Hybrid Regulator System for Satellite Directing Enactment and Energy longevity

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Abstract: Uniting the conventional attitude and energy regulator system is a viable solution for small satellites to advance the space works. In this hybrid attitude and energy regulator system (HAERS) a dual rotating reaction-wheel in the pitch axis is applied to replace the traditional battery for energy packing as well as to regulate the attitude of an earth orbiting satellite. Every reaction-wheel is to be regulated in the twisting mode. The hybrid attitude and energy contributions for the reaction-wheels' regulator design are also in the twisting mode. All related scientific representations accompanied by the significant transfer functions are shown in this research note. The essential mathematical calculations are performed using Matlab™ for studying the system performances. The goals of this work are to determine the HAERS attitude performance in the twisting mode regarding the ideal and non-ideal assessment circumstances for preferred reference missions. Simulation results are presented here for different size of small satellite such as Nano-satellite, Micro-satellite and Extended Micro-satellite.

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Keywords: Small satellite; energy regulator; attitude regulator

1. Introduction

Smaller satellites that are now suitable of performing tasks usually considered for larger more expensive satellites as there are lot of advances scientific fields such as computer technology, electronics, and material science have found ways to use. This has produced a lot of research attention in these smaller satellites for scientific investigation. One important feature for these satellites is hybrid attitude and energy regulation. Exact attitude is compulsory for not only the fruitful accomplishment of the satellite's mission goals, but also for its existence (Fan *et al.,* 2004). The system is liable for precisely pointing the satellite to its wanted targets while managing peripheral disturbances that may happen during orbit (Fan *et al.,* 2004). Satellite control can be accomplished through different resources such as developing the gravity gradient, engaging spin stabilization or three-axis stabilization. The most precise attitude regulator systems, which usually include momentum wheels or reaction wheels, have the capability to obtain pointing precisions of 10−4 degrees or improved (Psiaki, 2001).

There two main issues in on-board satellite. They are energy packing and attitude control. These two issues are solved by a unique device forming a "hybrid attitude and energy regulator system (HAERS)". Solar cells array is used for spacecraft power generation. This solar array can be attached either to the spacecraft peripheral, or to articulate solar panels. A power source is required during the eclipse periods and the peak power demands. Which is normally supplied from energy packing device like a battery made of electrochemical cells, such as nickel cadmium, nickel hydrogen or lithium ion cells. There are some limitations with these chemical batteries. The lifetime of a satellite directly depends on the life of its power supply unit. Lifetime of battery is limited with the number of charge-discharge cycles. Again, the alternate energy supply can be produced by reaction-wheels which have a higher depth of discharge, a extended lifecycle and it is the temperature independence. The concept for using reaction-wheels is to convert an electrical energy to a revolving (kinetic) energy for packing using a motor to whirl up the reaction-wheel.

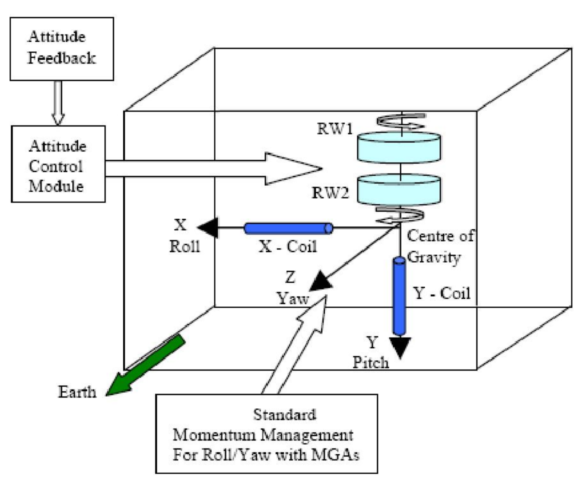


Figure 1: Onboard double rotating reaction-wheel setup

Then, a generator is operated by the reaction-wheel assembly shown in figure 1. It transforms mechanical energy to an electrical energy when it is needed by the spacecraft at non-eclipse period. Accommodating extended charge/discharge rate, a reaction-wheel energy packing system can be simpler and less massive than compared to a battery-operated system.

Spinning reaction-wheels can also perform the attitude control for spacecraft in space application. By incorporating the energy packing and attitude regulatory functions, substantial mass savings is ensured [Guyot *et al*., 1999]. The HEARS consists of a composite reaction-wheel, a motor-generator, magnetic bearings, and regulator elements for the attitude and energy operation system (Guyot *et al.*, 1999; Barde, 2001). An extended revolving speed is predictable with the purpose of accomplishing an extended energy packing capability (Gautheir *et al.,* 1987 & Kirk *et al.,* 1997). In the past years, the use of this type of system was restricted for large satellites (Roithmayr, 1999). Magnetic bearing causes magnetic interfering to the iron parts of the motor-generator (Scharfe *et al.,* 2001) for small satellites. Consequently, using ironless motor-generator for this hybrid system is crucial, that will ensure the HEARS reaction-wheels to be regulated efficiently in a twisting mode. In the present article each reaction-wheel is regulated strictly in the twisting mode. In contrast, the speed mode regulated reaction-wheel has been deeply investigated in the references. The goals of the present object are to accomplish a full perceptive and a close analysis of the twisting mode model for the small satellites, i.e., Nano-satellite (10 kg), Micro-satellite (50 kg) and Extended Micro-satellite (100 kg).

