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FUZZY THRUSTER WHEEL MOMENTUM DAMPING APPLIED UNDER ACTUATED LOW EARTH ORBIT MICROSATELLITE

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Key words: Wheel desaturation, microsatellite, fuzzy damping and attitude control using thruster (FDACT).

This paper presents a study of the reaction wheel momentum desaturation and attitude control under actuator failure using thrusters torque for rigid earth pointing microsatellite. In order to solve the both problems reaction wheels saturation and attitude control, we propose a new fuzzy logic damping and attitude controller using pulse width modulation (PWM) cold-gas thruster (FDACT) and compared to the optimal controller based on infinite linear quadratic regulator (ILQR). Comparison of these approaches are performed to evaluate the performance of the control system during accurate nadir pointing control in terms of attitude error, minimum time and less energy consumption. The simulation results prove and illustrate the effectiveness of the proposed controller and its robustness under actuator failure.

1. INTRODUCTION

The nadir pointing satellites have as a goal the maintenance of attitude on a fixed direction in the local orbital reference in the presence of environmental disturbances torques. Nevertheless, the attitude and determination control are often closely linked and an artificial satellite is generally provided with an attitude and determination control system (ADCS). The ADCS is divided into three main assemblies: sensors, actuators and control computers. The sensors come in several varieties, including magnetometers, sun sensors, earth-horizon sensors, gyroscopes, accelerometers and star sensors. There are also several types of actuators, including reaction wheels, momentum wheels, magnetorquers, control-moment gyros (CMGs), and thrusters. Each stabilization, sensing, and control technique has its own advantages and disadvantages [1].

The reaction wheel is one of the key components of the high accuracy stabilization loop. That is because it will not only offer the control torque to the satellite, but also produce disturbance torque for the satellite attitude control. The disturbance torques over time may change direction so that the accumulated momentum of any of the wheels may either increase or decrease [2, 3]. In general, however, sooner or later, the rotational speed will reach the structural limit of the wheel. This then requires periodic interventions. They are referred to as desaturations and are intended to bring the rotational speed back to zero (or to a desired value). A number of relevant studies have been presented to deal with saturation, the minimal cost techniques can be implemented using magnetorquers [4–8]. There are a number of techniques for fast response but with higher costs can be implemented using thrusters [5, 9, 10]. Others investigate for optimal combined reaction wheel (RW) momentum damping by employing magnetorquers and/or thrusters [11–13]. All these papers use optimal and robust controllers but these controllers can’t ensure the attitude control under actuator (reaction wheel-RW- failure). To address this issue, we used the advantages of thrusters attitude control based on fuzzy logic controllers [14–17] and we propose a new fuzzy logic damping and attitude controller using pulse width modulation (PWM) cold-gas thruster (FDACT).

Our contribution, in this paper, combines techniques for attitude control and desaturation momentum wheels using PWM thruster to solve the saturation problem with a minimum firing time (minimum fuel consumption) and at the same time ensure the attitude control under actuator or failure wheel. Euler angles are useful kinematics parameters set to represent the orientation of spacecraft and will be used to describe the movement of attitude of a spacecraft in this paper. The proposed controller uses the Euler angles, angular velocities and angular momentum feedback to solve the problem aforementioned. This controller has two roles, first desaturation wheel and second ensures attitude control under actuator. In this paper, a comparative study of the FDACT and the optimal controller ILQR [11] is presented to evaluate the performance of the control system during nadir pointing. In order to test the effectiveness of these controllers, its robustness in the presence of disturbances and firing time (fuel consumption) of thruster, we use Monte-Carlo method.

The remainder of the paper is organized as follows. Section 2 states the attitude dynamics of the spacecraft we are dealing with. Then, a description of the proposed FDACT and ILQR using PWM cold-gas thrusters is presented in Section 3. Following these descriptions, the simulation results and comparison of the control performance when using FDACT and ILQR are presented in Section 4. Finally, the conclusion of this work is presented in Section 5.

