wjert, 2024, Vol. 10 Issue 11, 01-20 Review Article ISSN 2454-695X

World Journal of Engineering Research and Technology
WJERT
www.wjert.org SJIF Impact Factor: 7.029

AUTONOMOUS VEHICLE CONTROL, PART IV: CAR YAW RATE CONTROL USING P-D, I-SECOND-ORDER COMPENSATORS AND PD-PI, 2DOF-2 CONTROLLERS COMPARED WITH A PID CONTROLLER

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Article Received on 25/08/2024 Article Revised on 15/09/2024 Article Accepted on 05/10/2024

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ABSTRACT

This paper is the fourth in a series of research papers presenting the control of power turbines using compensators and controllers from the second generation of compensators and PID controllers. It handles the control of car yaw angle using P-D and I-second order compensators, PD-PI and 2DOF-2 controllers with comparison with the use of a PID controller from the first generation of PID controllers. The proposed compensators/controllers are tuned using multiple approaches including the MATLAB optimization toolbox. The step time response of the control system using the four proposed compensators/controllers is presented and compared with using a PID controller to control the same yaw rate and the time-based characteristics are compared. The comparison reveals the best compensator/controller among the five compensators/controllers depending on a quantitative comparison study.

KEYWORDS: Autonomous vehicle control, car yaw angle control, P-D compensator, I-second order compensator, PD-PI controller, 2DOF-2 controller, PID controller, compensators/controllers tuning.

INTRODUCTION

Autonomous vehicle control helps in making everything in the car under control for passenger comfort and safety. Here I am presenting the control of a very important variable in car dynamics which is the yaw rate. Yaw rate is responsible for lateral car stability and hence accident occurrence. Research activities are dealing with this important subject as clear from the next literature survey.

Sivashankar and Ulsoy (1998) described a method for vehicle yaw rate estimation using two accelerometers and a steer angle sensor. They presented simulation results and experimental validation based on test data from a vehicle driven on a test track.[1] Brennan and Alleyne (2001) developed yaw rate controller using the vehicle rear wheels to improve the steering performance where a model reference controller commanded the rear wheels. They obtained experimental results indicating a significant performance improvement over proportional yaw rate controllers. They used second-order transfer function models for the vehicle yaw with rear and front wheels steering action.[2] Anwar (2005) presented theoretical development and experimental results of a vehicle yaw stability control system based on generalized predictive control technique. The controller predicted the future yaw rate and controlled the te yaw rate at present time based on the future yaw rate error. Experimental results showed that the proposed control scheme provided as effective control of the yaw stability of the vehicle.[3]

Canale and Fagiano (2008) introduced a model predictive control scheme to improve vehicle yaw rate dynamics by mean of rear active differential. They investigated the use of nonlinear predictive control to examine their effectiveness in the vehicle stability control context. They compared with an enhanced IMC structure handling input constraints.[4] Zhou and Liu (2010) designed a yaw stability control system to make the yaw rate follow its reference. Based on the sliding mode and back stepping approach, their cascade control system was combined with tire/road force observer and yaw stability controller. They designed the yaw stability controller using a yaw rate model and in the back stepping framework, the brake torque was calculated. Simulation results showed that the proposed controller can maintain vehicle stability for active safety.[5]

Emirler et al. (2013) stated that '*vehicle yaw rate is the key parameter that needs to be known by a yaw stability control system*'. They presented the estimation of a vehicle yaw rate using a virtual sensor containing kinematic relations and a velocity-scheduled Kalman filter for the dynamic estimation part of the virtual sensor. They applied an actual read testing and estimated the yaw rate and compared it with the actual yaw rate measured by a commercial yaw rate sensor.[6] Sen, Chekyaborty and Sutradhar (2015) presented the estimation of yaw rate and lateral motion/velocity of the vehicle. They considered a simplified model of the vehicle during turning and presented the dynamic equations of the vehicle states. They conducted computer simulation to verify the proposed approach showing the effectiveness and robustness of estimating the yaw rate and lateral dynamics.[7] Ahmed and Abunada (2018) studied the control of vehicle yaw stability by using two vehicle models one linear and one nonlinear and used a fuzzy PID control to tune the PID controller parameters and generate effective step time response. They concluded that through simulation results, the control system based on fuzzy PID controller improved the stability and handling the vehicle significantly.[8] Liu, Assadian and Mallen (2020) provided a comparative study of SISO and MIMO Youle controller output observer and various types of Kalman filters: linear Kalman filter extended Kalman filter, unscented Kalman filter in estimating the yaw rate and sideslip of the vehicle. They tested the robustness of those estimators under plant parameters and environmental uncertainties. They compared the yaw angle estimation result using the estimation approach with a simple kinematic model approach.[9]

