C12　Study on Control Efficiency with 2-speed Transmission for Variable Shape Attitude Control

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Abstract

Multi-speed transmission systems are widely used in the Electrical Vehicle (EV) industries that improves the adaptability in various kinds of driving situations. Which is possibly be a way to improve the control efficiency for satellite attitude control systems. In this paper, we studied the VSAC system with a 2-speed transmission to verify it. The VSAC system is a new attitude control system, that controls the attitude of a satellite using the reaction force, which generated when it rotates its solar paddles. While different mission requires different level of control accuracy and rapidity. Therefore, applying a 2-speed transmission system shall improve the control efficiency of VSAC system, which enables the control mode to change between High resolution & Low Speed mode and Low Resolution & High Speed mode. To verify and evaluate the transmission system, a satellite simulation model with VSAC system is developed in the Matlab/Simulink.

1. Introduction

Small sized satellite industry is gradually rising these years. Compared to larger satellites, nano/micro-satellites require a shorter development period and lower cost, which then brings a faster investment return, that encourages the interests of industries and universities in small satellite development. These satellites are designed for various kinds of missions, that the speed and accuracy requirement various in a large scale depending on the mission requirements. Corresponding to that, various types of actuators including reaction wheels (RWs), control moment gyroscope (CMGs), magnetic torquers, thrusters and Nutation dampers, etc. are developed. Apart from these, the Variable Shape Attitude Control (VSAC) system is proposed. The VSAC system controls the attitude of the satellite by rotating its solar array paddles, based on the law of conservation of angular momentum, which gives the system a property of fast response and stable attitude control, and takes up less resources including space, energy, etc. The procedure of a attitude control using VSAC system is shown in figure 1. This research proposed a way to improve the control efficiency of the VSAC system by applying a multi-speed transmission to VSAC drive system, solar paddle of the satellite, which enables the control mode to change between High resolution & Low Speed mode and Low Resolution & High Speed mode.

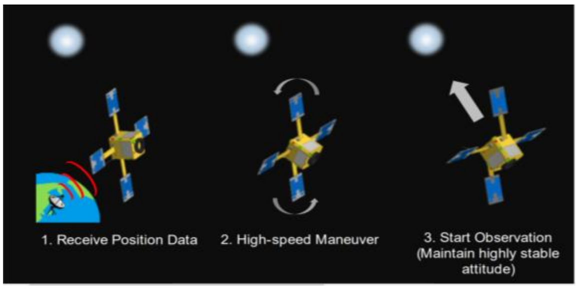


Figure 1 Procedure of VSAC system

2. Verification of a 2-speed transmission for the VSAC system

As we know, the VSAC system controls the attitude of the satellite main body by the reaction force that is generated when the satellite transmission system drives the solar paddles to rotate. Applying a ratio changeable transmission for the paddle drive system shall be able to let the VSAC system to perform a Slow & Accurate attitude control under high gear ratio and a Quick & Rough attitude control under low gear ratio. The performance of the 2-Speed VSAC is shown in figure 2.

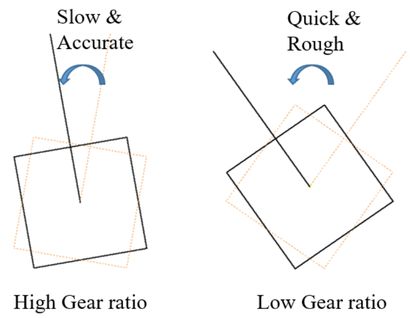


Figure 2 Performance of 2-Speed VSAC

To verify the feasibility a 2-speed transmission for the VSAC system, a 30kg class single-armed satellite system is studied in this section. As shown in figure 3, the satellite system we considered in this chapter, is a one-armed satellite, whose rod and paddle rotates on the X-Y plane around the Z-axis. A motor is mounted between the rod and the main body. Each parameter of the simulation model is shown in the table 1[1])

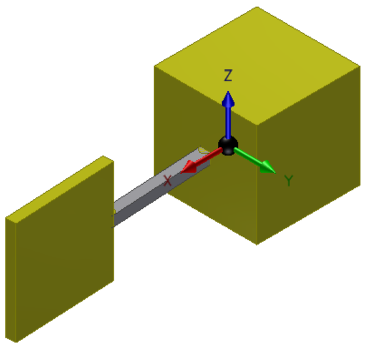


Figure 3 One-armed satellite model

Table 1 Dynamic parameters of the one-armed satellite model

Item	Main body	Rod	Paddle
Mass [kg]	30	0.1	1
Sizing [m]	0.3×0.3×0.3	0.3	0.3×0.3

The paddle and the rod are rigidly connected and rotates together around the hinge h_i between the main body of the satellite and the rod at an angular speed of $\dot{\phi}$. Define the rotation vector of hinge h_i as $\boldsymbol{e_i} = [0\ \ 0\ \ 1]$.