2. ATTITUDE DYNAMICS

The angular momentum of a spacecraft may be written as [18]

$$\boldsymbol{H} = \boldsymbol{I}\omega_B^I + \boldsymbol{h}\,, \tag{1}$$

where $\boldsymbol{I}$ is the inertia tensor, ω_B^I angular velocity vector in the body fixed coordinate frame, and $\boldsymbol{h}$ is the total angular momentum exchange devices. According to the Newton’s 2nd law, the rotational equations of motion of such a spacecraft may be written in the body fixed frame as [18]

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$$I\dot{\omega}_B^I = N_M + N_T + N_{ext} - \omega_B^I \times \left(I\omega_B^I + h\right) - \dot{h}, \quad (2)$$

where N_{ext} is the sum of other external torques acting on the spacecraft (i.e. gravity gradient torque, aerodynamic torque, *etc.*), N_M is the torque vector by 3-axis magnetorquers and N_T applied torque vector by 3-axis thrusters. The control torque for a spacecraft controlled using momentum exchange devices maybe written as:

$$N_c = v\left(-\dot{h} - \omega_B^I \times h\right), \quad (3)$$

where h is the wheel angular momentum and $v = [v_1\ v_2\ v_3]$ is the actuator effectiveness vector The case $v_i(t) = 1$ indicates that the i^{th} reaction wheel (RW) is working normally, and $0 < v_i(t) < 1$ corresponds to the case in which the i^{th} actuator partially loses its effectiveness.

Additional differential equations that relate body rates to the attitude parameters (i.e., quaternion, Euler angles, etc.) are also needed to describe the spacecraft attitude. The rate of change of the quaternion is given by [18]

$$\dot{q} = (1/2)\Lambda(q)\omega_B^o, \text{ where } \Lambda(q) = \begin{bmatrix} q_4 & -q_3 & q_2 \\ q_3 & q_4 & -q_1 \\ -q_2 & q_1 & q_4 \\ -q_1 & -q_2 & -q_3 \end{bmatrix}. \quad (4)$$

The angular body rates referenced to the orbit coordinates can be obtained from the inertially referenced body rates by using the transformation matrix A [18]

$$\omega_B^o = \omega_B^I - A\Omega_0, . \quad (5)$$

where $\Omega_0 = [0\ \omega_0\ 0]^T$ is an orbital rate vector.

3. THRUSTERS WHEEL MOMENTUM DAMPING DESIGN

3.1. OPTIMAL LINEAR QUADRATIC REGULATOR

Different algorithms desaturation using thrusters for perfect nadir pointing case are developed. The main objective of optimal control is to minimize the cost function. In perfect nadir pointing case, optimal feedback control laws are obtained to adjust the momentum vector of wheels, h, towards reference point which selected as zero in the damping case for the general model. Cost function of general linear quadratic regulator (LQR) Controller is [10–12]

$$J = (1/2)\int_0^{t_f} \left\{ h^T F\, h + N_T^T R\, N_T \right\} dt, \quad (6)$$

where t_f is the final integration time, F and R are two symmetric positive 3-by-3 matrix. These matrixes are assumed diagonals. ILQR control law can be computed by generating an immediate solution for each point of orbit. This is done without using the "LQR backwards integration" and without solving the equation Riccatti OFF-LINE. For each sampling time, we can solve the following equation Riccatti

$$0 = -K_\infty A - A^T K_\infty - F + K_\infty R^{-1} K_\infty, \quad (7)$$

$$\text{where} \quad A = \begin{bmatrix} 0 & 0 & \omega_0 \\ 0 & 0 & 0 \\ -\omega_0 & 0 & 0 \end{bmatrix}. \quad (8)$$

3.2. FUZZY DAMPING AND ATTITUDE CONTROLLER USING THRUSTERS (FDACT)

In this section, we propose the new thrusters wheel momentum damping design based on fuzzy controller.

Fuzzy logic control is introduced by Mamdani based on Lofti Zadeh's [19] earlier development of linguistic approach and system analysis on fuzzy sets. It is difficult to find a command that put a relationship between the desaturation of the wheels and the attitude control, our new controller (FDACT) solves the problem without the use of an observer and above all we minimize energy consumption. The idea is to continue controlling the attitude even though the angular momentum of wheel is zero. So this controller combines the both control laws (desaturation and attitude control) in a single controller and assures both functions even in case of failure of the wheels. This controller admits three inputs attitude error (A_{err}), angular velocity error (ω_{err}) and wheel momentum (h) and one output U_f. A fuzzy logic controller has been developed where ten fuzzy labels: Negative Big (NB), Negative Medium (NM), Negative Small (NS), Negative (N), Positive Small (PS), Positive Medium (PM), Positive Big (PB), Positive (P), Zero (Z) and Zero Small (ZS) have been defined for the input-output variables. The membership functions for A_{err}, ω_{err}, h and command U_f are shown in Figs. 1–4 respectively. Also, 28 control rules were used are shown in Table 1.