Emirler and Guvenc (2022) studied the problem of vehicle lateral stability using active front wheel steering and individual braking. They stated that: 'vehicle lateral stability control means keeping the vehicle yaw rate and sideslip angle within the desired values'. They obtained the desired yaw rate from a single track vehicle model and considered the desired sideslip angle as 'zero'. They tested the proposed controller using a nonlinear single-track vehicle model and the CarMaster vehicle model.[10] Yahagi and Suzuki (2023) proposed the virtual reference feedback tuning method for tuning of a gain-scheduled PI controller for vehicle yaw rate control without need to a vehicle model and using a single experimental date. They used a desired yaw rate of 0.5 rad/s.[11] Ricco et al. (2024) considered an integrated system including sensitive and active suspension to control yaw, roll and pitch excited by driving actions. They proposed two real time capable implicit nonlinear model predictive control formulations compared with a passive vehicle. They assessed the proposed algorithms through an experimentally validated simulation model with results that showed best performance.[12]

Controlled Vehicle Yaw Rate

Brennan and Alleyne[2] used yaw models for vehicle front and rear steering in the form of a second-order plus one integrator transfer function. Omitting the integrator element from the transfer function produces the transfer function for the yaw rate of the vehicle. Here in the present research I selected the front steering of the vehicle producing a yaw rate transfer function as a process to be controlled, $G_p(s)$ given by[2]

$$G_p(s) = 13480 / (s^2 + 10.3s + 180)] \qquad (1)$$

It is a second order process having natural frequency and damping ratio given by:

$\omega_n = 13.4164$ rad/s

and $\zeta = 0.3838$

The yaw rate of the vehicle is a key parameter in assigning the safety of vehicle driving during turning. It must not avoid a specific limit depending on the vehicle speed. Regarding this limit a transportation expert consider 20 deg/s as an aggressive limit for vehicle speeds between 70 and 110 km/h.[13] Other considers the limit as 27 and 30 deg/s for 40 and 50 km/h respectively.[14]

The step time response of the yaw rate process having the dynamics defined by Eq.1 for step input magnitude of 0.2 and 1 V with a yaw rate limit of 20 deg/s is shown in Fig.1 as generated by the '*step*' command of MATLAB.[15]

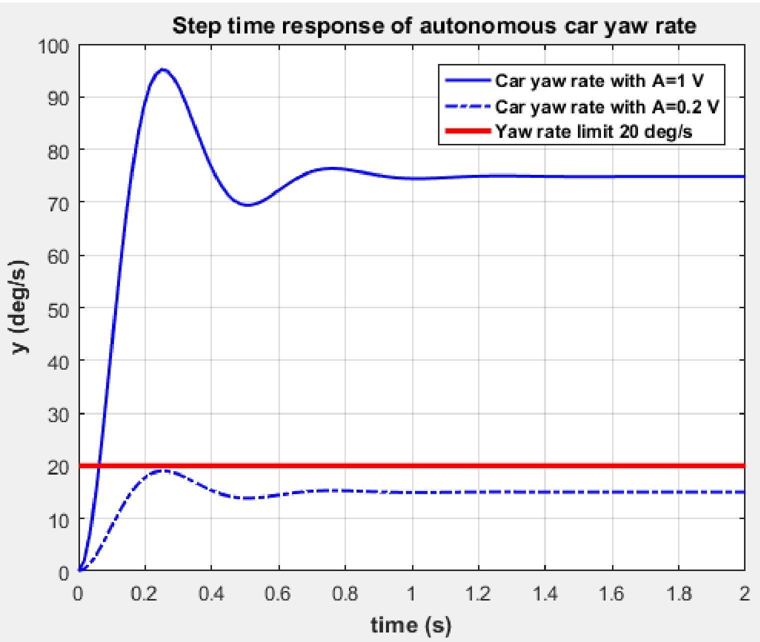

Figure 1: Step time response of the car yaw rate for two input step levels.

