Pages: 83-94/ Vol. 15/ Issue 2 / Summer- Fall 2022

Journal of Aerospace Science and Technology

www:jast.ias.ir

Scientific-Research Article

Three-Axis Satellite Attitude Control with Fractional-Order PID Controller in the presence of Uncertainty and Disturbance

Amirreza Kosari[1]*, Elahe Khatonabadi[2], Vahid Bohlouri[3]

1-2- Faculty of New Sciences and Technologies, University of Tehran, Tehran, Iran
3- Department of Electrical Engineering, Technical and Vocational University, Tehran, Iran

ABSTRACT

***Keywords**: Satellite Attitude Control, Fractional-Order, PID Controller, Reaction Wheel, Uncertainty*

In this paper, the control of a three-axis rigid satellite attitude control system with a fractional order proportional-integral-derivative (PID) controller is investigated in the presence of disturbance and parametric uncertainties. The reaction wheel actuator with the first-order dynamic model is used to control the attitude of the satellite. Uncertainties are considered in satellite moment inertia, actuator model, and amplitude and frequency of external disturbances. External disturbances are modeled with two fixed and periodic parts, and uncertainty is also considered in the disturbance model. The integer order controller is also used for the same conditions to compare the results with the fractional order controller. The usual Granwald-Letinkov definition is used to solve integrals and fractional order derivatives. The mean absolute of the pointing error of the satellite pointing maneuver has been selected as an objective function of the optimization problem. The controller gains in integer and fractional order are obtained by the particle swarm evolution algorithm (PSO) optimization method. The performance index has been studied in terms of the controller response time and the standard deviation of the mentioned uncertainties and external disturbance. The results show that the fractional order controller performs more accurately and more robust than the integer order controllers in the face of uncertainty and disturbance.

Introduction

Presently, many satellites with different missions and applications are orbiting the earth and providing various services. The attitude determination and control subsystem has the task of stabilization, pointing, appropriate orientation, and maneuvers of the satellite. Reaction wheels, thrusters, and magnetic torques are used as actuators to control and stabilize the attitude of satellites [1]. Compared to other actuators, reaction wheels generate a continuous angular torque, causing stabilization and more accurate

1 Professor (corresponding Author) **Email:** kosari_a@ut.ac.ir
2 Msc
3 Assistant Professor

DOI: 10.22034/jast.2022.321251.1109
Submit: 23. Dec. 2021/ Accepted: 11. April 2022
Print ISSN:2345-3648 Online ISSN: 1735-2134

maneuvering of satellites. Reaction wheels have advantages over thrusters and magnetic torquers, which have led to more use in attitude control. Thrusters usually generate intense, fast, and discrete torques, and are less used in precise control of the satellite's attitude [2]. Magnetic torquers are dependent on the earth's magnetic field and the altitude of the satellite and generate a very small torque. The reaction wheel can generate an adequate continuous torque. This actuator is particularly efficient in the precise pointing mode of satellites, although saturation and the need for desaturation are also disadvantages of the reaction wheel [3,4].

In the satellite attitude control system, given the satellite's orbital conditions, many uncertainties can reduce the control efficiency and accuracy. Uncertainty has either an internal factor and originates from inside the spacecraft, or an external factor and returns to the space environment. Most of the external uncertainties are environmental disturbances, and most of the internal uncertainties are related to satellite parameters. Therefore, it is necessary to design the satellite control system in terms of uncertainty and disturbances [5].

Today, different controllers such as proportional-integral-derivative (PID) are used for satellite attitude control. Despite their limitations, these controllers are widely used in the space industry [6]. In this regard, a lot of research has been done on these controllers in spacecraft attitude control, for example, references [7-10] can be mentioned. These researches can be separated in terms of the presence or absence of disturbances, single-axis or three-axis, rigid or elastic model, consideration of uncertainty, type of actuator, type of sensor and estimator, type of control law, and type of modeling.

For example, in terms of robustness of the control in the face of disturbances, we can refer to [11], in which a PID controller is used for satellite attitude control and stabilize in the face of disturbances and changes in the moment of inertia. In reference [12], the three-axis satellite attitude control by combining two thruster actuators and a reaction wheel has been investigated.

In terms of modifying the control law, reference [13] proposed a modified PID controller with the observer algorithm for single-axis satellite attitude control with a thruster actuator and and pulse-width pulse-frequency (PWPF) modulation. In reference [14], by modifying the model and adding a reference model, it has been tried to improve the satellite attitude control with a PID controller in the presence of disturbances. Another approach has been to tune the control gains with optimization methods, in references [15] and [16], robust optimization with thruster actuator has been used for satellite attitude control while considering uncertainty.

The evolution of the theory of fractional calculus and the development of its applications have led to the use of this method in the control loop, which mainly improves efficiency. This theory can be investigated from the two perspectives of improving the quality of modeling and increasing the efficiency of controllers. Fractional calculus has helped have more accurate modeling of processes by providing a wider platform for dynamic models. Considering that classic controllers are a special type of fractional controllers, their use can improve the performance of control systems [17]. The idea of designing the first fractional order control system goes back to Bode in 1945 [18]. In reference [17], fractional calculus and how to implement the fractional order integral and derivative are reviewed, also fractional order PID controllers are introduced and how to set them up is discussed. The study of fractional order PID controller by biquadratic approximation method in the design of derivative operator has been done in reference [19]. In reference [20], a new method for the design and analysis of the fractional order PD controller has been presented, where it is designed using the gain crossover frequency method and the desired phase margin. In reference [21], the tuning of fractional order controllers by constrained optimization methods and autonomous tuning methods has been investigated. Studies have also been done on the methods of tuning the control gains, for example, references [22,23] has used Ziegler-Nichols rules to tune the gains of the fractional order PID controller.

One of the applications of fractional order PID controllers is in satellite attitude control. In this regard, in reference [24], a study has been done on fractional order and integer order PID controllers for satellites. As a result, the fractional order PID controller has a visible improvement over the integer order PID controller. In reference [25], the fractional order controller has been used in spacecraft rendezvous control. In reference [26], the fractional order controller is used to control the stability of a satellite, where the response of the fractional order controller is faster and has less overshoot. In reference [27], the design of fractional order controllers for satellite three-axis stability has been investigated. In reference [28], an integer-order and fractional-order PD controller with a sliding mode control algorithm is also used for the satellite attitude maneuver.