The control process is shown in the figure 4. Assume θ_T is the target angle that we need the satellite to rotate around the Z axis. Define $\theta_{eE} = \theta_T - \theta_E$ as the predicted error angle (measured by sensors). The purpose of this control system is to let the on-board computer (OBC) control the satellite main body to reach $\theta_{eE} = 0$. Based on the θ_{eE}, the PD control block calculates a control signal for the motor, then the motor rotates its rotor at a certain speed, which will rotate the encoding disk on the encoder at the same time. The encoder will keep on reading the rotation of the encoder grating and infer a rotating velocity of the motor shaft $\dot{\emptyset}_E$. The velocity will then be used to calculate the predicted rotate angle θ_E of main body around Z axis, and it is calculated in the OBC. The status of hardware is described by $\ddot{\emptyset}_G$, $\emptyset_G$, and $\dot{\theta}$, θ. Where, ϕ_G is the rotation angle of the output shaft of the gear model, which is also the rotated angle of the satellite paddle. And θ is the rotated angle of the main body of the satellite. Where the gear box in this verification is a simplified model, and the input and the output of the of the gear model is defined as $\dot{\phi}_G = n\dot{\phi}$, n is the transmission ratio of the gear model.

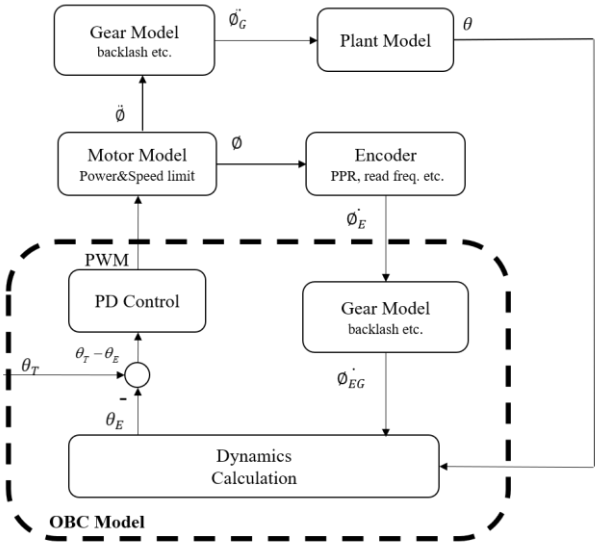
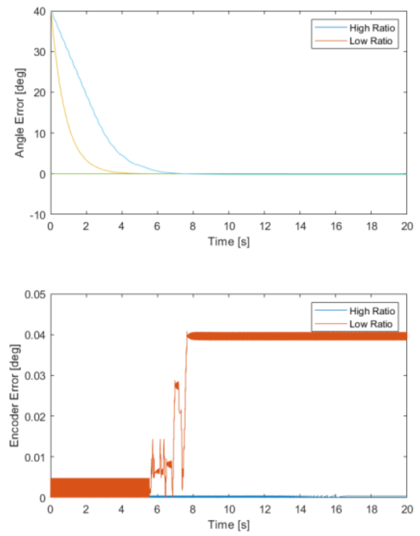


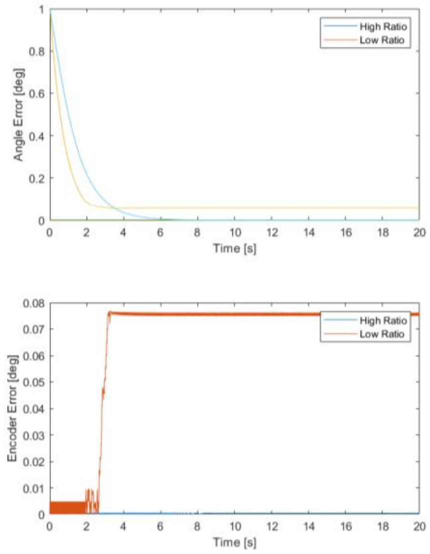
Figure 4 System diagram of the one-armed satellite simulation model

The system will finally be evaluated by the actual error angle $e_\theta = \theta_T - \theta_{Final}$ and encoder error $e_E = \phi - n\phi_E$, where θ_{Final} is the final attitude of the satellite. To observe the perform differences under large target angle $\theta_T = 40\text{deg}$ and small target angle $\theta_T = 1\text{deg}$, two simulations are conducted with intuitional transmission ratio of 1000 and 100 for an easy understanding. The results are shown in figure 5, table 2 and table 3.