COMMENTS

- The yaw rate process is stable.
- It has a maximum percentage overshoot of 98.66 %.
- It has a settling time of 0.6265 s (i.e. less than one seconds).
- It has a steady-state error of -73.88 deg/s.

This process is an example of processes with very bad dynamics (even it is a stable one) because of its very large maximum overshoot (bad stability) and steady-state error (violating the allowable limit of the yaw rate (dangerous driving activity). Any good controller or compensator has to overcome those problems as we will see in the next sections.

Controlling the Car Yaw Rate Using a P-R Compensator

The P-R compensator was introduced by the author to control a highly oscillating second-order-like process in 2022.[16] The P-R compensator is composed of two control elements: a proportional mode in the feedforward path just after the error detector [$G_{c1}(s)$] in a standard block diagram loop for process control and a derivative control mode in the feedback path of the loop [$G_{c2}(s)$]. The two elements have the transfer functions

$$G_{c1}(s) = K_{pc} \text{ and } G_{c2}(s) = K_d s \qquad (2)$$

Where: K_{pc} = compensator proportional gain.

K_d = compensator derivative gain.

The P-D compensator has only two parameters (K_{pc} and K_d) to be tuned to satisfy the objectives of using the compensator to control the car yaw rate and provide good control system performance for reference and disturbance inputs. The tuning procedure used is as follows

- The structure of the proposed compensator will not generate a step time response with zero steady-state error. The steady-state error of the control system will be function of the proportional parameter of the compensator. Here we can set any desired value for the steady-state error, say 0.0001. This action reveals the proportional gain of the compensator as

$$K_{pc} = 0.01335 \qquad (3)$$

- The second characteristics which may be used in tuning the compensator is the settling time of the control system. The settling time of a second order control system (which is the case with using a P-D compensator) is function of its natural frequency and damping ratio [$T_s \approx 4/(\omega_n\zeta)$].[17] The natural frequency and damping ratio of the control system with P-D compensator is function of both gains of the compensator. With the proportional gain given in Eq.3, the derivative gain using the settling time equation will be

$$K_d = 0.044454 \qquad (4)$$

- The transfer function of the closed-loop control system using Eqs.1, 2, 3 and 4 for reference input tracking and that for disturbance input using the block diagram of the control system will be used to generate the unit step time response of the control system using the step command of MATLAB[15] given in Fig.2.

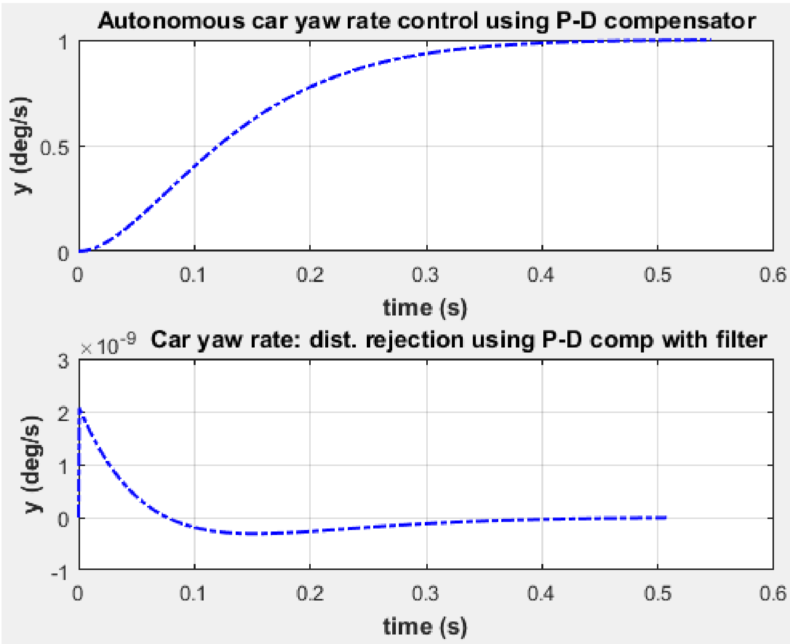

Figure 2: Step time response of the yaw rate using a R-D compensator.

