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Control of a Boost-Glide Rocket Engine using PD-PI, PI-PD and 2DOF Controllers

Galal Ali Hassaan

Emeritus Professor, Department of Mechanical Design & Production, Faculty of Engineering, Cairo University, Egypt

A B S T R A C T

This research paper investigates the control of a rocket engine through its step time response to reference and disturbance inputs. The paper proposes three controllers from the second generation of the PID controller: PD-PI, PI-PD and 2DOF controllers. The three controllers are tuned using the MATLAB optimization toolbox and a suitable performance index. The performance of the control system using the three controllers is compared with the performance using a PI-DF and fuzzy-PID controller. The comparison takes the form of graphical and quantitative form. Detailed conclusion is performed to help automatic control engineers and scientists to be able to select proper controller for their application.

Keywords: Rocket engine control, PD-PI controller, PI-PD controller, 2DOF controller, controller tuning, control system performance.

1. Introduction

Rockets and missiles play an important role in military and space activities. They require sophisticated types of control to help in achieving their objectives with high accuracy. Extensive work is devoted to finding types of control systems suitable for rocket control. This paper is a stone in this great building aiming at providing good rocket control. Now we start by taking an idea about the efforts of researchers in this important aspect: rocker control systems. Lorenzo and Murgrave, 1992 introduced a brief introduction to intelligent control systems for rocket engines. They presented the fundamentals of rocket engine control including baseline and multivariable controllers. Jackson, 2010 explored several aspects of the missile flight control system such as: its role in the overall missile system, its subsystems, types of flight control systems, design objectives and challenge. He presented a second-order model for the actuator transfer function and some types of flight control systems such as: acceleration control system, attitude control system, flight path angle control system. He presented an example with time and frequency domain analysis. Rodriguez, 2011 in his study of nozzle vector model for a low cost mini-launcher investigated the selection of the control system, launcher dynamic equation. He derived the rocket transfer function between the nozzle deflection and the output attitude angle as a third-order dynamic system. This covered Vanguard rocket and Wiki-launcher. He applied the conventional PID controller to control the rocket and tuned it for the longitudinal lateral rotation dynamic motions. The kick due to the use of the PID controller was there in all the reference input step time response for the three rocket motions.

Roy, Goswami, Sanyal and Sanyal, 2013 investigated the pitch attitude control of a booster rocket. They developed the mathematical model and used MATLAB to draw the tracking step input time response and Bode plot for different values of the coefficient of rate feedback. They considered a dynamic model for the rocket pitch angle as an integrator plus second order pole. They used an amplifier as a controller (P-controller) resulted in a maximum overshoot as large as 10.3 %. Sumathi and Usha, 2014 investigated the use of PID control and LQR theory to control the pitch and yaw attitude of a rocket engine. Because of the deficiencies of PID and LQR controllers, they combined the PID with a fuzzy logic controller. They compared the performance of the control system using PID, LQR and fuzzy-PID controllers. All over their analysis, they used a pre-used second-order transfer function model for the rocket engine. Zhang, Lv and Lei, 2015 built a longitudinal loop model and designed the missile longitudinal loop control system based on using a conventional PID controller. They tuned the controller and through simulation they plotted the reference input tracking step time response for the pitch angle, trajectory inclination and attack angle. Fawzy, Dorrah and Abdelrahman, 2017 studied the control of trajectory a flight path of 6DOF flying body model using fractional PID controller and gain schedule fractional PID controller using a nonlinear flying model. The design of the proposed gain schedule fractional PID controller gave the best response for pitch and yaw angles.

Lee, Ahu and Roh, 2018 proposed an integrated design optimization for the gain schedule and bending filter for the longitudinal control of a rocket during ascent flight. They considered the rocket dynamic models for the pitch/yaw motion of a rocket and presented a case study for an actual sound rocket using the proposed framework. Sun, Chen and He, 2019 provided a technique to obtain the first-order time constant of the autopilot and frequency domain gain and phase margin of the autopilot. They presented the block diagram comprising three loop autopilot of the missile and derived the transfer functions for the missile dynamics. Dinesh et al., 2020 reviewed cascaded linear quadratic regulator for an autopilot missile. They derived the transfer function of the rocket between the roll angle of the missile and the fin deflection. They presented control structures for series cascaded system, combined control with LQR and the missile roll autopilot with transfer function for each element. They compared the time response with cascaded linear quadratic regulator with that using SMC controller and concluded that the former gave better results. Fan, Bai, Liu and Zhang, 2021 proposed design and verification a boost-glide rocket attitude control system based on the use of a PID controller. They derived the mathematical model of the rocket and derived the transfer function of its pitch angle, yaw angle and roll angle. Thy adjusted the PID controller parameters and presented the open-loop and closed-loop transfer functions for the pitch angle and presented the Nyquist diagram, Bode plot and reference input step time response of the control system for the pitch angle.