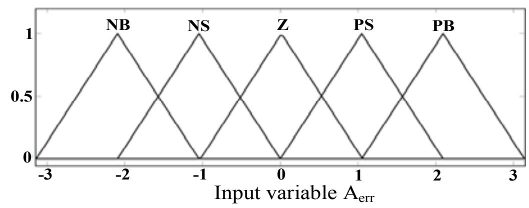


Fig. 1 – The first input (A_{err}) membership functions.

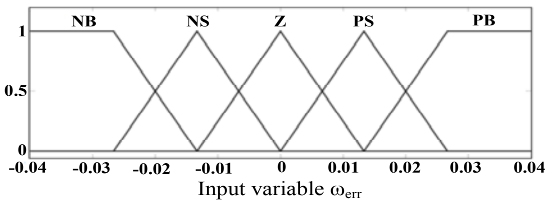


Fig. 2 – The second input (ω_{err}) membership functions.

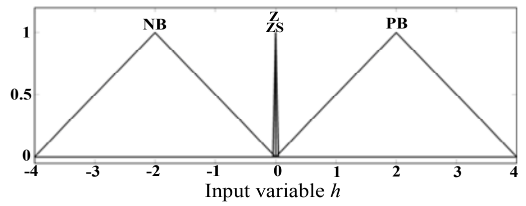


Fig. 3 – The third input (h) membership functions.

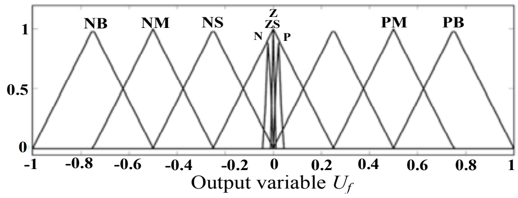


Fig. 4 – The output ($\boldsymbol{U_f}$) membership functions.

Table 1

Fuzzy control rules

A_{err} \ h	ω_{err}	ZS	NB	Z	PB
NB	NB	PB			
	NS	PB			
	Z	PM			
	PS	PS			
	PB	Z			
NS	NB	PM			
	NS	PM			
	Z	PS			
	PS	Z			
	PB	PS			
Z	NB	PS			
	NS	PS			
	Z	Z	P	ZS	N
	PS	NS			
	PB	PS			
PS	NB	PS			
	NS	Z			
	Z	NS			
	PS	NM			
	PB	NM			
PB	NB	Z			
	NS	NS			
	Z	NM			
	PS	NB			
	PB	NB			

Thrusters produce thrust by expelling propellant in the opposite direction. Figure 5 shows an arrangement of six thrusters used in the satellite and Fig. 6 shows the general block diagram of desaturation wheels and attitude control. Reaction thrusters are by nature on-off device, in our work we used cold gas thrusters and the pulsing of thrusters is done by pulse width modulation (PWM). The torque components provided on the satellite by i^{th} thruster can be written as [5]

$$\boldsymbol{N}_{Ti} = \boldsymbol{r}_i \times \boldsymbol{F}_i = \boldsymbol{B}_i\, \boldsymbol{F}_i\,, \tag{9}$$

$$\boldsymbol{N}_{Ti} = \begin{bmatrix} r_{yi}\sin(\beta_i)\cos(\alpha_i) - r_{zi}\sin(\alpha_i) \\ r_{zi}\cos(\beta_i)\cos(\alpha_i) - r_{xi}\sin(\beta_i)\cos(\alpha_i) \\ r_{xi}\sin(\alpha_i) - r_{yi}\cos(\beta_i)\cos(\alpha_i) \end{bmatrix}, \tag{10}$$

where the vector $\boldsymbol{r}_i$ describe the position of the i^{th} reaction thruster in the satellite from the center of mass. $\boldsymbol{F}_i$ is the thrust level, β_i is the elevation, and α_i is the azimuth. The total torque can be expressed as the sum of equation (9):

$$\boldsymbol{N}_T = \sum_{i=1}^{6}(\boldsymbol{N}_{Ti}) = \boldsymbol{B}_i\, \boldsymbol{U}_{\mathrm{TH}}\,. \tag{11}$$

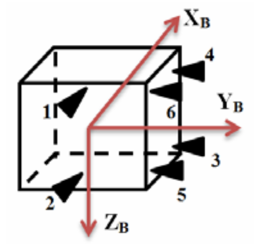


Fig. 5 – Arrangement of six thrusters.