COMMENTS

➢ The R-D compensator provided a reference input tracking unit step time response having the following characteristics

- Maximum percentage overshoot: zero
- Settling time: 0.382 s
- Steady-state error: 0.0009 deg/s

➢ The success of the R-D compensator to reject the disturbance input is measured by the following characteristics

- Maximum yaw rate step time response: 2.07 x 10^{-9} deg/s
- Minimum mold temperature step time response: 0.31 x 10^{-9} deg/s
- Settling time to zero (approximate): 0.4 s.

Controlling the Car Yaw Rate Using an I-second Order Compensator

The I-second order compensator is a novel compensator introduced by the author for the control of the yaw angle. It belongs to the second generation of control compensators introduced by the author since 2014. It is located in the feedforward path of a single-loop control system receiving its input from the error detector and feeding its output to the yaw rate process. It is composed of two units: an integral unit and 2/2 sub-compensator unit cascaded with the integrator unit. The I-second order compensator has the transfer function, $G_c(s)$ given by

$$G_c(s) = (K_i/s)\,(\omega_{n2}^2/\omega_{n1}^2)(s^2+2\zeta_1\omega_{n1}s+\omega_{n1}^2)/\,(s^2+2\zeta_2\omega_{n2}s+\omega_{n2}^2) \qquad (5)$$

Where: K_i = integral gain of the integral unit.

ω_{n1} = natural frequency of the 2/2 sub-compensator quadratic zero.

ζ_1 = damping ratio of the 2/2 sub-compensator quadratic zero.

ω_{n2} = natural frequency of the 2/2 sub-compensator quadratic pole.

ζ_2 = damping ratio of the 2/2 sub-compensator quadratic pole.

- When assigning the closed-loop transfer function of the control system of the yaw rate control, the compensator transfer function $G_c(s)$ in Eq.5 is multiplied by the process transfer function $G_p(s)$ in Eq,1. The quadratic zero of the $G_c(s)$ has the same shape as the quadratic pole of $G_p(s)$. Equating them will eliminate both of them from the closed-loop transfer function of the control system (this assigns ω_{n1} and ζ_1 of he compensator.

- Now, we are left with the three compensator parameters: Ki, ω_{n2} and ζ_2 to be tuned using the ITAE performance index[18] and the MATLAB optimization toolbox.[19]

- The closed-loop transfer function of the control system of the car yaw rate for reference and disturbance inputs are obtained from the single-loop block diagram of the control system.

- Now, the five tuned parameters of the I-second order compensator are given by

$$K_i = 7704.738;\ \omega_{n1} = 13.41641;\ \zeta_1 = 0.38386;\ \omega_{n2} = 144.484;\ \zeta_2 = 0.6158 \qquad (6)$$

- The unit step time response of the control system with the I-second order compensator is obtained for both reference and disturbance inputs using the transfer functions derived from the single-loop block diagram of the control system using the MATLAB command '*step*'[15] and shown in Fig.3.

COMMENTS

- The I-second order compensator provided a reference input tracking step time response having the following characteristics
  - Maximum percentage overshoot: zero
  - Settling time: 0.0437 s
  - Steady-state error: zero.

- The success of the I-second order compensator to reject the disturbance input is measured by the following characteristics (with second-order high pass filter)
  - Maximum mold temperature step time response: 2.085×10^{-9} deg/s
  - Minimum mold temperature step time response: 0.446×10^{-9} deg/s
  - Settling time to zero (approximate): 0.80 s.

