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RESEARCH ARTICLE

Autonomous Vehicles Control, Part IX: Ship Roll Angle Control using I-PD, PD-PI and 2DOF-1 Controllers Compared with a PI Controller

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Abstract. This is the 9th part in a series of research papers investigating autonomous vehicle control. The paper presents the proposal of using three of the second generation of PID controllers presented by the author since 2014 (I-PD, PD-PI and 2DOF-1 controllers). The controllers are tuned for the control of the ship roll angle, the roll angle limit is assigned and plotted with the optimal step time response of the ship roll angle and comparison with conventional PI controller is presented and the best controller for the purpose of ship roll angle control is assigned.

Keywords: Ship roll angle control, I-PD controller, PD-PI controller, 2DOF-1 controller, PI controller, controller tuning

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1. Introduction

Ship roll angle is one of the motions experienced by ship maneuvering excited by waves and winds causing uncomfortable journey and side effects for passenger and goods and also ship safety. Some of mechanical devices are used to reduce ship roll through the use of controllers to response to the disturbance inputs acting of the ship. This paper presents three controllers from the second generation of PID controllers introduced by the author in 2014 to control one of the mechanical devices used in ship roll angle control. We start by taking an idea about the efforts paid by some researchers in this important aspect over the last 24 years.

Tzeng and Wu (2000) described a ship stabilizing fin controller based on the internal model control (IMC) technique. The controller shaped the output sensitivity function relating wave disturbance to ship roll motion for good disturbance rejection. They achieved good roll reduction for sinusoidal disturbance. They used 0/2 order model for roll angle-fin transfer function [1]. Moaleji (2006) investigated the application of modern control techniques, power saving and different tank configuration when using anti-roll tanks to reduce ship roll. He applied current advanced technological and computational techniques and developed two feedforward control strategies to control the pumps used in active tanks. He used regression to predict incident wave motion used as input to tank-pump system and control the actuating pumps with adaptive inverse controller [2].

Milanov and Chutukova (2009) presented extensive experimental investigations of shallow water effect on a containership standard maneuver parameters. They investigated the effect of shallow water on rudder, course and yaw rate. They used first-order and second-order Nomoto models and identified their parameters for different dimensionless water depth values [3]. Perez and Blanke (2010) presented the development of various ship roll motion control systems and discussed their performance assess, applicability of different models and previous control techniques. They discussed some devices used for roll damping (fins, rudder and gyrostabilizers). They presented transfer function models for the roll angle having 2/4 order for rudder-roll damping [4].

Hammoud (2012) described ship motions using differential equations and introduced several working points to assign a multi-controller structure for ship motion improvement through the use of IMC structure to cast easily into PID format. He used a 0/1+integrator for the heading angle-rudder angle transfer function [5]. Liu, Jin, Grimble and Katebi (2015) developed a factorized nonlinear generalized minimum variance control law for a combined roll and yaw motion control using rudder and fins. They demonstrated the effectiveness of their technique on a simulational nonlinear ship model where they achieved 93 % of roll reduction [6].

Alujevic et al. (2019) determined analytically how the natural frequency and damping ratio of the U-tube anti-roll tank are tuned to maximize the power absorbed by the tank. They found that this tuning reduced also the average kinetic energy of the ship roll [7]. Meuro and Nabergoj (2021) presented a methodology to determine the damping coefficient by fitting the roll decay curves using a least-square fitting through a differential evolution algorithm of global optimization. They compared with the predictions using other methods showing that their algorithm was capable of performing good regression on the experimental data [8].

Deleanu, Dumitrache and Turef (2022) outlined that stabilizing fins generate an opposite moment to the wave and wind excitation roll moments. They presented numerical results for using a PID controller to damp the roll motion of a fishing ship equipped with fin stabilizer system sailing in regular waves. They showed that the stabilizing fins were effective only for relatively high ship speeds [9].

Rezaei and Tabatabaei (2023) designed an adaptive fractional –order sliding mode controller to control the ship roll motion. They claimed that the designed controller was robust to uncertain parameters in ship roll and fin actuator dynamics as shown through numerical simulations [10]. Fan, Yu and Wang (2024) investigated the effect of fin stabilizers on mitigating roll motion through computational fluid dynamic simulations over a range of fin angles and ship speeds. Their results showed that fin stabilizers reduce significantly roll motion. Their work highlighted the need of selecting adequate fin area at the dominant ship speed and ensuring effective anti-roll effect with fin-hull interaction [11].

