\ 0 & (m - Y_{\dot{v}}) & -(mz_G + Y_{\dot{p}}) & (mx_G - Y_{\dot{r}}) & 0 & 0 \\ 0 & -(mz_G + K_{\dot{v}}) & (I_{xx} - K_{\dot{p}}) & -K_{\dot{r}} & 0 & 0 \\ 0 & (mx_G - N_{\dot{v}}) & -N_{\dot{p}} & (I_{zz} - N_{\dot{r}}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$f(x, \delta) = \begin{bmatrix} X^*_{hyd}(x) + X_\delta + m(vr + x_G r^2 - z_G pr) \\ Y^*_{hyd}(x) + Y_\delta - mur \\ K^*_{hyd}(x) + K_\delta + mz_G ur \\ N^*_{hyd}(x) + N_\delta - mx_G ur \\ p \\ r \end{bmatrix} \tag{4}$$

For analyzing the linearized model, it is a common practice to decouple the surge equation from the others. Thus, the reduced state vector is $x = \begin{bmatrix} v & p & r & \phi & \psi \end{bmatrix}^T$. The linearized models are obtained straightforward from (1) as:

$$\dot{x} = H^{-1}\left[\left.\frac{\partial f(z,u,\delta)}{\partial z}\right|_{\bar{z},\bar{u},\bar{\delta}} x + \left.\frac{\partial f(z,u,\delta)}{\partial z}\right|_{\bar{z},\bar{u},\bar{\delta}} \delta \right] = H^{-1}\left[Ax + B\delta\right] \tag{5}$$

where the *A* and *B* are given in (6) and (7)

$$A = \begin{bmatrix} Y_{|u|v}|u| & Y_{|u|p}|u| & -mu + Y_{ur}u & Y_{uu\phi}u^2 & 0 \\ K_{|u|v}|u| & K_{up}u + K_p & K_{ur}u & W\overline{G}\,\overline{M}_T + K_{uu\phi}u^2 & 0 \\ N_{|u|v}|u| & 0 & N_{|u|r}|u| - mx_G u & N_{|u|u\phi}|u|u & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix} \tag{6}$$

$$\boldsymbol{B} = \begin{bmatrix} \boldsymbol{Y}_{ext} \\ \boldsymbol{K}_{ext} \\ \boldsymbol{N}_{ext} \\ \mathbf{0} \\ \mathbf{0} \end{bmatrix} \tag{7}$$

where:
u^2 and $|u|u$: the square term of the surge speed which represent the forces and moments associated with the roll motion,
Y_{ext}, K_{ext}, N_{ext} : possible contribution from external disturbance, rudders, propellers, bow thrusters and other devices.

Based on ship specification given in Table 1, it can be derived the mathematical model for SIGMA-e warship as:

$$\dot{x} = \begin{bmatrix} -0.066422 & 0.014261 & 0.666875 & 9.631995\times10^{-3} & 0 \\ 0.023389 & -0.139478 & -0.261273 & -0.168492 & 0 \\ 2.00943\times10^{-4} & 2.779796\times10^{-6} & 0.01108 & 2.889237\times10^{-4} & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 \end{bmatrix} \tag{8}$$

Table 1. SIGMA-e specification

No.	Parameters	Value
1	*Overall Length of the Ship* (L_{OA})	106 m
2	*Length of the Waterline* (L_{WL})	101,07 m
3	*Breadth* (B)	14 m
4	*Mass of Ship* (m)	2423 Ton
5	*Velocity* (U)	15,43 m/s
6	*Draught* (D)	3,7 m
7	*Depth*	8,75 m
8	*Sea Water Density* (ρ)	1014 Kg/m^3
9	*Coefficient Block* (CB)	0,441

2.2 Rudder model

As an actuator, the common widely used rudder model can be shown in [20]. Figure 2 shows the block diagram of rudder model, represent:

- Magnitude saturation: the move of rudder is limited within specific maximum angles, *i.e.* $-\delta_{\max} \le \delta \le \delta_{\max}\ (rad)$,
- Slew rate saturation: the rudder rate motion is limited by a maximum value $\dot{\delta}_{\max}(rad/\sec)$
- Time delay: the main servo generates most of delay between the rudder command δ_C and the actual rudder angle δ.

