International Journal of Computer Techniques -– Volume 12 Issue 2, 2025
www.ijctjournal.org

RESEARCH ARTICLE OPEN ACCESS

Autonomous Vehicle Control, Part XV: Farm Tractor Yaw Rate Control using I-first order, Feedforward 2/2 Second-order Compensators and PD-I, PD-PI Controllers compared with a P Controller

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Abstract:

This paper is the fifteenth in a series of research papers presenting the control of autonomous vehicles. It handles the control of the yaw rate of a farm tractor using an I-first order, feedforward 2/2 second-order compensators, PD-I and PD-PI controllers from the second generation of PID controllers compared with a P controller from the first generation of PID controllers. Some efficient tuning techniques for the proposed compensators/controllers are applied with relevant performance indices. The step time response of the control system using the four investigated compensators/controllers is presented and compared and the time-based characteristics are extracted and compared. The comparison reveals the best compensator/controller among the four ones presented depending on a graphical and quantitative comparison study for reference input tracking.

Keywords — Autonomous control, farm tractor yaw rate control, I-first order compensator, 2/2 second-order compensator, PD-I controller, PD-PI controller, controller tuning.

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I. INTRODUCTION

Field trailers play important roles in land leveling, land ploughing, land cultivation, plant weeding, transporting of manure and agricultural products [1]. Because they work in difficult circumferences, its automatic control is so important. Here we handle of the operation parameters of tractors that affects its functional operation: the yaw rate. We start by presenting a literature review about the trailer yaw rate control since 2002:

Bevly, Gerdes and Parkinson (2002) presented the identification of a model for the farm tractor's yaw dynamics to improve the tractor's yaw control at higher speeds and understand the controller limitations. They presented experimental results indicating the capability of the yaw model to provide lateral control of the tractor to within 40 mm at speeds up to 8 m/s [2]. Junyusen et al. (2005) described the development of a trajectory controller for a trailer towed by an agricultural vehicle. The objective of the control system was to navigate the trailer by tracking the desired trajectory. They proved through simulation that a forward controller could guide the trailer to its destination without errors. They introduced also a feedback controller based on a linearized system model, pole placement technique and optimal control. They concluded that the optimal controller showed better trajectory tracking than the pole-placement controller [3]. Karmi and Manu (2006) investigated tractor yaw dynamics for the application in a tractor driving simulator. They measured the tractor yaw rate at different forward speeds in response to a range of steering angle frequencies. They showed that the bicycle model accurately predicted the tractor yaw rate at low frequencies while at high frequencies the consideration of tire relaxation length was necessary [4]. Benton and Bevly (2009) presented an application of a model reference adaptive control system to control the lateral position of a farm tractor tracking a straight path. The proposed control system was implemented to compensate the yaw rate variations by adapting the feedforward yaw rate controller. They applied the control algorithm on a John Deere 8420 farm tractor and presented experimental results. They identified a ½ transfer function model for the yaw rate/steering angle dynamics of the tractor [5].

Kayacan, Kayacan, Romon and Saeys (2013) studied yaw dynamics modeling and identification of an autonomous tractor and developed three yaw dynamics models for various types of soil conditions. Two of the derived models identified the yaw dynamics accurately and an empirical second-order model gave reasonable results. They identified 0/2, 1/3 and 2/4 transfer function models [6]. Milani (2015) in his M. Sc. Thesis investigated the potential of active steering control of the maneuverability and stability of tractor-semitrailer combination. He studied some of the available dynamic models in the literatures and presented one of them suitable for the objectives of his study with implementation of MATLAB simulation [7]. Plessen and Bemporad (2017) presented a method for the control of autonomous low speed agricultural machine. They used offline reference trajectory generation tailored for high precision closed-loop tracking using linear time-varying model predictive control. They discussed three design methods for generating smooth reference trajectories [8].

