DOI: https://doi.org/10.62985/j.huit_ojs.vol26.no2E.393

ATTITUDE CONTROL AND STABILIZATION OF SATELLITES USING REACTION WHEELS

Vu Van Thu*, Hoang Anh Phuong, Nguyen Thanh Thao, Ngo Quyet Tien

Faculty of Basic Engineering, Air Force Officer College, Khanh Hoa, Vietnam

*Email: *vuvathuqhx10@gmail.com*

Received: 14 December 2025; Revised: 11 March 2026; Accepted: 8 April 2026

ABSTRACT

This paper presents a study on the dynamic modeling of a satellite–reaction wheel system in MATLAB/Simulink, the design and optimization of the controller using Simulink Design Optimization, and the assessment of system accuracy and stability under random disturbance torques via Monte Carlo simulations. The results provide a basis for further research on satellite attitude control and stabilization systems.

Keywords: Satellite, attitude control, stabilization, reaction wheel, MATLAB/Simulink, Monte Carlo simulation.

1. INTRODUCTION

The rapid development of global space and satellite technology has increased the demands for accuracy, stability, and reliability in control systems. The development of high-performance satellite systems requires the study, modeling, and validation of dynamic models to determine optimal control parameters from the early design stage [1], [2].

In the space environment, where aerodynamic forces are negligible, satellites cannot rely on conventional navigation methods. Therefore, attitude determination and control using reaction wheels is considered an effective solution to maintain satellite orientation and stability during operation.

This study focuses on developing a dynamic model of a satellite–reaction wheel system in the MATLAB/Simulink environment, as well as designing and optimizing a PID controller using Simulink Design Optimization. In addition, the Monte Carlo simulation method is employed as an experimental approach to evaluate the accuracy and stability of the system under random disturbance torques.

The results demonstrate the effectiveness of the modeling and controller optimization approach, and highlight the important role of simulation techniques in the design and evaluation of satellite control systems.

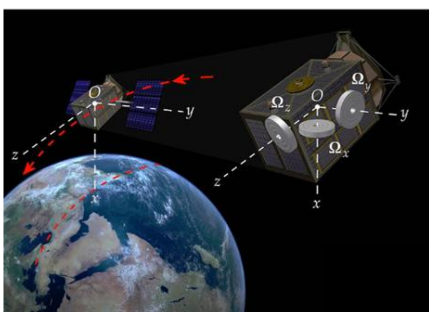

Fig. 1. Illustrations of satellite attitude and stabilization using reaction wheels

2. THEORETICAL BACKGROUND

2.1. Reaction Wheel System

The reaction wheel (E-RW) system is an electromechanical system consisting of an electric motor and a flywheel mounted on the same axis (Figure 2). The inertia characteristics of the E-RW system are defined by the moment of inertia J_{E-RW}.

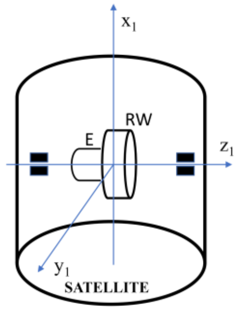

Fig. 2. Satellite model with a reaction wheel system

The angular velocity Ω_z of the reaction wheel can be controlled by adjusting the voltage u(t) applied to the motor stator coils, expressed as:

$$M_{E-RW} = K_u u(t) + K_\Omega \Omega_z(t) \quad (1)$$

Where K_u is the electromechanical gain coefficient, representing the relationship between the control voltage and the angular acceleration of the reaction wheel. This parameter depends on motor characteristics such as the torque constant and the moment of inertia of the reaction wheel; K_Ω is the damping coefficient, representing the effects of resistive factors such as mechanical friction and electromagnetic losses;. Ω_z is the angular velocity of the reaction wheel about its axis of rotation.