In addition, in reference [29], an attempt has been made to implement a Fractional Order Sliding Mode Control (FOSMC) for a small satellite with reaction wheels. In this paper, a conventional sliding mode controller was initially considered to deal with the dynamic uncertainties of the satellite attitude. To improve the attitude control performance, a FOSMC was designed accordingly. In reference [30], a Fractional Order Non-singular Sliding Mode Control (FONTSM) was developed, which guarantees the desired deployment performance of the satellite system connected to space.

As mentioned, some research has been done in the field of satellite attitude control with a fractional order controller, but it seems necessary to investigate the three-axis attitude control performance of a satellite with a fractional order controller in the presence of disturbances and uncertainty. Therefore, in this article, the fractional order controller is investigated for the three-axis attitude control of a rigid satellite with the assumption of external disturbances and uncertainty.

Satellite attitude control with reaction wheel

Satellite Attitude Determination and Control Subsystem (ADCS) is responsible for pointing, orientation, and stabilization. Usually, magnetic torquer, thruster, and reaction wheel are used as actuators in controlling satellites. The on-off thruster generates torque discretely and with nonlinear dynamics. The magnetic actuator is highly dependent on the earth's magnetic field to generate torque and is mostly used in low-altitude and close-to-earth orbits. By creating angular momentum, reaction wheels generate the necessary torque continuously and independently of the orbital height. The main problem of wheels is their saturation [2]. In this article, due to the appropriate characteristics of reaction wheels, they are used as control actuators.

In this section, the satellite three-axis attitude control with reaction wheel and fractional order controller is investigated. In Figure 1, the block diagram of the satellite three-axis attitude control with fractional order PID controller is drawn. In this figure, the input angles are applied to the controller and the dynamics of the satellite are changed by stimulating the reaction wheel. In this figure, φ, θ, and ψ are the angles of the first, second, and third axes, respectively. Also, ω_x , ω_y and ω_z are the angular velocities of the first, second, and third axes.

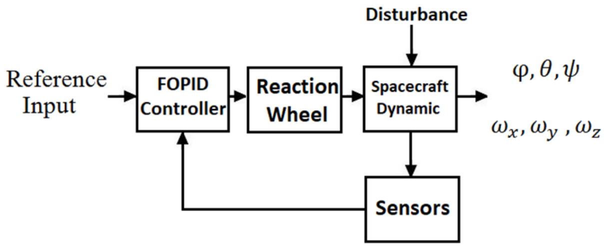


Figure 1. Block diagram of three-axis attitude control of the satellite

The three-axis dynamic equations of the satellite are presented in equation (1) with the assumption that the multiplicative moment of inertia is zero. In these equations, the variables M_x, M_y and M_z are the generation moments around the first, second, and third axes, respectively. Also, $\dot{\omega}_x$, $\dot{\omega}_y$ and $\dot{\omega}_z$ are the angular accelerations of the first, second, and third axes, respectively. The moment of inertia of the first, second, and third axes is specified by J_x, J_y and J_z respectively.

$$\begin{aligned} M_x &= J_x\dot{\omega}_x + \omega_y\omega_z(J_z - J_y) \\ M_y &= J_y\dot{\omega}_y + \omega_x\omega_z(J_x - J_z) \\ M_z &= J_z\dot{\omega}_z + \omega_y\omega_x(J_y - J_x) \end{aligned} \quad (1)$$

In order to investigate more precisely and facilitate the writing of mathematical equations, the satellite single-axis attitude control with the fractional order PID controller and the actuator model are drawn in Figure 2. In this figure, the variable θ is the angle of the satellite, θ_{ref} is the desired input angle, ω_y is the angular velocity, K_P is the proportional gain, K_D is the derivative gain, K_I is the integral gain, μ is the fractional derivative exponent, λ is the fractional integrator exponent, u is the control signal, and M_c is the control torque, M_y is the generation torque of the second axis, M_d is the disturbance torque and M is the total torque applied to the satellite dynamics. In the modeling of the reaction wheel, sometimes the ideal model and sometimes the first-order dynamics are considered [22]. The more accurate model is the first-order dynamics along with the saturation block, which is used in this article due to the limitations of practical implementation. It should be noted that due to the presence of the saturation block, the control system has become nonlinear. In the block diagram of Figure 2, T is the time constant of the reaction wheel, K is the wheel gain coefficient.

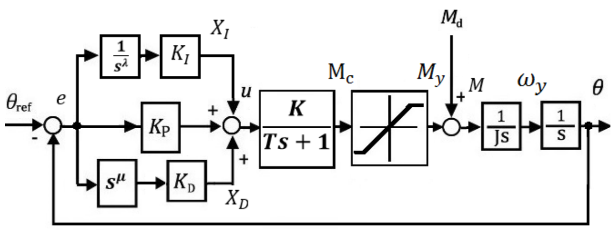


Figure 2. Block diagram of satellite single-axis attitude control with fractional order PID controller and reaction wheel model

In the block diagram of Figure 2, assuming that the exponent of the fractional derivative and the exponent of the fractional integral are units, the mathematical equations and relations are extracted as follows.

$$e(t) = \theta_{ref} - \theta \tag{2}$$

$$u(t) = K_P e(t) + X_D + X_I \tag{3}$$

$$M = M_y + M_d \tag{4}$$

$$M_y = \begin{cases} M_{c_{max}} & \text{for} \quad M_c > M_{c_{max}} \\ M_c & \text{for} \quad M_{c_{min}} \leq u \leq M_{c_{max}} \\ M_{c_{min}} & \text{for} \quad M_c < M_{c_{min}} \end{cases} \tag{5}$$

In this regard, the equations $M_{c_{max}}$ and $M_{c_{min}}$ are the maximum and minimum torque generated by the control actuator, respectively. Also, the state equations of the block diagram in Figure 2 are as follows.

$$\dot{\theta} = \omega_y \tag{6}$$

$$\dot{\omega}_y = \frac{M}{J} \tag{7}$$

$$\dot{X}_I = K_I e \tag{8}$$

$$\dot{e} = \frac{X_D}{K_D} \tag{9}$$

$$\dot{M}_c = \frac{Ku - M_c}{T} \tag{10}$$

Satellite attitude control with fractional order controller

Classic calculus has been developed over time according to human needs, and after that, fractional calculus has been established. Fractional order derivative and fractional order integral are generalizations of the classic derivative and classic integral. In fractional calculus, Gamma functions, Beta functions, and Mittag-Leffler functions are the main and widely used functions, which are presented below [17].

