DESIGN OF A FUZZY PID CONTROLLER FOR APPLICATION IN SATELLITE ATTITUDE CONTROL SYSTEM

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Abstract: *In this paper, a fuzzy proportional-integral-derivative (PID) controller is designed to be applied in the satellite attitude control system equipped with reaction wheels. An analysis of the scaling factor is developed to verify its influence during an attitude maneuver. The settling time and the pointing accuracy are the mission requirements that control system have to satisfy. The equations and theoretical concepts are introduced throughout this paper. The results showed that the adequate selection of the scaling factor contributes to the improvement of control results.*

Keywords: *Fuzzy PID controller, attitude control system.*

1 Introduction

The attitude control system determines and controls the orientation of a vehicle in space. The information provided by attitude sensors is processed and filtered by an estimator state. Hence, this signal is compared with a reference. The error between the estimated state and the reference will be used by the control algorithm to activate the actuators appropriately in order to reduce or eliminate this error. Several control techniques can be used in the controller. Well-known proportional-integral-derivative (PID) controller is the most widely used in industrial application because of its simple structure. However, control techniques which based on fuzzy logic and modified PID controllers are alternatives to conventional control methods.

Control strategies such as PID controllers are expressed in mathematical functions. Fuzzy logic control, on the other hand, makes use of human knowledge and experience to perform the control in a scheme similar to the human strategy, thus realizing an intelligent control. The design of a fuzzy logic controller involves the construction of control rules and the parameter tuning. This paper shows the study of the parameter tuning of a fuzzy PID controller of a satellite. The modeling and simulation of an attitude maneuver of a satellite equipped with reaction wheels and fuzzy PID controller was developed. In order to analysis the behavior of the fuzzy PID controller response, different values of the scaling factor – parameter of membership functions that define the fuzzy sets – have been investigated.

The paper is organized as follow. In Section 2, mathematical model of the attitude movement of a satellite are presented as well as the reaction wheel models. Section 3 shows the general structure of a fuzzy PID controller. Section 4 discusses the simulation results. Finally Section 5 provides conclusions.

2 Concepts and equations of the satellite attitude movement

Different reference axis frames are chosen for different spacecraft tasks. In this paper, we adopted the *orbit reference frame* ($\mathbf{X_R}$, $\mathbf{Y_R}$, $\mathbf{Z_R}$) as the reference coordinate frame in which the satellite is to be three-axis attitude-stabilized. The origin of this frame moves with the center of mass of the satellite in the orbit. The $\mathbf{Z_R}$ axis points toward the center of mass of the earth. The $\mathbf{X_R}$ axis is in the plane of the orbit, perpendicular to the $\mathbf{Z_R}$ axis, in the direction of the velocity of the spacecraft. The $\mathbf{Y_R}$ axis is normal to the local plane of the orbit, and completes a three-axis right-hand orthogonal system. The *satellite´s axis frame* is defined by $\mathbf{X_B}$, $\mathbf{Y_B}$ and $\mathbf{Z_B}$ and has its origin at the center of mass of the spacecraft. This frame is used as orientation for the attitude control and determination system. The *inertial axis frame* ($\mathbf{X_I}$, $\mathbf{Y_I}$, $\mathbf{Z_I}$) has its origin at the center of mass of the earth.

The spacecraft attitude can be represented by Euler axis and principal angle, Euler angles, Euler symmetric parameters (quaternion), Rodrigues parameters (Gibbs vector) and modified Rodrigues parameters (Tewari, 2007). The quaternions were used in the computations to avoid singularities in the results because their use do not require trigonometric calculations. However, representation by Euler angles has more physical sense and serves to present the graphical results in this paper.

Equation (1) is the required kinematic relationship between the Euler angles, ϕ, θ, ψ, and the angular velocity ($\boldsymbol{\omega}$) in the form of three, coupled, nonlinear first-order ordinary differential equations for 3-2-1 rotations sequence.

$$\begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix} = \frac{1}{c\theta} \begin{bmatrix} c\theta & s\phi s\theta & c\phi c\theta \\ 0 & c\phi c\theta & -s\phi c\theta \\ 0 & s\phi & c\phi \end{bmatrix} \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} + \frac{\omega_0}{c\theta} \begin{bmatrix} s\psi \\ c\theta c\psi \\ s\theta s\psi \end{bmatrix} \tag{1}$$

where $c\beta \equiv \cos\beta$ and $s\beta \equiv \sin\beta$, and ω_0 is the orbital angular velocity.