Sagliano et al., 2022 investigated the use of structured H∞ control for the aerodynamic descent phase of a reusable rocket. They proposed a unified control strategy for attitude and position for pitch and yaw through an augmented PID-like controller. They adopted a PID-like control law for roll control. Sopegno, Livreri, Stefanovic and Valavanis, 2023 compared the applicability, tuning and performance of three controllers applied on a finless rocket during its boost phase. They compared the LQR, LQG and PID controllers and evaluated the overall control performance in terms of maximum overshoot, rise time settling time and steady-state error. They used a third-order transfer function for the launcher system. Their tuned PID controller revealed maximum overshoot above 6.8 %.

Nomenclature

C(s)	Laplace transform of the control system output
D(s)	Laplace transform of the disturbance input of the control system
$G_c(s)$	Controller transfer function
$G_p(s)$	Process transfer function
$G_{PD}(s)$	Transfer function of the PD-control mode
$G_{PDPI}(s)$	Transfer function of the PD-PI controller
$G_{PI}(s)$	Transfer function of the PI-control mode
K_d	Derivative gain parameter
K_i	Integral gain parameter
K_{pc}	Proportional gain parameter
PD-PI	Proportional Derivative – Proportional Integral controller
PID	Proportional Integral Derivative controller
PI-DF	Proportional Integral – Derivative Filter controller
PI-PD	Proportional Integral – Proportional Derivative controller
R(s)	Laplace transform of the reference input of the control system
s	Laplace operator
U(s)	Laplace transform of the controller output
2DOF	Two Degree of Freedom controller

2. Controlled Rocket Engine

The rocket engine is attached to the rocket body in a way to allow relative motion between them to allow the engine thrust to change the pitch and you during flying. Many mechanical techniques are available for this purpose. Fig. 1 shows one of those techniques (Yagmur, Bayar, Sen & Serbest, 2022). The angular position of the engine is changed using a hydraulic cylinder joined to engine and to the rocket body.

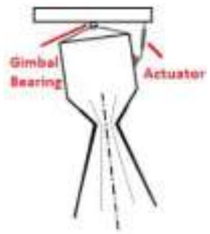

Fig. 1 Rocket engine joined with rocket body.

Sumathi and Usha, 2014 used a second-order transfer function model for the rocket engine. This model is used in this research to investigate the success of the proposed controllers to control the rocket engine and suppress the disturbance input using the same tuned parameters of the controllers. On the other hand it will be possible to compare with the controllers used by the authors. The rocket engine model, $G_p(s)$ is given by:

$$Gp(s) \quad = \frac{1}{526s^2+1000\,s+100} \qquad (1)$$

To investigate and appreciate the dynamics of the rocket engine its unit step time response is drawn using the MATLAB command 'step' (mathworks, 2023) which is shown in Fig.2.

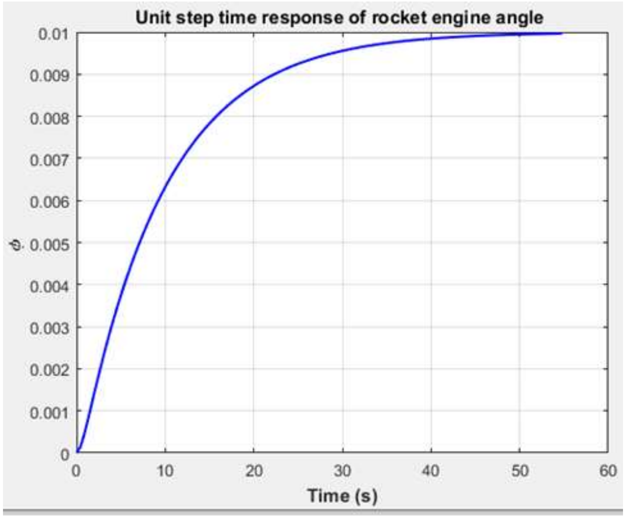

Fig. 2 Step time response of the rocket engine.