$$\Gamma(z) = \int_0^\infty e^{-t} t^{z-1} dt \quad z \in \mathbb{R}^+ \cup \{0\} \tag{11}$$

$$\beta(z . \omega) \triangleq \int_0^1 \tau^{z-1}(1 - \tau)^{\omega-1} d\tau \quad Re(z) > 0. Re(\omega) > 0 \tag{12}$$

$$E_\alpha(z) \triangleq \sum_{K=0}^{\infty} \frac{z^k}{\Gamma(\alpha k + 1)}. \quad \alpha > 0 \tag{13}$$

The fractional order integral is a generalization of the integer order. According to the definition of the fractional order integral of the function $f(t)$ of order α in the interval from a to t, it can be obtained by rewriting Cauchy's formula based on the gamma function as a generalization of the factorial function as follows.

$${}^{RL}_{a}I^{\alpha}_{1} f(t) \triangleq \frac{1}{\Gamma(\alpha)} \int_a^t (t-\tau)^{\alpha-1} f(\tau) d\tau. \quad \alpha \in \mathbb{R}^+ \tag{14}$$

The symbol ${}^{RL}_{a}I^{\alpha}_{1} f(t)$ means Riemann-Liouville fractional integral operator. The function $f(t)$ from a (lower limit of integral) to t (upper limit of integral) for $t > \alpha$ and α is the order of integration. To define the fractional order derivative, the generalized concept of fractional order integral is used. In this way, the operator derived from the fractional order of 0.7 is defined as an integral with the fractional order of 0.3 of the function, along with the first-order derivative of that function. This definition is called Riemann-Liouville fractional order derivative. In this way, the derivative of order α of function $f(t)$ is defined as follows.

$$ {}_{a}^{RL}D_t^{\alpha} f(t) \triangleq \frac{d^m}{dt^m}\{{}_{a}^{RL}I_t^{m-\alpha} f(t)\}. \quad \alpha \in \mathbb{R}^+ \tag{15} $$

In the above equation, $\lceil m \rceil = \alpha$, or in other words, m is equal to the smallest integer greater than α. The symbol used for the Riemann-Liouville fractional derivative operator is the symbol ${}_{a}^{RL}D_t^{\alpha}$. Fractional order derivative has other definitions, and one of these definitions is Grunwald-Latinkov fractional order derivative. This definition is mostly used for calculation purposes. This definition is as follows.

$$ {}_{a}^{GL}D_t^{\alpha} f(t) = \lim_{h\to 0} \frac{\sum_{r=0}^{N}(-1)^r \binom{\alpha}{r} f(t-rh)}{h^{\alpha}} \tag{16} $$

Here, according to the generalization of the concept of integral and derivative, it is possible to consider the fractional order integral and derivative in the structure of the PID controller and obtain a generalized structure as follows.

$$ C(s) = K_p + \frac{K_i}{s^{\lambda}} + K_d s^{\mu} \tag{17} $$

In the above structure, λ specifies the order of integral and μ specifies the order of derivative. The controller described by the above function is called a fractional order PID controller or FOPID or $PI^{\lambda}D^{\mu}$ controller. This controller is actually a generalized form of the classic PID controller. In this controller, the relation between input e(t) and output u(t) will be as follows [3].

$$ u(t) = K_p e(t) + K_i\, {}_{0}^{RL}I_t^{\lambda} e(t) + K_d\, {}_{0}^{C}D_t^{\mu} e(t) \tag{18} $$

PID controller is used as the most practical controller in the industry to control different systems. The fractional order PID controller has five tunable control parameters K_p, K_d, K_i, λ and μ. Therefore, compared to the classic PID controller, it has two more degrees of freedom, which can increase the capabilities of this controller.The fractional calculus tool improves the efficiency of control loops by improving the efficiency of controllers. For this reason, the use of fractional order controllers has attracted the attention of engineers all over the world in recent years and many studies have been done in this field. Due to the popularity of the fractional order controller and its control features, in this article, the fractional order PID controller is used to improve the satellite attitude control, and its controllability compared to the integer order controller is investigated.

Attitude control optimization with fractional order controller

In this section, optimization with an evolutionary algorithm based on the Particle Swarm Optimization (PSO) method is used to select the most appropriate control gains for the satellite attitude control system. The PSO algorithm is inspired by the collective behavior of birds or fish, which is specifically related to evolutionary strategy. The particle swarm algorithm searches through a series of factors. These factors, known as particles, travel along paths that are statistically or precisely determined. Each particle is affected by its best position and the best position of the whole group. But it should move randomly. Each particle (i) is defined by its position vector (xi) and its velocity vector (vi). In each iteration of this algorithm, each particle obtains a new location based on its new velocity vector. In Table 1, PSO optimization parameters and their numerical values are given.

Table 1 - Optimization conditions by PSO method

Numerical value	Parameter
50	Number of particles
400	iteration Number of
10^{-6}	Error goal
Number of iteration	Stopping criteria

In order to compare the performance of the fractional order controller, the integer order controller is also optimized with the same conditions. To show the performance of the PID controller, the PD controller is also examined and its control gains are selected from the optimization process. The absolute value of the pointing error in the point to point attitude maneuver is determined as the optimization objective function. In this optimization, K_p and K_d for classic PD controllers and K_p, K_d and μ for fractional PD controller was considered as optimization variables. Also, for the classic PID controller, K_p, K_d, and K_i gains, and for the fractional order PID controller, K_p, K_d, K_i gains, λ and μ were considered as optimization variables. Uncertain optimization parameters are the moment of inertia, reaction wheel model, disturbances and reference input angle. The optimization equation is as follows.

$$\begin{aligned} &\text{Find } (K_P.\ K_D.\ K_I.\ \mu.\ \lambda) \\ &\text{Minimizing } PI \\ &\text{Subject to } (\text{Max}(|\text{Err}|) - 0.5) \leq 0 \\ &0.1 \leq K_P.\ K_D.\ K_I \leq 200 \\ &0 < \mu.\lambda < 2 \end{aligned} \quad (19)$$

where the performance index is equal to

$$PI = \{\sqrt{|e_1{}^2 + e_2{}^2 + e_3{}^2|}\} \quad (20)$$

$$\begin{aligned} e_1 &= |\varphi_{ref} - \varphi| \\ e_2 &= |\theta_{ref} - \theta| \\ e_3 &= |\psi_{ref} - \psi| \end{aligned} \quad (21)$$

Simulation and numerical solution as well as optimization have been done according to the values in Table 2. Control gains for PD and PID controllers for two cases of integer order and fractional order and for three axes x, y, and z of the satellite are obtained from the optimization process and are presented in Table 3. The optimization process continues using the particle swarm method (PSO) until the stopping criterion is reached.