The satellite's relative motion equation along the horizontal axis z_1 is:

$$\frac{d\omega_z}{dt} = \frac{1}{J_z}(M_{E-RW} + M_D)$$
$$\frac{d_\varphi}{dt} = \omega_z \quad (2)$$

Where M_{E-RW} is the control torque from the reaction wheel; M_D is the disturbance torque; J_z is the satellite inertia.

The conservation of angular momentum for the satellite–reaction wheel system is expressed as follows:

$$K_z(t) = J_z \omega_z(t) = J_{E-RW} \Omega_z(t) = const$$

If initially $K_z(t_0) = 0$, then any changes in the satellite or wheel angular velocity will maintain $K_z(t_0) = 0$. Therefore, we have:

$$\Omega_z(t) = -\frac{J_z}{J_{E-RW}} \omega_z(t) \quad (3)$$

That is: $\omega_z(t) = -\dfrac{J_{E-RW}}{J_z}\Omega_z(t)$

From (2) and (3), thus we have:

$$M_{E-RW}(t) = K_u u(t) - K_\Omega \frac{J_z}{J_{E-RW}}\omega_z(t) = K_u u(t) - K_\omega \omega_z(t)$$

Where: $K_\omega = \dfrac{J_z}{J_{E-RW}} K_\Omega$

The system transfer function:

$$W_u^{\omega_z}(s) = K_u \frac{\dfrac{1}{J_z s}}{1 + \dfrac{K_\omega}{J_z s}} = \frac{\dfrac{K_u}{K_\omega}}{\dfrac{J_z}{K_\omega}s + 1} = \frac{K_{SAT}}{T_{SAT}s + 1}$$

Where: $K_{SAT} = \dfrac{K_u}{K_\omega}$, $T_{SAT} = \dfrac{J_z}{K_\omega}$

Thus, the transfer function of the satellite–reaction wheel system can be represented by a first-order inertial element.

The transfer function describing the disturbance torque–satellite angular velocity system is:

$$W_{M_D}^{\omega_z} = \frac{\dfrac{1}{J_z s}}{1 + \dfrac{1}{J_z s}K_{\omega_z}} = \frac{K_{M_D}}{T_{SAT}s + 1}$$

Where: $K_{M_D} = \dfrac{1}{K_\omega}$

2.2. Satellite Attitude and Stability Control System

The reaction wheel-based satellite control system is a closed-loop system, where the control signal $\varphi^*(t)$ is capable of compensating for disturbance torques [3]. For example, the desired attitude angle $\varphi^*(t)$ may represent the orientation of the satellite's axis toward the center of the Earth. When the satellite moves along a circular orbit around the Earth, this angle, measured in the inertial reference frame, varies harmonically with a period equal to the satellite's orbital period.

The controller used is proportional–integral–derivative (PID) controller, which generates the control command $u(t)$ according to the following equation:

$$u(t) = K_P\hat{\varepsilon}(t) + K_I\int_0^t \hat{\varepsilon}(t)dt - K_D\hat{\omega}_Z(t)$$

Where: $\hat{\varepsilon}(t) = \varphi^*(t) - \hat{\varphi}(t)$ is the error between the current attitude angle, measured by the navigation system, and the desired attitude angle of the satellite; $\hat{\omega}_Z(t)$ is the instantaneous angular velocity of the satellite, measured by the navigation system; K_P, K_I, K_D are the parameters of the PID controller.

3. MODELING OF THE SATELLITE–REACTION WHEEL ATTITUDE AND STABILITY CONTROL SYSTEM IN MATLAB/SIMULINK

To model the satellite–reaction wheel attitude and stability control system in MATLAB/Simulink, the process is carried out in three steps:

Step 1: Develop the control program (M-file):

- Initialize the system data and calculate the system coefficients and parameters.