It has the time-based characteristics:

- Maximum percentage overshoot: zero
- Settling time: 40s
- Steady state error: 0.99

The step time response of the rocket engine using the transfer function in Eq.1 outlines a fact that it has bad dynamics through its large steady-state error and high settling time. A good controller has to deal with those deficiencies and produce control system with zero steady-state error and fast time response. This will be the goal of the proposed controllers.

3. Controlling the Rocket Engine using a PD-PI Controller

The PD-PI controller was introduced by the author as one of the second generation of PID controllers introduced by the author starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used the PD-PI controller to control a number of processes having bad dynamics such as: first-order delayed processes (Hassaan, 2014), highly oscillating second-order process (Hassaan, 2014), integrating plus time delay process (Hassaan, 2014), delayed double integrating process (Hassaan, 2015) and third-order process (Hassaan, 2020). A PD-PI controller has the transfer function, Gc(s) given by (Hassaan, 2023):

$$GPDPI(s) = \frac{KdKpc2s\,^\wedge 2+(KdKi+Kpc1Kpc2)s+Kpc1Ki}{s} \qquad (2)$$

Where: K_{pc1} = proportional gain of the PD-mode of the PD-PI controller

K_d = derivative gain of the PD-mode

K_{pc2} = proportional gain of the PI-mode.

K_i = integral gain of the PI-mode

The structure of the control system of the engine rocket with a feedforward controller is shown in Fig.3.

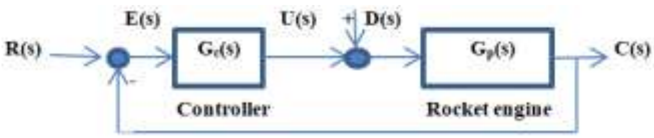

Fig. 3 Control system of the rocket engine.

According to the block diagram of the control system shown in Fig.3, the objective of the controller is to:

- Provide a reference input tracking step time response with good performance.
- Suppress the effect of the disturbance input on the control system output.

The transfer function of the closed-loop control system is derived using Fig.3 as follows:

- For a reference input with D(s) set to zero:

$$C(s)/R(s) = \frac{Gc(s)Gp(s)}{1+Gc(s)Gp(s)} \quad (3)$$

- For a disturbance input with R(s) set to zero:

$$C(s)/D(s) = \frac{Gp(s)}{1+Gc(s)Gp(s)} \quad (4)$$

Now, combining Eqs.1 through 4 gives the transfer functions of the control system in terms of the controller gain parameters K_{pc1}, K_d, K_{pc2} and K_i.

The PD-PI controller is tuned using the MATLAB optimization toolbox (Lopez, 2014) , the control system transfer function in Eq.3 an 'Integral of Square Error' (ISE) performance index. The tuning results are as follows:

K_{pc1}= 6.39628, K_d = 56.69456 , K_{pc2} = 89.68074 , K_i = 85.17705 (5)

The unit step time response for both reference and disturbance inputs using the PD-PI controller to control the rocket engine is shown in Fig.4.

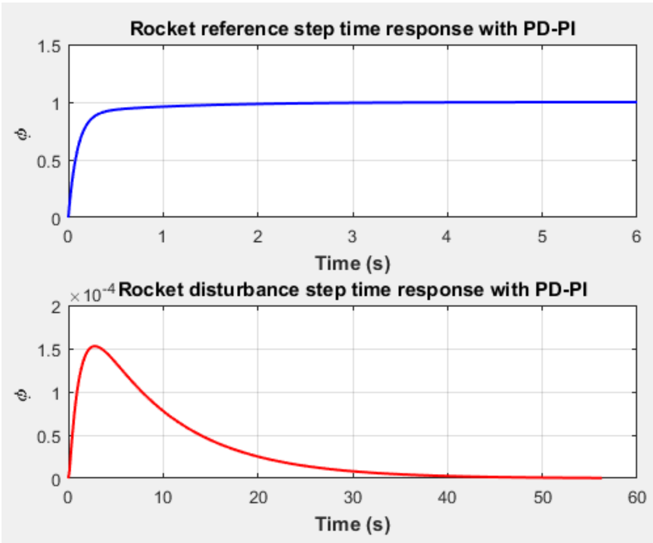

Fig. 4 Step time response using a PD-PI controller.