Purbowaskito and Telaumbanua (2019) stated that 'development of autonomous tractor yaw rate dynamics control system is a challenging study because of the changes of its dynamics'. They implemented an observer based optimal controller to control the yaw rate of an autonomous tractor through simulation. The used the linear quadratic regulator the optimal control algorithm and the Kalman-Bucy filter as a state observer. They claimed that their proposed linear quadratic regulator control satisfied yaw rate control results and the Kalman-Bucy filter provided satisfied estimation results [9]. Zhu et al. (2024) derived a nonlinear 3DOF dynamic model for a steering control strategy for a four-wheel steering hillside tractor. They used a fuzzy PID control algorithm and the model was validated by simulation and relevant experiments. They showed that using fuzzy PID control algorithm reduced the average settling time to 0.1 s and the steady-state yaw rate to 0.038 rad/s [10]. Lei et al. (2025) designed a dual-trajectory collaborative control model based on nonlinear under actuation characteristics of the tractor-trailer system and law of passive trailer steering. They constructed an energy function optimum control parameter to balance the system trajectory tracking performance and lateral control stability. They claimed that experimental results showed good agreement between the predicted trailer trajectory and the collaborated control strategy [11].

II. THE CONTROLLED TRACTOR YAW RATE AS A PROCESS

Kayacan et al. investigated the modeling and identification of an autonomous agricultural tractor [12]. They derived transfer function models between the steering angle of the steering mechanism and the yaw rate of the tractor having ½, 1/3 and 2/4 orders [12]. They proposed a block diagram structure to control the tractor yaw rate shown in Fig.1. I called it structure I of the tractor yaw rate process. In this structure a P controller (one of the PID first generation controllers) to control the steering mechanism of the tractor producing an steering angle δ as an input to the tractor yaw rate variable. The transfer functions of the steering structure [$G_s(s)$] and tractor yaw rate second-order model [$G_t(s)$] are as follows [12]:

$G_s(s) = 1.1705/[s(0.13s+1)]$ (1)

$G_t(s) = 291/ (s^2+10.9s+242)$ (2)

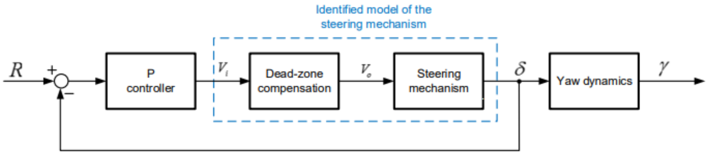

Fig.1 Block diagram of a farm tractor yaw rate control [12].

Eq.2 represents a second-order process having the following characteristics:

- Natural frequency: 15.556 rad/s
- Damping ratio: 0.3503
- Steady-state error: -0.1995 (for a unit step input)
- Maximum overshoot: 31.144 %

The proportional (P) controller will not improve the dynamic performance of the control system of the tractor yaw rate using the block diagram in Fig.1. A new structure is proposed as follows:

- The single-loop of the steering mechanism in Fig.1 is used to tune the proportional gain using analytical tuning technique giving:

  $K_{pc} = 1.642953$ (3)
- The transfer function of the loop will be in cascade with the tractor yaw rate model in Eq.2 giving the transfer function of the steering mechanism-tractor yaw rate (structure 2),$G_{st}(s)$ given by:

  $G_{st}(s) = b_0/(a_0s^4+a_1s^3+a_2s^2+a_3s+a_4)$ (4)

Where:

$b_0 = 559.615257$; $a_0 = 0.13$
$a_1 = 2.4170$; $a_2 = 44.283076$
$a_3 = 262.96153$; $a_4 = 465.38451$ (5)

The new process of the structure 2 defined by Eq.4 having parameters of Eq.5 has the dynamics of the tractor yaw rate for a desired yaw rate of 0.3 rad/s time response generated using the 'step' command of MATLAB [13] shown in Fig.2 for a specific farm tractor. The yaw rate limit of the tractor is chosen as 0.35 rad/s [14].

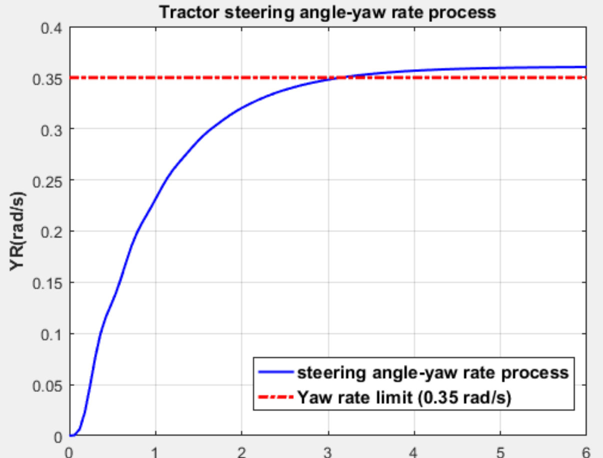

Fig.2 Farm tractor unit step yaw rate time response.