- Build the satellite-reaction wheel system model and configure the controller gains K_P, K_I, K_D

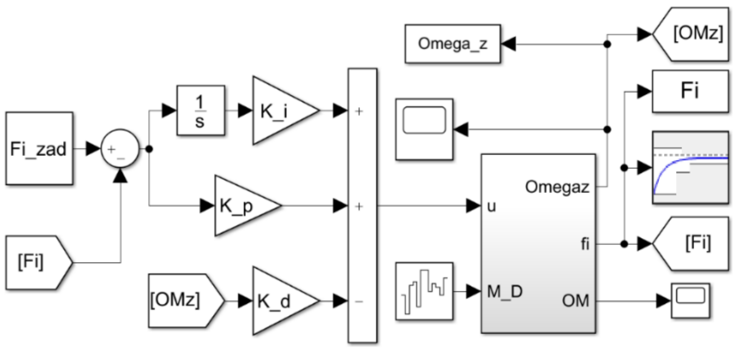

Fig. 3. Simulation model of the satellite–reaction wheel attitude and stability control system

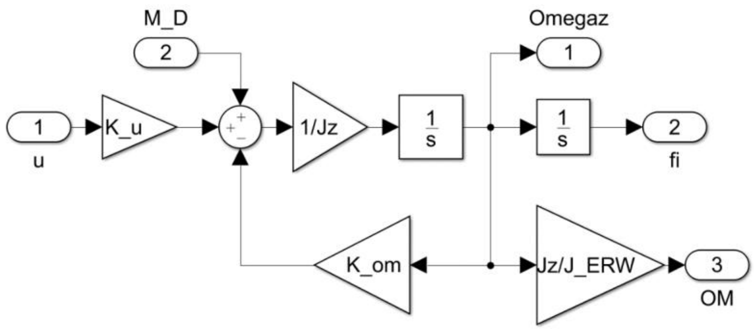

Fig. 4. Model of the satellite–reaction wheel system

Step 2: Simulate the system over the transient period and evaluate the control performance. If the system performance does not meet the requirements, use the “Check Step Response Characteristics” tool to optimize the controller gains [4].

Step 3: Analyze the system accuracy using the Monte Carlo method:

- Add a Band-Limited White Noise block to the model.

- Setup: noise intensity N_η, noise simulation step.

- In the simulation settings: select the Euler method with a fixed step, and set the simulation time (sample length) to 2000 s.

- Run the simulation.

- In the MATLAB control program, use the functions “mean” and “cov” to compute the estimates of the mean $\hat{m}_{\Delta\varphi}$, variance $\hat{D}_{\Delta\varphi}$, standard deviation $\hat{\sigma}_{\Delta\varphi}$, and confidence interval 3σ.

4. SYSTEM EVALUATION AND SIMULATION RESULTS

The research and system evaluation consist of two stages:

Stage 1: Determine the values of the controller gains K_P, K_I, K_D so that the system ensures stability and meets the specified control performance requirements.

Consider the satellite–reaction wheel system with $J_z = 50\,kg.m^2$, $J_{E-RW} = 0{,}5\,kg.m^2$, $K_u = 100$, $K_\omega = 50$. The system's transient response is shown in Figure 5:

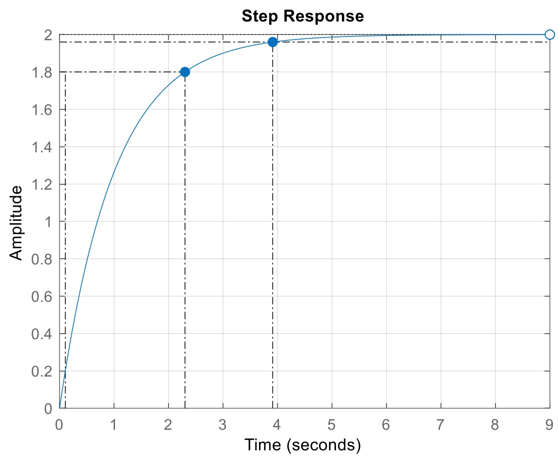

Fig. 5. Transient response of the satellite–reaction wheel system

With the initial controller gains, the system's transient response does not satisfy the specified performance criteria. The system still exhibits oscillations and a long settling time, which not only degrades control quality but also affects the physical–mechanical characteristics of the satellite. Therefore, it is necessary to adjust and optimize the controller parameters.