2. Ship Roll Angle as a Process

Milanov and Chotukova investigated roll motion of a containership in shallow water [3]. They presented models for the ship roll motion in deep and shallow water. We are going to consider their model of the containership in deep water as a transfer function $G_p(s)$ between roll angle φ(s) and rudder angle δ(s). It is given by [3]:

$$G_p(s) = K(1+T_4s)/[(s^2+2T_1T_2s+T_2)(1+T_3s)] \quad (1)$$

Where for deep water maneuvering:

$$K = 0.1684;\ T_1 = 0.103;\ T_2 = 0.786$$
$$T_3 = 8.902;\ T_4 = 44.89 \quad (2)$$

The unit step time response of the ship roll angle due to a unit step rudder input (1 rad magnitude) is generated using the process model in Eq.1 and its parameters in Eq.2 using the step command of MATLAB [12] and shown in Fig.1.

COMMENTS:

- It has an oscillating nature with very large maximum overshoot.
- Maximum overshoot: 652.2 %.
- Settling time: 65 s.
- Steady state error: -0.28 rad.
- Any proposed successful controller has to cope with this large overshoot and settling time and eliminates completely the steady-state error.

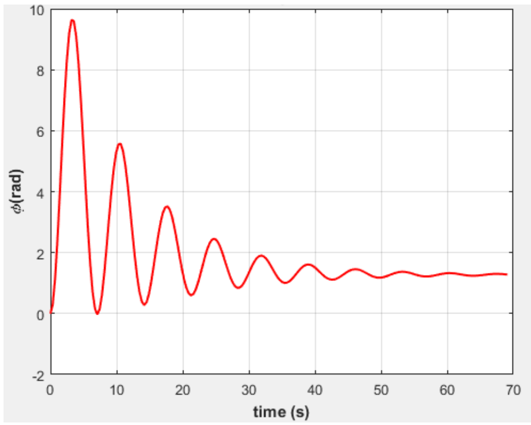

Fig.1 Ship roll unit step time response as a process.

3. Controlling the Ship Roll Angle using an I-PD Controller

The I-PD controller was one of the second generation of PID controllers introduced by the author in 2014. It was applied by the author to control a number of processes having bad dynamics to examine its applicability. This application included: high oscillating second-order process [13], delayed double integrating process [14], third-order process [15], Aljazari turbine speed control [16], IMM mild packing pressure [17], liquefied natural gas tank level [18], IMM cavity gate pressure [19], IMM ram velocity [20], furnace temperature [22], BLDC motor speed [23].

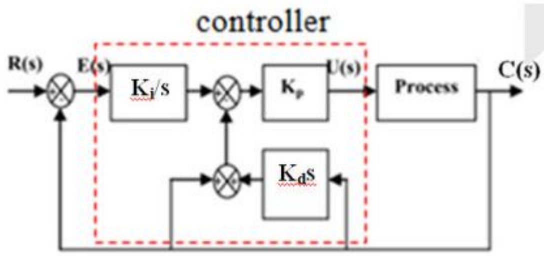

Fig.2 I-PD controller structure [13].

The I-PD controller has a structure shown in Fig.2. The integral and proportional control modes lie in the forward path while the derivative control mode lies in the feedback path. The controller has three gain parameters: Ki, Kp and Ki to be tuned to adjust the performance characteristics of the closed loop control system and overcome the deficiencies of the controlled ship roll angle.

The I-PD controller is tuned as follows:

- The transfer function of the control system is derived using the block diagram in Fig.2, the transfer function of the ship roll angle in Eq.1 and the control modes of the I-PD elements in Fig.2.
- The time response of the control system (for the roll angle φ) is obtained for a unit step input of the rudder angle δ using the step command of MATLAB [12].
- An error function is defined between the step input magnitude and the step time response of the ship roll angle.
- An ITAE error function is chosen as a performance index to be minimized by an appropriate optimization technique [24].
- The ITAE was minimized as function of the I-PD controller parameters using the MATLAB optimization toolbox [25].