A quarternion is a special set composed of four mutually dependent scalar parameters, q_1, q_2, q_3, q_4, such that the three form a vector, called the *vector part*, and the fourth, q_4, represents the *scalar part*. The kinematic equation represented by quarternion is shown by Eq. (2).

$$\dot{\mathbf{q}} = \frac{1}{2} \begin{bmatrix} 0 & \omega_x & -\omega_y + \omega_0 & \omega_x \\ -\omega_z & 0 & \omega_x & \omega_y + \omega_0 \\ \omega_y - \omega_0 & -\omega_x & 0 & \omega_z \\ -\omega_x & -\omega_y - \omega_0 & -\omega_z & 0 \end{bmatrix} \mathbf{q} \tag{2}$$

The instantaneous attitude depends not only upon the rotational kinematics, but also on rotational dynamics which determine how the attitude parameters change with time for a specified angular velocity. Assuming that $\mathbf{X_B}$, $\mathbf{Y_B}$, $\mathbf{Z_B}$ are the principal axes of inertia, the Eq. (3) represents the three scalar Euler´s moment equations (Sidi, 1997).

$$\begin{aligned} M_x &= I_x \dot{\omega}_x + \omega_y \omega_z (I_z - I_y) \\ M_y &= I_y \dot{\omega}_y + \omega_x \omega_z (I_x - I_z) \\ M_z &= I_z \dot{\omega}_z + \omega_x \omega_y (I_y - I_x) \end{aligned} \tag{3}$$

where I_x, I_y, I_z are the moments of inertia, and M_x, M_y, M_z are the components of the total external moment vector acting on the body, which is equal to the inertial momentum change of the system. The kinematic equations, along with Euler´s equations of rotational dynamics, complete the set of differential equations needed to describe the changing attitude of a rigid body under the influence of a time-varying torque vector ($\mathbf{M}$).

Momentum exchange devices are actuators that allow changing the distribution of momentum inside the satellite, without altering the total inertial momentum of the entire system. The device consists of an electrical motor on whose axis is assembled a flywheel designed to increase its angular momentum of inertia and so deliver momentum to the satellite´s body as part of the attitude control system (ACS). The reaction wheel is a kind of momentum exchange device and is used primarily to provide the satellite with sufficient torque for various attitude maneuvering tasks (Sidi, 1997). Souza (1987) presents the design and study of an experimental model of a reaction wheel.

In this paper, we adopted the reaction wheel model suggested by Souza (1981), whose block diagram is shown in Fig. (1).

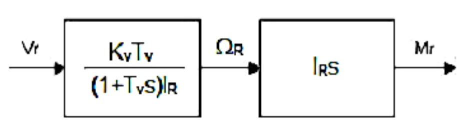

Figure 1. Block diagram of the reaction wheel.

Equation (4) shows the transfer function between the torque (output) and the voltage (input) and Eq. (5) shows the transfer function between the angular velocity of the reaction wheel and the torque provided.

$$\frac{M_r}{V} = \frac{K_v T_v s}{(1+T_v s)} \tag{4}$$

$$\frac{\Omega_R}{M_r} = \frac{1}{I_R s} \tag{5}$$

where M_r is torque provided by reaction wheel, V is the voltage input applied at wheel motor, K_v is the wheel gain, T_v is the time constant, Ω_R is angular velocity of the reaction wheel and I_R is its moments of inertia. The wheel parameters (K_v and T_v) are given by Eq. (6) and (7), respectively.

$$K_v = \frac{M_{R\max}}{V_{R\max}} \tag{6}$$

$$T_v = \frac{I_R \Omega_{R\max}}{M_{R\max}} \tag{7}$$

where Ω_{Rmax} is the maximum angular velocity; M_{Rmax} is the maximum torque and V_{Rmax} is the maximum input voltage.

3 Fuzzy logic control

Fuzzy logic controllers are as functional as the more conventional controllers, but they manage complex control problems through heuristics and mathematical models provided by fuzzy logic, rather than via mathematical models provided by differential equations. This approach is useful for controlling systems whose mathematical models are nonlinear or for which standard mathematical models are simply not available. Creating machines to emulate human knowledge in control gives us a new way to design controllers for complex plants whose mathematical models are not easy to specify (Nguyen et al., 2003).