Time-based characteristics of the control system with a PD-PI controller:

With reference input:

- Maximum percentage overshoot: zero.

- Settling time: 1.75s

- Steady-state error: zero

With disturbance input:

- Maximum time response: 0.000152

- Time of maximum time response: 2.5s

- Settling time: 40s

4. Controlling the Rocket Engine using a PI-PD Controller

The PI-PD controller was introduced by the author as one of the second generation of PID controllers introduced by him starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used the PI-PD controller to control a number of processes having bad dynamics such as: highly oscillating second-order process (Hassaan, 2014), double integrating process (Hassaan, 2015), third-order process (Singer, Elgamil and Hassaan, 2020) and greenhouse temperature (Hassaan, 2023). The structure of a PI-PD controller in the block diagram of a control system controlling a process is shown in Fig. 5 (Hassaan, 2023). It comprises two sub-controllers: PI-control mode in the feedforward path receiving the error signal and a PD-control mode in a feedback loop with the controlled process. The transfer functions of the two control modes are as follows:

$G_{PI}(s) = K_{pc1} + (K_i/s)$ and $G_{PD}(s) = K_{pc2} + K_d s$ (6)

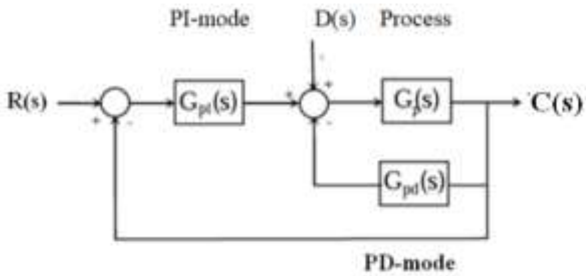

Fig. 5 Control system of the rocket engine using a PI-PD controller.

The transfer functions of the control system incorporating the PI-PD controller are derived from the block diagram of Fig. 5 and given by:

- For reference input with D(s) set to zero:

$$C(s)/R(s) = \frac{GPI(s)Gp(s)}{1+Gp(s)\{GPI(s)+GPD(s)\}} \quad (7)$$

- For disturbance input with R(s) set to zero:

$$C(s)/D(s) = \frac{Gp(s)}{1+Gp(s)\{GPI(s)+GPD(s)\}} \quad (8)$$

Now, combining Eqs.1, 6 and 7 gives the transfer functions of the control system in terms of the controller gain parameters K_{pc1}, K_i, K_{pc2} and K_d.

The PI-PD controller is tuned using the MATLAB optimization toolbox (Lopez, 2014) , the control system transfer function in Eq.7 and 'Integral of Time multiplied Absolute Error' (ITAE) performance index. The tuning results are as follows:

K_{pc1}= 139.9828 , K_i = 17.4286 , K_{pc2} = 0.38785 , K_d = 7.97485 (9)

The unit step time response for both reference and disturbance inputs when the PI-PD controller is used to control the rocket engine is shown in Fig.6.

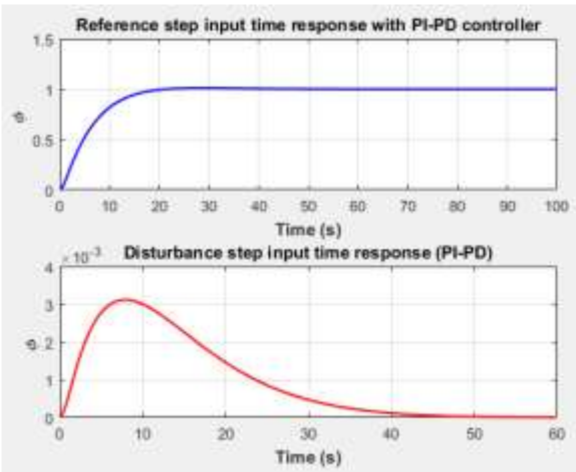

Fig. 6 Step time response using a PI-PD controller.