This work is performed as follows: First, a satellite reference mission is chosen to demonstrate the HEARS investigation. Then, the system block diagram is developed with the required transfer functions along with the necessary mathematical models. The models are simulated through Matlab™ for studying the performance of all the three small satellites stated previously. Finally, the HEARS performance is discussed for the ideal and non-ideal test cases from the attitude enactment standpoint. It is significant to remark that the satellite attitude criterion of the twisting mode is of paramount importance herein. The HEARS energy packing performances are given in the references.

2. Task and Approaches

The earth satellite mission is selected to examine the attitude performance of small satellites. The reaction-wheel assembly (2 reaction-wheels) is fixed on the pitch axis. Consequently, the active attitude control is involved upon pitch axis. The bias momentum stabilization is used for this satellite; thus, the stiffness for the roll/yaw plane is required. Some reference missions are maintained for all the test satellites, i.e. Nano-satellite, Micro-satellite and the Extended Micro-satellite. The common constraints for this mission are given in Table 1.

Table 1. Task Specifications

Constraints	**Description**
• Mission duration	: 3 years
• Orbit	: Circular at 500 km with inclination of 53°
• Eclipse period $T_{eclipse}$	: 36.4 minutes
• Attitude accuracy (Local Vertical/ Local Horizontal coordinate frame (LVLH))	: Roll(X) and Pitch(Y) < 0.2°, Yaw(Z) 0.5°
• Initial bias angular momentum	
○ 0.4 Nms (Nano-satellite)	
○ 1.4 Nms (Micro-satellite)	
○ 5.8 Nms (Extended Micro-satellite)	

The initial reaction-wheel speed is set to 1000 rad/s, and the expected maximum reaction-wheel speed is about 45000 rpm for the mission. To satisfy the total peak power requirement of the satellites, two counter rotating reaction-wheels are operated simultaneously; the power to be supplied by each reaction-wheel is half of the necessity. Spinning-up or spinning-down the counter rotating reaction-wheels will occur continuously because of the energy necessity. The attitude command will always brake one reaction-wheel and speed-up its counter rotating associate. The speed pattern of the two counter rotating reaction-wheels will be in such a manner so that the reaction-wheel speeds will converge to defuse the outward disturbance twisting. Hence, the system's bias momentum will drop regarding the orbital period.

3. HAERS Design

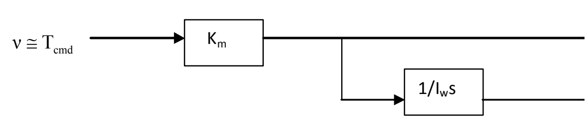


Figure 2: A twisting mode reaction-wheel.

Figure 2 shows a twisting regulated reaction-wheel where the applicable transfer functions for the prompted reaction-wheel twisting T_w and the subsequent speed Ω_w are

$$\frac{T_w}{T_{cmd}} = K_m \,, \qquad (1)$$

$$\frac{\Omega_w}{T_{cmd}} = \frac{K_m}{I_w s} \,. \qquad (2)$$

Here, s represents the Laplace variable and the motor-generator twisting constant K_m is supposed as unity. Herein twisting control method, the magnetic bearings deliver a frictionless motion. The attitude regulator architecture is presented in Figure 3. For instance, satellite motion is affected by the reaction-wheel twisting force; an alike oppositely revolving partner must be engaged to negotiate for the twisting produced throughout the charging and discharging stages (Guyot *et al.,* 2001).

Each reaction-wheel is regulated in the twisting mode as stated before. The attitude regulating toque T_{cmd} is produced by the Proportional-Derivative (PD) regulator. The attitude regulatory architecture is proposed with a dual feedback attitude input, angular acceleration ω_y and the angle θ_y. These may be created from a gyroscope or star sensor, respectively. It can be noted that $T^{s/w1}$ is a projection matrix from the satellite coordinate frame to the first reaction-wheel coordinate structure and $T^{w1/s}$ is a projection matrix from the first reaction-wheel coordinate structure to the satellite coordinate structure. Both contain a scalar value of unity. In contrast, $T^{s/w2}$ and $T^{w2/s}$ are the projection matrices for the second reaction-wheel and contain a scalar value of -1. It is supposed that the roll (I_x) and yaw (I_z) inertias are alike.