In this study, the step response performance criteria are defined in the MATLAB/Simulink environment with the following specifications: the step is applied at t=0 s, with an initial value of 0 and a final value of 1. The rise time is limited to 2 s (corresponding to 80% rise), and the settling time is required to be less than 4 s with a tolerance of ±5%. The maximum overshoot is set to 10%, while the undershoot is constrained to 0%.

Based on these criteria, the optimization process is carried out to improve the system's response performance. The results show that the transient response of the system after optimization is significantly improved compared to the initial case, as illustrated in Fig. 6.

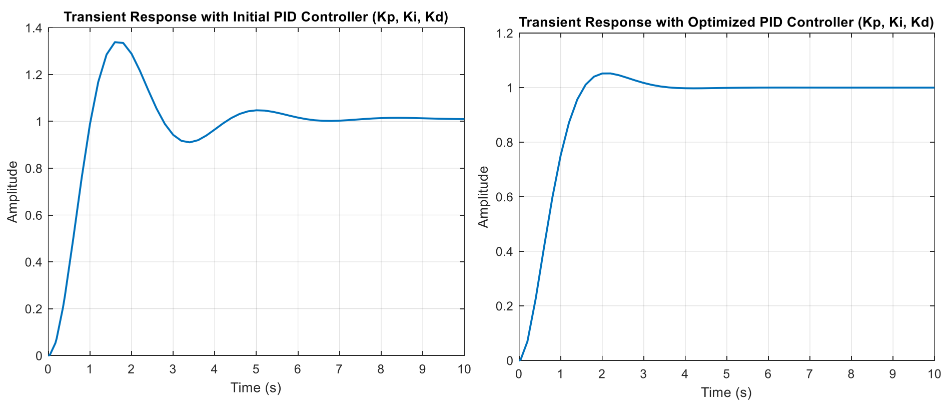

Fig. 6. Transient response of the system before and after optimizing the controller parameters

Stage 2: Statistical evaluation under random disturbances

In this stage, the system's accuracy in maintaining the prescribed satellite attitude angle under random disturbance torques is evaluated using a Monte Carlo–based stochastic simulation approach. The simulation is conducted over a duration of 2000 s, in which disturbance torques are modeled as zero-mean random noise and applied to the system dynamics.

To eliminate the influence of initial transients, the first 200 samples are discarded, and the remaining data are used for statistical analysis. The system performance is then evaluated in terms of the mean value, standard deviation, and confidence interval of the attitude angle.

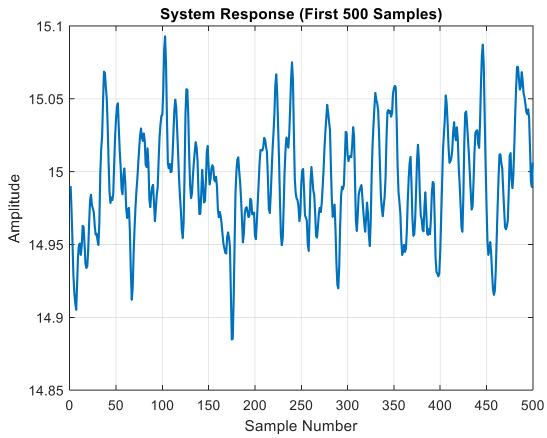

Fig. 7. Transient response of the system (first 500 samples)

Fig. 7 presents the system response over the first 500 samples of the steady-state segment, which is representative of the system behavior. The results show that the mean value of the rotation angle $\hat{m}_{\Delta\varphi} = 15.0005^0$ is very close to the setpoint of 15^0. The $\pm 3\sigma$ variation lies within the range [14.8799, 15.1211], indicating small oscillations, and the standard deviation demonstrates that the system remains stable under disturbances. Therefore, the optimized PID controller ensures high accuracy, reasonable settling time, and minimizes physical–mechanical impacts on the reaction wheel.