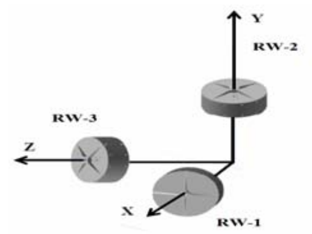


Fig. 7 – Classical 3 wheels configuration.

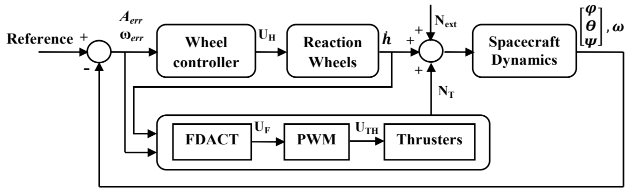


Fig. 6 – Block diagram of desaturation wheels and attitude control.

4. SIMULATION RESULTS

The simulation results presented in this section were obtained with an orbit and attitude propagator simulator which models the actual low earth orbit (LEO) microsatellite dynamics over a specified period of time developed in MATLAB/SIMULINK environment. The attitude was run for 600 s, the microsatellite simulation parameters are detailed below (see Table 2). For this application, the proposed new fuzzy thruster wheel momentum damping controller is applied; the satellite is equipped with three reaction wheels in standard configuration (see Fig. 7) and six thrusters. This simulation were implemented to investigate the performance of reaction wheel momentum damping controllers analyzed and compared in terms of settling times, power consumptions and actuator (RW) failure. The cold gas thruster works in a PWM mode, the thruster torque has a constant value of 40 milli-Nm during the active firing period. The reaction wheels give a maximum angular momentum of 4 Nms and the maximum wheel torque is 0.015 Nm. We assume that we take into account the gravity gradient torque and aerodynamic as external torque.

To study the comparison performance of the proposed controller (FDACT) and ILQR, three cases are simulated:

Case 1– All actuators (wheels and thrusters) are healthy.

Case 2– Actuator failure (one wheel).

Case 3– Static simulations.

Table 2

Satellite simulation parameters

Parameters	Value
Inertia [kgm^2]	diag [40.45 42.09 40.36]
Initial attitude [deg]	[–5,5,10]
Initial attitude rate [degs^{-1}]	[0,–0.06,0]
Attitude reference [deg]	[0, 0, 0]
Initial wheel angular momentum	[1.2, –0.8 ,–2]
Maximum wheel torque [Nm]	0.015
Maximum momentum [Nms]	4
$\boldsymbol{F}$	diag [0.01, 0.01, 0.01]
$\boldsymbol{R}$	diag [10, 10, 10]

4.1. CASE 1– HEALTHY ACTUATORS

This case shows the ideal situation when no actuator faults occur. Figure 8 illustrates wheels momentum without using thrusters, it is clear that wheels are saturated (no momentum damping). Figure 9 presents the angular momentum reaction wheel using ILQR and FDACT controllers for wheels desaturation using thruster. This shows that the response of desaturation has settling time of 449.8 s and 205.9 s respectively using ILQR and FDACT. It is clear that FDACT is faster than ILQR during the thruster wheel momentum damping. The total firing time of thrusters is approximately 92.71 s and 81.06 s respectively using ILQR and FDACT during an active control window of 600 s (see Fig. 10); the system consumes less energy if using FDACT.

Figure 11 shows the energy consumption by wheels using the two laws, it is approximately 1536 mW using both controllers ILQR and FDACT but the system response is faster when using FDACT compared to ILQR. It can be seen from Table 3 that the magnitude of the root mean square error (RMSE) indicates that the angular error is approximately 0.04° using both controllers.

