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AUTONOMOUS VEHICLE CONTROL, PART XIII: ROCKET YAW ANGLE CONTROL USING I-SECOND ORDER, FEEDFORWARD 2/2 SECOND-ORDER, FEEDBACK PD COMPENSATORS COMPARED WITH A PD CONTROLLER

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ABSTRACT

This paper is the thirteenth in a series of research papers presenting the control of autonomous vehicles using compensators and controllers from the second generation of control compensators and PID controllers. It handles the control of rocket yaw angle using I-second order, feedforward 2/2 second-order and feedback PD compensators with comparison with the use of a PD controller from the first generation of PID controllers. The proposed compensators are tuned using multiple approaches including zero-pole cancellation, desired characteristics and MATLAB optimization toolbox. The step time response of the control system using the three proposed compensators is presented and compared with using a PD controller to control the same rocket yaw angle and the time-based characteristics are compared. The comparison reveals the best compensator among the four presented compensators/controllers depending on a qualitative and quantitative comparison study.

KEYWORDS: Autonomous rocket yaw angle control, I-second order compensator, feedforward 2/2 second-order compensator, feedback PD compensator, PD controller, compensators tuning.

INTRODUCTION

Modern rockets have to be designed for stable flight against external disturbances and internal disturbances due to weight reduction by fuel consumption. Making a rocket stable requires a control system helping to stabilize the rocket and steer it through using fins and canards to help the rocket to change its course.[1] Here is a short survey of research work handling the problem of autonomous rocket flight control since 2002.

Burchett and Costella (2002) investigated the use of a small number of short duration lateral pulses acting as a control device to reduce the dispersion of a direct fire rocket. They presented a control law combining model prediction control and linear projectile theory for lateral pulse jet control of an atmospheric rocket.[2] Shtessel, Shkolnikov and Levant (2005) investigated a two-loop guidance and flight control system designed in the combined state space of kinematics and rocket dynamics. They verified the performance of the designed control system through computer simulation using miniature hypervelocity –kinetic energy inter-cepter planar model.[3] 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]

Gupta, Saxena, Singhal and Ghosh (2008) stated that lateral pulsejets were used by a flight control system to assist the rocket to follow a command trajectory. They applied a study to explore the feasibility of reducing the dispersion of an artillery rocket using lateral pulsejets and and trajectory correction flight control system. They applied simulation and evaluated the robustness of their methodology.[4] Jackson (2010) explored several aspects of missile control system including its role, subsystems, types, design objectives and challenges. He presented a numerical example for pitch acceleration control in time and frequency domains.[5]

Tekin, Atesegln and Leblebicioglu (2013) studied two linear autopilot structures and proposed an additional term related to short period dynamics of boost phase. They defined control, guidance algorithms and proposed alternative maneuvering technique to reduce side slip angle during vertical flight.[6] Hassaan (2014) outlined that Muslim scientists in the Medieval Centuries were the first people to use rockets for military purposes as documented by Hassan Al-Rammah from the 13th century AC and Ibn Oronbugha Al-Zardakash in the 15th century. He presented four models of different military rockets from the 13th and 15th

centuries.[7] Malyuta et al. (2015) described the development and testing pf a reaction control system for a FALCO-4 rocket model using cold gas jet at low speeds. They presented the dynamic model of the rocket and a control scheme based on decoupled PID controllers for the roll, pitch and yaw angles. The presented transfer functions for pitch angle (0/2 model) and roll angle (integral model).[8] 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] Buysse, Steyn and Schutte (2017) presented a flight control system for a reusable first stage rocket booster. They presented a control algorithm and designed classical feedback controllers to follow a pitch-up trajectory and stabilized lateral motion. Their controller consisted of a fast inner-loop tracking velocity references and slow outer-loop controlling the attitude.[9]

Yuan, Sun and Lin (2020) tested the configuration items of flight control software introducing the software characteristics and gave the testing strategies, methods and environment. They analyzed the results of the test.[10] Fan et al. (2021) analyzed the design process of a control system for a boost-glide rocket using an improved PID controller based on the small perturbation theory. They verified the attitude control system using 6DOF simulations. They stated that experimental results revealed that the mean and standard deviation of the error between simulation and experimental values was below 0.5 degree.[11] Kwiek and Figat (2023) presented the result of wind tunnel tests of a rocket designed to space tourism application. They investigated how the configuration of the side plate affects the stability of the rocket and studied the efficiency of the side plates for low and high angle of attack. The compared experimental and numerical results in case of low angle of attack.[12] Carrillo, Frias and Mata (2024) presented a mathematical model for a solid-fuel sounding rocket. They used a LQR methodology to find the control gain and proposed trajectories for servomotor tracking to follow a proposed path in the x-z plane.[13]