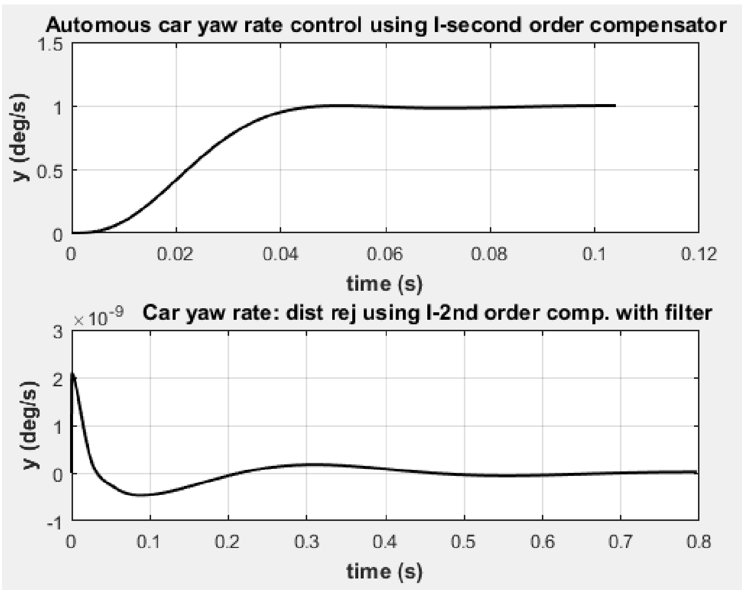

Figure 3: Step time response of the car yaw rate using an I-second order compensator.

Controlling the Car Yaw Rate Using a PD-PI Controller

The PD-PI controller was introduced by the author to control a large number of difficult processes since 2014.[20,45] PD-PI controller is composed of two elements: PD-control mode, $G_{c1}(s)$ in cascade with a second PI-control mode, $G_{c2}(s)$ just after the error detector.

The two elements have transfer functions given by

$G_{c1}(s) = K_{pc1} + K_d s$

and $G_{c2}(s) = K_{pc2} + K_i/s$ (7)

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 (K_{pc1}, K_d, K_{pc2} and K_i) to be tuned to satisfy the objectives of using the controller to control the car yaw rate and provide good control system performance for reference and disturbance inputs.

- To control yaw rate for reference input tracking, the transfer function of the closed loop control system is derived using the block diagram and Eqs.1 and 7.

- Before starting any tuning approach for any proposed controller I try to assign a set of guessed values for the controller gain parameters to provide a feasible guessed values for the optimization technique used in the tuning process.

- Doing this with the PD-PI controllers and the yaw rate process after few trials I have got wonderful step time responses even without any optimal tuning procedure. I took a decision not to proceed further and consider of the controller gain sets I tried as follows

$K_{pc1} = 15$, $K_d = 60$

$K_{pc2} = 0.2$, $K_i = 0.02$ (8)

- Using the closed-loop transfer function of the closed-loop control system for reference and disturbance inputs using the controller parameters in Eq.8, the unit step time response is shown in Fig.4.

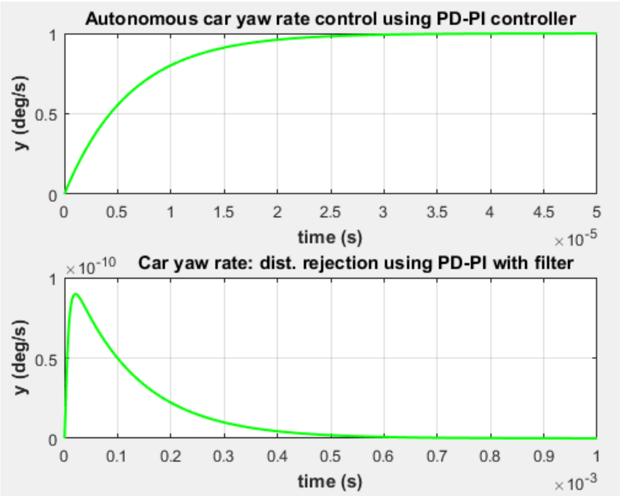

Figure 4: Step time response of the car yaw rate using a PD-PI controller.

COMMENTS

➢ The PD-PI controller provided a reference input tracking step time response having the following characteristics

- Maximum percentage overshoot: zero
- Settling time: 0.0242 ms
- Steady-state error: zero.

➢ The success of the PD-PI controller to reject the disturbance input is measured by the following characteristics (with second-order high pass filter)

- Maximum mold temperature step time response: 8.977 x 10^{-11} deg/s
- Minimum mold temperature step time response: zero
- Settling time to zero (approximate): 0.50 ms.