COMMENTS:

- The yaw rate process (structure 2) has the time-based characteristics:
  - Maximum overshoot: zero
  - Settling time: 1.563 s
  - Steady-state error: -0.06 rad/s
- It has a non-zero steady-state error.
- It has a 1.563 s settling time which may be improved through using a reasonable controller or compensator.
- Its step time response with 0.3 rad/s step magnitude violates the 0.35 rad/s upper limit of the yaw rate which has to be compensated by a good controller/compensator.

III. CONTROLLING THE TRACTOR YAW RATE USING AN I-FIRST ORDER COMPENSATOR

- The I-First order compensator is one of the second generation of control compensators introduced by the author in 2014. The author used the I-first order compensator in September 2024 to control an autonomous car longitudinal velocity [15]. It has the transfer function $G_{I1st}(s)$ given by:

$G_{I1st}(s) = (K_i/s)[(s+z)/(s+p)]$ (6)

Where:

K_i = integral gain of the compensator
z = compensator zero
p = compensator pole

- The I-first order compensator is set in a single-loop control system block diagram just before the process and after the error detector receiving the error signal and as input.
- In order to use the zero/pole cancellation technique in the tuning process of the I-first order compensator, the process transfer function in Eq.4 has to be written in poles format as follows:

$$G_{st}(s) = b_0 / \{(s+p_1)(s+p_2)(s^2+c_1s+c_2)\} \qquad (7)$$

Where:

$p_1 = 1.153188$, $p_2 = 12.122596$
$c_1 = 5.316524$, $c_2 = 256.0784$

- The I-first order compensator is tuned for the optimal settling of its three parameters as follows:
    - The zero/pole cancellation technique [16] is applied of the open-loop transfer function of the block diagram loop for tractor yaw rate control. The compensator zero (in Eq.6) is chosen to cancel the simple pole $(s+p_1)$ of the yaw rate process (in Eq.7) providing the value of the compensator zero as:

      $$z = 1.153188 \qquad (8)$$

    - The transfer function of the closed-loop control system, YR(s)/R(s) can be deduced using Eqs.6, 7 and 8 in a unit feedback single loop control system.
    - The ITAE performance index [17] is function of the error of the control system which is function of the compensator parameters K_i and p. Minimizing the ITAE using the MATLAB optimization toolbox [18] reveals the two compensator parameters as:

      $$K_i = 0.606882 \ , \ p = -9.841707 \qquad (9)$$

- The unit step time response for reference input tracking using the compensator transfer function in Eq.6, process in Eq.7 and the tuned compensator parameters in Eqs.8 and 9 is obtained using the command 'step' of MATLAB [13] as shown in Fig.3 for a reference step input of 0.3 rad/s magnitude.

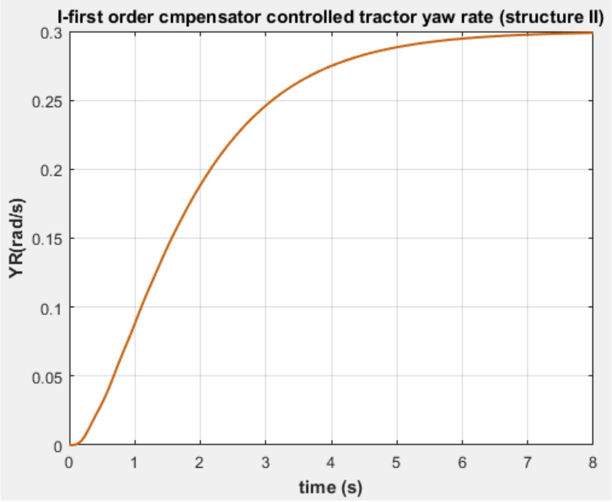

Fig.3 Tractor yaw angle control using an I-first order compensator.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 5.83 s (compared with 1.54 s for P controller)
- Steady-state error: zero (compared with -0.0607 rad/s for P controller)