Controlled rocket yaw angle

Malyuta et al.[8] in their study of active rocket model stabilization decoupled the pitch, roll and yaw motions giving their transfer function models. Their yaw angle transfer function, $G_p(s)$ is given by[8]:

$$G_p(s) = 2.7802 / (s^2 + 0.278s + 1.3901)] \quad (1)$$

It is a second order underdamped process having an oscillating step time response.

The unit step time response of the rocket yaw angle process having the dynamics defined by Eq.1 is shown in Fig.1 as generated by the '*step*' command of MATLAB.[14]

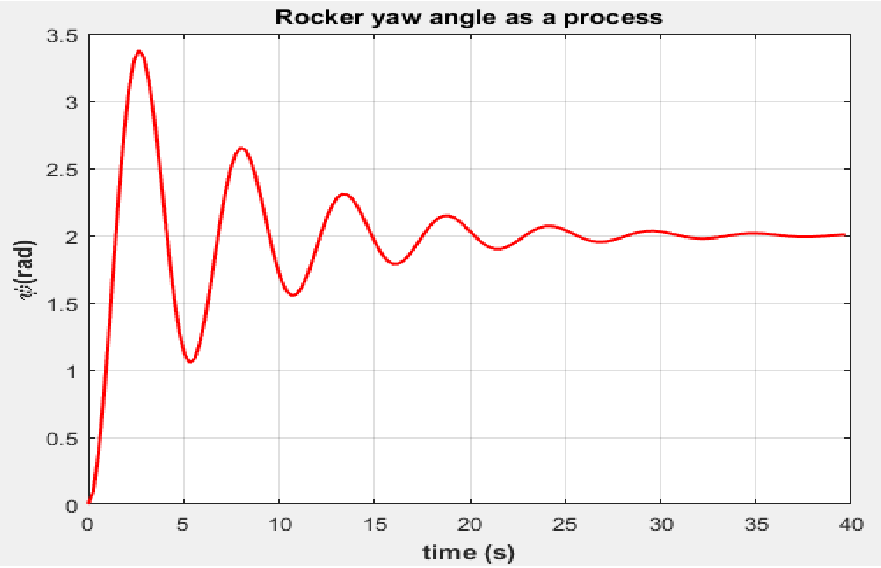

Figure 1: Unit step time response of the rocket yaw angle.

Comments

- The yaw angle process is stable.
- It has a maximum percentage overshoot of 68.3578 %.
- It has a settling time of 27.57 s (for ± 2 % tolerance).
- It has a steady-state error of -1.00586 rad.

This process is an example of processes with bad dynamics because of its very large maximum overshoot (bad stability) and large steady-state error. Any good compensator has to overcome those problems as we will see in the next sections.

Controlling the Rocket Yaw Angle Using an I-second order Compensator

The I-second order compensator was introduced by the author to control the yaw rate of an autonomous vehicle in November 2024.[15] The I-second order compensator is composed of two control elements: an integral mode [$G_{c1}(s)$] in cascade with a second-order control mode in the feed forward path just after the error detector [$G_{c2}(s)$] in a standard block diagram loop for process control. The transfer function of the I-second order compensator $G_c(s)$ is given by:

$$G_c(s) = G_{c1}(s)\, G_{c2}(s) = (K_i/s)(s^2+b_1s+b_2)/(s^2+a_1s+a_2) \qquad (2)$$

Where: K_i = compensator integral gain.

b_1, b_2 = parameters of the second-order control mode numerator.

a_1, a_2 = parameters of the second-order control mode denominator.

