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

M Y Santoso¹, I Munadhif², A Wahidin³, Ruddianto¹, Fathulloh³ and R T Soelistijono³
¹Safety Engineering Study Program, Shipbuilding Institute of Polytechnic Surabaya, Indonesia
²Automation Engineering Study Program, Shipbuilding Institute of Polytechnic Surabaya, Indonesia
³Shipbuilding Engineering Study Program, Shipbuilding Institute of Polytechnic Surabaya, Indonesia

E-mail: yusuf.santoso@ppns.ac.id, iimunadhif.its@gmail.com, aangwahidin@gmail.com, ruddianto@yahoo.com, pakfathulloh@gmail.com, rachmad.tri@gmail.com

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
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 discuss 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].](image)

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

\[ x = H^{-1} f(x, \delta) \] (1)

where \( \delta \) is the rudder angle,

\[
x = \begin{bmatrix} u & v & p & r & \phi & \psi \end{bmatrix}^T \]

where

\[
x = \begin{bmatrix} u & v & p & r & \phi & \psi \end{bmatrix}^T \]

\[
H = \begin{bmatrix} m - X_u & 0 & 0 & 0 & 0 & 0 \\
0 & m - Y_v & - (mz_G + Y_p) & (mx_G - Y_r) & 0 & 0 \\
0 & - (mz_G + K_p) & I_{xx} - K_y & - K_v & 0 & 0 \\
0 & (mx_G - N_v) & I_{rr} - N_p & (I_{zz} - N_z) & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 \\
0 & 0 & 0 & 0 & 0 & 1 \\
\end{bmatrix} \]

\[
f(x, \delta) = \begin{bmatrix} X_{hyd}^*(x) + X_\delta + m[vr + x_G r^2 - z_G pr] \\
Y_{hyd}^*(x) + Y_\delta - m ur \\
K_{hyd}^*(x) + K_\delta + m z_G ur \\
N_{hyd}^*(x) + N_\delta - mx_G ur \\
p \\
r \end{bmatrix} \]

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

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

\[
A = \begin{bmatrix}
Y_{[|\nu|]} u & Y_{[|\nu|]} u & -mu + Y_{v}u & \gamma_{u}u^{2} & 0 \\
K_{[|\nu|]} u & K_{w}u + K_{p} & K_{w}u & WGM_{r} + K_{u}u^{2} & 0 \\
N_{[|\nu|]} u & 0 & N_{[|\nu|]} u - mx_{u}u & N_{[|\nu|]} u |u| & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0
\end{bmatrix}
\tag{6}
\]

\[
B = \begin{bmatrix}
Y_{ext} \\
K_{ext} \\
N_{ext} \\
0 \\
0
\end{bmatrix}
\tag{7}
\]

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:

\[
\dot{x} = \begin{bmatrix}
-0.066422 & 0.014261 & 0.666875 & 9.631995 \times 10^{-3} & 0 \\
0.023389 & -0.139478 & -0.261273 & -0.168492 & 0 \\
2.00943 \times 10^{-4} & 2.779796 \times 10^{-6} & 0.01108 & 2.889237 \times 10^{-4} & 0 \\
0 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 1 & 0
\end{bmatrix}
\tag{8}
\]

### Table 1. SIGMA-e specification

| No. | Parameters                          | Value     |
|-----|------------------------------------|-----------|
| 1   | Overall Length of the Ship (LOA)   | 106 m     |
| 2   | Length of the Waterline (LWL)      | 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 (\( \rho \))     | 1014 Kg/m³|
| 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. \(-\delta_{\text{max}} \leq \delta \leq \delta_{\text{max}} \text{ (rad)}\).
- Slew rate saturation: the rudder rate motion is limited by a maximum value \(\dot{\delta}_{\text{max}} \text{ (rad/sec)}\).
- Time delay: the main servo generates most of delay between the rudder command \(\delta_c\) and the actual rudder angle \(\delta\).

![Figure 2. Simplified block diagram of the steering machine model [20].](image)

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:

\[
y(s) = h(s)\sigma(s)
\]

where \(\sigma(s)\) 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:

\[
h(s) = \frac{K_\omega s}{s^2 + 2\zeta\omega_0 s + \omega_0^2}
\]

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

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

\[
\omega_0 = 0.88 \frac{g}{v} - 0.4 \sqrt{\frac{g}{H_3}}
\]

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.
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 $K_p'$ to get $K_p$ value, fuzzy $K_d'$ to get $K_d$ value, and fuzzy alpha ($\alpha$) to get $K_i$ value. Figure 4 shows input membership functions for fuzzy system, while Figure 5 depicts the outputs.