IV. CONTROLLING THE TRACTOR YAW RATE USING A FEEDFORWARD 2/2 SECOND-ORDER COMPENSATOR

- The feedforward 2/2 second-order compensator was introduced by the author in September 2024 as one of the second generation control compensators introduced by the author since 2014. It was introduced to control the longitudinal velocity of an autonomous car [19].
- The feedforward 2/2 second-order compensator has the transfer function $G_{c2by2}(s)$ given by:

$$G_{c2by2}(s) = K_c(s^2+b_1s+b_2)/(s^2+a_1s+a_2) \qquad (10)$$

Where:

K_c = compensator gain

b_1, b_2 = parameters of the compensator quadratic zero

a_1, a_2 = parameters of the compensator quadratic pole

- The 2/2 second-order compensator has five gain parameters to be tuned to optimize the performance for the control system.
- This compensator is set in a single control-loop control system as explained in the I-first order compensator.
- The transfer function of the control system comprising the 2/2 second-order compensator and the tractor yaw rate process is derived using the block diagram of the control system and Eqs.10 and 7.
- The compensator gain parameters are tuned as follows:

- The zero/pole cancellation technique [16] is used to cancel the compensator quadratic zero with the quadratic pole of the tractor yaw rat process in the open-loop transfer function $G_{c2by2}(s)G_{st}(s)$. This step reveals the compensator parameters of its quadratic zero as:

  $b_1 = 5.3165245$, $b_2 = 256.0784$ (11)

- The transfer function of the closed-loop system incorporating the 2/2 second order compensator is derived using the block diagram of the control system and Eqs.7,10 and 11.
- The structure of the closed-loop transfer function of this control system reveals a non-zero steady-state error. The steady-state error is used as a desired characteristic to improve the accuracy of the control system. This condition tunes the parameter a_2 of the compensator quadratic pole. That is:

  $a_2 = 0$ (12)

- We are now left with two 2/2 second-order compensator parameters K_c and a_1. The MATLAB optimization toolbox [18] is used to minimize an ISTSE (Integral Square Time multiplied by Square Error) performance index [20] revealing the following optimal values for K_c and a_1:

  $K_c = 743.3148$, $a_1 = 1.120204 \times 10^5$ (13)

- The step time response of the control system using the transfer function of the closed-loop control system and the compensator parameters in Eqs,11, 12, 13 is drawn by the help of MATLAB 'step' command [13] and shown in Fig.4 for a reference step input of 0.3 rad/s magnitude.

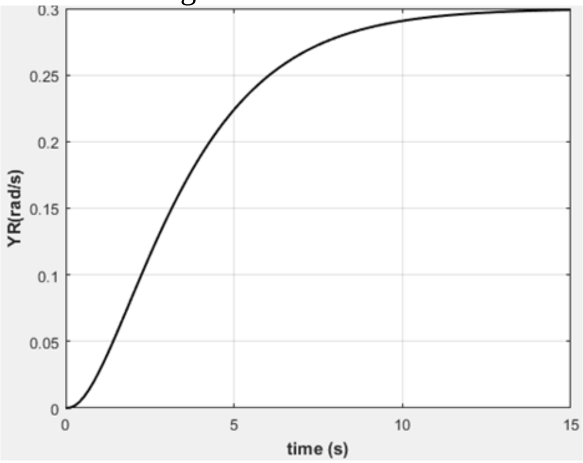

Fig.4 Tractor yaw angle control using a feedforward second-order compensator.

COMMENTS:

- Maximum overshoot: zero
- Settling time: 11 s (compared with 1.54 s for P controller)
- Steady-state error: zero (compared with -0.0607 rad/s for P controller)

V. CONTROLLING THE TRACTOR YAW RATE USING A PD-I CONTROLLER

- The PD-I controller was introduced by the author in March 2018 to control second-order-like processes [21]. It is composed of two cascaded control mode elements: PD and I just after the error detector of a single-loop block diagram of the control system [21].
- The PD-I controller has a transfer function $G_{PDI}(s)$ given by:

  $G_{PDI}(s) = (K_{pc}+K_d s)(K_i/s)$ (14)

  Where:

K_{pc} = proportional gain of the PD control mode.