The tuning results are as follows:

K_{pc} = 31.513114; K_i = 2.851744;
K_d = 0.1033906 (3)

The optimized unit step time response of the ship roll angle is shown in Fig.3 as generated using the closed-loop transfer function of the control system in Fig.2 and the controller parameters in Eq.3.

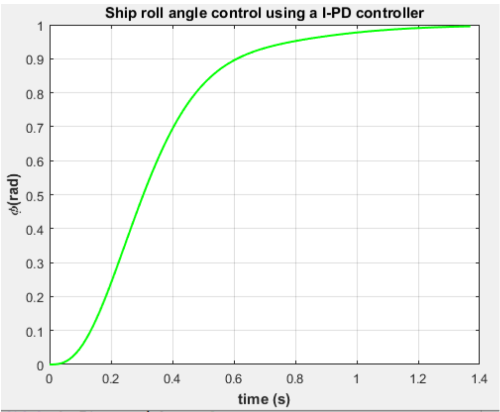

Fig.3 Ship roll unit step time response using an I-PD controller.

COMMENTS:

- Maximum overshoot: zero compared with 652.2 % for an uncontrolled ship roll angle.
- Settling time: 1.03 s compared with 65 s for an uncontrolled ship roll angle.
- Steady state error: zero compared with -0.28 rad for an uncontrolled ship roll angle.

4. Controlling the Ship Roll Angle using a PD-PI Controller

The PD-PI controller was one of the second generation of PID controllers introduced by the author in 2014. He applied the PD-PI controller to control various processes having bad dynamics [16-23] and [26-46]. The PD-PI controller is composed of a PD control mode cascaded with a PI control mode in the feedforward path of a single-loop block diagram of the control system just after the error detector. The PD-PI controller has the transfer functions $G_{PD}(s)$ and $G_{PI}(s)$ given by:

$$G_{PD}(s) = K_{pc1}+K_d s \;; \quad G_{PI}(s) = K_{pc2}+(K_i/s) \quad (4)$$

Where K_{pc1}, K_d, K_{pc2} and K_i are the four gain parameters of the PD-PI controller.

- The four gain parameters of the PD-PI controller are tuned by minimizing an ITAE performance index [24] using the MATLAB optimization toolbox [25]. The tuning results are as follows:

K_{pc1} = 20.1510 ; K_d = 179.3750
K_{pc2} = 1.0510 ; K_i = 0.0115 (5)

- The unit step time response of the control system for the ship roll angle using the proposed PD-PI controller using its gain parameters in Eq.5 is shown in Fig.4.

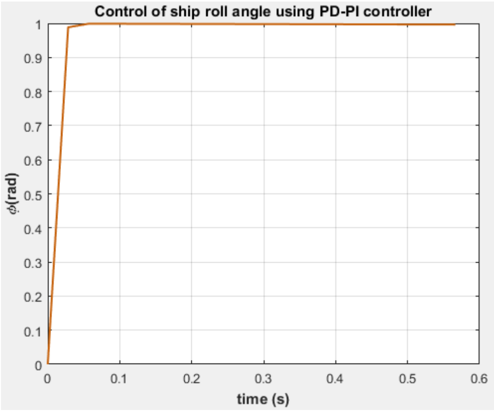

Fig.4 Ship roll unit step time response using a PD-PI controller.

COMMENTS:

- Maximum overshoot: zero compared with 652.2 % for an uncontrolled ship roll angle.
- Settling time: 0.028 s compared with 65 s for an uncontrolled ship roll angle.
- Steady state error: zero compared with -0.28 rad for an uncontrolled ship roll angle.

5. Controlling the Ship Roll Angle using a 2DOF-1 Controller

The 2DOF controller was one of the second generation of PID controllers introduced by the author in 2014. He applied the 2DOF controller to control various processes having bad dynamics [16-23], [31], [33-35] and [38-46]. The structure of the 2DOF-1 controller is shown in Fig.5 where it is composed of two control elements of transfer functions $G_{c1}(s)$ in the feedforward path after the error detector and $G_{c2}(s)$ in the feedback path of the inner loop of the control system block diagram [47].