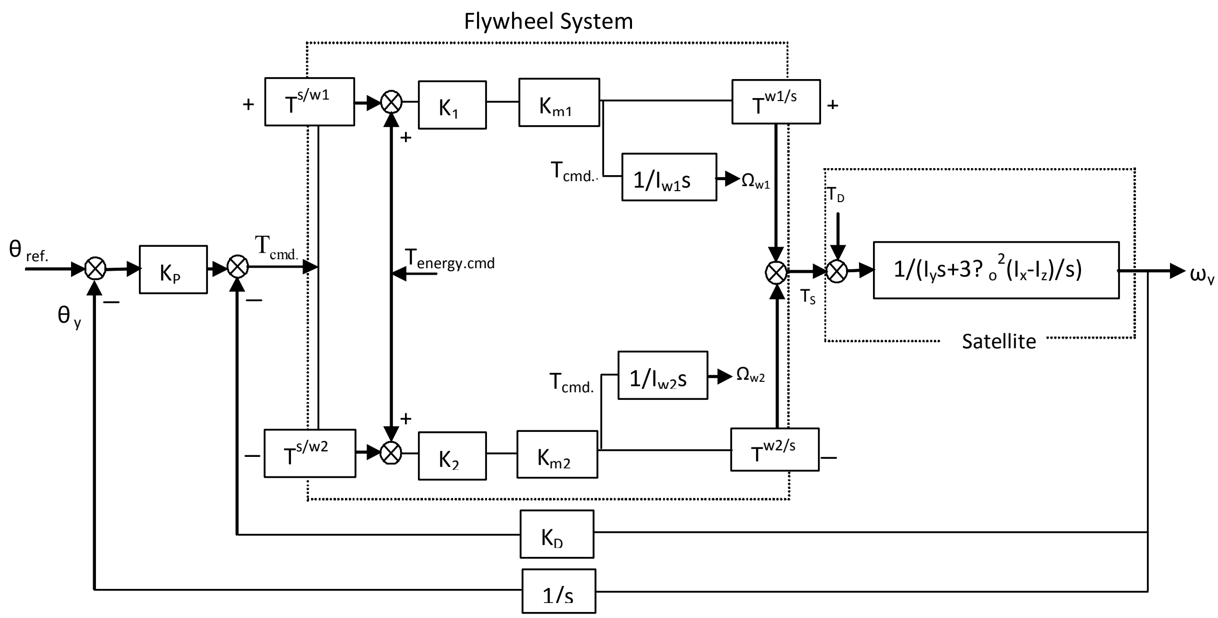


Figure 3: A twisting mode HEARS attitude régulation structure

Moreover, the inertias for both reaction-wheels and supplementary constants are assumed to be identical, i.e.

$I_x = I_z$,

$I_{w1} = I_{w2} = I_w$,

Then

$K_1 = K_2 = K$.

Let $2KKm = 1$; Therefore, the related transfer function of pitch dynamics is

$$\frac{\theta_y}{\theta_{ref.}} = \frac{1}{1 + \frac{K_D}{K_P} s + \frac{I_y}{K_P} s^2} \qquad (3)$$

or,

$$\frac{\theta_y}{\theta_{ref.}} = \frac{1}{1 + 2\zeta \frac{s}{\omega_n} + \frac{s^2}{\omega_n^2}} \,. \qquad (4)$$

Active control loop damping ratio $\zeta = 1$ is chosen to remove every overshoot of the attitude command. Then the transfer function is derived considering the disturbance toques, which is

$$\frac{\theta_y}{T_D} = \frac{1}{I_y s^2 + K_D s + K_P} \,. \qquad (5)$$

The reaction-wheels are oppositely rotating such that the resulting twisting force produced throughout the charging-discharging processes will be resolved.

4. The HEARS Performances

The steady state attitude error can be assessed from Eq. (5). The analogous natural frequency for the closed loop system is also investigated. The proportional and derivative control gains K_P and K_D are evaluated too. Then, the HEARS would be ready for testing. Considering all the internal and outward disturbances the HEARS models are examined through mathematical treatments for different test case of ideal and non-ideal situation integrating all the evaluated constraints.

5. An Ideal HEARS

Study was done to examine the efficiency of an ideal HEARS when only the outward disturbance twisting force acting on the satellite are taken in to account. The motor-generator factors are taken as unity and the inertias of dual reaction-wheels are at their nominal standards. Other significant parameters will be determined in the subsequent sections.

An ideal HEARS for a Nano-satellite

Supplementary mission constraints are described as underneath:

- Peak power : 7 W and 4.2 Wh packing capacity
- Mass : 10 kg for a size of 0.22×0.22×0.22 m^3
- Reaction-wheel inertia I_w : 1.3×10^{-3} kgm^2
- Pitch disturbance $T_{D.Y}$: 4.2×10^{-6} Nm + 3.4×10^{-6} (sin $\Omega_o t$) Nm

The evaluated constraints are: K_P = 0.003 Nm/rad for proportional control gain, ω_n = 0.29 rad/s for natural frequency and ζ = 1 for damping ratio. The estimated derivative attitude regulatory gain is about K_D = 0.03 Nms/rad. The system is stable because the closed loop poles are found on the left side of the imaginary axis.

The speeds for first and second reaction-wheels are shown in Figures 4(c) and 4(d). Speed of the first reaction-wheel was set to 1000 rad/s initially for this simulation process. Figure 4(a) displays that the attitude accuracy exists inside the pointing budget. Bias reaction-wheel speed is presented in Figure 4(b); it produces the essential bias angular momentum through the pitch axis to deliver stiffness for the roll/yaw plane. It makes lawful significant for the developed HEARS architecture by this ideal simulation. This test authenticates the developed numerical model and demonstrates that the HEARS is a prospective candidate to substitute the conventional attitude regulatory system.