5. DISCUSSION

The simulation results indicate that the reaction wheel–based satellite control system, after optimization, exhibits a relatively fast transient response of approximately 3–4 s. In contrast, practical satellite systems typically require longer response times (approximately 10–12 s) to reduce actuator stress and avoid excessive mechanical loads. This discrepancy is mainly attributed to the simplified nature of the proposed model, which is primarily intended for controller design and performance evaluation.

Specifically, the current model does not account for important practical constraints such as actuator saturation, sensor delays, time-varying parameters, or cross-axis dynamic coupling. As a result, the obtained fast response represents an idealized performance. Nevertheless, it demonstrates that the PID controller, when properly tuned, is capable of achieving fast and stable tracking under nominal conditions. However, in real applications, a trade-off between response speed and system robustness must be carefully considered.

Furthermore, the Monte Carlo–based simulation results show that the system maintains high tracking accuracy under random disturbance torques, with the mean value remaining close to the desired setpoint and a relatively small standard deviation. This indicates that the control system exhibits a certain degree of robustness against stochastic perturbations. However, since the evaluation is conducted under simplified assumptions, further validation under more realistic disturbance models and uncertainties is required.

Overall, the results of this study provide a useful basis for the development of more advanced models and control strategies. Future work should focus on incorporating actuator limitations, multi-axis coupling effects, and comparing the PID controller with more advanced control methods (e.g., robust or nonlinear control) to improve the practical applicability of the system.

6. CONCLUSION

This study successfully developed and simulated a reaction wheel–based satellite attitude and stabilization control system in MATLAB/Simulink, while simultaneously optimizing the PID controller using the Simulink Design Optimization tool. The Monte Carlo simulation results demonstrate that the system maintains a stable attitude angle with minimal deviation, exhibits reasonable transient response, and withstands the effects of random disturbance torques. The proposed method provides a foundation for the development and evaluation of more complex satellite control systems in future studies.

Acknowledgment: The author would like to express sincere gratitude to Associate Professor Dr. V. T. Bobronikov for his dedicated guidance and valuable support throughout the course of this research. The author also gratefully acknowledges the Faculty of Fundamental Engineering and colleagues for providing favorable conditions that enabled the completion of this study.

REFERENCES

[1] N. T. Phuong Ha and H. Thai Hoang, *Automatic Control Theory*. Ho Chi Minh City: National University Publishing House, 2018, (in Vietnamese).

[2] A. A. Lebedev and L. S. Chernobrovkin, *Dynamics of Unmanned Aerial Vehicles*. Moscow, USSR: Oborongiz Publishing House, 1962, (in Russian).

[3] V. T. Bobronikov, *System Analysis in Engineering Research*. Moscow, Russia: Moscow Aviation Institute (MAI) Press, 2018, (in Russian).

[4] MathWorks, *MATLAB and Simulink*, Version R2023a. Natick, MA, USA: The MathWorks, Inc., 2023.

[5] J. R. Wertz, *Spacecraft Attitude Determination and Control*. Dordrecht, The Netherlands: Springer, 2012.

[6] M. J. Sidi, *Spacecraft Dynamics and Control: A Practical Engineering Approach. Cambridge*, U.K.: Cambridge University Press, 1997.

[7] H. Schaub and J. L. Junkins, *Analytical Mechanics of Space Systems*, 4th ed. Reston, VA, USA: American Institute of Aeronautics and Astronautics (AIAA), 2018, doi: https://doi.org/10.2514/4.105210

[8] B. Wie, *Space Vehicle Dynamics and Control*, 2nd ed. Reston, VA, USA: American Institute of Aeronautics and Astronautics (AIAA), 2008.

[9] K. Ogata, *Modern Control Engineering*, 5th ed. Upper Saddle River, NJ, USA: Prentice Hall, 2010.

[10] R. C. Dorf and R. H. Bishop, *Modern Control Systems*, 13th ed. Harlow, U.K.: Pearson, 2017.