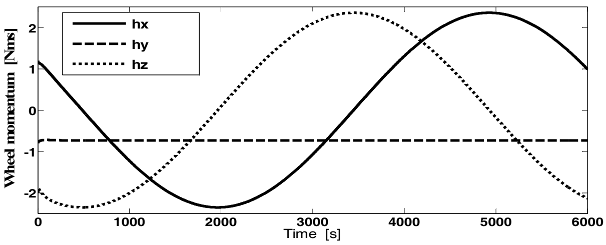
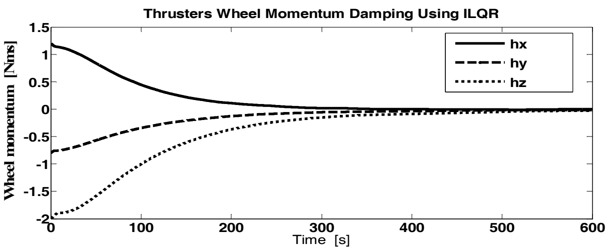
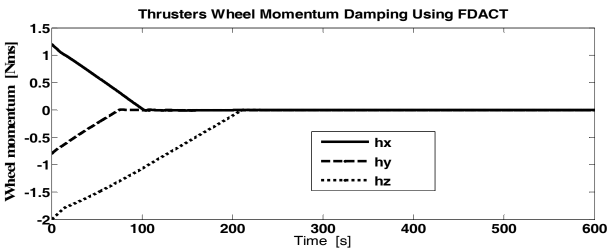


Fig. 8 – Reaction wheel momentum during saturation.



(a)



(b)

Fig. 9 – Reaction wheel momentum damping using thrusters: a) ILQR; b) FDACT.

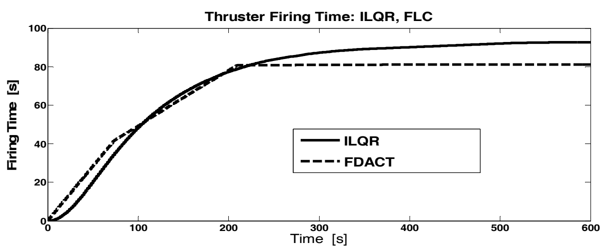


Fig. 10 – Thruster firing time.

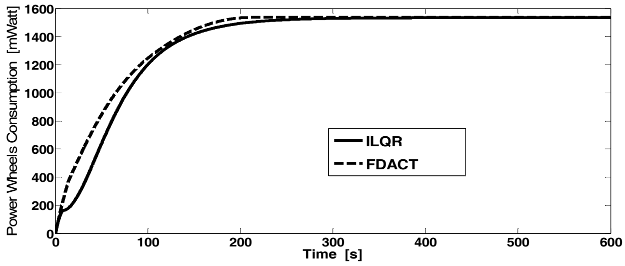


Fig. 11 – Power wheels.

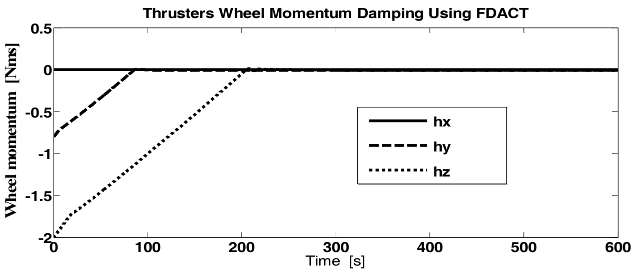
Table 3

The comparison of the controllers with healthy actuators

Damping methods	ILQR	FDACT
Thruster firing time (s)	92.71	81.06
Power wheels consumption (mW)	1536	1535
Attitude error (deg)	0.04	0.03

4.2. CASE 2 – ACTUATOR FAILURE

In this case, three reaction wheels with six PWM thrusters are employed and failure of one of the wheels or the thrusters is investigated. Figures 12–14 display the angular momentum wheels and Figs. 15–17 present the attitude error during nadir attitude pointing using thruster wheel desaturation based on FDACT and ILQR; failure of one of the wheels is investigated (RW-1, RW-2 and RW-3 respectively). In these three cases, the system the response is faster when using FDACT compared to ILQR, the desaturation of the reaction wheels is ensured when using the both controllers (see Figs. 12–14). When we use FDACT, the system reaches to desired Euler angles in 359.75 s, 321.8 s and 354.59 s for RW-1, RW-2 and RW-3 failure respectively (see Figs. 15a, 16a and 17a) and Fig. 18 shows thruster firing time for these three cases; but the system becomes unstable when we use ILQR (see Figs. 15b, 16b and 17.b).