An ideal HEARS for a Micro-satellite

Additional operation constraints are illustrated as below:

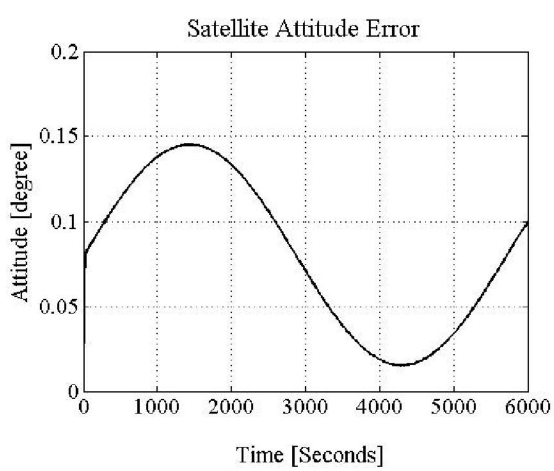
- Peak power : 35 W and 21 Wh packing capacity
- Mass : 50 kg for a size of 0.6×0.6×0.6 m^3
- Reaction-wheel inertia I_w : 5.5×10^{-3} kgm^2
- Pitch disturbance $T_{D.Y}$: 9.03×10^{-6} Nm + 6.02×10^{-6} (sin $\Omega_o t$) Nm

The selected proportional and derivative attitude control gains are K_P = 0.008 Nm/rad and K_D = 0.1983 Nms/rad, respectively. The natural frequency is ω_n = 0.0365 rad/s and the damping ratio ζ = 1. The closed loop poles are on the left side of the imaginary axis and, hence, the system is stable. Figures 5(c) and 5(d) show the speed for first and second reaction-wheels. The speed of first reaction-wheel was set to 1000 rad/s initially. The attitude error remains within the pointing budget as shown in Figure 5(a). Figure 5(b) shows the required bias reaction-wheel speed, it produces the necessary bias angular momentum through the pitch axis to supply stiffness for the roll/yaw plane.

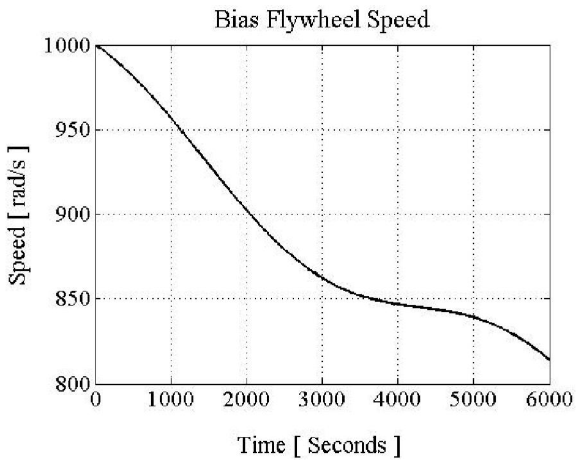
An ideal HEARS for an Extended Micro-satellite

The additional mission constraints are:

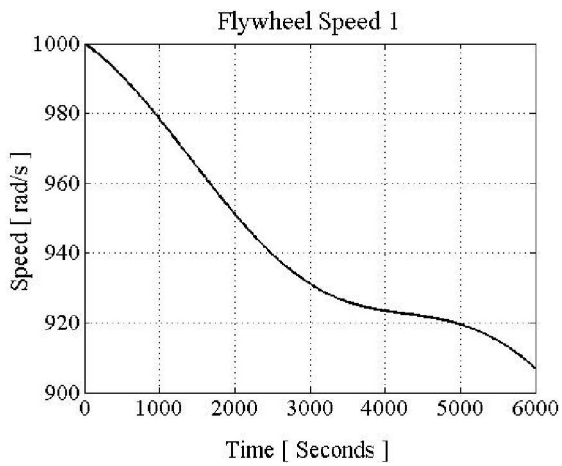
- Peak power : 98 W and 60 Wh packing capacity
- Mass : 100 kg for a size of 1×1×1 m^3
- Reaction-wheel inertia I_w : 15.5×10^{-3} kgm^2
- Pitch disturbance $T_{D.Y}$: 3.34×10^{-5} Nm + 2.81×10^{-5} (sin $\Omega_o t$) Nm



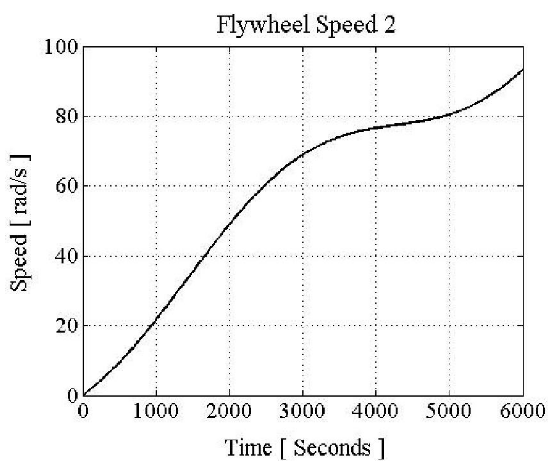
4(a)



4(b)



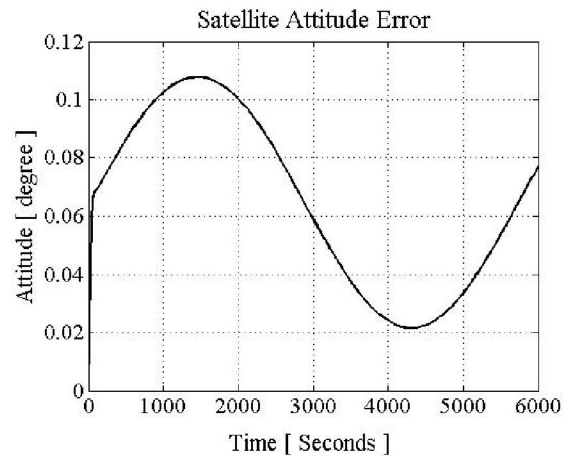
4(c)