The transfer function of the I-second order compensator in Eq.2 has only five parameters (K_i, b_1, b_2, a_1 and a_2) to be tuned to satisfy the objectives of using the compensator to control the rocket yaw angle and provide good control system performance for reference input tracking. The tuning procedure used is as follows:

- First we start by tuning some of the compensator parameters using the zero/pole cancellation technique.[16] When $G_c(s)$ of Eq.2 is multiplied by $G_p(s)$ of Eq.1 in the open-loop transfer function, $G_c(s)G_p(s)$ we equate the quadratic zero of $G_c(s)$ and the quadratic pole of $G_p(s)$ revealing the values of b_1 and b_2 of the compensator. That is:

$$b_1 = 0.278,\ b_2 = 1.3901 \qquad (3)$$

- The remaining compensator parameters are K_i, a_1 and a_2. They are tuned by minimizing an ITAE performance index[17] using the MATLAB optimization toolbox.[18] The output of this tuning technique is as follows:

$$K_i = 0.1098875,\ a_1 = 3.813455,\ a_2 = 18.526119 \qquad (4)$$

- The transfer function of the closed-loop control system using Eqs.1, 2, 3 and 4 for reference input tracking is used to generate the unit step time response of the control system using the 'step' command of MATLAB[14] given in Fig.2.

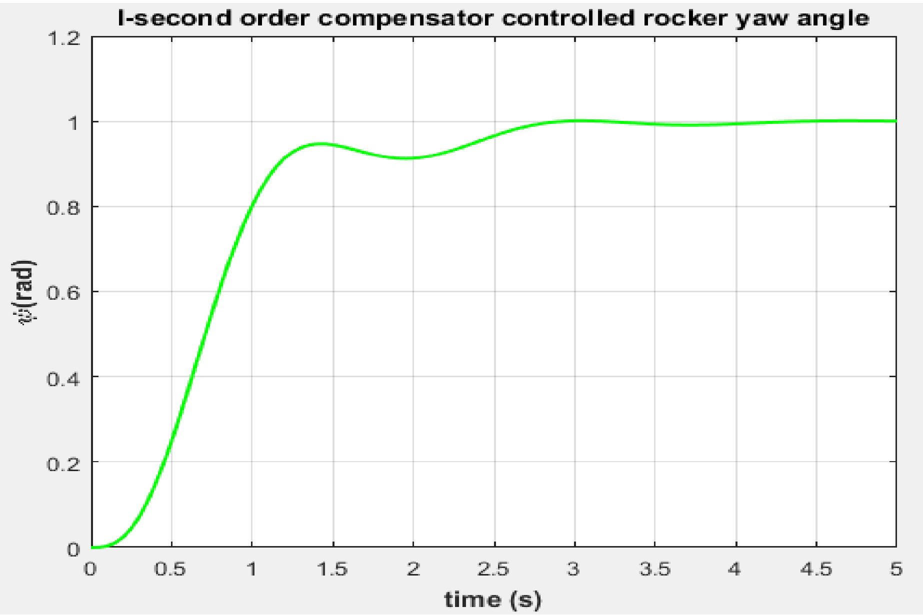

Figure 2: Step time response of the rocket yaw angle using an I-second order compensator.

Comments

- The I-second order compensator provided a reference input tracking unit step time response having the following characteristics:
- Maximum percentage overshoot: 0.092 %
- Settling time: 2.622 s
- Steady-state error: zero

Controlling the Rocket Yaw Angle Using a 2/2 Second-Order Compensator

The 2/2 second-order compensator was introduced by the author in 2014 for the control of a very slow second-order-like process.[19] It belongs to the second generation of control compensators introduced by the author starting from 2014 till now. 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 has a transfer function, $G_c(s)$ given by:

$G_c(s) = K_c (s^2+b_1s+b_2)/ (s^2+a_1s+a_2)$ (5)

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 parameters to be tuned for accepted performance of the control system incorporating the rocket yaw angle. They are tuned as follows:

- The zero/pole cancellation technique[16] is used to assign the quadratic zero parameters of the compensator giving the parameters b_1 and b_2 as in Eq.3.
- Now, the transfer function of the control system incorporating the 2/2 second-order compensator (Eq.5) and the rocket yaw angle process (Eq.1) in a single loop block diagram structure becomes:

$M(s) = 2.7802/(s^2+a1s+a_2+2.7802K_c)$ (6)

- Now, using the following desired characteristics of the closed-loop control system defined by Eq.6:
- Unit damping ratio.
- Zero steady-state error.
- Settling time of 1 s for ± 2 % tolerance.
- The result is providing the following compensator parameters:

$K_c = 5.754982$, $a_1 = 8$, $a_2 = 0$ (7)

- The unit step time response of the control system with the 2/2 second-order compensator with its parameters given by Eqs.3 and 7 and the transfer function given by Eq.6 is obtained using the MATLAB command '*step*'[14] and shown in Fig.3.