Table 2- Numerical values of parameters in optimization and numerical solution

$\varphi_{ref}.\ \theta_{ref}.\psi_{ref}$	30	deg
J_x	7.9	Kg/m^2
J_y	10	Kg/m^2
J_z	8.9	Kg/m^2
$\omega_{z0}\ \omega_{y0}.\ \omega_{x0}.$	0	deg/sec
$\varphi_0.\ \theta_0.\ \psi_0$	0	deg
K	1	-
T	0.2	sec
h	0.001	sec
M_d	$0.01\sin(0.1\,t) + 0.0002$	Nm

Table 3- Control gains obtained from optimization

Fractional integral exponent	Fractional derivative exponent	Derivative gain	Integral gain	Proportional gain	Controller type	Axis
–	–	3.44	–	0.60	PD	x
–	1.12	15.83	–	2.42	FOPD	
–	–	17.08	0.04	1.59	PID	
0.36	0.97	16.18	0.50	2	FOPID	
–	–	2.65	–	0.38	PD	y
–	1.15	17.16	–	2.31	FOPD	
–	–	18.13	0.05	1.51	PID	
0.52	0.95	19.01	0.45	2.17	FOPID	
–	–	2.49	–	0.35	PD	z
–	1.11	16.16	–	3.01	FOPD	
–	–	18.79	0.05	1.62	PID	
0.62	0.93	17.18	0.30	1.98	FOPID	

Discussion and results

The results of the simulation and numerical solution of the satellite three-axis control block diagram have been studied and analyzed in this section. To study the time response, Figures 3 and 4 are drawn. In these two figures, the angle and angular velocity of the satellite's three axes are plotted for fractional and integer order controllers, while the control gains are obtained from the optimization process in the presence of disturbances.

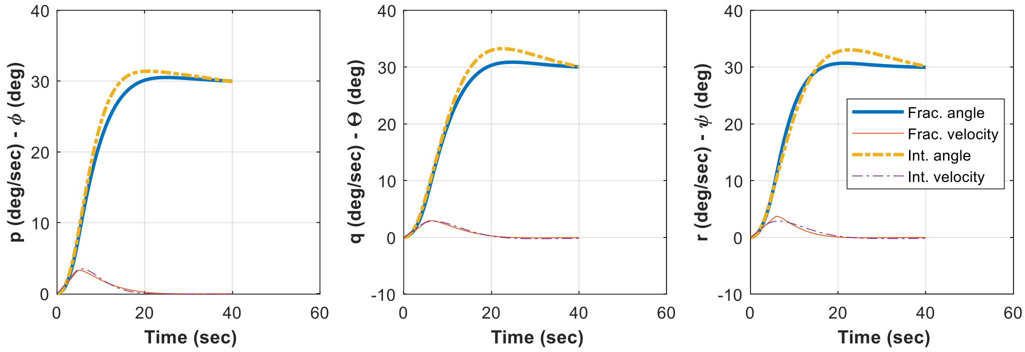


Figure 3- Time response of satellite three-axis attitude control with classic and fractional order PD controller

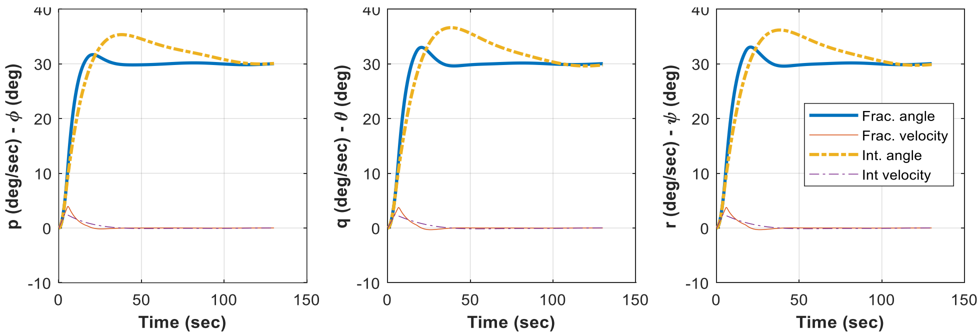


Figure 4- Time response of satellite three-axis attitude control with classic and fractional order PID controller

The results of these two figures show that both the integer and fractional order controllers performed well, but in comparison between the two mentioned controllers, the fractional order controller has better accuracy and less overshoot. In addition, the angular velocity diagrams are also drawn. A large increase in angular velocity during the maneuver of the satellite is not desirable, so the angular velocity graph has also been checked. To check the accuracy of attitude and angular velocity more precisely, the limit cycle diagrams for three axes of the satellite, two types of PD and PID controllers, and integer order and fractional order control have been drawn in figures 5 and 6 in the presence of external disturbances. According to the figure, the amplitude of the limit cycle in the fractional-order controller is less than the integer-order controller. This error reduction shows the more appropriate performance of the fractional controller in this problem. Also, comparing the two control algorithms PD and PID, it is clear from the two figures that the PD algorithm has better accuracy than PID.