K_d = derivative gain of the PD control mode.

K_i = integral gain of the I control mode.

- It has three gain parameters K_{pc}, K_d and K_i tuned as follows:
  - The transfer function of the PD-I controller is written in the form of a simple zero as follows:

    $G_{PDI}(s) = (K_d K_i/s)\,[s + (K_{pc}/K_d)]$ (15)
  - The zero/pole cancellation technique [16] is used to cancel the compensator simple zero in Eq.15 with the simple pole (s+1.153188) of the tractor yaw rate process in Eq.7 in the open-loop transfer function $G_{PDI}(s)G_{st}(s)$. This step reveals the following relationship between the compensator K_{pc} and K_d parameters:

    $K_{pc} = 1.153188K_d$ (16)
  - The transfer function of the closed-loop system incorporating the PD-I controller is derived using the block diagram of the control system and Eqs.7 and 15.
  - The closed-loop transfer function of the closed-loop control system incorporating the PD-I controller has the parameters ($K_d K_i$) in its numerator and denominator. Therefore, to simplify the tuning process, this term is replaced by one parameter K_{di} which has to be tuned for optimal performance of the control system.
  - The proposed tuning approach is minimizing an ITAE performance index [17] using the MATLAB optimization toolbox [18] revealing the optimal K_{di} as:

    $K_{di} = K_d K_i = 11.1250$ (17)
  - Let Ki =1 and use Eq.16 and 17 gives the three PD-I controller parameters K_{pc} and K_d and K_i as:

    $K_{pc} = 12.829216$, $K_d = 11.1250$

    $K_i = 1$ (18)
- Using the closed-loop transfer function of the closed-loop control system and the PD-I controller gain parameters in Eq.18 for reference input tracking of 0.3 rad/s desired yaw rate, the step time response is generated using the MATLAB command '*step*' [13] and shown in Fig.6.

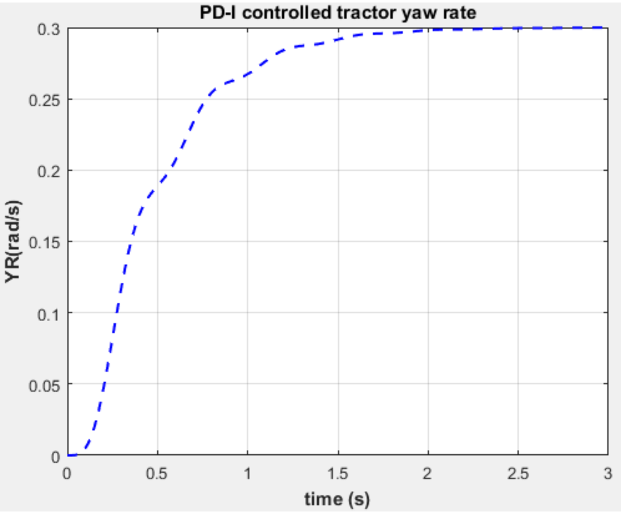

Fig.5 Tractor yaw angle control using a PD-I controller.

COMMENTS:

- ➢ Maximum overshoot: zero
- ➢ Settling time: 1.58 s (compared with 1.54 s for P controller)
- ➢ Steady-state error: zero (compared with -0.0607 rad/s for P controller)

VI. CONTROLLING THE TRACTOR YAW RATE USING A PD-PI CONTROLLER

- The PD-PI was introduced by the author in April 2014 to control first-order-delayed processes as one of the second generation PID controllers [22]. It is composed of two cascaded control modes (PD and PI) located after the error detector in a single-loop control system incorporating the controller and controlled process.
- A PD-PI controller has the transfer function $G_{PDPI}(s)$ given by:

$G_{PDPI}(s) = (K_{pc1}+K_d s)[K_{pc2}+(K_i/s)]$ (19)

Where:

K_{pc1} = proportional gain of the PD control mode
K_d = derivative gain of the PD control mode
K_{pc2} = proportional gain of the PI control mode
K_i = integral gain of the PI control mode