Comments

- ➢ The 2/2 second-order compensator provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: zero
- Settling time: 1.452 s
- Steady-state error: zero

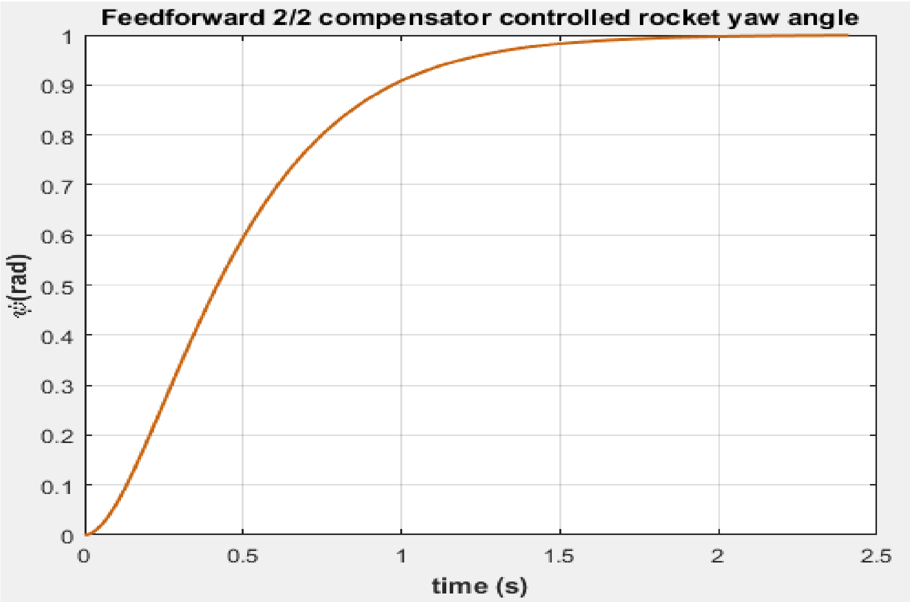

Figure 3: Step time response of the rocket yaw angle using a 2/2 second-order compensator.

Controlling the Rocket Yaw Angle Using a Feedback PD Compensator

The feedback PD compensator was introduced by the author to control underdamped second-order processes in 2014.[20] It is composed of a PD-control mode element set in the feedback path of a single-loop block diagram. Its transfer function $G_{PD}(s)$ is given by:

$$G_{PD}(s) = K_{pc} + K_d s \tag{8}$$

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

K_d = derivative gain of the PD-control mode.

- The feedback PD compensator has two gain parameters (K_{pc}, K_d) to be tuned to satisfy the objectives of using the controller to control the rocket yaw angle and provide good control system performance for reference input tracking. The compensator is tuned as follows:

- To control the rocket yaw angle for reference input tracking, the transfer function of the closed loop control system is derived using the single-loop block diagram with process in the feedforward path and the feedback compensator in the feedback path and using Eqs.1 and 8. The transfer function of the closed-loop is:

$$M(s) = 2.7802/(s^2+(0.278+2.7802K_d)s+1.3901+2.7802K_{pc}) \quad (9)$$

- Eq.9 depicts a standard second-order control system.
- The control system using the feedback PD compensator has non-zero steady-state error. For a zero steady-state error, Eq.9 reveals:

$$K_{pc} = 0.5 \quad (10)$$

- Now, we are left with the derivative gain K_d of the compensator. We can tune it for either a zero maximum overshoot or a desired settling time. I choose the maximum overshoot as the tuning condition. It is well known from the dynamics of second-order systems that the maximum overshoot is zero for critical damped second-order systems. Applying this condition of unit damping ratio on the damping ratio deduced from Eq.9 reveals K_d as:

$$K_d = 1.099484 \quad (11)$$

- Now, using the closed-loop transfer function of the closed-loop control system in Eq.9 and the tuned compensator parameters in Eqs.10 and 11, the unit step time response is given in Fig.4 using the step command of MATLAB.[14]