Time-based characteristics of the control system with a PI-PD controller:

With reference input:

- Maximum percentage overshoot: 1.01 %
- Settling time: 18 s
- Steady-state error: zero

With disturbance input:

- Maximum time response: 0.00311
- Time of maximum time response: 8s
- Settling time: 50s

5. Controlling the Rocket Engine using a 2DOF Controller

Several 2DOF controllers were introduced by the author as members of the second generation of PID controllers introduced by him starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used the 2DOF controllers to control a number of processes having bad dynamics such as: highly oscillating second-order process (Hassaan, 2015), delayed double integrating process (Hassaan, 2015), second-order-like processes Hassaan, 2018), gas turbine speed control (Hassaan, 2022) and greenhouse temperature (Hassaan, 2023). The structure of the 2DOF controller in the block diagram of a control system controlling a process is shown in Fig. 7 (Hassaan, 2022). It comprises two sub-controllers: PID-control mode in the feedforward path receiving the error signal and a PD-control mode in a feedforward loop receiving the reference input of the control system as an input to this sub-controller mode. The transfer functions of the two control modes are as follows:

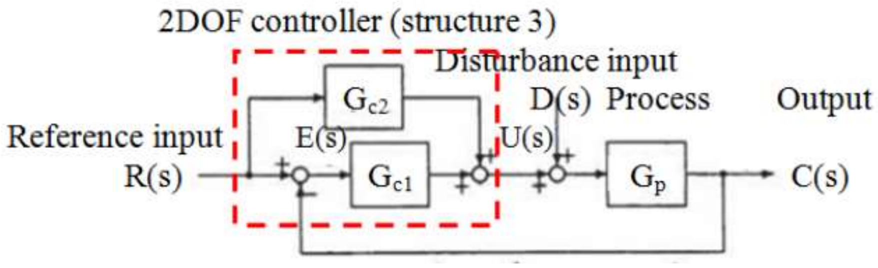

Fig. 7 Control system of the rocket engine using a 2DOF controller.

$$Gc1(s) = \frac{Kd2s\text{^}2 + Kpc1s + Ki}{s}$$

and (10)

$$Gc2(s) = \frac{Kd2s + Kpc2}{1}$$

This structure of the 2DOF controller has four gain parameters to be tuned to produce good performance for the control system of the rocket.

The transfer functions of the control system incorporating the 2DOF controller shown in Fig. 7 are derived from the block diagram and given by:

- For reference input with D(s) set to zero:

$$C(s)/R(s) = \frac{Gp(s)\{Gc1(s) + Gc2(s)\}}{1 + Gp(s)Gc1(s)} \quad (11)$$

- For disturbance input with R(s) set to zero:

$$C(s)/D(s) = \frac{Gp(s)}{1 + Gp(s)Gc1(s)} \quad (12)$$

Combining Eqs.1, 10 and 11 gives the transfer functions of the control system in terms of the controller gain parameters K_{pc1}, K_i, K_{d1}, K_{pc2} and K_{d2}.

The 2DOF controller is tuned using the MATLAB optimization toolbox (Lopez, 2014) , the control system transfer function in Eq.7 and 'Integral of Absolute Error' (IAE) performance index. The tuning results are as follows:

K_{pc1}= 99.99814 , K_i = 4.91543 , K_{d1} = 10.00593 , K_{pc2} = 82.9656 , K_{d2} = 20.0052 (13)

The unit step time response for both reference and disturbance inputs when the 2DOF controller is used to control the rocket engine is shown in Fig.8.

Time-based characteristics of the control system with a 2DOF controller:

With reference input:

- Maximum percentage overshoot: 2.015 %
- Settling time: 14.80 s
- Steady-state error: -0.0075

With disturbance input:

- Maximum time response: 0.000153
- Time of maximum time response: 2.77 s
- Settling time: 40 s