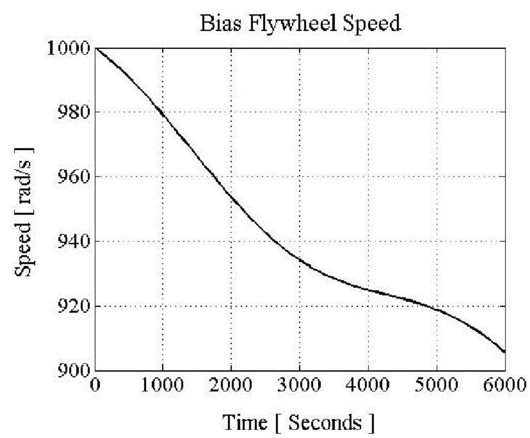
4(d)

Figure 4: An Ideal HEARS performance for an orbit – Nano-satellite.

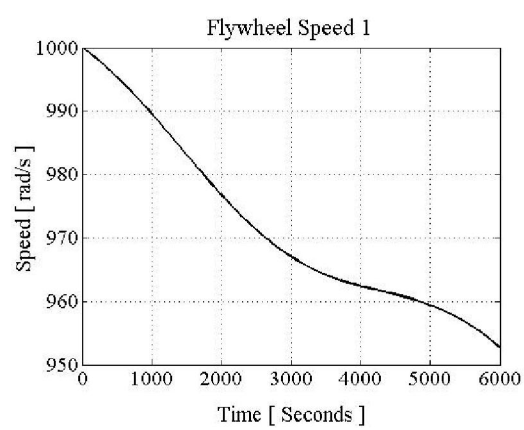
The calculated proportional and derivative attitude control gains are K_P = 0.0327 Nm/rad and K_D = 0.9489 Nms/rad, respectively. The natural frequency is ω_n = 0.0626 rad/s and the damping ratio ζ = 1. The closed loop poles are on the left side of the imaginary axis, Consequently, the system is stable. The speeds for first and second reaction-wheels are shown in Figures 6(c) and 6(d). The speed of the first reaction-wheel was set to 1000 rad/s initially. In addition, the attitude accuracy and the bias momentum continue within their pre defined budgets; see Figures 6(a) and 6(b), respectively.



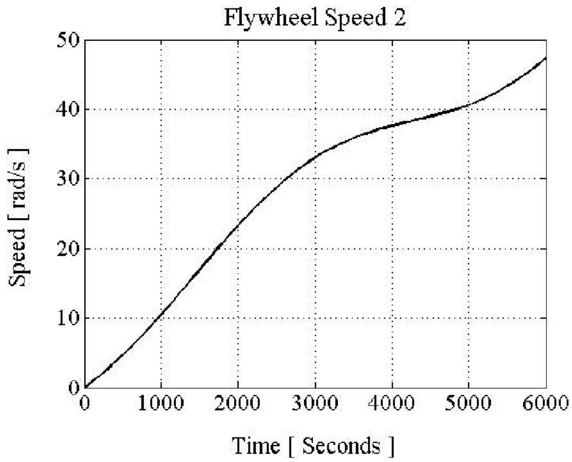
5(a)



5(b)

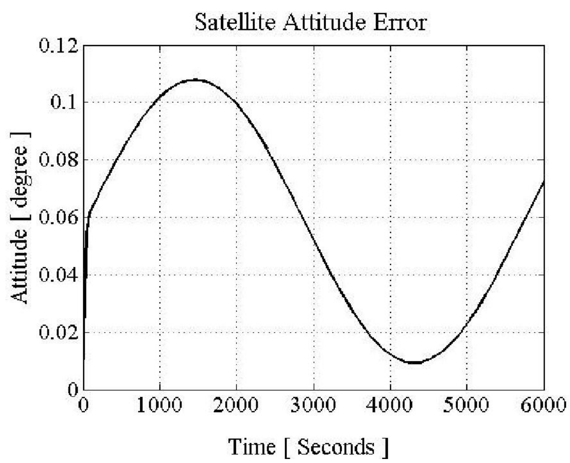


5(c)

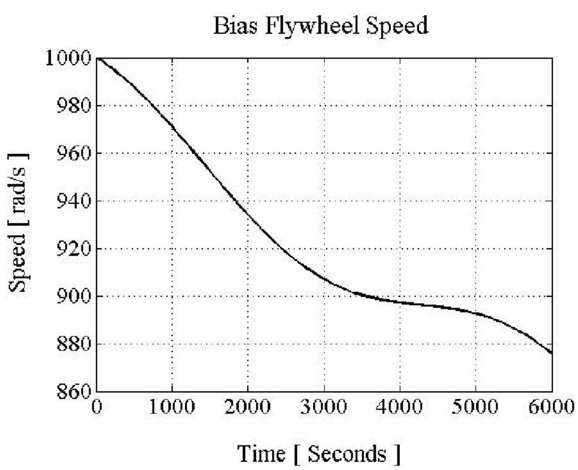


5(d)

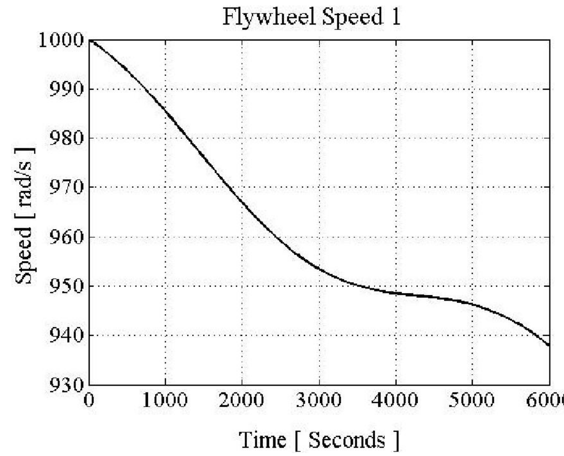
Figure 5: An Ideal HEARS performance for an orbit – Micro-satellite.



