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Autonomous Vehicles Control, Part X: Underwater Vehicle Pitch Angle Control using PD-I, I-PD Controllers and I-First Order, I-Second Order Compensators Compared with a PD Controller

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Abstract:

This paper investigates the tuning of PD-I, I-PD controllers and I-first order, I-second order compensators from the second generation of PID controllers and control compensators when used to control the pitch angle of an autonomous underwater vehicle (AUV). The controllers and compensators proposed are tuned using a hybrid approach based on zero/pole cancellation and an optimization technique using an ITAE performance index. The tuning results are presented and applied to generate the unit step time response for reference input tracking. A transfer function from previous work is used. The characteristics of the step time responses are compared with those of a PD conventional controller from the first generation of PID controllers. The best controller/compensator for the control of the AUV pitch angle is assigned.

Keywords — **Autonomous underwater vehicles, pitch angle control, PD-I controller, I-PD controller, I-first order compensator, I-second order compensator, PD controller, compensator/controller tuning.**

I. INTRODUCTION

Autonomous underwater vehicles have large number of applications such as pipeline inspection, mapping of sea floor, investigating the physical, chemical and biological properties of sea and ocean water and research [1]. This is the tenth research paper in the series of research papers aiming at investigating the control of autonomous vehicles focusing on presenting some compensators and controllers from the second generation of control compensators and PID controllers, tuning them and comparing there performance with a conventional PD controller from the first generation of PID controllers.

Here are some of the research efforts regarding control of the autonomous underwater vehicles:

Kim, Kim and Choi (2002), estimated the hydrodynamic coefficients using two nonlinear observers (sliding mode and extended Kalman filter). They evaluated their performance by comparing the estimated coefficients with the obtained values using a planar-motions test. They showed that the controller with their estimated values maintained the desired depth and path with sufficient accuracy [2]. Li, Lee and Jun (2004) presented an adaptive nonlinear controller for diving control of an autonomous underwater vehicle. They designed the adaptive controller using a back stepping method and presented numerical studies to illustrate the effectiveness of their proposed control scheme [3]. Josserand (2006) developed a sliding mode control for the heading and depth control of the Robotics Underwater Vehicle (RUV) class. He designed and constructed an experimental RUV to compare the performance of the proposed sliding mode controller with a conventional PID controller [4].

Liang, Pang, Wang and Wang (2009) developed and verified a 6DOF nonlinear model for an AUV with fins. They achieved motion simulation with output checked with AUV dynamic data collected experimentally [5]. Dius and Hajiyev (2011) modelled a high speed AUV and developed a navigation system based on a Kalman filter technique. They presented the step time response of the roll, pitch and yaw angle in response to a rudder step input [6]. Syahroni and Choi (2012) presented an optimal regulator for depth control simulation of an AUV using an open control platform. They presented the step time response of the AUV with and without their proposed control scheme for a desired depth of -5 m [7]. Shafei and Banazadeh (2014) investigated the modeling and control of a variable mass AUV with 6DOF. They used a multiple modeling approach in the controller design and used simulation results to reveal the effect of the multiple controller for set point tracking [8].

Vahid and Javanamard (2016) investigated the design and control of depth and pitch of an AUV using a PD controller to control the vehicle pitch and an outer P-loop control with state feedback to control the AUV depth. They used linear model for pitch and depth motions [9]. Wu et al. (2018) designed a L1 adaptive controller with anti-windup compensator to achieve robustness and fast time response of the AUV. They applied the proposed control approach to the pitch channel to the 6DOF vehicle model with strong nonlinearity and investigated the effectiveness of the proposed control strategy through simulation [10]. Abtahi, Alishahi and Yazdi (2019) presented an identification method for the hydrodynamic coefficients of an AUV using the equations of motion. They devised an optimal fusion algorithm estimating the required data accuracy. They used a reliable controller to excite the AUV plane dynamics and investigate the performance and accuracy of the identification and fusion algorithms through a 6DOF numerical simulation [11].