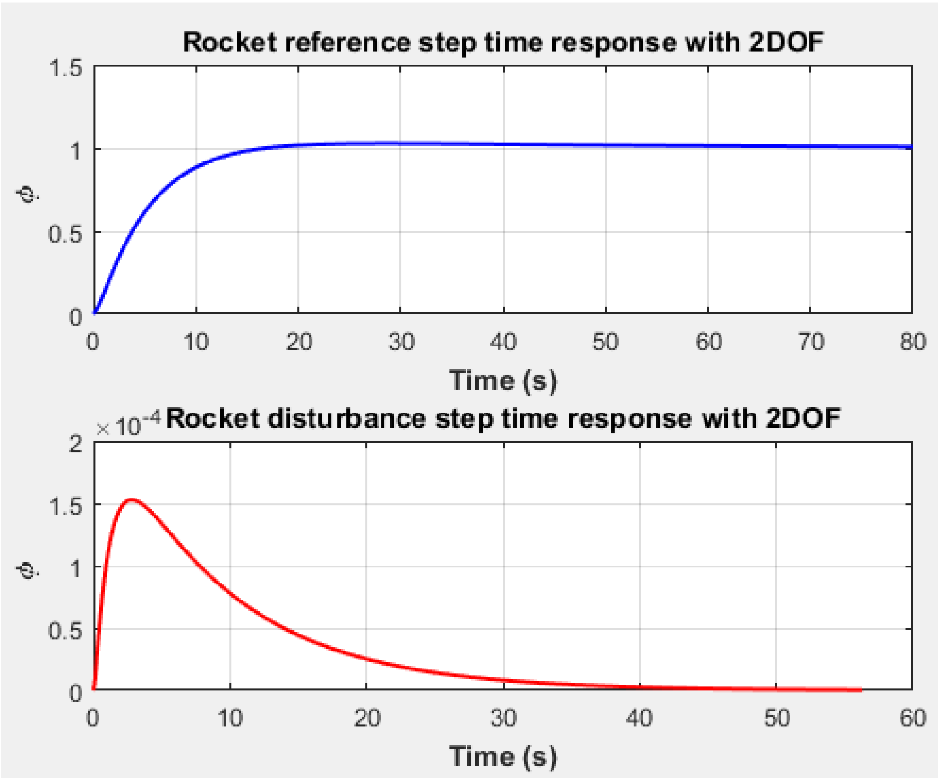

Fig. 8 Step time response using a 2DOF controller.

6. Comparison with Other Controllers

The performance of the control system used for the rocket control is compared graphically and numerically when using the proposed three controllers, a PI-DF controller and a fuzzy-PID controller (Sumathi & Usha, 2014). A graphical comparison of the performance of the control system with the five controllers is shown in Fig. 8 for the reference input of the control system.

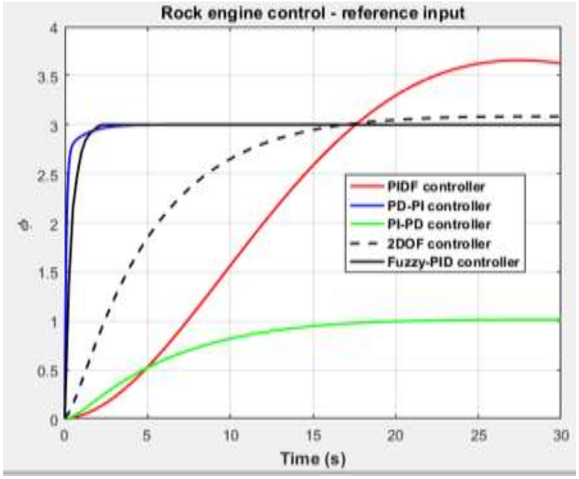

Fig. 8 Comparison of reference input step time response using five controllers.

A quantitative comparison for the time-based specifications of the rocket-engine control systems is shown in Table 1 for reference input of the control system.

Table 1 – Time-based characteristics for reference input.

Controller	Maximum overshoot (%)	Settling time (s)
PI-DF (Sumathi & Usha, 2014)	21.9▼	66▼
Fuzzy-PID (Sumathi & Usha, 2014)	0	2.70
PD-PI (present work)	0	1.75
PI-PD (present work)	1.01	18
2DOF (present work)	2.015	14.5

▼The values of the maximum overshoot and settling time are different than those provided by Sumathi & Usha, 2014 because I relied on plotting the time response using their PI-DF controller using the step command of MATLAB for their gain parameters of the controller.

A graphical comparison of the performance of the control system with four controllers (excluding the fuzzy-PID controller) is shown in Fig. 9 for the disturbance input of the control system.