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

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

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

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 $\alpha$, 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 $\alpha$ 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 $\alpha = a_i$ \hspace{1cm} (13)

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

$e(t)$ 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 $\alpha$ 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 $\alpha$ 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 $\alpha$ are given in Table 2.
When the \( K_p' \), \( K_d' \) and \( \alpha \) are obtained, the PID parameters for FGS-PID can be determined using:

\[
K_p = \left( K_{p, \text{max}} - K_{p, \text{min}} \right) K_p' + K_{p, \text{min}} \\
K_d = \left( K_{d, \text{max}} - K_{d, \text{min}} \right) K_d' + K_{d, \text{min}} \\
K_i = K_p^2 \left( \frac{\alpha K_d}{K_p} \right)
\] (14a)

(14b)

(14c)

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

\[
K_{p, \text{min}} = 0.32K_u, \quad K_{p, \text{max}} = 0.6K_u \\
K_{d, \text{min}} = 0.08K_uT_u, \quad K_{d, \text{max}} = 0.15K_uT_u
\] (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.
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](image)

![Figure 10. Roll response for moderate sea condition](image)

| 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    |
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.

References
[1] Akbar R, Aisjah A S 2014 Realtime Least Square Estimator Design for Sigma Class Extended 3 Meter Scale Model National Maritime Seminar IX Hang Tuah University (Surabaya, Indonesia, 2014)
[2] Perez T and Blanke M 2012 Ship roll damping control Annual Reviews in Control 36-1 129-147
[3] Amerongen J and Lemke V N 1978 Optimum steering of ships with an adaptive autopilot Fifth Ship Control Systems Symposium (Annapolis, USA)
[4] Lauvdal T and Fossen T I 1998 Rudder roll stabilization of ships subject to input rate saturation using a gain scheduled control law Conference on Control Applications in Marine Systems (CAM's98) (Fukuoka, Japan) 121-127
[5] Sgobbo J N and Parsons M 1999 Rudder/fin roll stabilization of the USCG WMEC 901 class vessel Marine Technology and SNAME News 36-3 157-170
[6] Goodwin G, Perez T, Seron M, and Tzeng C Y 2000 On the fundamental limitations for rudder roll stabilization of ships 39th IEEE Conference on Decision and Control (Sydney, Australia) 4705-4710
[7] Chun H H, Chun S H, and Kim S Y 2001 Roll damping characteristics of a small fishing vessel with a central wing Ocean Engineering 28-12 1601–1619
[8] Santoso M Y, Su S F, Aisjah A S 2013 Nonlinear Rudder Roll Stabilization using Fuzzy Gain Scheduling – PID Controller for Naval Vessel Proceedings of 2013 International Conference on Fuzzy Theory and Its Application (Taipei, Taiwan) 94-99
[9] Munadhif I, Aisjah A S, and Masroeri A A 2015 Perancangan Sistem Kendali Kestabilan Kapal Perang Kelas SIGMA Saat Bermanuver Menggunakan Fuzzy Gain Scheduling - PID Seminar Nasional Teknologi Informasi dan Multimedia 2015 (Yogyakarta, Indonesia) 4.3-15 – 4.3-18
[10] Alarcin F and Gulez K 2007 Rudder roll stabilization for fishing vessel using neural network approach Ocean Engineering 34-12 1811–1817
[11] van der Klugt P G M 1987 Rudder roll stabilization Delft: Delft University of Technology PhD Thesis Report
[12] Syai’in M and Soeprijanto A 2010 Neural network optimal power flow (NN-OPF) based on IPSO with developed load cluster method World Academy of Science, Engineering and Technology 72 48-53
[13] Syai’in M and Soeprijanto A 2012 Regular paper combination of generator capability curve constraint and statistic-fuzzy load clustering algorithm to improve NN-OPF performance J. Electrical Systems 8-2 198-208
[14] Syai’in M, Soeprijanto A, and Yuniarno, E M 2011 New Algorithm for Neural Network Optimal Power Flow(NN-OPF) including Generator Capability Curve Constraint and Statistic-Fuzzy Load Clustering International Journal of Computer Applications 36-7
[15] Zhao Z Y, Tomizuka M, and Isaka S 1993 Fuzzy gain scheduling of PID controllers IEEE Transactions on System, Man, and Cybernetics 23-5 1392-1398
[16] Nejim S 2000 Rudder roll damping system for ships using fuzzy logic control OCEANS 2000 MTS/IEEE Conference and Exhibition (Providence, RI)1137-1143
[17] Aisjah A S, Masroeri A A, Efendi M A, Djatmiko E B, Ariyawan W D, and Iskandariyanto F A 2012 Fuzzy Control for Optimizing Ship Tracking in Karang Jamuang – Tanjung Perak *The Journal for Technology and Science* 23-4 118-125

[18] SNAME 1950 Nomenclature for treating the motion of a submerged body through a fluid (*New York, USA*)

[19] Perez T and Blanke M 1988 Mathematical Ship Modeling for Control Application *Technical University of Denmark, Technical Report*

[20] van Amerongen J 1982 Adaptive steering of ships - A model reference approach to improved manoeuvring and economic course keeping *Delft University of Technology PhD Thesis Report*

[21] Pierson W J and Moskowitz L 1963 A proposed spectral form for fully developed wind seas based on the similarity theory of S. A. Kitaigorodskii *Technical Report U.S. Naval Oceanographic Office Contract 62306-1042*

[22] Goodrich G 1969 Development and design of passive roll stabiliser *Transactions of The Royal Institution of Naval Architects* 111 81–88

[23] International Maritime Organization (IMO) 2002 *Resolution: Standard for Ship Maneuverability MSC.137-76*