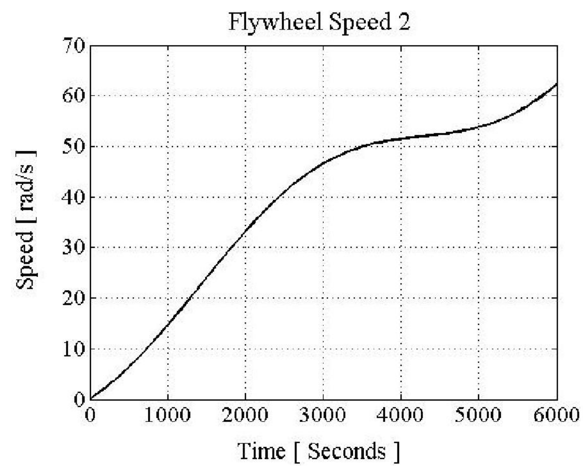
6(a)



6(b)



6(c)



6(d)

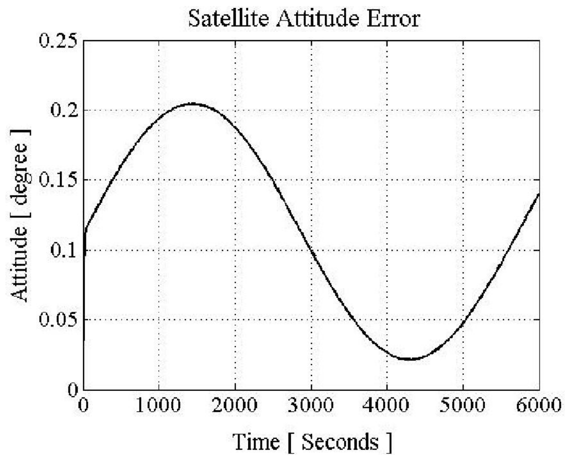
Figure 6: An Ideal HEARS performance for an orbit – Extended Micro-satellite.

6. A Non Ideal HEARS

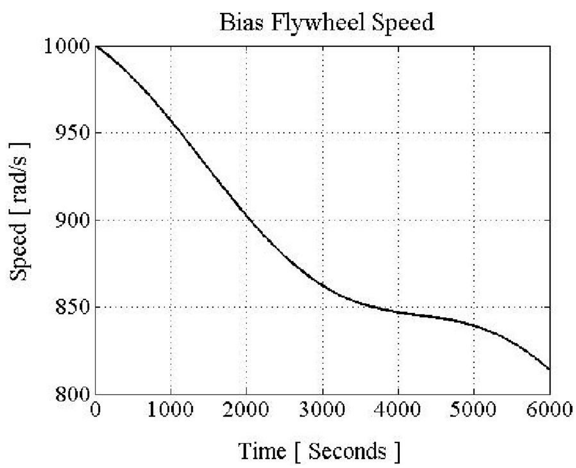
The non-ideal HEARS statistical evaluation is accomplished with the internal disturbances and the outward disturbance twisting force acting on the satellite. The comparative differences between the motor-generator twisting constants and the reaction-wheels' inertias generate the internal gain errors. Consequently, the system was tested for the comparative difference of 2% in the motor-generator factors and for the 1% comparative difference in the reaction-wheel inertias.

A non-ideal HEARS for a Nano-satellite

The performances for non-ideal test case are presented in Figure 7. Due to these relative differences in the motor/generator constant and in the reaction-wheels' inertias, the attitude accuracy slightly exceeds its budget; see Figure 7(a). Even though these errors have an influence on the satellite's attitude, the system bias momentum is conserved as in the ideal case, see Figure 4(b). Consequently, only the attitude accuracy for the pitch axis has increased. In contrast, if the value of the control stiffness K_P is enlarged by 2% in this test case; then, the satellite pitch angle/attitude performance respects the pointing requirementt as exposed in Figure 8(a).