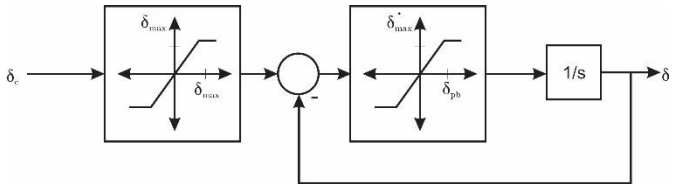


Figure 2. Simplified block diagram of the steering machine model [20].

2.3 Wave model

Sea waves are the main cause of roll motion. Waves can be described using frequency spectrum, e.g., Pierson-Moskowitz (PM) spectrum [21]. Linear approximation is commonly used by ship control engineer, because its simplicity and applicability. The approximation from PM spectrum can be determined by:

$$y(s) = h(s)\omega(s) \tag{9}$$

where $\omega(s)$ is a zero-mean Gaussian white noise with power spectrum and $h(s)$ is a transfer function to be determined.

A second order transfer function with damping for PM spectrum waves model was introduced in [22], and is written as:

$$h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} \tag{10}$$

Where $K_\omega = 2\zeta\omega_0\sigma_\omega$ is gain constant, σ_ω is a constant that represent the wave intensity, ζ is damping coefficient, and ω_0 is dominant wave frequency.

For PM spectrum, the dominant frequency spectrum can be defined as:

$$\omega_0 = 0.88\frac{g}{v} = 0.4\sqrt{\frac{g}{H_3}} \tag{11}$$

where $H_3 = 0.21V^2/g$ is the significant wave height in wind speed *V*.

2.4 RSS with FGS-PID

RSS utilizes the rudder for roll stabilization, which is controlling the ship heading and reducing its roll motion simultaneously. Figure 3 depicts a decoupled control system design can be used to obtain roll damping. FGS-PID is used for the yaw controller and roll damper.

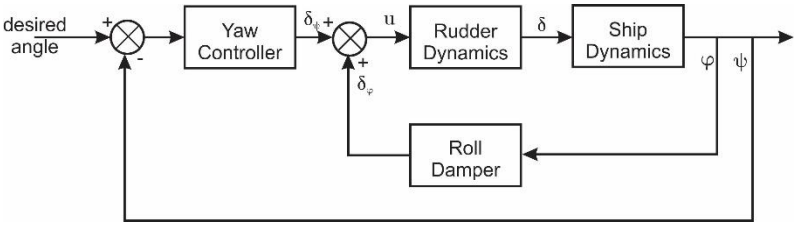


Figure 3. RSS design block diagram.

One of the methods which applied for adjusting gain values automatically based on environment conditions is FGS-PID. This method merging the advantages of fuzzy system in terms of adaptation and PID controller in terms of simplicity in control. The fuzzy system utilizes rule bases for tuning the three PID parameters. There are three constructed fuzzy system, i.e., fuzzy *Kp'* to get *Kp* value, fuzzy *Kd'* to get *Kd* value, and fuzzy alpha (α) to get *Ki* value. Figure 4 shows input membership functions for fuzzy system, while Figure 5 depicts the outputs.

$$\mu_{small}(x) = -\frac{1}{4}\ln x \tag{12a}$$

$$\mu_{big}(x) = -\frac{1}{4}\ln(1-x) \tag{12b}$$

where μ is value of membership function, $0 \le \mu \le 1$.

In fuzzification process, the membership function for inputs is triangular membership function which consists of seven membership functions: N represents *negative*, P for *positive*, ZO for *approximately zero*, S for *small*, M for *medium*, and B for *big*. Then, NM represents *negative medium*, PB for *positive big*, and so on.

For the output, *fuzzy* K_p' and *fuzzy* K_d' have two membership function: *Big* and *Small*, defined in (12). Figure 2.9 shows the membership functions for *fuzzy* K_p' and *fuzzy* K_d'. While for *fuzzy* α, the membership functions are singleton membership functions consists of *Small* (M), *Medium Small* (MS), *Medium* (M) and *Big* (B).

The value of K_p', K_d', and α are determined by a set of fuzzy rules. For the *i*th rule, it is:

if *e(t)* is A_i and $\Delta e(t)$ is B_i, then K_p' is C_i, K_d' is D_i, and $\alpha = \alpha_i$ (13)

where $i = 1,2,\ldots m$.

e(t) is error signal, i.e. difference between the set-point and the measured value

$\Delta e(t)$ is error rate.