Jantapremjit, Daengchart and Wilson (2021) described a modeling and control design scheme of an underwater glider and presented a simplification for the complex nonlinear model. Their work covered depth and pitch angle control design using PID and LQR controllers. They investigated the performance of the proposed controllers through simulation and experimentally [12]. Lipko (2022) investigated the identification of the mathematical model of an AUV and comparison of the simulation results with real data. He obtained the transfer functions of the horizontal movement in the form of ½ transfer function models from left and right motor control signals [13]. Liu et al. (2023) investigated the use of optimized PID controller based on improved particle swarm optimization to control an underwater remotely operated vehicle. They compared the improved PSO-PID controller with a conventional PID controller and concluded that the PSO-PID controller showed certain improvement. They used a 0/2 + integrator transfer function for the vehicle lateral motion [14]. Bhattacharya and Amadadappac (2024) developed a method to avoid collisions underwater. They used FLC and system identification with standard vehicle depth and pitch control dynamic parameters with equations of TUUV vehicles. They used depth, depth rate, pitch, trajectory and tracking as outputs. The deep reinforcement learning controller helped avoiding collision with moving obstacles underwater [15].

II. THE CONTROLLED UNDERWATER VEHICLE (AUV) PITCH ANGLE AS A PROCESS

Valid and Javanamard (2016) presented a modeling scheme for an AUV for its pitch angle and depth [8]. The AUV they modeled had a 0/2 transfer function model for its pitch angle, $G_\theta(s)$ given by:

$G_\theta(s) = -1.70 / (s^2+10.6s+14.8)$ (1)

This process has two simple poles p_1 and p_2:

$p_1 = 1.654 \quad , \quad p_2 = 8.945$ (2)

The unit step time response of the AUV pitch angle process using the model in Eq.1 is evaluated and drawn using the '*step*' command of MATLAB [16] and shown in Fig.1.

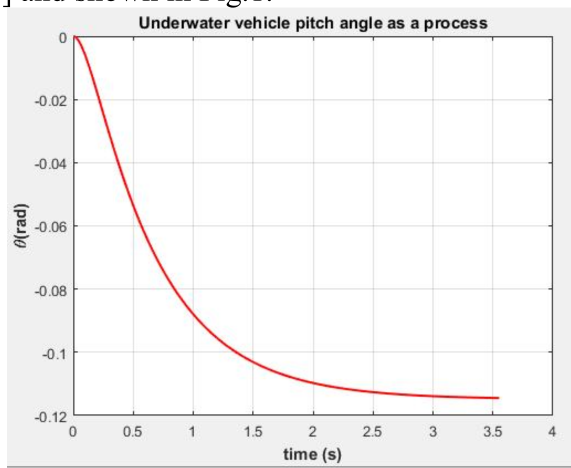

Fig.1 AUV pitch angle step time response as a process.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 2.40 s
- Steady-state error: 1.11447 rad

This process is another example of processes with bad dynamics. It has large steady-state error. Any proposed compensator/controller has to face this challenge and produce control system for the AUV pitch angle with accurate and smooth change of pitch angle without oscillation.

III. AUV PITCH ANGLE CONTROL USING A PD-I CONTROLLER

A PD-I controller was proposed by the author in 2018 to control second-order-like processes [17] as one of the second generation of PID controllers introduced by the author since 2014 to replace the first generation of PID controllers. The structure of the PD-I controller as proposed by the author is shown in Fig.2 [17].

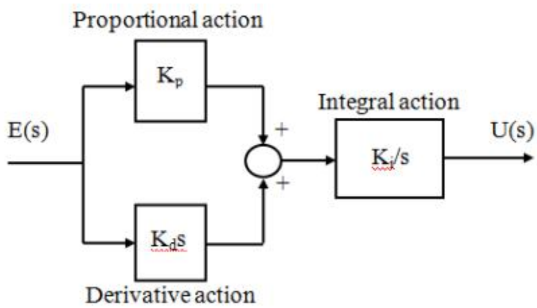

Fig.2 Structure of the PD-I controller.