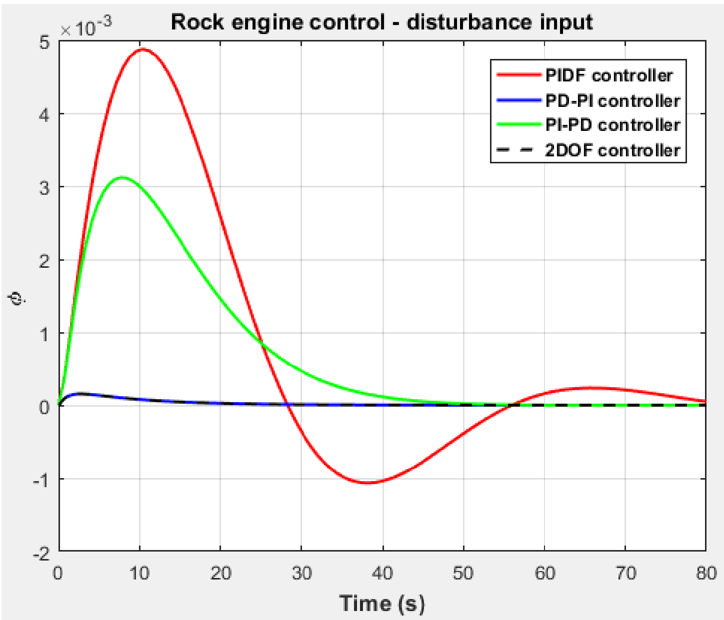

Fig. 9 Comparison of disturbance input step time response using four controllers.

The time-based characteristics of the disturbance step time response are compared in Table 2.

Table 2 – Time-based characteristics for unit disturbance input.

Controller	Maximum time response (degree)	Settling time (s)
PI-DF (Sumathi & Usha, 2014)	0.00487	82
PD-PI (present work)	0.000152	40
PI-PD (present work)	0.0031	50
2DOF (present work)	0.000153	40

7. Conclusions

- The paper investigated the control of a gamble rocket engine using three of the second generation of PID controllers.
- The controllers proposed for this purpose was the PD-PI, PI-PD and 2DOF controllers.
- The three controllers were tuned using the MATLAB optimization toolbox and an error-based performance index.
- The performance of the control system was evaluated through the maximum percentage overshoot and the settling time for reference input tracking.
- For the disturbance input, the control system was evaluated through the maximum value of the rocket engine step time response and its settling tome to its steady-state value.
- The three proposed controllers were compared with a PI-DF and fuzzy-PID controllers from previous research work.
- The controlled rocket engine as a process to be controlled had bad dynamics when excited by a step input in terms of a large steady-state error (0.99 degrees) and large settling time (40 s).
- The PD-PI controller could compete with all the presented controllers in this study. It resulted in a control system without any overshoot or steady-state error and a settling time of only 1.75 s compared with 2.7 s for the fuzzy-PID controller. It could suppress the disturbance input unit step time response to almost zero maximum time response (0.000152 degree) compared with 0.00487 degree for the PI-DF controller. The disturbance step time response settled to zero in about 40 s compared with 82 s with the PI-DF controller.
- The PI-PD controller could generate a reference input tracking unit step response with 1.01 % maximum overshoot compared with 21.9 % with the PI-DF controller and a settling time of 18 s compared with 66 s for the PI-DF controller. It could suppress the disturbance step time response to 0.0031 degree compared with 0.00487 degree for the PI-DF controller and 50 s settling time to zero compared with 82 s for the PI-DF controller.
- The 2DOF controller could generate a reference input tracking unit step response with 2.015 % maximum overshoot compared with 21.9 % with the PI-DF controller and a settling time of 14.8 s compared with 66 s for the PI-DF controller. It could suppress the disturbance step time response to 0.000153 degree compared with 0.00487 degree for the PI-DF controller and 40 s settling time to zero compared with 82 s for the PI-DF controller.
- The MATLAB optimization toolbox has proven through applications in the field of controller tuning that it is a reliable technique for controller tuning purposes.

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BIOGRAPHY

GALAL ALI HASSAAN:

- Emeritus Professor of System Dynamics and Automatic control.
- Has got his B.Sc. and M.Sc. from Cairo University in 1970 and 1974 respectively.
- Has got his Ph.D. in 1979 from Bradford University, UK under the supervision of Late Prof. John Parnaby.
- Now with the Faculty of Engineering, Cairo University, Egypt.
- Research on Automatic Control, Mechanical Vibrations, Mechanism Synthesis and History of Mechanical Engineering.
- Published more than 300 research papers in international journals and conferences.
- Author of books on Experimental Systems Control, Experimental Vibrations and Evolution of Mechanical Engineering.
- Member of the Editorial Board of a number of international journals.
- Reviewer in some international journals.