Figure (2) shows the basic configuration of a fuzzy logic control (FLC), which comprises four principal components: a fuzzification interface, a knowledge base (KB), decision-making logic, and a defuzzification interface (Lee, 1990).

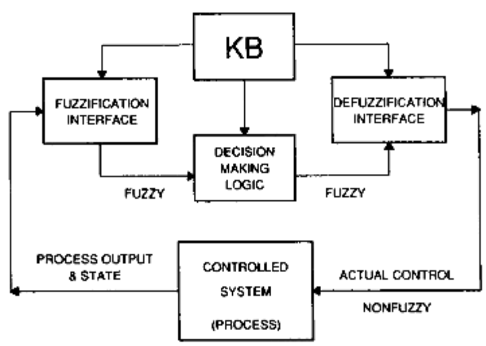

Figure 2. Basic configuration of fuzzy logic controller (FLC).

The *fuzzification* interface measures the values of input variables, performs a scale mapping that transfers the range of values of input variables into corresponding universe of discourse and performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets. The *knowledge base* comprises the knowledge of the application domain and the attendant control goals. It consists of a data base and a linguistic (fuzzy) control rule base. The *decision-making logic* is the kernel of an FLC; it has the capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions employing fuzzy implication and the rules of inference in fuzzy logic. The *defuzzification* interface performs the following functions: a scale mapping, which converts the range of values of output variables into corresponding universe of discourse; and defuzzification, which yields a nonfuzzy control action from an inferred fuzzy control action (Lee, 1990).

The fuzzy PID controller used in this paper has two inputs and one output. These are error, change of error and control signal, respectively. The overall structure of used controller is shown in Fig. (3).

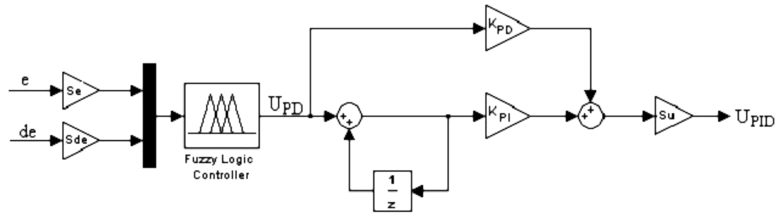

Figure 3. Block diagram of the fuzzy PID controller.

The fuzzy PID controller signal is given by Eq. (8) (Çetin and Demir, 2008).

$$U_{PID}(t) = S_u\left[K_{PI}\sum_{i=0}^{t} U_{PD}(i) + K_{PD}U_{PD}(t)\right] \tag{8}$$

The linguistic labels used to describe the fuzzy sets were “Negative Big” (NB), “Negative Medium” (NM), “Negative Small” (NS), “Zero” (ZE), “Positive Small” (PS), “Positive Medium” (PM), “Positive Big” (PB). Inputs and outputs are all normalized in the interval of [-1, 1]. The membership functions are shown in Fig. (4).

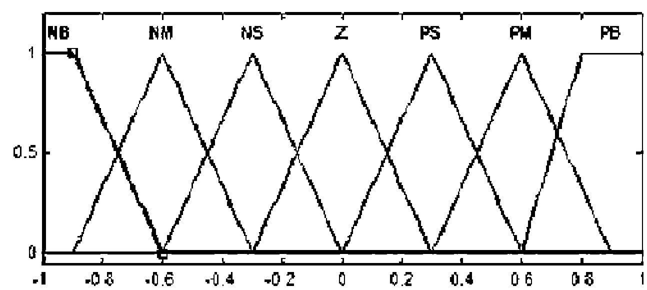

Figure 4. Membership functions.

Parameter tuning affects the shape of fuzzy sets. Actual interval of variables is obtained by using scaling factors which are Se, Sde and Su. The adequate selection of the scaling factor contributes to the improvement of control results.

The fuzzy control rule is in the form of: **IF** e = E_i and de = dE_j **THAN** $U_{PD} = U_{PD(i,j)}$. The table rules used in this paper is similar to that proposed by Çetim and Demir (2008) and is shown in Fig. (5). The Mamdani type is the structure of the rule base. The fuzzy rules are extracted from fundamental knowledge and human experience about the process. These rules contain the input/output relationships that define the control strategy. Each control input has seven fuzzy sets so that there are at most 49 fuzzy rules.

de/e	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	ZE
NM	NB	NB	NM	NS	NS	ZE	PS
NS	NB	NM	NS	NS	ZE	PS	PM
ZE	NM	NS	NS	ZE	PS	PS	PM
PS	NM	NS	ZE	PS	PS	PM	PB
PM	NS	ZE	PS	PS	PM	PB	PB
PB	ZE	PS	PM	PM	PB	PB	PB

Figure 4. Rule table of the fuzzy PID controller.