- The PD-I controller has the transfer function, $G_{PDI}(s)$ given by:

$$G_{PDI}(s) = (K_{pc}+K_d s)(K_i/s) \quad (3)$$

- The controller zero in Eq.3 is written in a standard form as follows:

$$G_{PDI}(s) = (K_d K_i/s)[(K_{pc}/K_d)+s] \quad (4)$$

- The PD-I controller is tuned as follows:
  - The zero/pole cancellation technique is proposed [18].
  - The controller zero in Eq.4 is set equal to the simple pole s+1.6544 of Eq.2. The result of which is relating the controller proportional gain K_{pc} to its derivative gain K_d through:

$$K_{pc} = 1.6544\, K_d \quad (5)$$

  - Now, the closed-loop transfer function of the control system loop for the AUV pitch angle control will have a 0/2 order which can be written in terms of the natural frequency and damping ratio of the second order transfer function.
  - Setting the damping ration of the second-order control system to a unit value (critical damping) for minimum settling time and zero overshoot reveals the following relation between the derivative gain Kd and its integral gain Ki:

$$K_d = -11.76737/K_i \quad (6)$$

  - This means that the tuning process of the PD-I controller is reduced to the optimal adjustment of its integral gain K_i while te other two gain parameters can be calculated using Eqs.6 and 5.
  - An ITAE performance index [19] and the MATLAB optimization toolbox [20] is used for this purpose providing the following tuned PD-I controller parameters in collaboration with Eqs.6 and 5:

$$K_{pc} = -194.6887 \;;\; K_d = -117.67936$$
$$K_i = 0.10 \quad (7)$$

- The unit step response of the AUV pitch angle when using a PD-I controller to control it is generated using its closed loop transfer function and the tuned gain parameters of the controller as given by Eq.7. The result is shown in Fig.3.

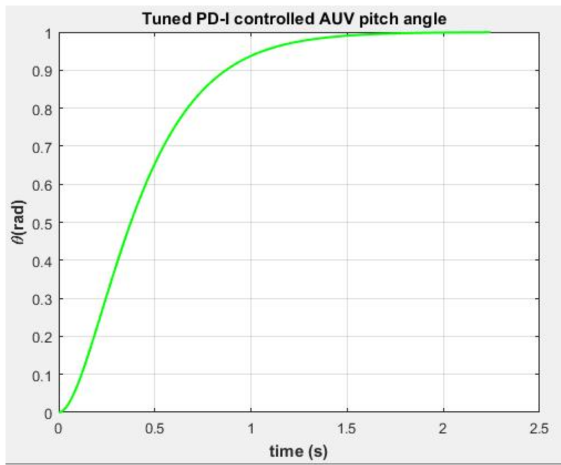

Fig.3 AUV pitch angle control using a PD-I controller.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 1.3045 s
- Steady-state error: zero

IV. AUV PITCH ANGLE CONTROL USING AN I-PD CONTROLLER

- The I-PD controller is one of the second generation controllers introduced by the author starting from 2014 to replace the first generation of PID controllers. The author introduced the I-PD controller to control a highly oscillating second-order process [21].

- The structure of the I-PD controller in a single loop control loop for the control of the AUV pitch angle is shown in Fig.4.

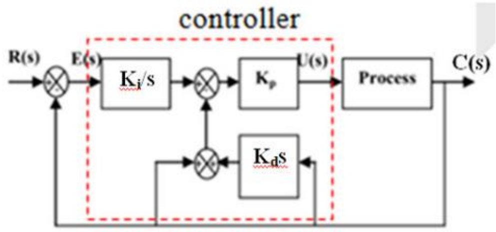

Fig.4 Structure of an I-PD controller [22].

- An I-PD controller comprises three control elements of integral, proportional and derivative actions arranged as depicted in Fig.4. It has three gain parameters:

K_i: integral gain of the I-control mode.

K_{pc}: proportional gain of the P-control mode.

K_d: derivative gain of the D-control mode.

- The I-PD controller is tuned as follows:
- The zero/pole cancellation technique [18] is used to elate the proportional gain K_{pc} of the I-PD controller to its derivative gain K_d as in Eq.5.
- The ITAE performance index [19] is minimized by the MATLAB optimization toolbox [20] to tune the integral and derivative gain parameters of the I-PD controller.
- The tuning results are as follows:

$K_i = -20.00$; $K_{pc} = .8222$

$K_d = 0.500$ (8)

- Using the block diagram in Fig.4, the process transfer function in Eq.1 and the I-PD controller elements transfer functions, the transfer function of the control system between the AUV pitch angle as output and the stern angle as input can be easily derived.
- The 'step' command of MATLAB is used to plot the unit step time response of the control system [16] using the derived closed-loop transfer function. It is shown in Fig.5.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 1.085 s
- Steady-state error: zero