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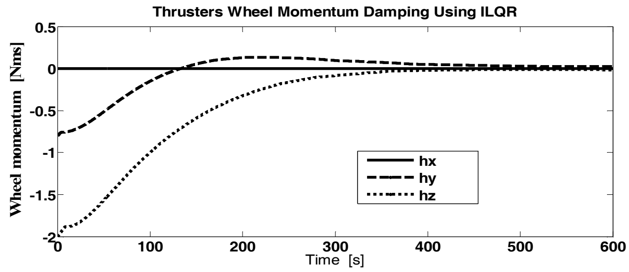
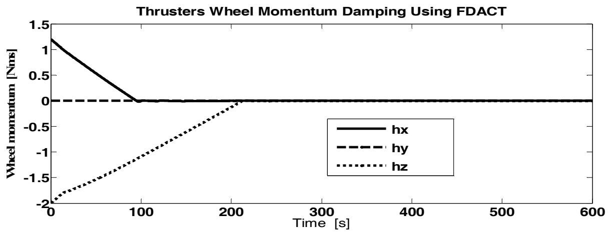


b)

Fig. 12 – RW momentum damping in RW-1 failure: a) FDACT; b) ILQR.



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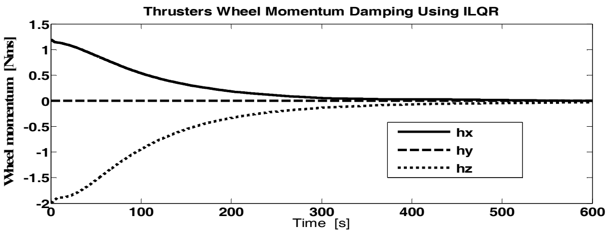
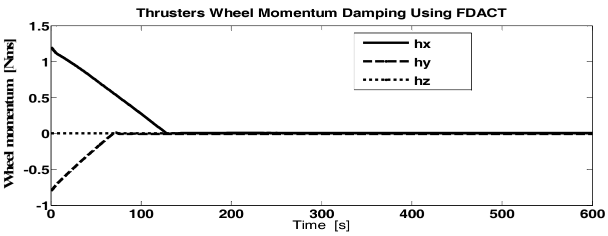


b)

Fig. 13 – RW momentum damping in RW-2 failure:
a) FDACT; b) ILQR.



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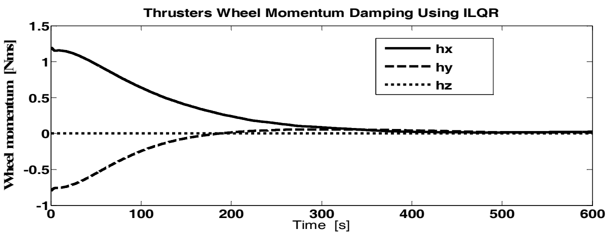
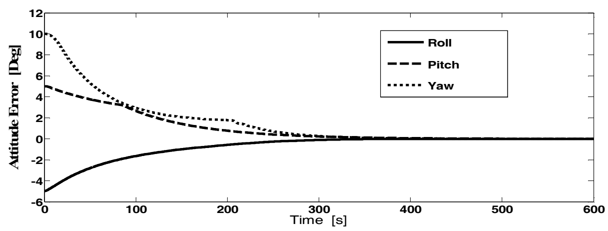


b)

Fig. 14 – RW momentum damping in RW-3 failure:
a) FDACT; b) ILQR.



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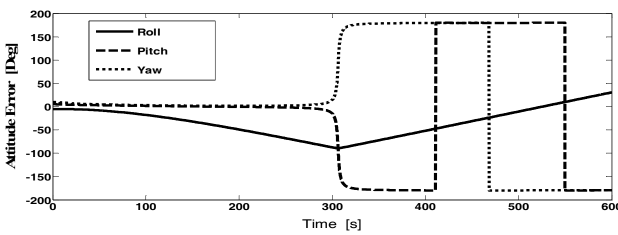
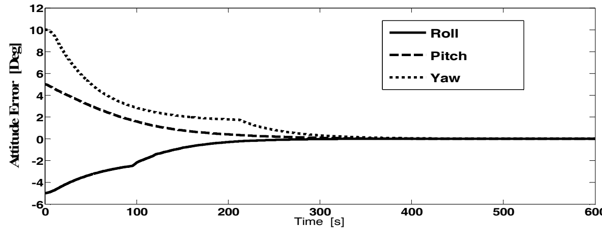


b)

Fig. 15 – Attitude control in RW-1 failure using:
a) FDACT; b) ILQR.