The rule base may be resulted from a desired process time response. For instance, if a big control signal must be generated to achieve a fast rise time, the PID controller should have a large proportional gain, a large integral gain, and a small derivative gain for generating a big control signal. As a result, K_p' is set to Big, K_d' is set to Small, and α is set to 2 or S. Another example, to avoid a large overshoot, a small control signal has to be produced. Then, K_p' is set to Small, K_d' is set to Big, and α is set to B. This rule represents a small proportional gain, a large derivative gain, and a small integral gain. Thus, the tuning rules for K_p', K_d', and α are given in Table 2.

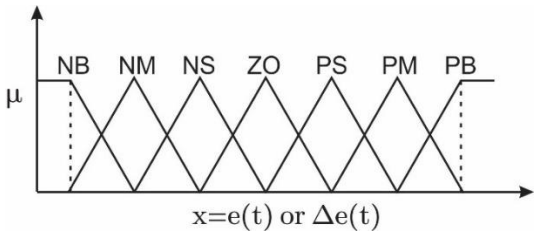


Figure 4. Fuzzy input membership function [15].

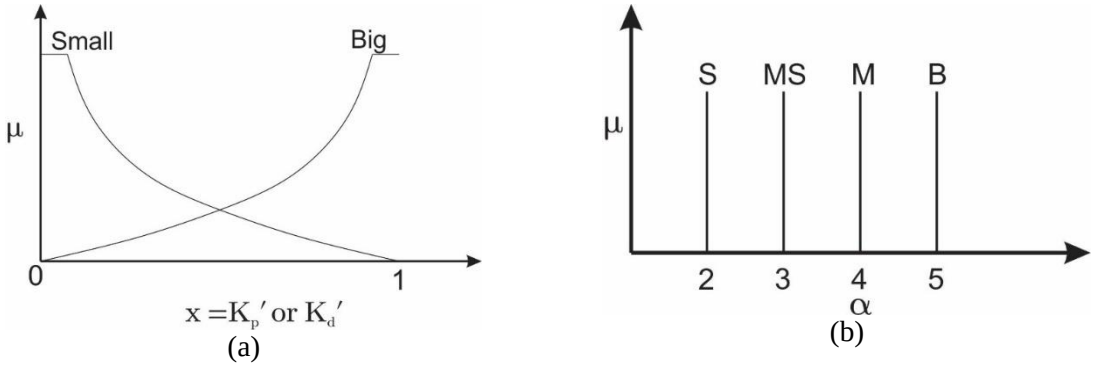


Figure 5. Fuzzy output membership function: (a) for *Kp'* and *Kd'*, (b) for α [15]

Table 2. Rule base for *Kp'*, *Kd'* and α [15]

K_p', K_d', α		***error rate, $\Delta e(t)$***						
		NB	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
Error, e(t)	**NB**	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2
	NM	S,B,3	B,B,3	B,S,2	B,S,2	B,S,2	B,B,3	S,B,3
	NS	S,B,4	S,B,3	B,B,3	B,S,2	B,B3	S,B,3	S,B,4
	ZO	S,B,5	S,B,4	S,B,3	B,B,3	S,B,3	S,B,4	S,B,5
	PS	S,B,4	S,B,3	B,B,3	B,S,2	B,B3	S,B,3	S,B,4
	PM	S,B,3	B,B,3	B,S,2	B,S,2	B,S,2	B,B,3	S,B,3
	PB	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2	B,S,2

When the *Kp'*, *Kd'* and α are obtained, the PID parameters for FGS-PID can be determined using:

$$K_p = \left(K_{p.\max} - K_{p.\min} \right) K'_p + K_{p.\min} \tag{14a}$$

$$K_d = \left(K_{d.\max} - K_{d.\min} \right) K'_d + K_{d.\min} \tag{14b}$$

$$K_i = K_p^2 / \left(\alpha K_d \right) \tag{14c}$$

The ranges of K_p and K_d in (14) are determined using the rule:

$$K_{p.\min} = 0.32 K_u \ , \quad K_{p.\max} = 0.6 K_u$$

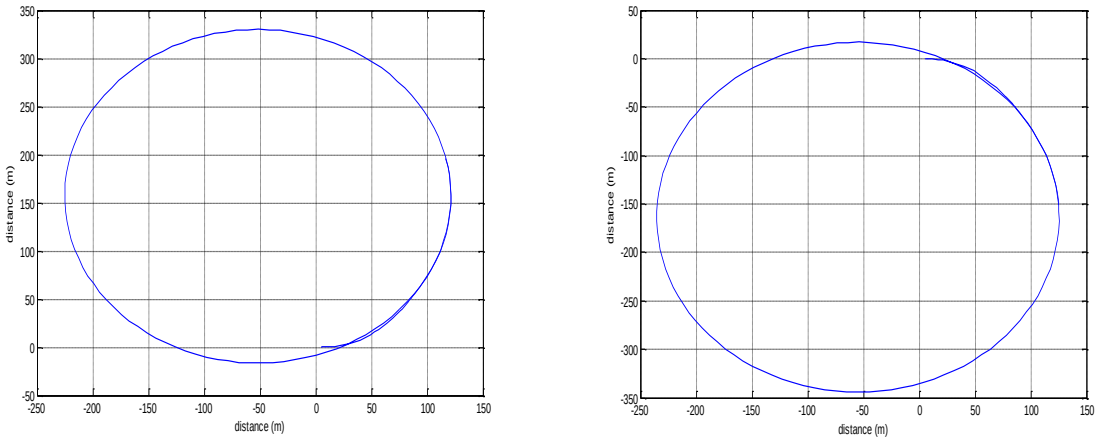
$$K_{d.\min} = 0.08 K_u T_u \ , \quad K_{d.\max} = 0.15 K_u T_u \tag{15}$$

where K_u and T_u are critical gain and period from oscillation when the P controller is applied to the system.

3. Main Results

In the following analysis, we consider the maneuverability of the ship and the implementation of FGS-PID to SIGMA-e warship in normal sea and disturbed sea conditions. There are three different disturbed sea conditions based on World Meteorological Organization (WMO), i.e., calm (rippled), moderate and rough sea. The results are simulated using block diagram code in Matlab Simulink®.

In order to find out the ship maneuverability, a turning circle test based on International Maritime Organization (IMO) Resolution MSC 137 (76) [23] was conducted. The test is applied to either port side and starboard side of the ship. Based on figure 6, it can be said that the designed ship complies with the standard. The tactical diameter of the turning circle is less than IMO criteria.



(a) (b)

Figure 6. Turning circle test result: (a) port side, (b) starboard side

Figure 7 and 8 depicts the simulation results in normal sea condition of yaw and roll motion, respectively. It can be shown that FGS-PID has better performance than conventional PID controller, in terms of overshoot and settling time. It corresponds to the data that given in Table 3.