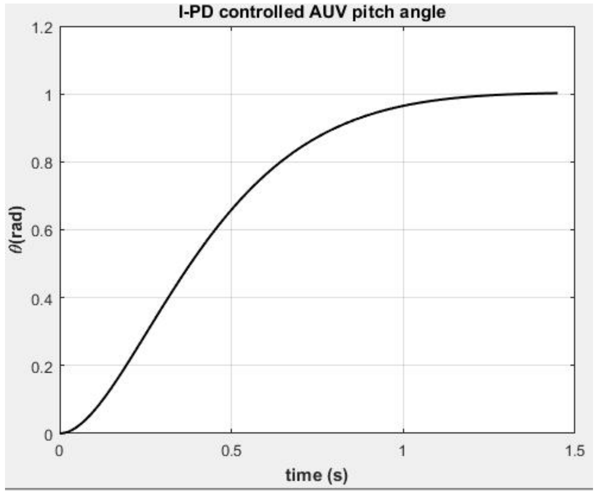

Fig.5 AUV pitch angle control using an I-PD controller.

V. AUV PITCH ANGLE CONTROL USING AN I-FIRST ORDER COMPENSATOR

- The I-first order compensator was first introduced by the author in September 2024 to control an autonomous car longitudinal velocity [23] as one of the second generation compensators introduced by the author starting from 2014 to replace the first generation of control compensators.
- The I-first order compensator consists of two control elements structured in cascade in the forward path of the closed-loop control loop of the AUV pitch angle. The first element is an integral mode having K_i/s transfer function where the second element has $(s+z)/(s+p)$ transfer function. Thus, the I-first order compensator has the transfer function $G_{I1st}(s)$ given by:

$G_{I1st}(s) = K_i(s+z)/[s(s+p)]$ (9)

Where K_i is its integral gain, z is its simple zero and p is its simple pole.

- The I-first order compensator has three gain parameters which have to be tuned for optimum performance for reference input tracking and good performance rejection.
- The unit step time response of the control system for a reference input is obtained

using the closed loop transfer function derived from the block diagram of the control system with reference input tracking, compensator transfer function in Eq.9, process transfer function in Eq.1 and the '*step*' command of MATLAB [16].

- The I-first order compensator is tuned as follows:
  - The zero-pole cancellation technique [18] is used to tune some of the compensator parameters. The simple zero of the compensator in Eq.9 is set equal to the simple pole s+1.6544 of the process (AUV pitch angle). This step reveals the zero of the I-first order compensator as:

    $z = 1.6544$ (10)
  - Now. The remaining compensator parameters are Ki and p. They are tuned through using an ITAE performance index [19] and MATLAB optimization toolbox [20]. They hybrid tuning approach followed reveals the following tuned parameters of the I-first order compensator:

    $K_i = -92.50$; $z = 1.6544$; $p = 9.60$ (11)
- The unit step time response of the control system for reference input tracking as generated by the MATLAB command '*step*' [16] using the I-first order compensator tuned gain parameters in Eq.11 and its transfer functions is shown in Fig.6.

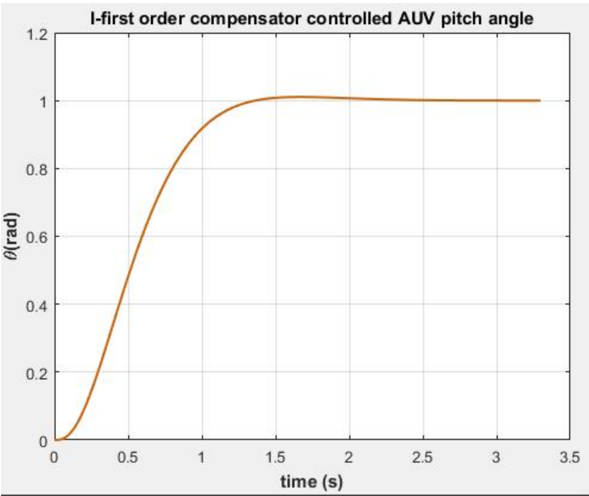

Fig.6 AUV pitch angle control using an I-first order compensator.