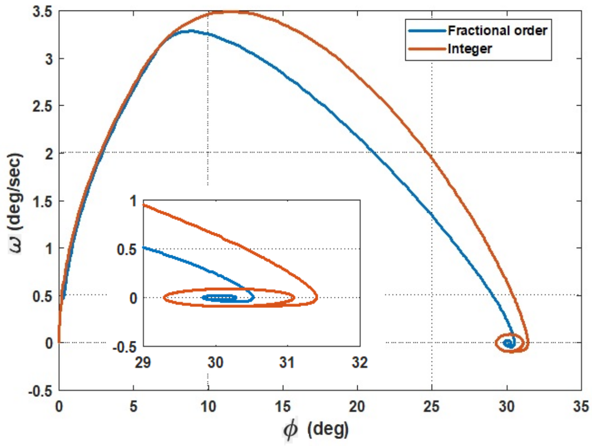


Figure 5- Limit cycle diagram of classic and fractional order PD controller

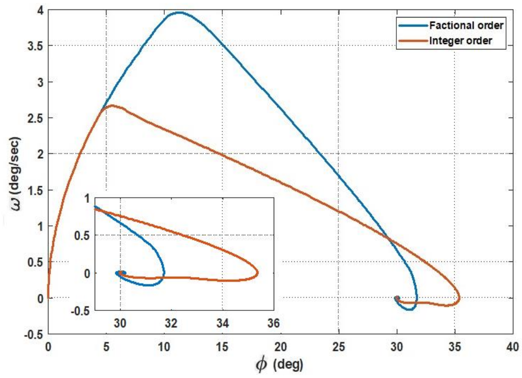
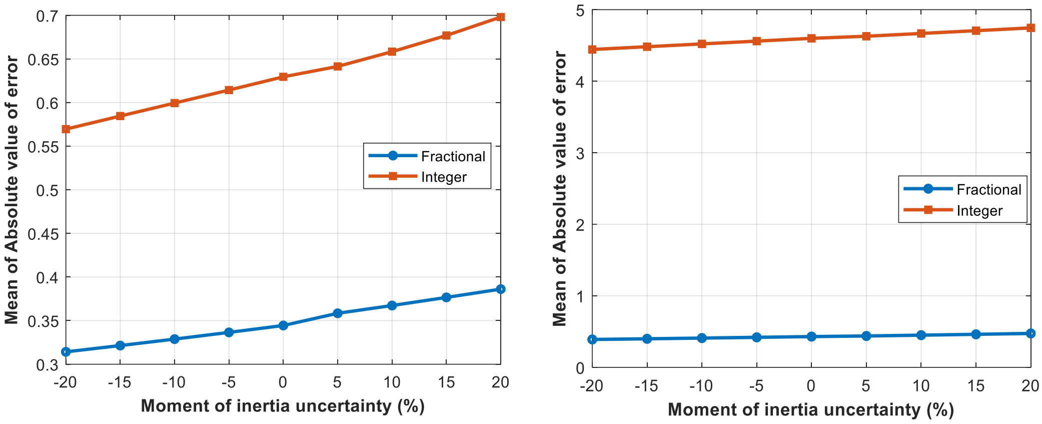


Figure 6- Limit cycle diagram of classic and fractional order PID controller

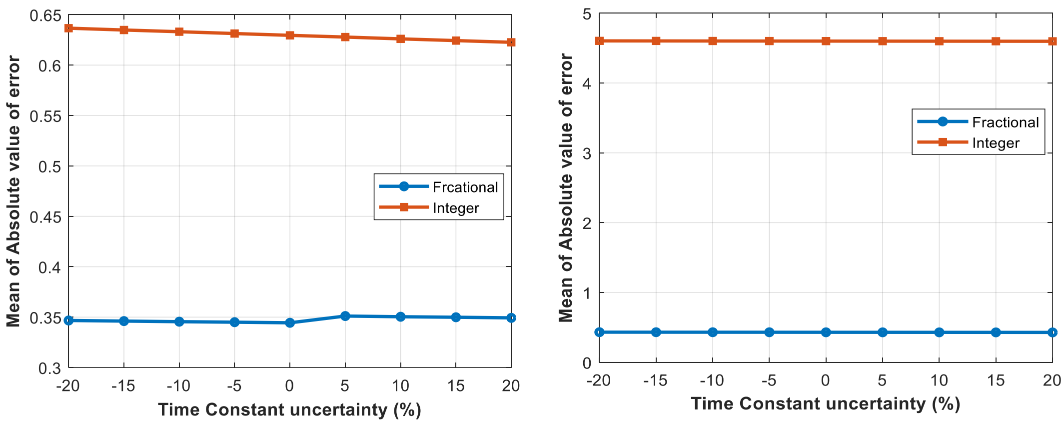
For a fair comparison of the results, it is necessary to check the performance index in terms of uncertainties and disturbances. For this purpose, Figures 7 to 10 study the satellite single-axis performance index for fractional and integer order controllers with PD and PID algorithms. In these figures, the vertical axis is the absolute mean value of the pointing error of the satellite attitude, which is considered in degrees. The horizontal axes are also the changes in the moment of inertia, reaction wheel time constant, input angle, and disturbances. In Figure 7, classic and fractional order PD and PID controllers are drawn under the efficacy of the uncertainty of the moment of inertia of the satellite in the range of -20% to +20%. As can be seen from the figure, the changes in the absolute value of the satellite pointing error relative to the uncertainty of the moment of inertia in the fractional order controller are much less than the changes in the absolute value of the error in the classic controller.



a-PD b-PID

Figure 7- Performance index according to the uncertainty of the moment of inertia

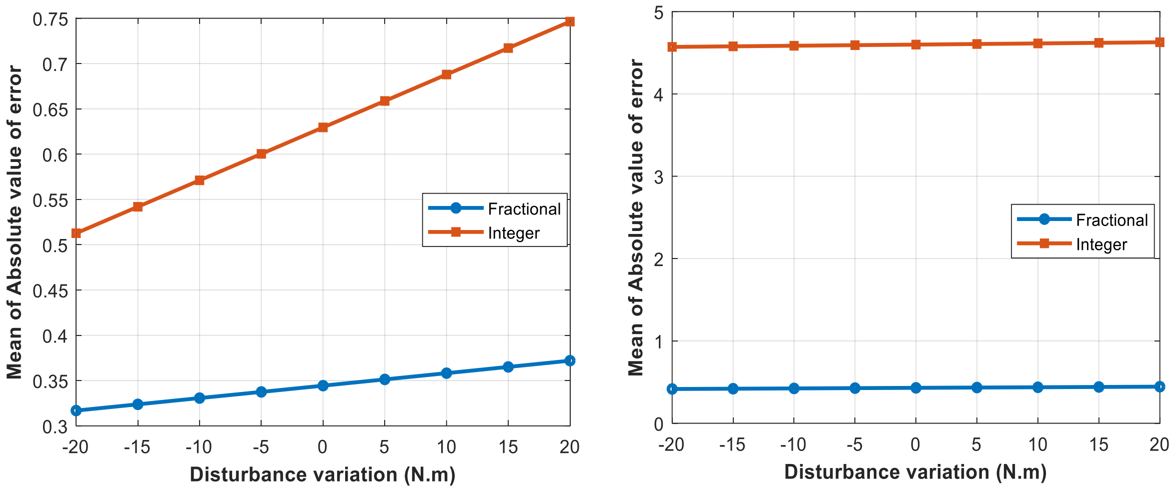
In Figure 8, the performance indexes in terms of uncertainty in the time-constant model of the reaction wheel for two controllers of integer order and fractional order have been studied. The uncertainty of the time constant model of the reaction wheel is in the range of -20% to +20% of the nominal value. According to this figure, the performance index is not very dependent on the time constant of the wheel, and the fractional order controller has less error than the integer order controller.