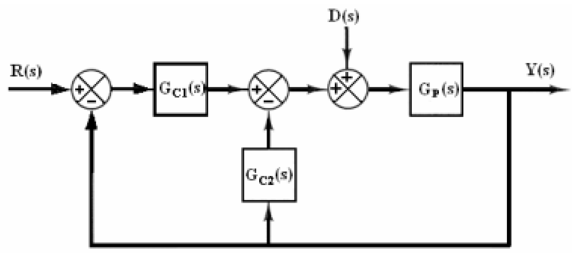

Fig.5 Structure of the 2DOF-1 in a block diagram loop with the controlled process [47].

The transfer functions of the two elements of the 2DOF-1 controller are selected to be:

$$G_{c1}(s) = K_{pc1} + (K_{i1}/s) \quad (6)$$
$$G_{c2}(s) = K_{pc2} + (K_{i2}/s) + K_d s \quad (7)$$

Where:

K_{pc1} is the proportional gain of the PI control mode.

K_{i1} is the integral gain of the PI control mode.

K_{pc2} is the proportional gain of the PID control mode.

K_{i2} is the integral gain of the PID control mode.

K_d is the derivative gain of the PID control mode.

The 2DOF-1 controller is tuned as follows:

- The pole/zero cancellation technique is used to cancel some of the process (ship roll angle) poles and zeros [48]. This is why the PID control mode is set as $G_{c2}(s)$. It represents a quadratic zero which cancels the process quadratic pole in the internal loop of the block diagram in Fig.5. This tuning step reveals the following relationships between K_{i2}, K_d of the PID control mode and K_{pc2}:

$$K_{i2} = 4.8543\, K_{pc2};\ K_d = 6.176\, K_{pc2} \quad (8)$$

- In the open-loop transfer function of the control system, the simple zero of the PI control mode is chosen to cancel the simple pole $1+T_{3s}$ of the ship roll angle. This action relates the integral gain K_{i1} to the proportional gain K_{pc1} through:

$$K_{i1} = K_{pc1}/2.902 \quad (9)$$

- This procedure leaves us only with two gain parameters K_{pc1} and K_{pc2} to be tuned using optimization.

- The MATLAB optimization toolbox is used for this purpose [25] minimizing an ITAE performance index function of the control system error [24].
- The application of this hybrid approach reveals the following optimal 2DOF-1 controller parameters:

K_{pc1}=1.00683x10^7 ; K_{i1} = -0.025058x10^7
K_{pc2} = 63.829492 ; K_{i2} = 714.27529
K_d = 2381.12884 (10)

- The unit step time response of the control system is drawn using the 'step' and 'plot' commands of MATLAB [12] using the tuned 2DOF-1 controller parameters in Eq.10 and shown in Fig.6.

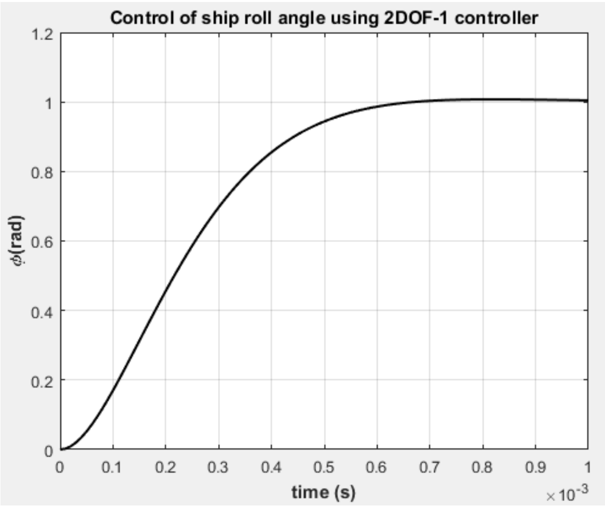

Fig.6 Ship roll unit step time response using a 2DOF-1 controller.

COMMENTS:

- Maximum overshoot: 0.295 % compared with 652.2 % for an uncontrolled ship roll angle.
- Settling time: 0.577ms compared with 65s for an uncontrolled ship roll angle.
- Steady state error: -0.0043 rad compared with -0.28 rad for an uncontrolled ship roll angle.