COMMENTS:

- Maximum overshoot: 1.047 %
- Settling time: 1.213 s
- Steady-state error: zero

VI. AUV PITCH ANGLE CONTROL USING AN I-SECOND ORDER COMPENSATOR

- The I-second order compensator is one of the second generation of control compensators introduced by the author starting from 2014 to replace the first generation control compensators. The author presented the I-second order compensator as a novel compensator in November 2024 to control an autonomous car yaw rate [24].
- The I-second order compensator consists of two cascaded control elements: an integral control mode element of gain Ki and a 2/2 control compensator element of parameters b_1, b_2 for its quadratic zero and a_1, a_2 for its quadratic pole.
- The I-second order compensator has the transfer functions:

$G_{I2nd}(s) = (K_i/s)(s^2+b_1s+b_2)(s^2+a_1s+a_2)$ (12)

- The I-second order compensator has five gain parameters K_i, b_1, b_2, a_1 and a_2 to be tuned to adjust the performance of the closed-loop control system.
- The transfer function of the closed-loop control system is derived from the block diagram using Eqs.1 for the AUV pitch angle and 12 for the I-second order compensator.
- The I-second order compensator is tuned as follows:
  - A hybrid tuning approach is used.
  - The zero/pole cancellation technique [18] is used to tune some of the compensator parameters. The quadratic zero of the compensator in Eq.12 is set equal to the quadratic pole of the process (AUV pitch angle) in Eq.1. This step reveals the two gain parameters of the quadratic zero of the I-second order compensator as:

    $b_1 = 10.6$, $b_2 = 14.8$ (13)

- Now. The remaining compensator parameters are K_i, a_1 and a_2. They are tuned through using an ITAE performance index [19] and MATLAB optimization toolbox [20]. They hybrid tuning approach followed reveals the following tuned parameters of the I-first order compensator:

  $K_i = -4.441083$; $a_1 = 2.9477316$

  $a_2 = 8.364997$ (14)

- The unit step time response of the control system for reference input tracking as generated by the MATLAB command '*step*' [16] using the I-second order compensator tuned gain parameters in Eqs.13 and 14 is shown in Fig.7.

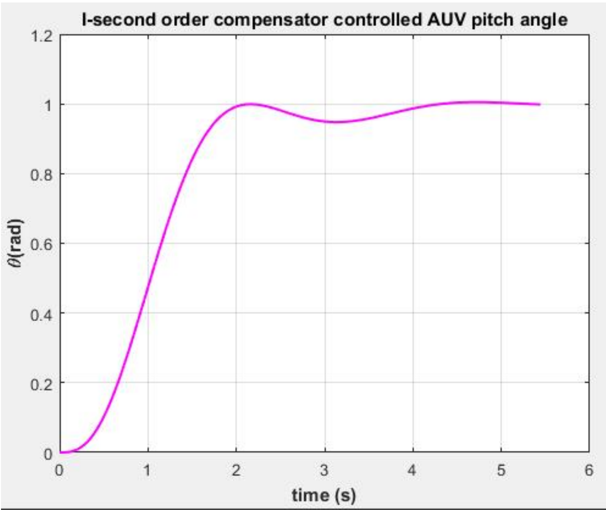

Fig.7 AUV pitch angle control using an I-second order compensator.

COMMENTS:

- Maximum overshoot: 0.502 %
- Settling time: 3.877 s
- Steady-state error: zero

VII. AUV PITCH ANGLE CONTROL USING A PD CONTROLLER

- PD controller is one of the controllers of the PID first generation controllers. It still finds place in process control [25],[26] .
- The transfer function of the conventional PD controller, $G_{PD}(s)$ is given by:

  $G_{PD}(s)= K_{pc}\ (1+T_d s)$ (15)

Where:

K_{pc} = proportional gain of the PD controller

T_d = time constant of the PD controller.

- Vahid and Javanmard [8] tuned a PD controller to control the AUV pitch angle and provided the following PD controller parameters:

  $K_{pc} = 0.2604$, $T_d = 0.21$ s (16)

- The unit step time response of the control system for reference input tracking is obtained using the closed loop transfer function derived from the block diagram of the control system, controller transfer function in Eq.15, process transfer function in Eq.1 and the '*step*' command of MATLAB [16]. It is shown in Fig.8.