4 Simulations and Results

Some considerations were done for the development of this work: the satellite is a rigid body; internal torques are null; reaction wheel friction is null; initial moment is null; constant disturbing torques of $1 \cdot 10^{-4}$ N.m in each axis; and a diagonal inertia matrix. The reaction wheel parameters are shown in Tab. (1).

Table 1. Reaction wheel parameters.

Parameters	Values	Time constant	Wheel gain
I_R	0.015 [kg.m^2]		
Ω_{Rmax}	7500 [rpm]	T_v = 20 [s]	K_v = 0.06
M_{Rmax}	0.6 [N.m]		
V_{Rmax}	10 [V]		

The simulation of an attitude maneuver of 30 degrees in the roll axis was performed. The initial condition is the following: 30° in the roll axis (ϕ); 0° in the pitch axis (θ); and 0° in the yaw axis (ψ). The mission requirements are: the maneuver must be performed in a maximum time of 180 seconds and reach an appointment accuracy of 0.05°. The simulation was performed varying the scaling factor of the error change between 1 and 2, with increment of 0.1.

The results of the attitude maneuver simulations in each axis (angular position as function of time) are reported in Figure (5).

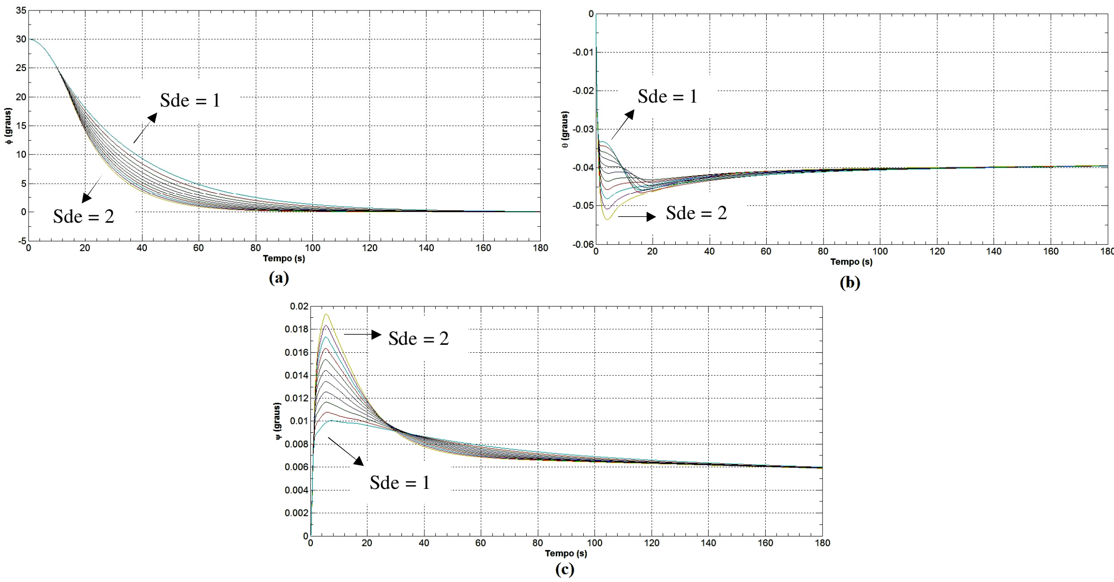

Figure 5. Angular position as function of time: (a) roll angle; (b) pitch angle; (c) yaw angle.

As it can be seen from Fig. (5), different kind of response can be achieved varying the scaling factor of the error change (Sde). In order to improve the visualization, Fig. (6a) shows the pointing accuracy in the roll axis as function of Sde and Fig. (6b) shows the settling time as function of Sde.