a-PD b-PID

Figure 8- The performance index according to the uncertainty of the time constant of the reaction wheel

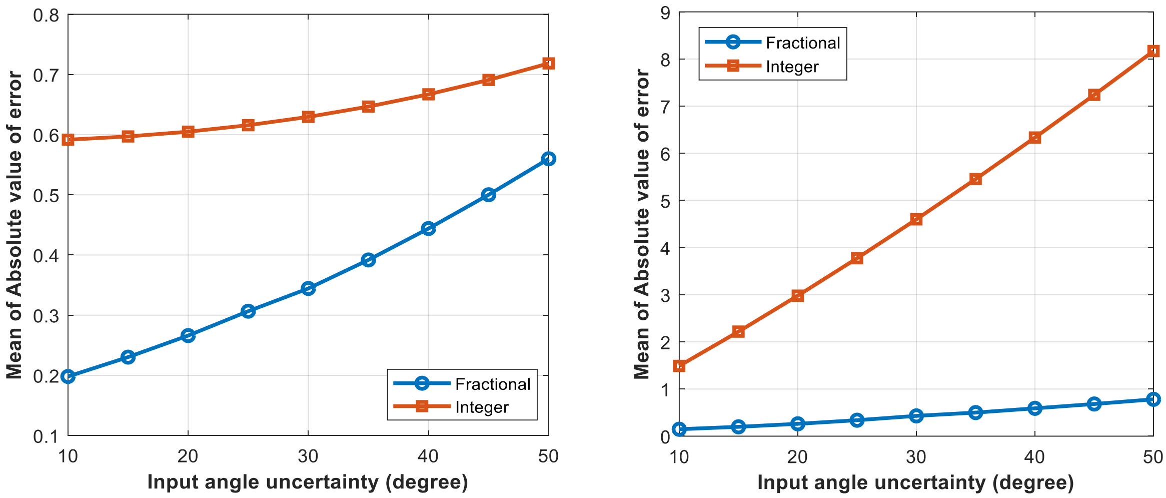
In Figure 9, the performance index is checked according to the uncertainty of the disturbance amplitude for the integer order and fractional order controller. The uncertainty of the amplitude of disturbances is in the range of -20% to +20% of the nominal value. According to this figure, with the increase in the amplitude of disturbances, the pointing error has increased. Although fractional order controller performance is more suitable than integer order.



a-PD b-PID

Figure 9- Performance index according to the uncertainty of the amplitude of disturbances

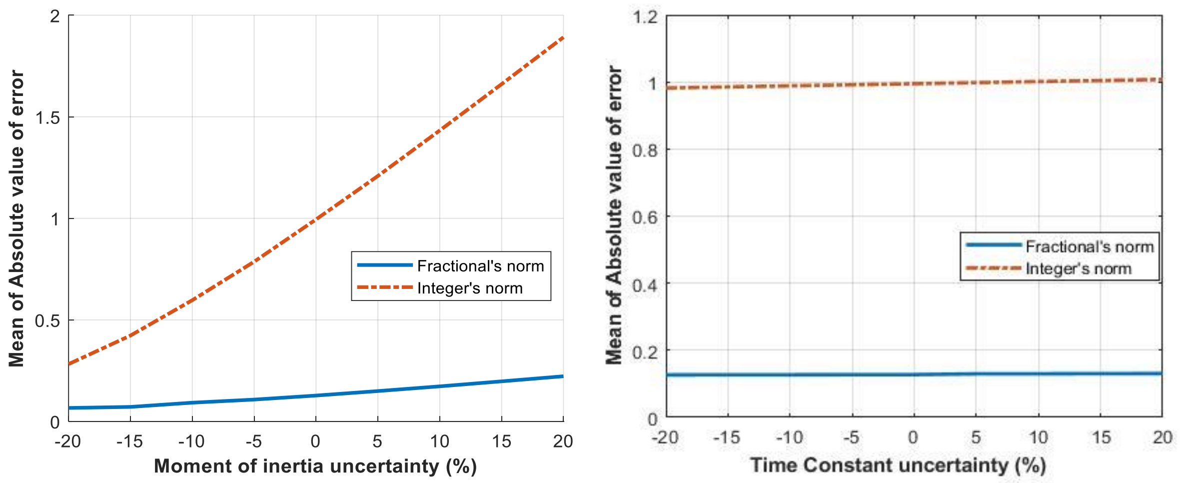
In Figure 10, it is possible to compare the performance of the integer order and fractional order controllers in terms of changes in the absolute value of the satellite pointing error in the presence of the uncertainty of the input angle from 10 to 50 degrees. As can be seen from Figure 10, the performance of the fractional controller is preferable to the integer order controller.