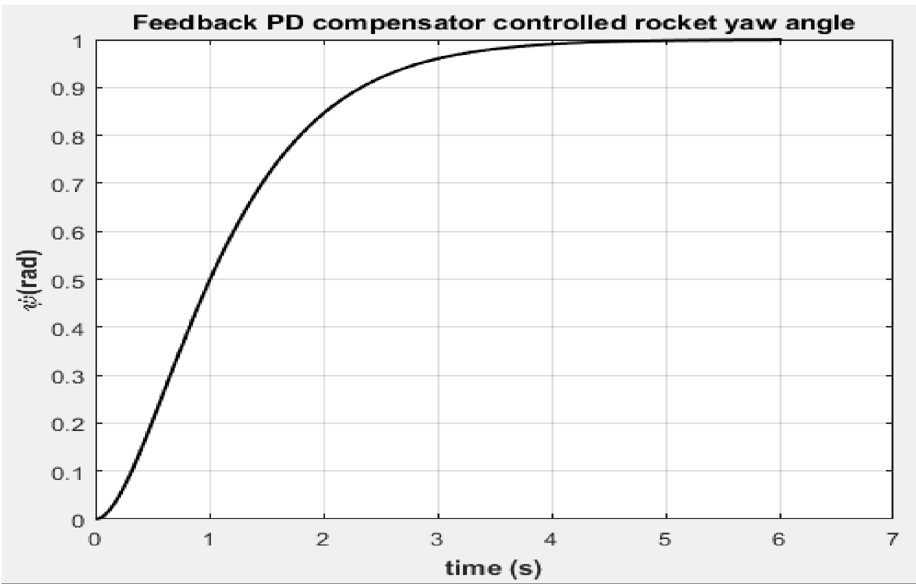

Figure 4: Step time response of the rocket yaw angle using a feedback PD compensator.

Comments

- The feedback PD compensator provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: zero
- Settling time: 3.5 s
- Steady-state error: zero

Controlling the Rocket Yaw Angle Using a Conventional PD Controller

- Conventional PID and PD controllers were proposed by Malyuta et al.[8] to control the rocket pitch (and yaw) angles of a FALCO-4 rocket model.
- They used the following transfer function for the PD controller[8]:

$G_{PD}(s) = K_{pc}(1+T_d s)$ (12)

Where: K_{pc} = proportional gain of the PD controller.

T_d = derivative time constant of the PD controller.

- They used the following gain parameters for the PD controllers[8]:

$K_{pc} = 5$, $T_d = 3$ (13)

- Using the process transfer function in Eq.1, the PD controller transfer function in Eq.12 with gain parameters in Eq.13 and the block diagram incorporating the PD controller and controlled rocket yaw angle process, the unit step time response of the control system using the MATLAB '*step*' command[14] is drawn and presented in Fig.5.

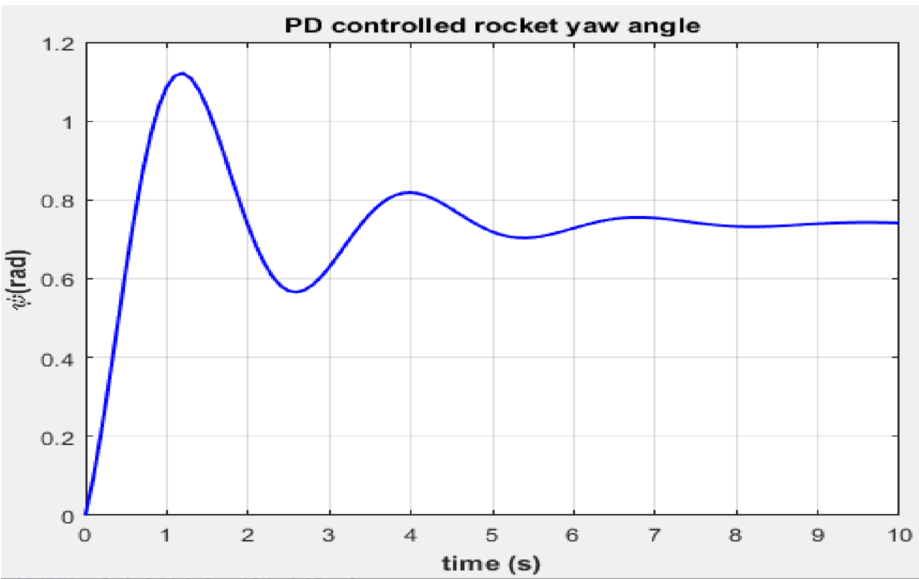

Figure 5: Unit step time response of the rocket yaw angle using a PD controller.