6. Controlling the Ship Roll Angle using a PI Controller

The PI controller is one of the first generation of PID controllers. It is still in use nowadays in controlling some of the industrial processes [49-53]. It has a transfer function given by Eq.6 with gain parameters K_{pc} and K_i. The PI controller is tuned using an ITAE performance index [24] minimized by the MATLAB optimization toolbox [25]. The tuned PI controller parameters are:

K_{pc} = 5.2140863 ; K_i = 32.3251893 (11)

The unit step time response of the control system using the PI controllers is drawn using the 'step' and 'plot' commands of MATLAB [12] and shown in Fig.7.

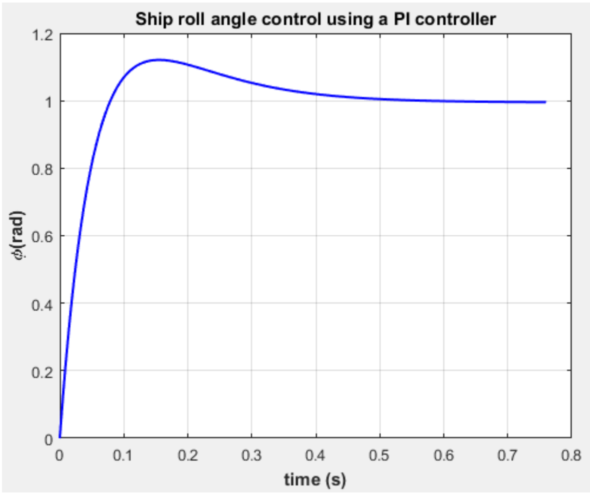

Fig.7 Ship roll unit step time response using a PI controller.

COMMENTS:

- Maximum overshoot: 12.08 % compared with 652.2 % for an uncontrolled ship roll angle.
- Settling time: 0.40 s compared with 65 s for an uncontrolled ship roll angle.
- Steady state error: zero compared with -0.28 rad for an uncontrolled ship roll angle.

7. Comparison of the Time-based Characteristics

The time-based characteristics of the control systems used to control the ship roll angle are compared as follows:

7.1. Graphical Comparison

- The step time response of the control systems used to control the ship roll angle was re drawn for a rudder step input of 0.33 rad for sake of graphical comparison because the unit step rudder input means 57.3 degrees which is very large from point of view of ship safe maneuvering.
- On the other hand I traced information sources of the limit of the ship roll angle for safe maneuvering. I found sources saying 20 degrees (0.349 rad) and other saying 30 degrees (0.5236 rad) [54]. Therefore, in the graphical comparison I drew two lines for the roll angle limit called 'lower limit' and 'upper limit' as depicted in Fig.8.

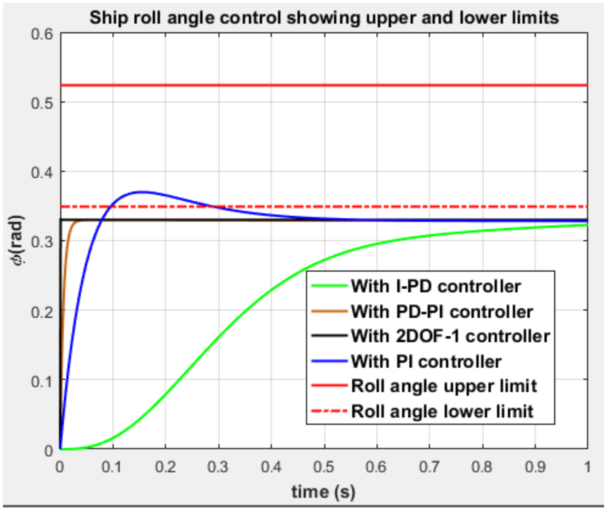

Fig.8 Step time response comparison.

7.2. Numerical Comparison

- The time-based characteristics of the control systems used to control the ship roll angle (extracted from Fig.8) are tabulated in Table 1 compared with those of uncontrolled ship roll angle.