- The PD-PI controller has four gain parameters to be tuned to optimize the performance for the control system.
- The PD-PI controller gain parameters are tuned as follows:
- ✚ The transfer function of the controller is written in the form of two simple zeros as:

$$G_{PDPI}(s) = (K_dK_{pc2}/s)[s+(K_{pc1}/K_d)][s+(K_i/K_{pc2})] \quad (20)$$

- ✚ The zero/pole cancellation technique [16] is used to cancel the two simple zeros of the PD-PI controller in Eq.20 with the two simple poles of the tractor yaw rat process of Eq.7 in the open-loop transfer function $G_{PDPI}(s)G_{st}(s)$. This step reveals the following relationship between the PD-PI controller parameters:

$$K_d = K_{pc1}/1.153188 \, , \; K_i = 12.122596K_{pc2} \quad (21)$$

- ✚ This tuning step reduces the tuning operation to the adjustment of only two controller parameters K_{pc1} and K_{pc2}.
- ✚ The author found that it was no need for sophisticated application of optimization techniques to tune the two controller parameters. Only few manual trials led to good results for the performance of the closed-loop control system incorporating the PD-PI controller and the yaw rate process of the tractor. The obtained controller parameters are:

$$K_{pc1} = 0.2 \; ; \; K_d = 0.173432$$
$$K_{pc2} = 4 \; ; \; K_i = 48.49038 \quad (22)$$

- The step time response of the control system is obtained for 0.3 rad/s reference yaw rate input from the derived closed-loop transfer function and the PD-PI controller parameters in Eq.22 and plotted using the MATLAB step command [13] as shown in Fig.6.

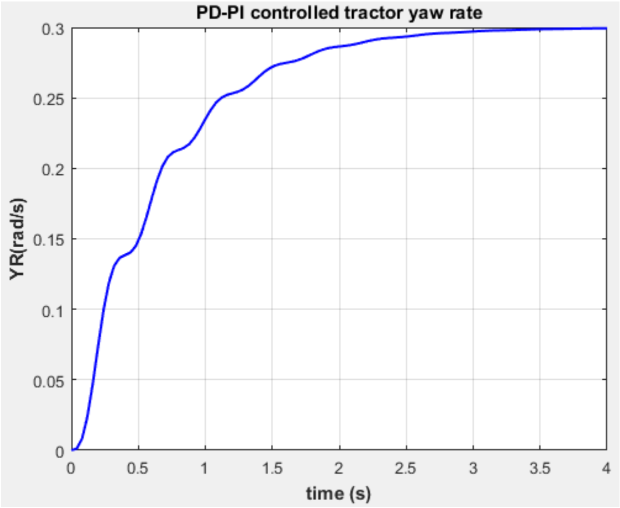

Fig.6 Tractor yaw angle control using a PD-PI controller.

COMMENTS:

- ➢ Maximum overshoot: zero
- ➢ Settling time: 2.55 s (compared with 1.54 s for P controller)
- ➢ Steady-state error: zero (compared with -0.0607 rad/s for P controller)

VII. CONTROLLING THE TRACTOR YAW RATE USING A P CONTROLLER

- The P controller was used by Kayacan et al. to control the yaw rate process of the tractor in the control scheme presented in Fig.1 [12].
- The optimal controller gain of 1.642953 obtained by the author for optimal steering angle control is used in the derivation of the step time response of the control system in Fig.1 for a reference input of 0.3 rad/s desired input.
- The closed-loop transfer function of the control system structure in Fig.1 is used to generate the step time response of the control system as shown in Fig.7.

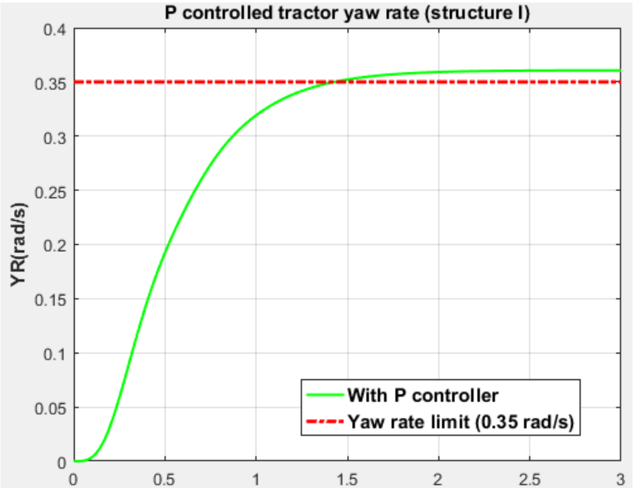

Fig.7 Tractor yaw angle control using a P controller.