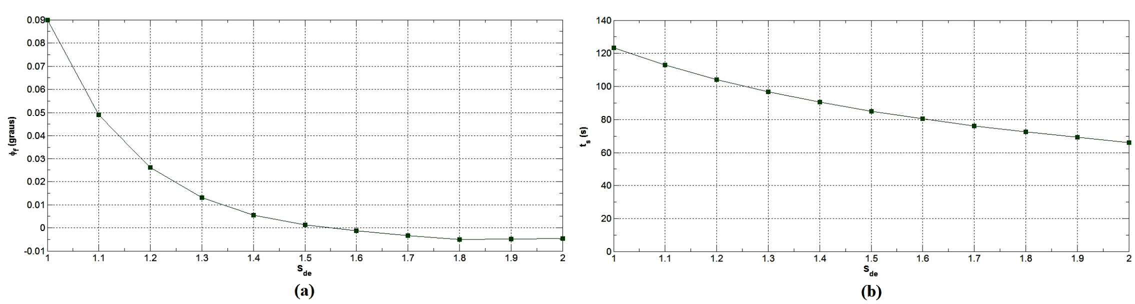

Figure 6. Mission requirements: (a) pointing accuracy x Sde; (b) settling time x Sde.

In Fig. (6a), it can be seen that a higher precision is obtained for higher values of Sde. The same tendency of decreasing can be seen in Fig. (6b), but less pronounced. Looking to results presented up to now, we can say that to attend the specifications, the value of Sde must be equal or higher than 1.3.

The angular velocity of the satellite as function of time is presented in Fig. (7). The angular velocity in pitch axis, Fig. (7b), reaches a value different of zero because of the orbital angular velocity considered in the modeling. According to Fig. (7a), the maximum overshoot increases as soon as the Sde increases.

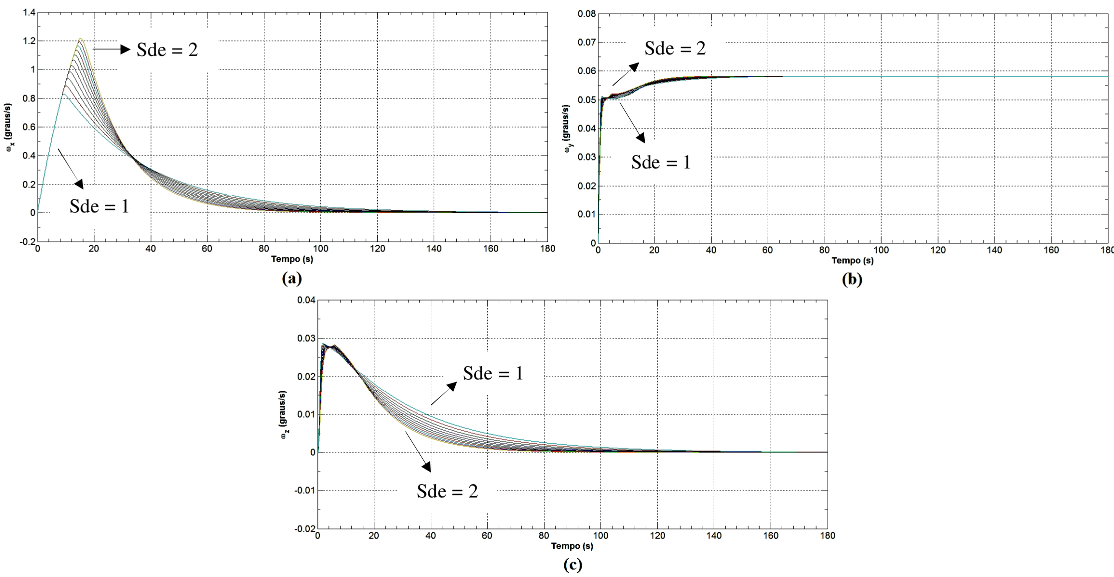

Figure 7. Satellite angular velocity as function of time: (a) roll axis; (b) pitch axis; (c) yaw axis.

The control signal send by fuzzy PID controller is defined as the input voltage to be applied in the reaction wheel. The behavior of this variable is reported in Fig. (8). Looking to Fig. (8a), we can see that the time of voltage saturation varies with the value of Sde.