Controlling the Car Yaw Rate Using a 2DOF-2 Controller

The 2DOF controller was introduced by the author to control a number of difficult processes since 2014 and used different structures of 2DOF control to control a variety of industrial processes with bad dynamics.[25,28,30,31,33,50]

The structure of the 2DOF controller used in the present work is shown in Fig. 5.[42] The 2DOF-2 controller is composed of two control elements having the same control mode structure for a PD control to simplify the analysis of the control system using the 2DOF control structure.[37]

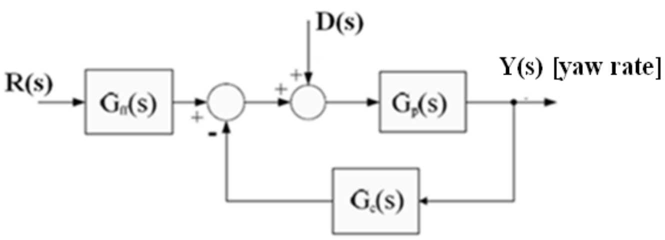

Figure 5: Car yaw rate control using a 2DOF-2 controller.[37]

The transfer functions of the 2DOF-2 controller are as follows

$G_{ff}(s) = K_{pc1} + (K_i/s)$

and $G_c(s) = K_{pc2} + (K_i/s) + K_d s$ (9)

Where: K_{pc1} = proportional gain of the PI-control mode.

K_i = integral gain of the PI and PID control modes.

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

K_d = derivative gain of the feedback PID control mode.

The 2DOF-2 controller has four gain parameters to be tuned to provide the required performance of the closed-loop system of the steam turbine control. The proposed controllers from the second generation of PID controllers proposed by the author have proven to be vey efficient in controlling difficult processes with bad dynamics. Here is another example. A preliminary guessed values was tried by the author prior to the optimal tuning of the 2DOF-2 controller gain parameters. The author found that they are more enough to give good performance parameters without further optimal tuning. A set of those trials are given by

$K_{pc1} = 0.050$; $K_i = 0.100$

$K_{pc2} = 0.048$; $K_d = 0.005$ (10)

- The closed loop transfer functions of the control system for both reference and disturbance inputs are derived from the block diagram in Fig.5 using the process transfer function in Eq.1 and the controller transfer functions in Eq.9 with the tuned controller parameters in Eq.10. The unit step time response of the control system is plotted using the step command of MATLAB and shown in Fig.6 for both inputs.

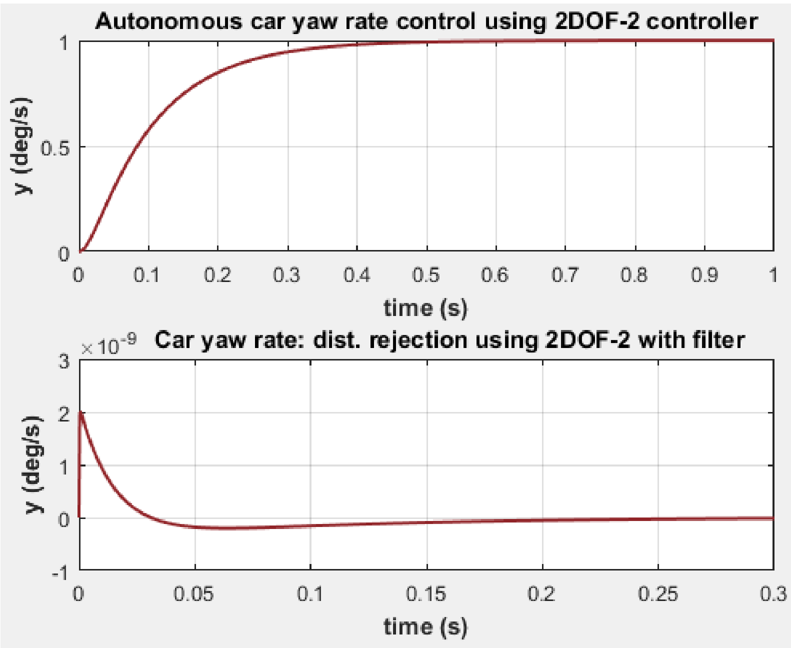

Figure 6: Step time response of the car yaw rate using a 2DOF-2 controller.

COMMENTS

- The 2DOF-3 controller provided a reference input tracking step time response having the following characteristics
  - Maximum percentage overshoot: zero
  - Settling time: 0.4035 s
  - Steady-state error: zero.

- The success of the 2DOF-2 controller to reject the disturbance input is measured by the following characteristics (with second-order high pass filter)
  - Maximum mold temperature step time response: 2.013 x 10^{-9} deg/s
  - Minimum mold temperature step time response: 0.199 x 10^{-9} deg/s
  - Settling time to zero (approximate): 0.3 s.