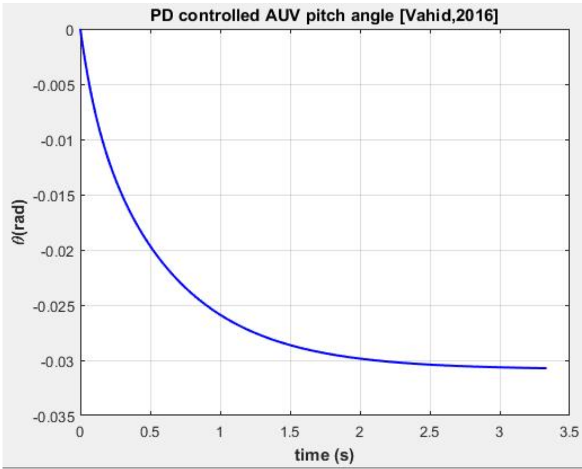

Fig.8 AUV pitch angle control using a PD controller.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 2.187 s
- Steady-state error: 1.0308 rad

VIII. COMPARISON OF TIME BASED CHARACTERISTICS

Graphical Comparison:

- The time-based characteristics of the control systems incorporating the proposed compensators/controllers proposed to control the AUV pitch angle are compared graphically through the step time response as depicted in Fig.9.

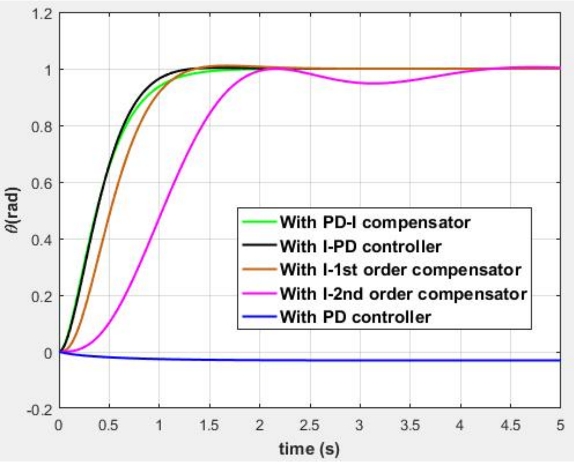

Fig.9 AUV pitch angle control using four controllers/compensators.

Numerical Comparison:

Numerical comparison for the time-based characteristics of the step time response for reference input tracking of the control system with the proposed controllers/compensators is presented in Tables 1 with comparison with the application of a conventional PD controller used to control the same process.

TABLE 1
TIME-BASED CHARACTERISTICS FOR REFERENCE INPUT TRACKING OF AN AUV PITCH ANGLE CONTROL

Controller/ compensator	PD-I controller	I-PD controller	I-1st compensator	I-2nd compensator	PD controlle
OS_{max} (%)	0	0	1.047	0.502	0
T_s (s)	1.3045	1.085	1.213	3.877	2.187
e_{ss} (rad)	0	0	0	0	1.0308

OS_{max}: Maximum percentage overshoot.
T_s: Settling time to ± 2% tolerance.
e_{ss}: Steady-state error.

IX. CONCLUSIONS

- The research work presented in this research paper handled the tuning of PD-I, I-PD controllers and I-first order, I- second order compensators proposed to control an autonomous AUV pitch angle..
- The paper presented four controllers/compensators from the second generation of PID controllers compared with a PD controller from the first generation.
- The controlled process (AUV pitch angle) was a stable one having 2.4 s settling time, 1.1145 rad steady-state error and zero overshoot.
- The four controllers were tuned using a hybrid approach based on zero/pole cancellation and MATLAB optimization toolbox with an ITAE performance index aiming at providing a good dynamic performance for the control system.
- All the proposed controllers/compensators succeeded to eliminate completely the steady-state error of the control system.
- The proposed PD-I and I-PD controllers succeeded to eliminate completely the maximum percentage overshoot of the control system.
- All the proposed controllers/compensators succeeded to eliminate completely the steady-state error of the control system compared with 1.0308 rad for the PD controller.
- The I-first order compensator could generate step time response having only 1.047 % maximum overshoot compared with 2.187 s for the PD controller.
- The I-second order compensator couldn't compete with the PD controller regarding the maximum overshoot and settling time but but it provided a zero steady state error compared with 1.0308 rad for the PD controller.
- The I-PD controller was selected as the best controller/compensator regarding reference input tracking providing zero steady-state error, zero maximum overshoot and minimum settling time compared with the other controllers/compensators investigated in the present study.

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