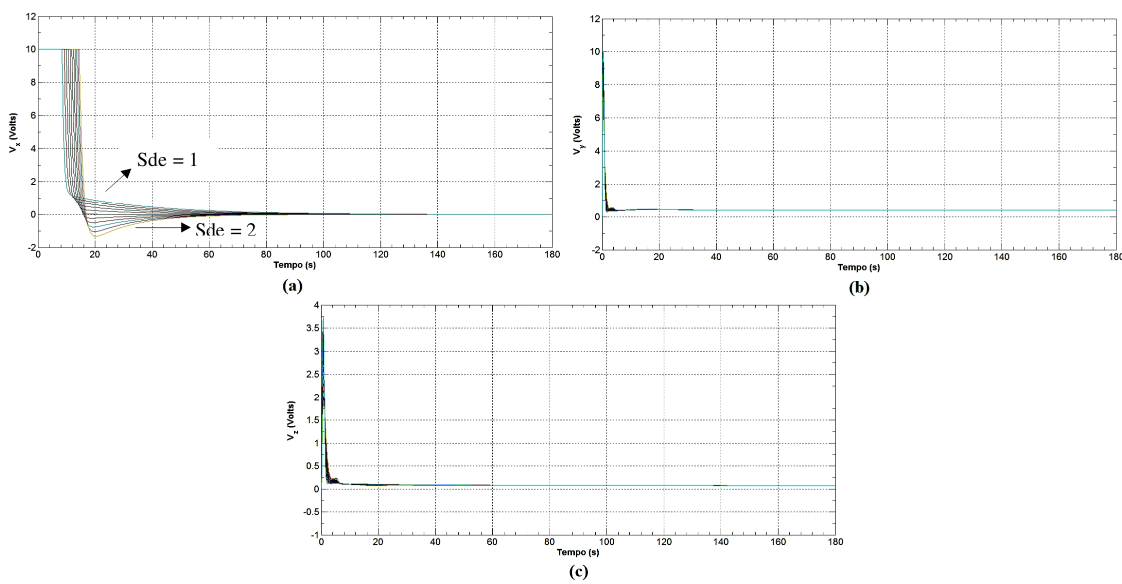

Figure 8. Input voltage as function of time: (a) roll axis; (b) pitch axis; (c) yaw axis.

Figure (9) shows the time of voltage saturation, in the roll axis, as function of Sde. We can see that how higher the Sde, higher will be the time of voltage saturation.

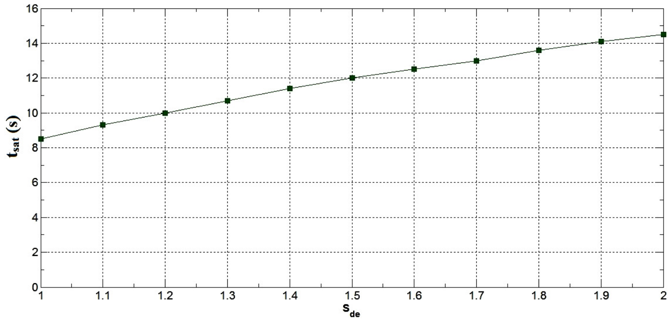

Figure 9. Time of voltage saturation, in the roll axis, as function of Sde.

The angular velocity of the reaction wheel, in each axis, is presented in Fig. (10). According to Fig. (10a), the reaction wheel reached a maximum angular velocity of almost 2800 rpm for a Sde equals to 1, and a maximum angular velocity of approximately 4000 rpm with a Sde equals to 2.