Controlling the Car Yaw Angle Using a Conventional PID Controller

- The conventional PID controller is the father controller in the first generation of PID controllers where the rest of its controllers are derived from it. It is still in use in a lot of automatic control applications.

- The PID controller was tuned by the author using an ITAE performance index[18] and MATLAB optimization toolbox.[19] The tuned PID controller gain parameters (K_{pc}, K_i and K_d) are as follows

$$K_{pc} = 0.0114175;\ K_i = 0.0914328 \text{ and } K_d = 0.0003454 \qquad (11)$$

- Using the process transfer function in Eq.1, the PID controller transfer function in Eq.9 with gain parameters given in Eq.11 and the block diagram incorporating the PID controller and controlled car yaw rate process, the transfer functions for both reference and disturbance inputs are derived and used to draw the unit step time response of the control system using the MATLAB '*step*' command.[15] The result is presented in Fig.7.

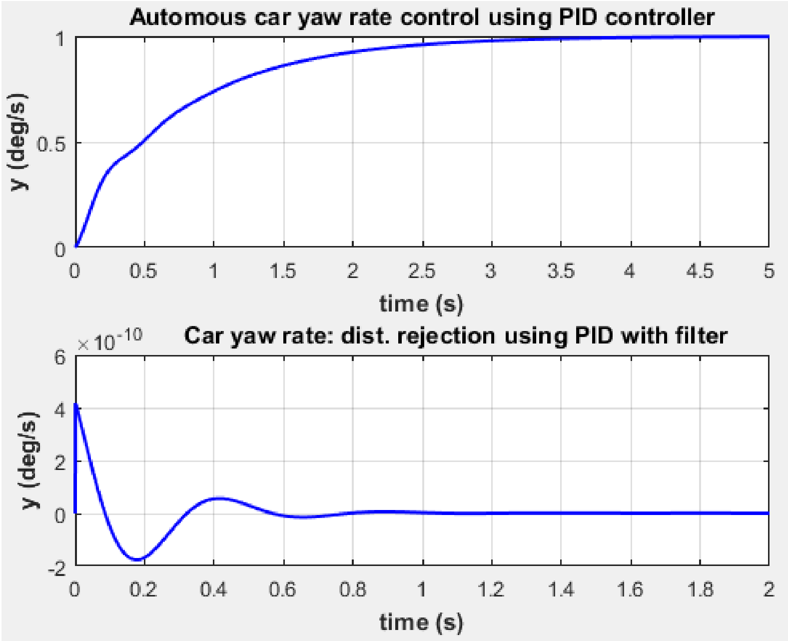

Figure 7: Step time response of the car yaw rate using a PID controller.

COMMENTS

➢ The PID controller provided a reference input tracking step time response having the following characteristics

- Maximum percentage overshoot: zero
- Settling time: 3.063 s
- Steady-state error: zero.

➢ The success of the PID controller to reject the disturbance input is measured by the following characteristics (with second-order high pass filter)

- Maximum mold temperature step time response: 4.1738 x 10^{-10} deg/s
- Minimum mold temperature step time response: 762 x 10^{-10} deg/s
- Settling time to zero (approximate): 2 s.

Car Yaw Rate Control Compared with the 20 deg/s Limit

- To investigate the success of the examined compensators/controllers relative to the yaw rate limit, the step time response of the control system was presented in one graph with the yaw rate limit.

- The step reference input was set to 15 deg/s magnitude (desired yaw rate) not to reach the yaw rate limit for speeds from 70 to 110 km/h.

- The result is presented in Fig.8 with the yaw rate limit drawn in red.