The result tells that the 2-speed transmission effectively improved the control ability of the satellite attitude control system by allowing satellites to change its motion between 2 control modes. Low gear-ratio satellite performs higher speed and relatively inaccurate control comparing to higher gear-ratio satellite. These results verified the capability of the application of the 2-speed transmission.



(a) Error Angle and encoder error with target angle $\theta_T = 40\text{deg}$



(b) Error Angle and encoder error with target angle $\theta_T = 1\text{deg}$

Figure 5 Error Angle and encoder error with different target angle and different transmission ratio

Table 2 Simulation result with target angle $\theta_T = 40\text{deg}$

Target Angle	40°	
Gear Ratio	1000	100
Final Angle Error θ_{Final}[deg]	-0.182	0.002
Average Encoder Angle Error $\bar{e}_E$[deg]	2.617×10^{-4}	0.0264

Table 3 Simulation result with target angle $\theta_T = 1\text{deg}$

Target Angle	1°	
Gear Ratio	1000	100
Final Angle Error θ_{Final}[deg]	1.6×10^{-3}	0.0574
Average Encoder Angle Error $\bar{e}_E$[deg]	3.115×10^{-4}	0.0652

3. Principle of 2-Speed transmission

To further develop the 2-speed VSAC system, a 2-speed planetary gear transmission is proposed in this paper. The gear sketch is shown in figure 6.

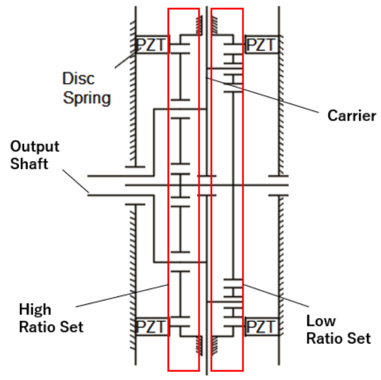


Figure 6 Gear sketch of the 2-speed planetary gear transmission

Components of a planetary gear set: sun gear, ring gear, planet gear and carrier are simplified into figure 7 (Carrier is neglected). The center of the carrier concentric with the center of the sun gear and rotates following the center of planet gears.

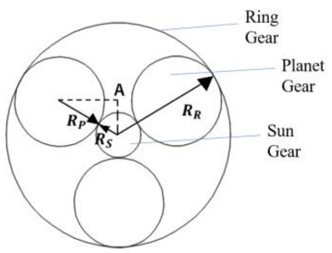


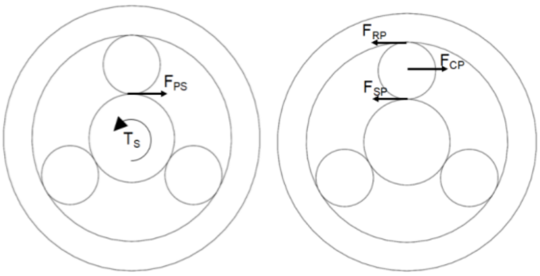
Figure 7 Planetary gear set sizes

Where, R_R is the radius of the ring gear, R_P is the radius of the planet gear, R_S is the radius of the sun gear.

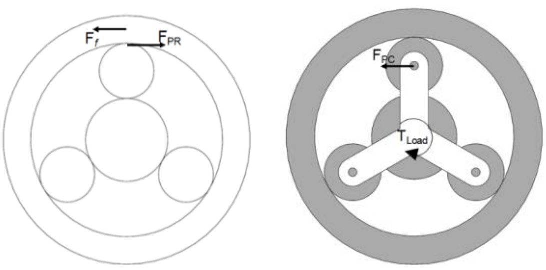
This 2-speed transmission applied 2 sets of planetary gear sets. Gear change mechanism between two sets of gear sets is realized by fixing and releasing the rotational degree of freedom (DOF) of each ring gear on the two sets of planetary gear sets. Which is completed by applying and withdrawing frictional force onto the ring gear. Piezoelectric actuator is utilized to generate pressure for the friction, considering properties as small displacement range and large applicable force rang.