7(a)

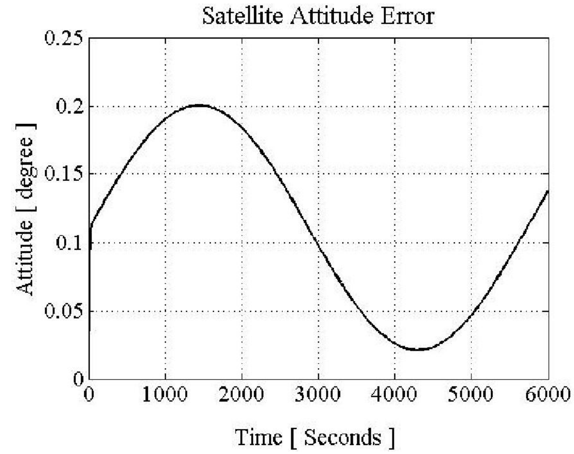


7(b)

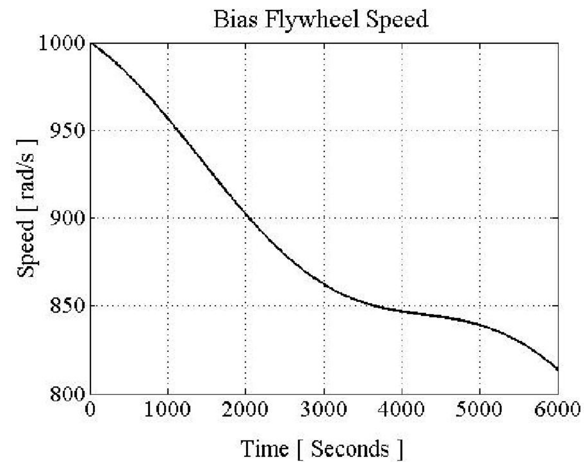
Figure 7: Non-ideal HEARS performance – Nano-satellite.

A non-ideal HEARS for a Micro-satellite

The architecture of Micro-satellite was also experienced for a relative motor/generator constant difference of 2% and a comparative difference in reaction-wheels' inertias of 1%. Due to these differences, the pitch attitude exceeds its pointing requirement in the similar fashion as in the non-ideal treatment for the Nano-satellite; see Figure 9(a). The proportional control stiffness K_P was enlarged by 2% to condense the pointing errors; see Figure 10(a). The additional system performances are not affected, e.g. bias reaction-wheel speed; see Figure 10(b).

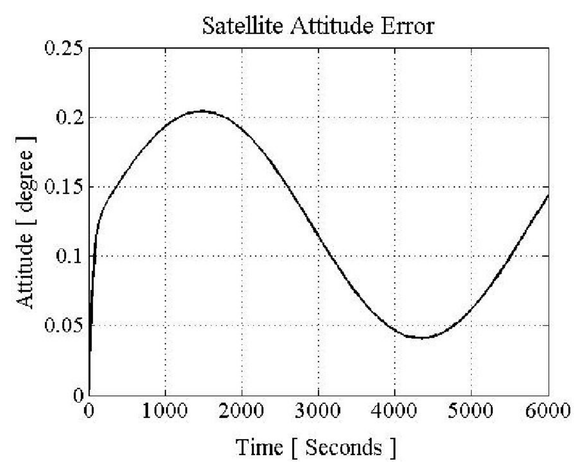


8(a)

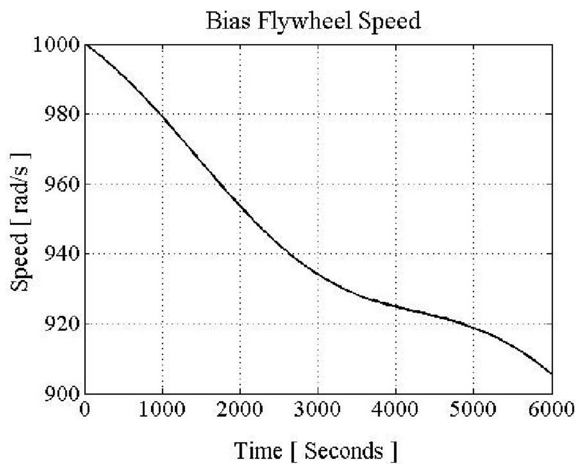


8(b)

Figure 8: *Improved Non-ideal HEARS performance – Nano-satellite.*



9(a)

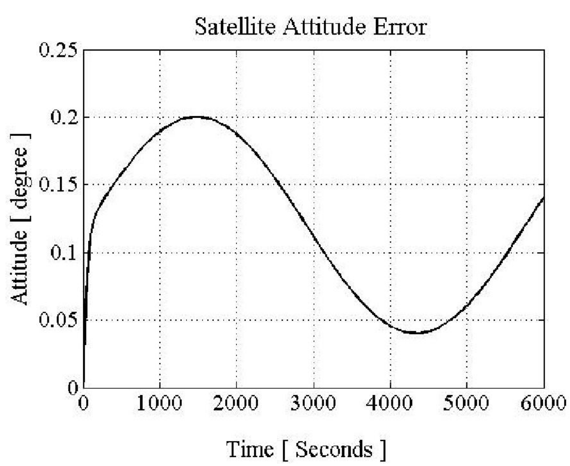


9(b)

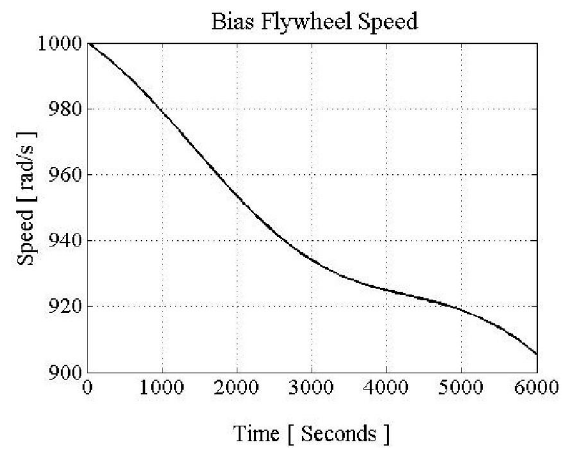
Figure 9: Non-ideal HEARS performance – Micro-satellite.