a- PD b-PID

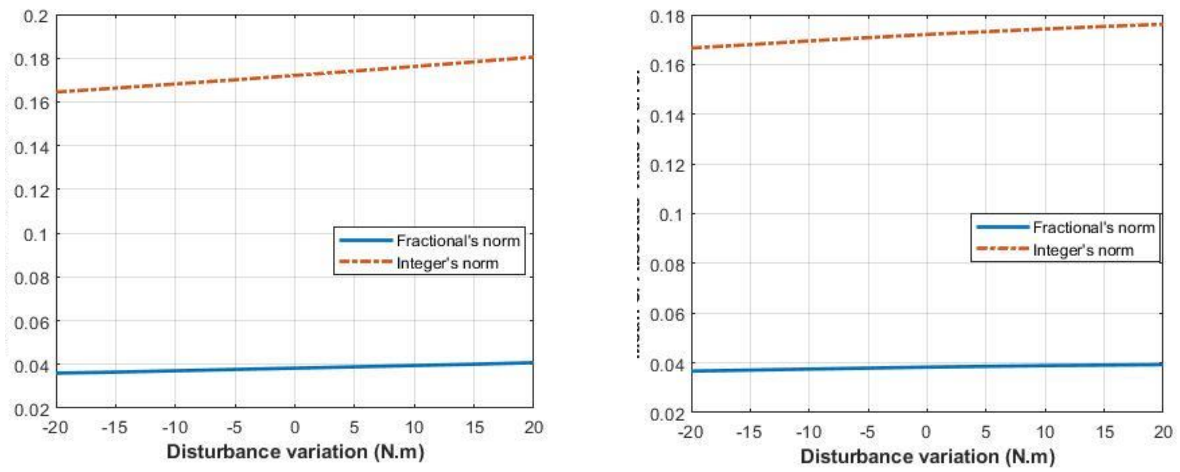
Figure 10- Performance index according to reference input uncertainty

In the following of this section, the results of the three-axis satellite couple control with classic and fractional order PD and PID controllers are presented. In figures 11 and 12, the three-axis performance index of the satellite in terms of the uncertainty of the moment of inertia of the satellite, the time constant of the actuator, the frequency of disturbances, and the amplitude of disturbances in the range of -20٪ to +20٪ of the nominal value are checked and compared by classic and fractional order controllers. According to these two figures, the performance of the fractional order controller is more suitable than the integer order controller.



(a) (b)

Figure 11- Performance index of three-axis according to uncertainty (a) moment of inertia, (b) time constant of the actuator



a-Amplitude of disturbances b- Frequency of disturbances

Figure 12- Performance index of the three-axis according to the uncertainty of disturbances

The three-axis and single-axis satellite attitude control performance index for integer and fractional PD and PID controllers were investigated in the presence of uncertainties of amplitude and frequency of disturbances, reaction wheel model, the moment of inertia, and reference input amplitude. The graphs generally show less pointing errors on the satellite attitude maneuver with the fractional order controller. Also, the PD controller has improved the time response characteristic of the satellite attitude control system compared to the PID controller.

By the study on the performance index, it is obtained from the drawn figures that the uncertainty in the parameters of the moment of inertia and the amplitude of disturbances have a greater effect on the pointing accuracy. One of the results obtained from this study is the improvement of the accuracy of attitude control in the presence of uncertainty and disturbance, which is achieved by the fractional order controller. Fewer changes in the performance index in terms of parameter changes in attitude control with fractional order controller have also been another achievement of this study.

Conclusion

In this paper, the three-axis attitude control performance of a rigid satellite with a fractional-order proportional-integral-derivative controller has been improved in the presence of disturbances and by considering parametric uncertainties. A reaction wheel with a first-order dynamic model and a maximum torque limitation has been used as a satellite attitude control actuator. Uncertainty in the moment of inertia of the satellite, actuator model, and reference input is considered. External disturbances were modeled with fixed and periodic parts, and the uncertainty of the amplitude and frequency of the disturbances was considered. To validate and compare fairly, in addition to the fractional order controller, the integer order controller was also checked for the same conditions. The absolute mean error of the pointing maneuver on the satellite attitude was selected as the objective function of the optimization, and the optimization constraints were added to the objective function by the penalty method to tune the gains of the integer and fractional order controllers by the particle swarm evolution algorithm (PSO). Comparison of the results by studying time response graphs, limit cycle, performance index graphs in terms of disturbance uncertainties, actuator model, the moment of inertia, and change of reference input for integer and fractional order PD and PID controllers has been done separately. The obtained results indicate less satellite pointing error with the fractional order controller and its higher robustness performance than the integer order controllers in the presence of uncertainty and disturbances. Also, the results show the high impact of the uncertainties of the moment of inertia and the amplitude of disturbances on the performance index in both controllers.