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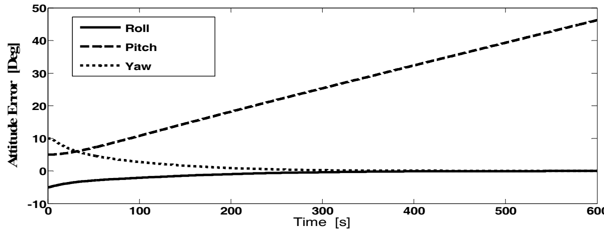
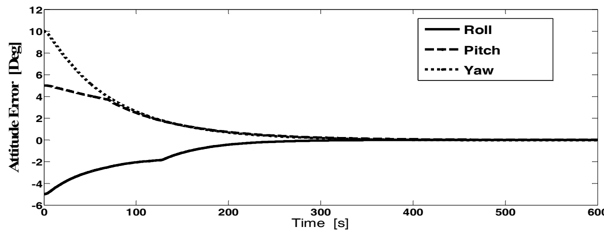


b)

Fig. 16 – Attitude control in RW-2 failure using:
a) FDACT; b) ILQR.



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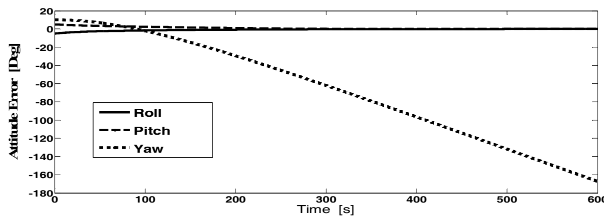

b)

Fig. 17 – Attitude control in RW-3 failure using:
a) FDACT; b) ILQR.

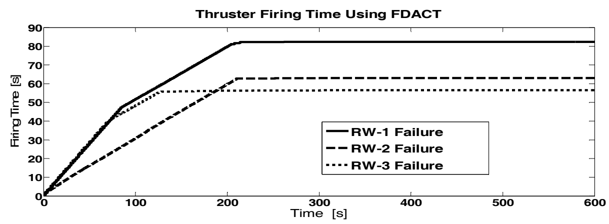

Fig. 18 – Thruster firing time in RW failure.

4.3. CASE 3 – STATIC SIMULATIONS

The static simulations consist of 2 500 Monte-Carlo runs by which the objective is to analyses the accuracy performance of the new FDACT and ILQR controllers system on low earth orbit satellite during nadir pointing control. For each Monte-Carlo run, an attitude and angle rates was picked randomly from a population that spanned the 2–1–3 Euler angle space; the starting attitude and Euler angle rates came from a uniform population between ±10 deg and ±0.01 deg.s^{-1} respectively [15]. The starting momentum wheel came from a uniform population between ±2 Nms. Deviation from nominal is 0.1 kgm^2 for the diagonal and off-diagonal terms of the spacecraft inertia tensor; a partial loss of wheel effectiveness fault is considered (±10 % pseudorandom noise).

The histogram of RMSE (nadir attitude pointing and attitude rate) and firing time of thrusters for all 2 500 Monte-Carlo runs are shown in Figs. 19–21, respectively.

Figures 19 and 20 confirm the dynamic control capabilities of these controllers with regard to the variation of the most critical parameters. But in some cases the use of ILQR committed an error bigger than using FDACT. Figure 21 indicates that for 2 500 runs the total firing time about 19 256 s and 16 407 s using the ILQR and FDACT respectively. This result shows that the PWM cold-gas thrusters based on FDACT has minimum fuel consumption compared to ILQR.