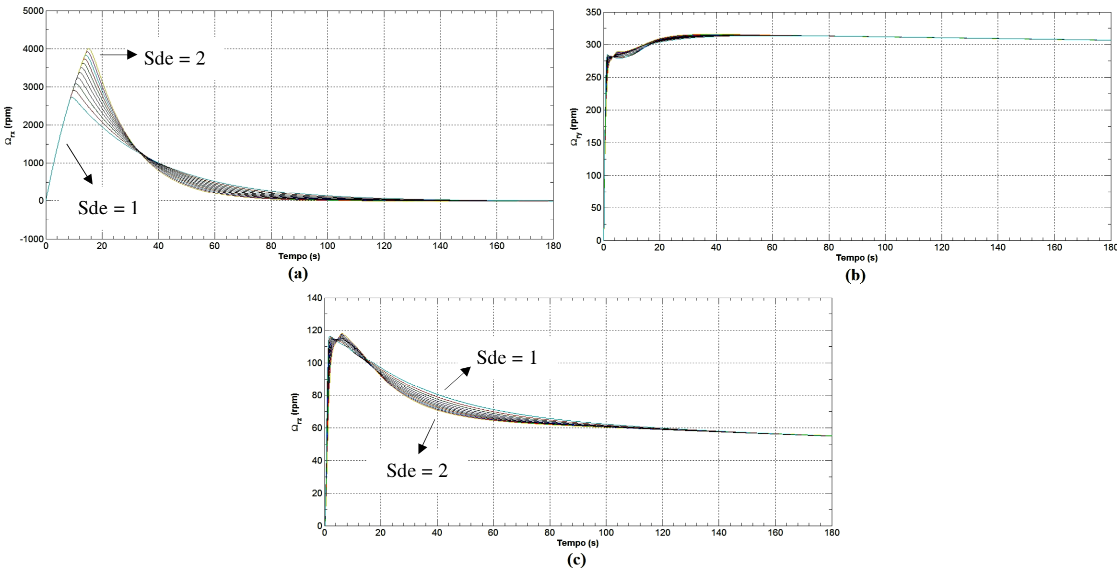

Figure 10. Reaction wheel angular velocity as function of time: (a) roll axis; (b) pitch axis; (c) yaw axis.

The torque applied by reaction wheel in each axis is presented in Fig. (11).

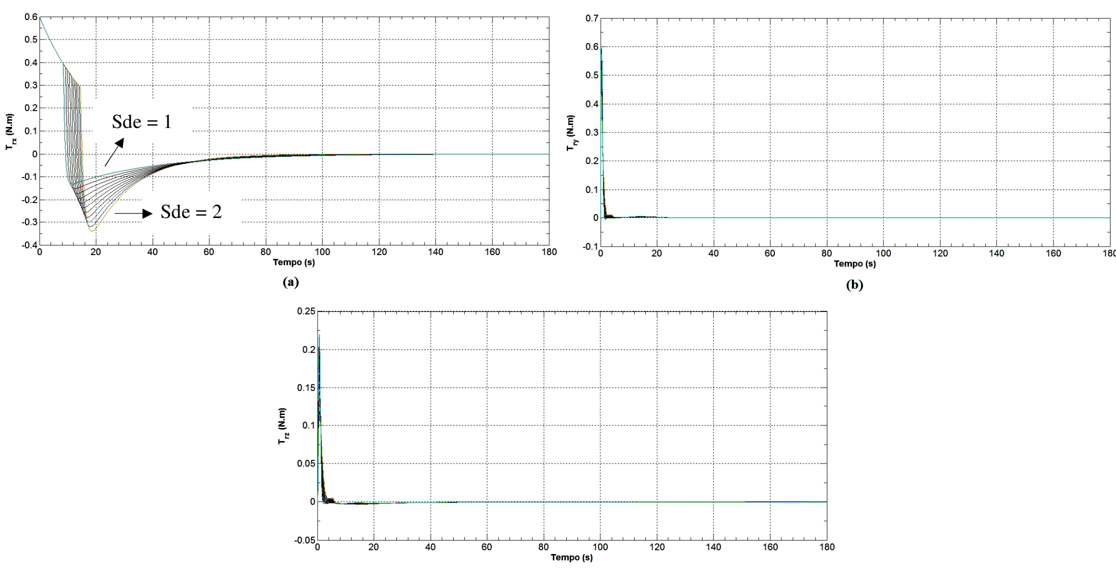

Figure 11. Torque applied by reaction wheel as function of time: (a) roll axis; (b) pitch axis; (c) yaw axis.

Based on the results presented in this paper, the value of 1.3 was chosen for the scaling factor of the change of error (Sde) as the best parameter to be used in the design of the fuzzy PID controller. This value represents a minimum settling time (96.9 s), a minimum time of voltage saturation (10.7 s), and a maximum pointing accuracy (0,01°), considering the mission requirements presented before.

5 Conclusions

This paper presented an attitude maneuver of a satellite equipped with reaction wheel and fuzzy PID controller. The performance of the controller has been analyzed for a range of values of Sde. The design of the fuzzy PID controller was carried out according to some mission requirements. The study allowed to choose the best value of Sde considering the following requirements: maximum pointing accuracy, minimum settling time and minimum time of voltage saturation. The influence of the scaling factor variation in the satellite attitude, like angular position and velocity, also were reported. The use of fuzzy PID controller can be an interesting alternative in design of attitude control system. However, it is necessary to carry out an investigation, analysis, modeling and simulation for the correct design of the control system, mainly in the case of complex systems, like artificial satellites.

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