COMMENTS:

➢ Maximum overshoot:	zero
➢ Settling time:	1.54 s
➢ Steady-state error:	-0.0607 rad/s

VIII. COMPARISON ANALYSIS

- To evaluate the effectiveness of using the proposed compensators/controllers, the step time response for reference input of 0.3 rad/s magnitude is compared with that using a tuned P controller.
- A graphical comparison is presented in Fig.8 for reference input tracking and a 0.3 rad/s desired altitude.
- A quantitative comparison for the time-based characteristics of the control systems proposed to control the quadrotor UAV is given in Table 1 for a reference step input tracking.

IX. CONCLUSIONS

- This research paper investigated the use of I-first order, feedforward 2/2 second order compensators and PI-D, PD-PI controllers from the second generation of PID controllers to control a farm tractor yaw rate.

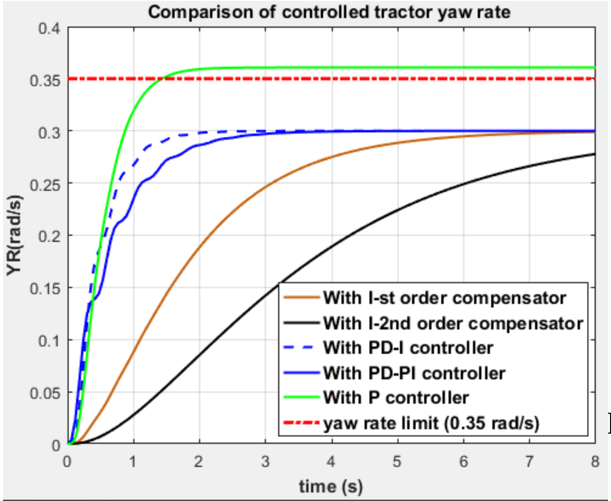

Fig.8 Tractor yaw rate control using two compensators and two controllers.

TABLE 1
TIME-BASED CHARACTERISTICS OF THE FARM TRACTOR YAW RATE CONTROL FOR REFERENCE INPUT TRACKING

Compensator/ controller	**OS_{max} (%)**	**T_s (s)**	**e_{ss} (rad/s)**
I-1st order compensator	0	5.830	0
Feedforward 2/2 2nd-order compensator	0	11	0
PD-I controller	0	1.580	0
PD-PI controller	0	2.550	0
P controller (structure I)	0	1.540	-0.0607

OS_{max} = maximum percentage overshoot
T_s = settling time to 2 % tolerance.
e_{ss} = steady-state error.

- The process under control (farm tractor yaw rate) was an example of processes with bad dynamics because of its large steady-state error.
- The performance of the proposed compensators/controllers was compared with that of a P controller from the first generation of PID controllers.
- Three tuning techniques were used in this study: manual setting of some of the controller parameters, using the pole/zero cancellation technique and using the MATLAB optimization toolbox.
- The four proposed compensators/controllers succeeded to eliminate completely the

maximum overshoot and the steady state error of the closed-loop control system for reference input tracking.

- The settling time of the step input tracking time response was 5.83, 11, 1.58, 2.55 and 1.54 s for the I-first order, feedforward 2/2 second-order compensators, PD-I and PD-PI controllers respectively compared with 1.54 s for the P controller.
- The steady-state error of the step input tracking time response was zero for the I-first order, feedforward 2/2 second-order compensators, PD-I and PD-PI controllers respectively compared with 1-0.0607 rad/s for the P controller.
- Obviously, the PD-I controller proved in this application to be the best compensator/controller because it provided the least settling time of 1.58s without any overshoot or steady-state error.
- The PD-PI controller comes next to the PD-I controller as the second-best controller as it provided settling time of 2.55 s without any overshoot or steady-state error.

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