Comments

- The PD controller provided a reference input tracking step time response having the following characteristics:
- Maximum percentage overshoot: 51.180 %
- Settling time: 5.955 s
- Steady-state error: 0.2583 rad

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

- The time-based characteristics of the control system for the rocket yaw angle are qualitatively compared in Fig.6 for reference input tracking.

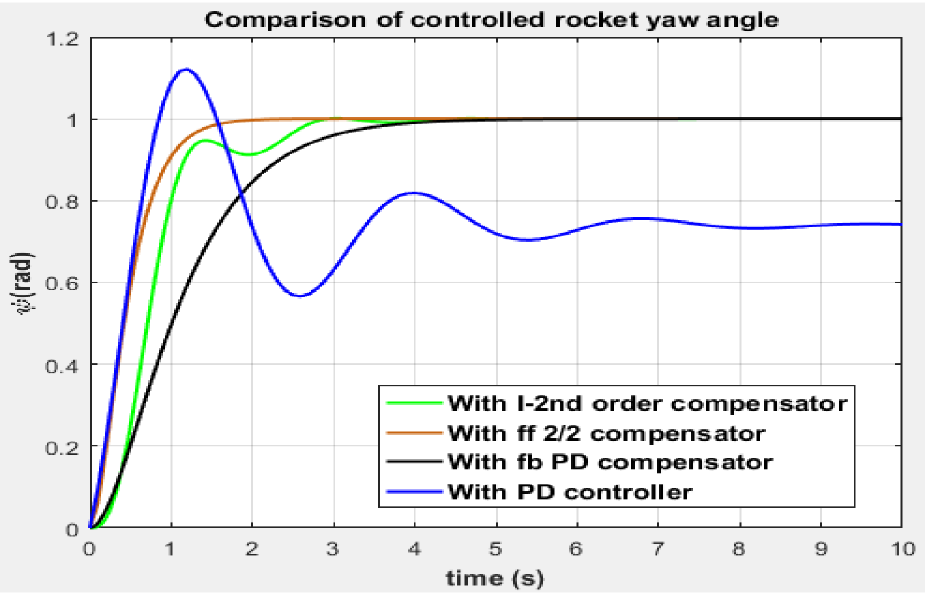

Figure 6: Comparison of the unit step time response of the rocket yaw angle.

- The time-based characteristics of the control system for the rocket yaw angle are quantitatively compared in Table 1 for reference input tracking.

Table 1: **Reference input time-based characteristics of the rocket yaw angle control using I-second order, feedforward 2/2 and feedback PD compensators compared with a PD controller.**

Compensator /controller	Un compensated	I-second order compensator	Feedforward 2/2 compensator	Feedback PD compensator	PD controller
OS_{max} (%)	68.358	0.092	0	0	51.180
T_s (s)	27.570	2.622	1.452	3.500	5.955
e_{ss} (rad)	-1.0058	0	0	0	0.2583

OS_{max}: Maximum percentage overshoot.

T_s: Settling time to ± 2 % tolerance.

e_{ss}: Steady-state error.

CONCLUSION

- The objective of the research paper was to investigate the use and tuning of I-second order, feed forward 2/2 and feedback PD compensators to control a rocket yaw angle with comparison with using a PD controller.
- The proposed three compensators are from the second generation of control compensators presented by the author since 2014.
- The three compensators were tuned using different tuning techniques based on zero-pole cancellation, desired closed-loop characteristics of the control system and using the MATLAB optimization toolbox.
- All the proposed compensators succeeded to provide a maximum percentage overshoot ≤ 0.092 % and a settling time ≤ 3.5 s for ± 2 % tolerance.
- The I-second order compensator succeeded to provide a 0.092 % maximum percentage overshoot (compared with 51.18% for the PD controller), zero steady-state error (compared with 0.2583 rad for the PD controller) and 2.622 s settling time (compared with 5.955 s for the PD controller).
- The feedforward 2/2 compensator succeeded to provide a zero maximum percentage overshoot (compared with 51.18 % for the PD controller), zero steady-state error (compared with 0.2583 rad for the PD controller) and 1.452 s settling time (compared with 5.955 s for the PD controller).
- The feedback PD compensator succeeded to provide a zero maximum percentage overshoot (compared with 51.18% for the PD controller), zero steady-state error (compared with 0.2583 rad for the PD controller) and 3.50 s settling time (compared with 5.955 s for the PD controller).
- Because of its outstanding time-based characteristics of the feedback PD compensator, it was chosen as the best compensator suitable to control the rocket yaw angle.

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