Table 1. Comparison of time-based characteristics of the ship roll angle with 0.33 rad step input

Controller	OS_{max} (%)	T_s (s)	φ_{max} (rad)	e_{ss} (rad)
Without control	652.2	65	3.178$^{\Delta}$	-0.092
I-PD controller	0	$3x10^{-5}$	0.33	0
PD-PI controller	0	0.028	0.33	0
2DOF-1 controller	0.295	0.00058	0.3324	0.00142
PI controller	12.08	0.40	0.370▼	0

OS_{max}: maximum overshoot

T_s: Settling time

φ_{max}: Maximum roll angle

e_{ss}: Steady-state error

Δ : Above upper limit of ship roll angle.

▼: Above low limit of ship roll angle.

8. Conclusions

The control of ship roll angle was investigated in this research paper using three controllers from the second generation of PID controllers: I-PD, PD-PI and 2DOF-1.

1. The use of the three controllers was compared with the use of PI controller from the first generation of PID controllers.
2. The controllers were tuned using either a hybrid technique based on using the pole/zero cancellation techniques and MATLAB optimization technique or only the MATLAB optimization technique.
3. The ITAE performance index was used in the tuning process of the controllers.
4. The controllers performance in controlling the ship roll angle was compared with the PI controllers graphically and quantitatively.
5. The I-PD controller could control the ship roll angle producing no overshoot compared with 12.08 % for the PI controller and with an 0.03 ms settling time compared with 400 ms for the PI controller.

6. The PD-PI controller could control the ship roll angle producing no overshoot compared with 12.08 % for the PI controller and with a 28 ms settling time compared with 400 ms for the PI controller.
7. The 2DOF-1 controller could control the ship roll angle producing 0.295 % maximum overshoot compared with 12.08 % for the PI controller and with an 0.577 ms settling time compared with 400 ms for the PI controller.
8. Two limits of the ship roll angle were assigned to set additional constraint of the controller's performance.
9. The proposed three controllers from the second generation didn't violate the lower limit of the roll angle (0.349 rad).
10. The ship roll angle without control violated the upper limit (0.5236 rad) while the PI controller violated the lower limit of the ship roll angle.
11. The I-PD controller was selected as the best controller for the ship roll angle for its perfect performance depicted in Fig.8 and Table 1.

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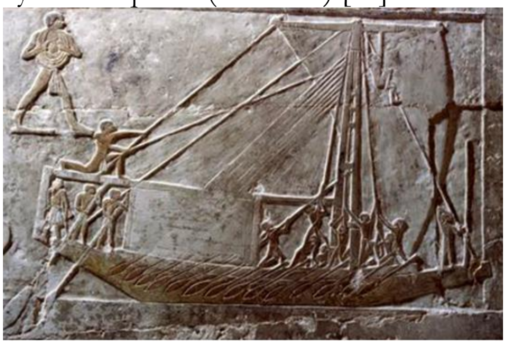
DEDICATION

Ancient Egyptian Civilization

- Why? : The builders of the greatest ancient civilization, the ancient Egyptians built ships for sea maneuvering since the days of Naqada I (4000 BC) [55].



Sea Ship relief from the first dynasty (3100-2900 BC) [55]

- They authorized using sea ships since the time of the first dynasty (3100-2900 BC).
- Pharaoh Hatshepsut of the 18th Dynasty (1479-1458 BC) build large trade ships maneuvered through the red sea to Punt Lands (Somalia now).
- They built not only trade ships but also warships to fight European invaders through the Mediterranean Sea.
- Pharaoh Necho II of the 26th Dynasty (610-595 BC) built ships to maneuver through the Mediterranean and Red seas. His ships sailed around Africa in 600 BC [55].
- They were the first sea people to sail around whole Africa,

BIOGRAPHY

Galal Ali Hassaan is an Emeritus Professor of System Dynamics and Automatic Control at the Faculty of Engineering, Cairo University, Egypt. He earned his B.Sc. and M.Sc. degrees from Cairo University in 1970 and 1974, respectively, and completed his Ph.D. in 1979 at Bradford University, UK, under the supervision of the late Prof. John Parnaby. His research interests include Automatic Control, Mechanical Vibrations, Mechanism Synthesis, and the History of Mechanical Engineering. Over his career, he has published more than 340 research papers in international journals and conferences. He is also the author of books on *Experimental Systems Control*, *Experimental Vibrations*, and *Evolution of Mechanical Engineering*. Prof. Hassaan serves as a member of the Editorial Board of the odaswa Journal and acts as a reviewer for several international journals.