Refrences

[1] Ley, W., Wittmann, K., & Hallmann, W. (Eds.). (2009). *Handbook of space technology* (Vol. 22). John Wiley & Sons.
[2] Sidi, M. J. (1997). *Spacecraft dynamics and control: a practical engineering approach* (Vol. 7). Cambridge university press.
[3] Bryson, A. E. (1994). *Control of spacecraft and aircraft*. Princeton university press.
[4] J. Wertz and H. Wittenberg, *Spacecraft Attitude Determination and Control*, vol. 24. Dordrecht: Springer Netherlands, 1979.
[5] Fuchs, M., Neumaier, A., & Girimonte, D. (2007). Uncertainty modeling in autonomous robust spacecraft system design. In *PAMM: Proceedings in Applied Mathematics and Mechanics* (Vol. 7, No. 1, pp. 2060041-2060042). Berlin: WILEY-VCH Verlag.
[6] M. Massoumnia,, "Linear Controllers Design," Sharif Univercity of Technology, 1394, (in persian),Accessed: Dec. 28, 2020. [Online]. Available: http://ganjineh.sharif.ir/resource/425314.
[7] A. Ghaedi and M. A. Nekoui, "3-Axes satellite attitude control based on biased angular momentum," in *2008 13th International Power Electronics and Motion Control Conference, EPE-PEMC 2008*, 2008, pp. 1054–1057, doi: 10.1109/EPEPEMC.2008.4635407.
[8] P. Sharma and V. G. Nair, "Tuning of PID controller using glowworm swarm optimisation on a satellite attitude control reaction wheel," *Int. J. Recent Technol. Eng.*, vol. 8, no. 2, pp. 4205–4210, 2019, doi: 10.35940/ijrte.B3404.078219.
[9] C. Pukdeboon, "Robust optimal pid controller design for attitude stabilization of flexible spacecraft," *Kybernetika*, vol. 54, no. 5, pp. 1049–1070, 2018, doi: 10.14736/kyb-2018-5-1049.
[10] S. S. Kumar, C. Shreesha, and N. K. Philip, "Robust PID controller design for rigid uncertain spacecraft using Kharitonov theorem and vectored particle swarm optimization," *Int. J. Eng. Technol.*, vol. 7, no. 2, pp. 9–14, 2018, doi: 10.14419/ijet.v7i2.21.11825.
[11] Y. Li, Z. Sun, and D. Ye, "Robust linear PID controller for satellite attitude stabilisation and attitude tracking control," *Int. J. Sp. Sci. Eng.*, vol. 4, no. 1, p. 64, 2016, doi: 10.1504/ijspacese.2016.078581.
[12] A. Kosary, A. Maani and H. Nejat Pishkonary, "Three-axis Satellite Atittude with a combination of Thruster and Reaction wheels," (in persian), vol. 11, no. 3, pp. 63–71, Dec. 2018, Accessed: Dec. 28, 2020. [Online]. Available: http://jsst.ias.ir/article_81073.html.
[13] S. M. Bazaz, V. Bohlouri, S. Hamid, and J. Naini, "Attitude Control of a Rigid Satellite with Pulse-Width Pulse-Frequency Modulation Using Observer-based Modified PID Controller," *Fac. Mech. Eng. Tarbiat Modares Univ. Tehran, Iran.*, vol. 16, no. 8, pp. 139–148, 2016, Accessed: Dec. 28, 2020. [Online]. Available: http://journals.modares.ac.ir/article-15-1094-en.html.
[14] V. Bohlouri, Z. Khodamoradi, and S. H. Jalali-Naini, "Spacecraft attitude control using model-based disturbance feedback control strategy," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 40, no. 12, pp. 1–18, Dec. 2018, doi: 10.1007/s40430-018-1478-9.
[15] V. Bohlouri, M. Ebrahimi, and S. H. J. Naini, "Robust optimization of satellite attitude control system with on-off thruster under uncertainty," in *2017 International Conference on Mechanical, System and Control Engineering, ICMSC 2017*, 2017, pp. 328–332, doi: 10.1109/ICMSC.2017.7959495.
[16] V. Bohlouri and S. H. Jalali-Naini, "Application of reliability-based robust optimization in spacecraft attitude control with PWPF modulator under uncertainties," *J. Brazilian Soc. Mech. Sci. Eng.*, vol. 41, no. 10, pp. 1–15, Oct. 2019, doi: 10.1007/s40430-019-1955-9.
[17] M. Tavazoei and M. Tavakoli-Kakhaki, "Fractional Order Systems and Controllers." (in persian), http://press.kntu.ac.ir/book_388060.html (accessed Dec. 28, 2020).
[18] F. Mainardi, "Short survey : An historical perspective on fractional calculus in linear viscoelasticity," *Fractional Calculus and Applied Analysis*, vol. 15, no. 4. pp. 712–717, 2012, doi: 10.2478/s13540-012-0048-6.
[19] R. El-Khazali, "Fractional-order PI λdμ controller design," *Comput. Math. with Appl.*, vol. 66, no. 5, pp. 639–646, Sep. 2013, doi: 10.1016/j.camwa.2013.02.015.
[20] H. Li, Y. Luo, and Y. Chen, "A fractional order proportional and derivative (FOPD) motion controller: Tuning rule and experiments," *IEEE Trans. Control Syst.*

Technol., vol. 18, no. 2, pp. 516–520, 2010, doi: 10.1109/TCST.2009.2019120.

[21] C. A. Monje, B. M. Vinagre, V. Feliu, and Y. Q. Chen, "Tuning and auto-tuning of fractional order controllers for industry applications," *Control Eng. Pract.*, vol. 16, no. 7, pp. 798–812, 2008, doi: 10.1016/j.conengprac.2007.08.006.

[22] D. Valério and J. S. Da Costa, "Ziegler-nichols type tuning rules for fractional pid controllers," in *Proceedings of the ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference - DETC2005*, 2005, vol. 6 B, pp. 1431–1440, doi: 10.1115/detc2005-84344.

[23] X. Li, G. Sun, S. Han, and X. Shao, "Fractional-Order Nonsingular Terminal Sliding Mode Tension Control for the Deployment of Space Tethered Satellite," vol. 14, no. 8, 2021, doi: 10.1109/TAES.2021.3061815.

[24] M. T. Nasri and W. Kinsner, "An evaluation of integer- and fractional-order controllers for small satellites," in *Proceedings of 2014 IEEE 13th International Conference on Cognitive Informatics and Cognitive Computing, ICCI*CC 2014*, 2014, pp. 30–38, doi: 10.1109/ICCI-CC.2014.6921437.

[25] N. Sarafnia, M. Malekzadeh, and J. Askari, "Fractional order PDD control of spacecraft rendezvous," *Adv. Sp. Res.*, vol. 62, no. 7, pp. 1813–1825, 2018, doi: 10.1016/j.asr.2018.06.040.

[26] G. Xing-wang, L. Ai-jun, G. Yang-yang, and W. Chang-qing, "Fractional order attitude stability control for sub-satellite of tethered satellite system during deployment," *Appl. Math. Model.*, vol. 62, pp. 272–286, 2018, doi: 10.1016/j.apm.2018.04.005.

[27] G. Sun and Z. H. Zhu, "Fractional order control of tethered satellite system deployment and retrieval," 2014, doi: 10.2514/6.2014-4132.

[28] D. Chakrabarti and N. Selvaganesan, "PD and PDβ based sliding mode control algorithms with modified reaching law for satellite attitude maneuver," *Adv. Sp. Res.*, vol. 65, no. 4, pp. 1279–1295, 2020, doi: 10.1016/j.asr.2019.11.005.

[29] S. M. Baviskar, P. Shah, and S. D. Agashe, "Tuning of fractional PID controllers for higher order systems," *Int. J. Appl. Eng. Res.*, vol. 9, no. 11, pp. 1581–1590, 2014, Accessed: Dec. 28, 2020. [Online]. Available: http://www.ripublication.com.

[30] Z. Ismail, R. Varatharajoo, and Y. C. Chak, "A fractional-order sliding mode control for nominal and underactuated satellite attitude controls," *Adv. Sp. Res.*, vol. 66, no. 2, pp. 321–334, 2020, doi: 10.1016/j.asr.2020.02.022.