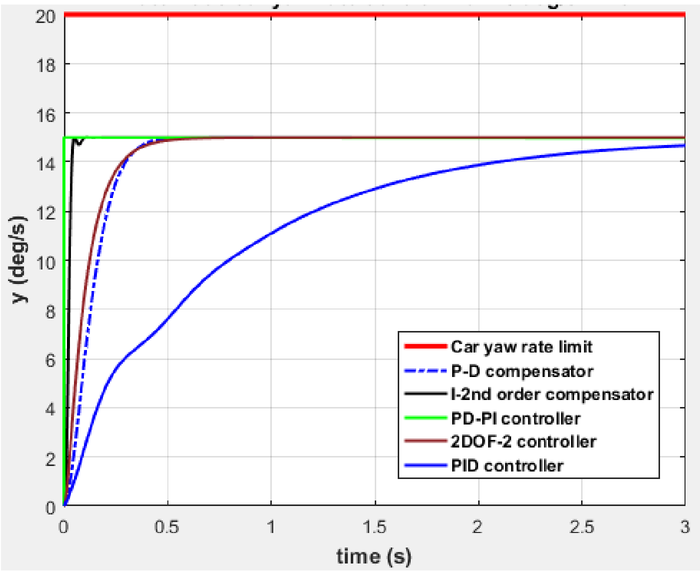

Figure 8: Car yaw rate control with 20 deg/s limit.

Characteristics Comparison of the Four Compensators/controllers with a PID controller

- The time-based characteristics of the control system for the car yaw rate are quantitatively compared in Table 1 for reference input tracking and Table 2 for disturbance input.

Table 1: **Reference input time-based characteristics of the car yaw rate control using P-D, I-second-order compensators and PD-PI, 2DOF-2, PID controllers.**

Compensator / controller	P-D compensator	I-second order compensator	PD-PI controller	2DOF-2 controller	PID controller
OS_{max} (%)	0	0	0	0	0
T_s (ms)	382	43.7	0.0242	403.5	3063
e_{ss} (deg/s)	0.0009	0	0	0	0

Table 2: **Disturbance rejection characteristics of the car yaw rate control using P-D, I-second-order compensators and PD-PI, 2DOF-2, PID controllers.**

Compensator / controller	P-D compensator	I-second order compensator	PD-PI controller	2DOF-2 controller	PID controller
y_{Dmax} (deg/s)	$2.07x10^{-9}$	$2.085x10^{-9}$	$8.977x10^{-11}$	0	$4.174x10^{-10}$
y_{Dmin} (deg/s)	$-0.31x10^{-9}$	$-0.466x10^{-9}$	0	403.5	$-1.762x10^{-10}$
T_{s0} (ms)	400	800	0.50	300	2000

CONCLUSION

- The objective of the paper was to investigate the use and tuning of P-D, I-second order compensators and PD-PI, 2DOF-2 controllers to control the car yaw rate with comparison with using a PID controller.
- The car yaw rate is an indication of car stability on the road avoiding accidents during excessive steering with high yaw rate.
- The proposed two compensators and two controllers are from the second generation of control compensators/controllers presented by the author since 2014.
- The four compensators and controllers were tuned using different tuning techniques based on pole cancellation, desired closed-loop characteristics of the control system and using the MATLAB optimization toolbox.
- A limit of 20 deg/s was imposed on the step time response using the proposed compensators/controllers to check the stability and safety of the car during turning.
- All the proposed compensators/controllers succeeded to eliminate completely the maximum percentage overshoot.
- The P-D compensator could generate a step time response with only 0.0009 deg/s for a unit step input while all the other compensators/controllers have eliminated completely the steady-state error.
- The proposed compensators/controllers from the second generation of control compensators/controllers could generate unit step time responses with settling time in the range of 0.0242 to 403.5 ms.
- The I-second order compensator succeeded to eliminate both maximum percentage overshoot and steady-state error with settling time of 43.7 ms compared with 3063 ms for the PID controller.
- The PD-PI controller succeeded to eliminate completely the maximum percentage overshoot and the steady-state error and generate a step response with 0.0242 ms settling time compared with 3063 ms for the PID controller. This is why the PD-PI controller was selected

as the best controller in the group of compensators and controllers used to control the car yaw angle.

- The 2DOF-2 controller succeeded to eliminate completely the maximum steady-state error and generate a step time response with 403.5 ms settling time compared with 3063 ms for the PID controller.

- The performance of the proposed compensators/controllers regarding disturbance rejection was excellent through the use of a high pass second-order filter receiving the disturbance input. Both maximum and minimum time responses were negligible indicating the success of all the presented compensators/controllers to suppress the input disturbance.

- All the proposed compensators/controllers succeeded to present successful disturbance rejection with the help of input second-order high pass filter with settling time to zero between 0.5 and 2000 ms. The PD-PI controller was the best among them providing settling time to zero of only 0.5 ms.

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