The procedure of ratio change is: When the piezoelectric actuator on the low (or high) ratio planetary gear set side extends (or compressed), it will apply (or release) normal force to the friction disc. During this period, the other piezoelectric actuator on the high (or low) ratio planetary gear set side be compressed (or extended), which releases (or applies) the normal force from (or to) the friction disc. Following the variation of the normal forces, the ring gear of the low (or high) ratio planetary gear set will be fixed and the other one released. Then the 2-speed planetary gear transmission will perform a low (or high) transmission ratio.

To develop the dynamic model for the 2-speed planetary gear transmission, forces between each component in one set of planetary gear set is shown in figure 8.



(a) Forces in Sun gear (b) Forces in Planet gear



(c) Forces in Ring gear (d) Forces in Carrier

Figure 8 Forces between each components of a set of planetary gear set

Where subscripts S, P, R, C stands for sun gear, planet gear, ring gear and carrier. F_{AB} (A, B=S, P, R, C) means force applied from gear A to gear B. θ_A $(A = S, P, R, C)$ are the rotated angles of each gear. $I_A(A = S, P, R, C)$ are the moment of inertia of each gear.

Each rigid body dynamic equations based on the forces shown in the figure 8, will be:

$$\ddot{\theta}_S I_S = T_S - nF_{PS}R_S \quad (1)$$

$$\ddot{\theta}_P I_P = F_{RP}R_P - nF_{SP}R_P \quad (2)$$

$$\ddot{\theta}_R I_R = F_f - nF_{PR}R_R \quad (3)$$

$$\ddot{\theta}_C (I_C + I_{Load}) = nF_{PC}R_C \quad (4)$$

Where, n is the number of the planet gear, T_S is the torque that applied onto the sun gear. I_{Load} is the load inertia.

Against the revolution of the planetary gear around the sun gear, we can set up a dynamic equation as follows:

$$m\frac{1}{R_C}\frac{d}{dt}\left(R_C^2\dot{\theta}_C\right) = F_{RP} + F_{SP} - F_{CP}$$

$$\Rightarrow mR_C\ddot{\theta}_C = F_{RP} + F_{SP} - F_{CP} \quad (5)$$

Where, m is the mass of the planetary gears.

Additionally, the kinematic relationship between θ_S, θ_P, θ_R, θ_C can be solved based on the diagram shown in figure 9.

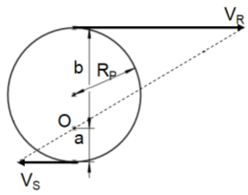


Figure 9 Kinematic relationship diagram

The diagram is developed based on the kinematic relationship between the planetary gear, sun gear and Ring gear. In the figure, point O is the instant center formed from the revolution and rotation of the planetary gear. a and b are the distances from the instant center to the dividing circle of the planetary gear. V_S and V_R is the linear velocity between the dividing circle of planetary gear and the sun gear, and planetary gear and the ring gear, respectively.

From the diagram, the kinematic relationship is established as:

$$\dot{\theta}_C = \frac{\dot{\theta}_R R_R - \dot{\theta}_S R_S}{2R_C} \quad (6)$$

$$\dot{\theta}_P = \frac{\dot{\theta}_R R_R + \dot{\theta}_S R_S}{2R_C} \quad (7)$$

So far, Eq (1) ~ Eq (7) makes the dynamic model of a planetary gear set. Considering the force relationships in the 2-speed planetary gear transmission as shown in the figure 10, the dynamic model can be established by combining the dynamic models of 2 sets of planetary gear sets. The dynamic model is shown in the following equations:

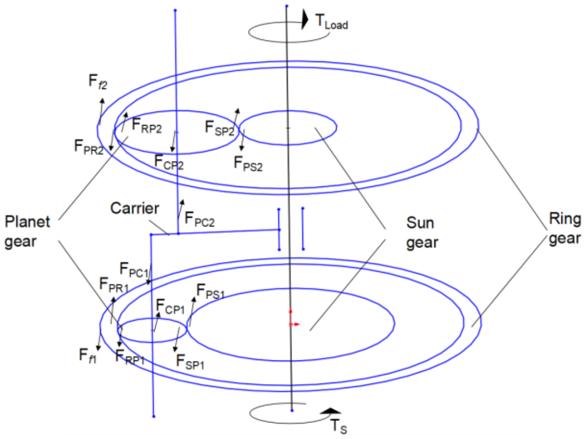


Figure 10 The diagram of 2-speed planetary gear transmission

$$\ddot{\theta}_S I_S = T_S - nF_{PS1}R_{S1} + nF_{PS2}R_{S2} \tag{8}$$

$$\ddot{\theta}_{P1} I_{P1} = F_{RP1}R_{P1} - F_{SP1}R_{P1} \tag{9}$$

$$\ddot{\theta}_{R1} I_{R1} = F_{f1}R_{R1} - nF_{PR1}R_{R1} \tag{10}$$

$$\ddot{\theta}_C I_C = nF_{PC1}R_{C1} - nF_{PC2}R_{C2} - T_{Load} \tag{11}$$

$$\ddot{\theta}_{P2} I_{P2} = F_{RP2}R_{P2} - F_{SP2}R_{P2} \tag{12}$$

$$\ddot{\theta}_{R2} I_{R2} = F_{f2}R_{R2} - nF_{PR2}R_{R2} \tag{13}$$

$$m_1 R_{C1} \ddot{\theta}_C = F_{RP1} + F_{SP1} - F_{CP1} \tag{14}$$

$$m_2 R_{C2} \ddot{\theta}_C = F_{CP2} - F_{RP2} - F_{SP2} \tag{15}$$

$$\ddot{\theta}_C = \frac{\ddot{\theta}_{S1}R_{S1} - \ddot{\theta}_{R1}R_{R1}}{2R_{C1}} \tag{16}$$

$$\ddot{\theta}_C = \frac{\ddot{\theta}_{S2}R_{S2} - \ddot{\theta}_{R2}R_{R2}}{2R_{C2}} \tag{17}$$

$$\ddot{\theta}_{P1} = \frac{\ddot{\theta}_{R1}R_{R1} + \ddot{\theta}_{S1}R_{S1}}{2R_{P1}} \tag{18}$$

$$\ddot{\theta}_{P2} = \frac{\ddot{\theta}_{R2}R_{R2} + \ddot{\theta}_{S2}R_{S2}}{2R_{P2}} \tag{19}$$

4. Conclusion

This research discussed about the feasibility of an application of a 2-speed transmission onto a satellite with VSAC system. The simulation result of the one-armed satellite with 2-Speed VSAC system shows that the transmission will effectively improve the performance of the attitude control. And as an important component of the 2-speed VSAC system, the 2-speed planetary gear transmission model is developed, that can be further utilized onto the observation of a ratio change performance during an attitude controlling procedure using the VSAC system.

Reference

1) 俵 京佑, 松永 三郎. (2018) 形状可変機構とリアクションホイールとを用いた 3 軸姿勢制御について. 8th Space Takumi Conference. UNISEC 2018-001
2) Kei Watanabe, Yuhei Kikuya, Yusuke Shintani, Kenichi Sasaki, Hiroki Ando, Tsuyoshi Nakashima, Kiyona Miyamoto, Kaoru Matsubara, Saburo Matunaga : Concept Design and Development of 30kg Microsatellite HIBARI for Demonstration of Variable Shape Attitude Control, 33rd Annual AIAA/USU Conference on Samll Satellites, Utah, U.S.A, August, 2018.
3) Pratyusha Biswas Deb, et al. Dynamic Model Analysis of a DC Motor in MATLAB. ISSN 2229-5518
4) Incze, János & Szabo, Csaba & Imecs, Mária. (2009). Modeling and Simulation of an Incremental Encoder Used in Electrical Drives. 10th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics
5) Nakagawa M, Abbes M A B, Hirogaki T, et al. Investigation of dynamic behavior of planet gears in planetary gear sets for three-axis driving[J]. Mechanical engineering journal, 2016, 3(1): 15-00338-15-00338.
6) Shin J W, Kim J O, Choi J Y, et al. Design of 2-speed transmission for electric commercial vehicle[J]. International Journal of Automotive Technology, 2014, 15(1): 145-150.
7) Zhang, Huibo, et al. (2018). Vibration Characteristics Analysis of Planetary Gears with a Multi-Clearance Coupling in Space Mechanism. Energies. 11. 2687. 10.3390/en11102687.