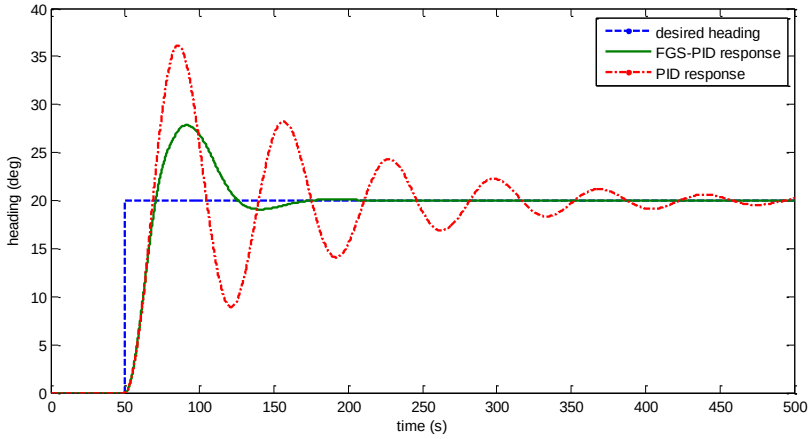


Figure 7. Yaw response for normal sea condition

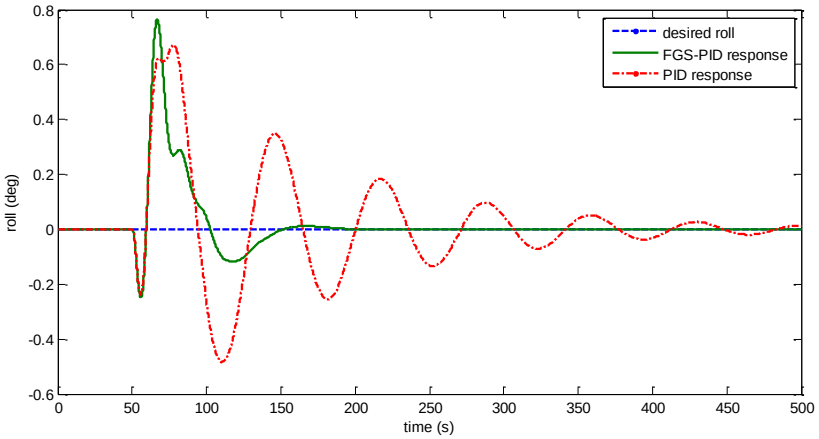


Figure 8. Roll response for normal sea condition

The simulation results in moderate sea condition for yaw and roll motion are depicted in Figure 9 and Figure 10, respectively. For calm (rippled) and rough sea condition, they have similar profile result with moderate condition. Calm (rippled) sea condition result has less ripples in the profile, while the rough sea condition result has more. Table 3 gives the detailed performances of controllers for all environment conditions.

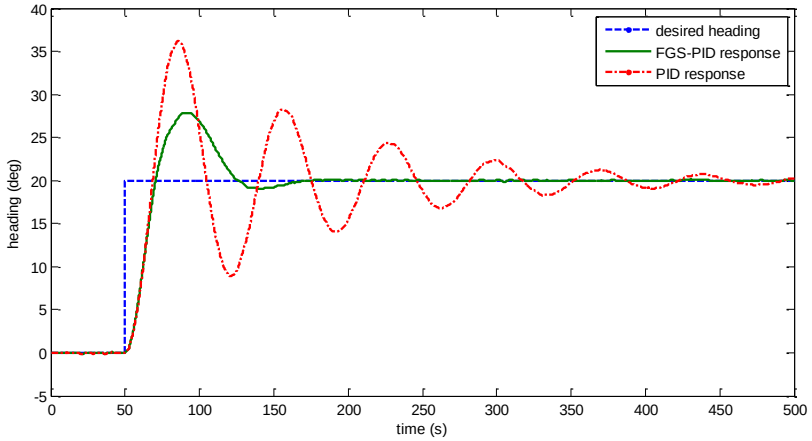


Figure 9. Yaw response for moderate sea condition

Table 3. Detailed simulation results

Sea condition	Controller	Yaw maximum overshoot (deg)	Yaw settling time (s)	Roll RMSE
Normal	FGS-PID	27.8555	120.5000	0.1129
	PID	36.1191	375.6000	0.1890
Calm (rippled)	FGS-PID	27.8559	120.5000	0.1130
	PID	36.1186	375.5000	0.1891
Moderate	FGS-PID	27.8299	120.6000	0.1139
	PID	36.1730	376.4000	0.1899
Rough	FGS-PID	27.8901	144.0000	0.1146
	PID	36.0530	371.1000	0.1906

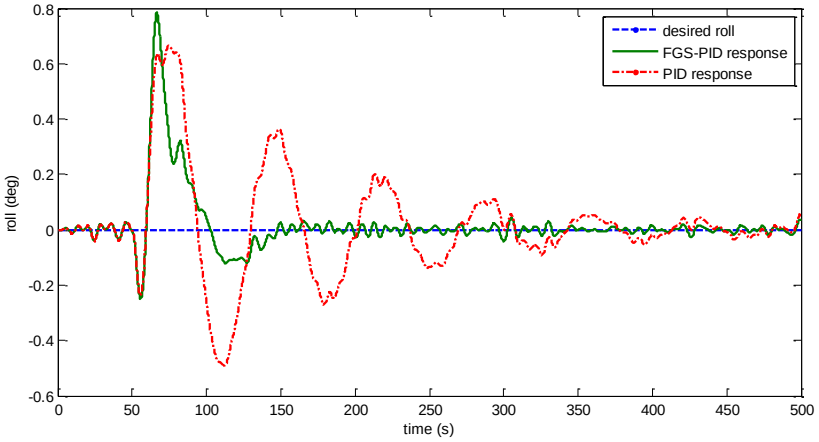


Figure 10. Roll response for moderate sea condition

4. Conclusions

In this paper simulation for applying FGS-PID to RSS of SIGMA-e warship is conducted. FGS-PID has superior performance in heading control and roll damping than conventional PID controller, either in normal or disturbed sea condition. It is shown that FGS-PID has more ability to adapt to the environmental changes compared to the conventional PID controller.

Acknowledgment

The authors would like to thank Shipbuilding Institute of Polytechnic Surabaya for funding to this research in the academic year of 2016.

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