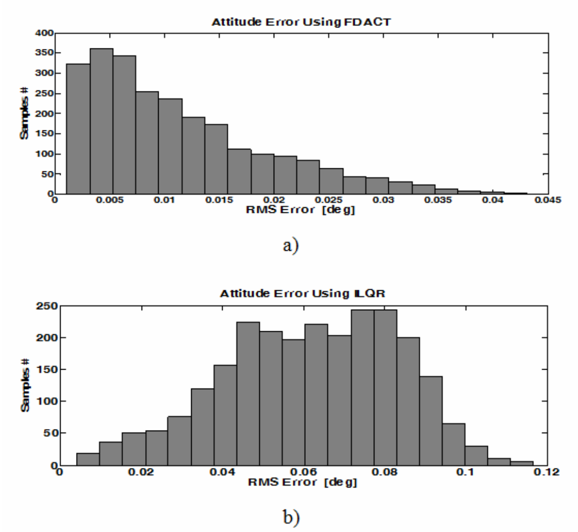

Fig. 19 – Histogram of RMSE of attitude error for 2 500 Monte-Carlo runs (number of occurrence N1 + N2 +···+ N20 = 2500): a) FDACT; b) ILQR.

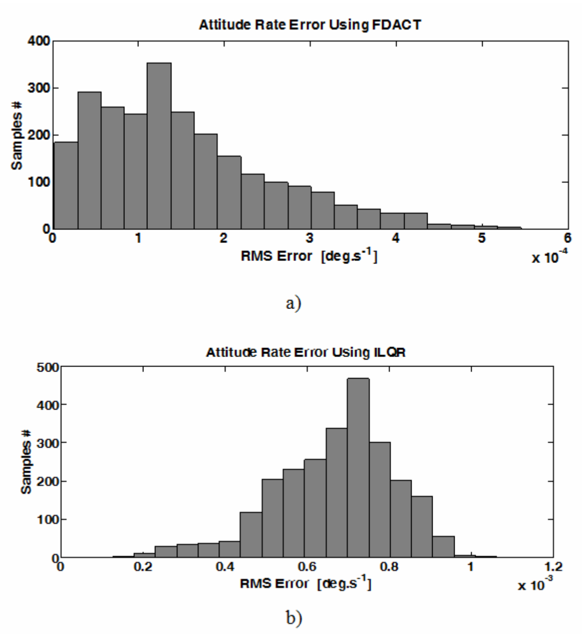

Fig. 20 – Histogram of RMSE of attitude rate error for 2 500 Monte-Carlo runs (number of occurrence N1 + N2 +···+ N20 = 2500): a) FDACT; b) ILQR.

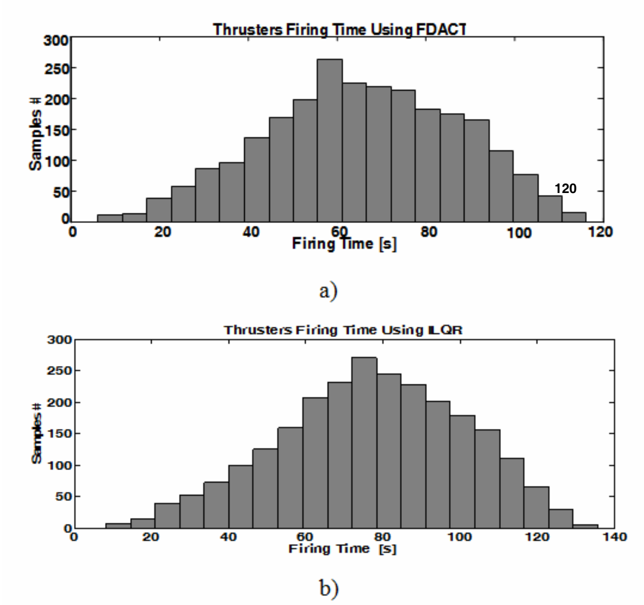

Fig. 21 – Histogram of firing time 2 500 Monte-Carlo runs (number of occurrence N1 + N2 +···+ N20 = 2500): a) FDACT; b) ILQR.

5. CONCLUSION

The primary focus of this paper is to propose a new damping wheel and attitude controller using PWM cold-gas thruster for low earth orbit microsatellite. The proposed thruster control algorithm based on fuzzy controller is designed and compared to the optimal controller ILQR. The proposed controller has two important roles; the first is the desaturation of the wheels, the second, attitude control under actuator failure. Different scenarios were held in order to validate our proposed approach using Monte-Carlo method and actuator failure is applied. The simulation results show that the proposed controller is faster and consumes less power compared against the ILQR controller. Even more, this controller can be applied, to thruster or/and magnetorquer reaction wheel momentum damping to improve system performance under actuator failure. Finally, it can be pointed out that employing fuzzy logic controller in thruster reaction wheel momentum damping provides power efficiency and actuator failure robustness in terms of system performances.

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