A non-ideal HEARS for an Extended Micro-satellite

Because of the comparative differences in the internal gains (2 %) and inertias (1 %), the outcome of this investigation illustrates the identical attitude error magnitude as in the preceding test case; see Figure 11(a). However, the bias reaction-wheel speed is well maintained as in the previous test. As the proportional control stiffness K_P is increased, the satellite pitch attitude is improved accordingly (Figure 12(a)), and the bias reaction-wheel speed remains similar, see Figure 12(b). As a final point it can be concluded that the HEARS demonstrates a favorable performance in this twisting mode architecture.

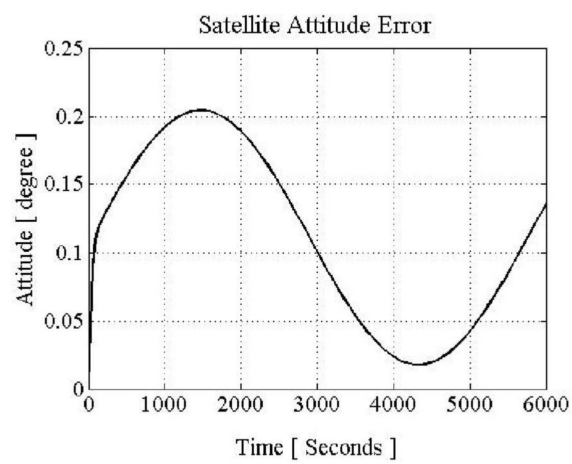


10(a)

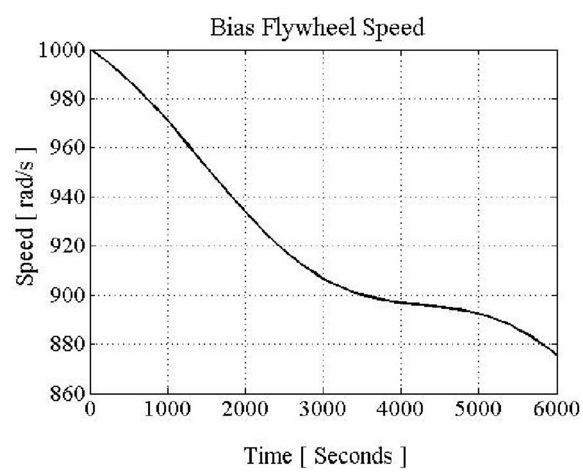


10(b)

Figure 10: Improved Non-ideal HEARS performance – Micro-satellite.

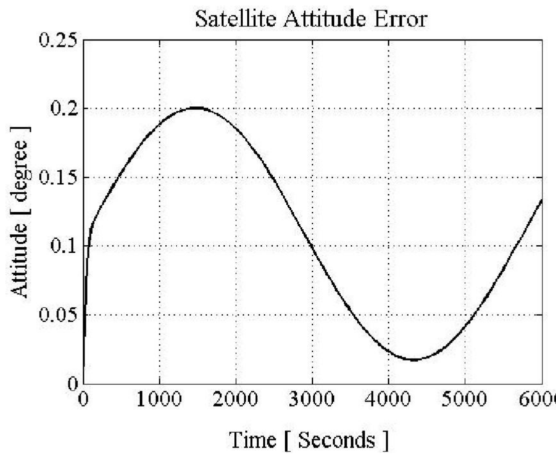


11(a)

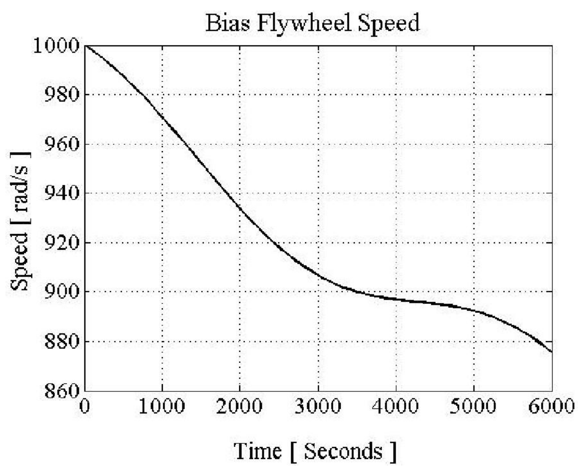


11(b)

Figure 11: *Non-ideal* HEARS *performance – Extended Micro-satellite.*



12(a)



12(b)

Figure 12: Improved Non-ideal HEARS performance – Extended Micro-satellite.

4. Conclusion

Two counter rotating reaction-wheels with a bias speed can concurrently perform the pitch attitude control, onboard energy packing, and provide passive roll/yaw attitude stiffness in small satellites. The HEARS twisting mode attitude analysis has been positively achieved in this investigation. The test results concerning the entire satellite test cases are satisfactory. It is established that the comparative differences of motor-generator factors and reaction-wheel inertias affect the satellite attitude criteria. Nevertheless, the satellite attitude performance can be enriched up to 4% by compression proportional gain of attitude controller. Regardless of these gain errors, the satellite pointing performance can still be preserved as prescribed by the stated missions.

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