Modeling and Simulation of Satellite Attitude Dynamics and Control System using Modelica

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Abstract. The control of attitude of a satellite is difficult to verify since several subsystems of different disciplines, e.g., flexible multibody dynamics, machines, electronics and control, are involved and strongly coupled. A traditional method is to model each single discipline subsystem with a domain specific software, and combine them through interfaces. However, the problems are that lots of interfaces between software have to be developed, and manual decoupling of systems should be considered during modelling process. In this Paper, models of the dynamics and the control system are established in a unified modelling software, MWorks, which is an Integrated Development Environment of Modelica. The model can be used to verify the satellite control strategy, and also provide an effective means for satellite attitude control system design. Moreover, on this basis, the whole satellite was modelled to access state parameters changes under the coupling of the dynamic subsystem, the attitude control subsystem, the power supply subsystem, the propulsion subsystem and the integrated electronic subsystem can be synthetically considered.

1. Introduction

With the rapid development of modern technology and increasing competition in satellite market, simulation technology as a means to improve the efficiency in development of satellite product, its importance has become increasingly prominent [1-2]. Satellite simulation involves the coupling of different fields such as mechanics, electricity and control. The current multi-domain simulation [3-4] mainly uses single domain software to establish a single discipline model and through the interface between software or the use of HLA to solve single-disciplinary simulation and co-simulation of some disciplines [5], but cannot support completely multi-system modelling and simulation [6], which has poor reusability and scalability about the models. At the same time, the traditional method is only used for specific satellite simulation, but cannot be directly used for other satellites.

Modelica has been widely used in aerospace because of its support for multi-domain unified modelling, object-oriented physical modelling, non-causal modelling, and continuous discrete mixed modelling [7]. Abroad in the development of satellite systems design and test process has been widely used digital prototyping technology to improve development efficiency and product quality, and achieved remarkable results. In 2009, Zhang H J [8] established the Modelica model of the satellite flywheel, considering the flywheel control, electrical appliances, mechanical properties, validated the Modelica language in satellite multi-domain modelling of the feasibility and effectiveness. In 2011, Xu W F [9] developed a multi-domain unified modelling and simulation platform for spacecraft, and carried out a number of simulations. However, it has not been reported on the simulation of satellite attitude dynamics and control. Therefore, this paper first builds dynamics and control model library of the satellite, and validates the satellite attitude control strategy. On the basis of the above, the satellite state change under the coupling of the dynamic subsystem, the attitude control subsystem, the power supply subsystem, the propulsion subsystem and the integrated electronic subsystem can be synthetically considered.
2. Models of Dynamics and Control System

2.1. System decomposition
In the case of a satellite being developed, the attitudes and the control implementation of satellite are verified to meet the design requirements during the unfoldment of the satellite moving parts. According to the principle of structural hierarchy, reusability and extensibility, the satellite dynamics and control System is decomposed of satellite cabin, solar arrays(structure parts), antenna, thruster, earth sensor, sun sensor and star sensor, attitude control and management unit, environment, and so on.

2.2. Main devices
2.2.1. Satellite cabin. Figure 1 shows the satellite cabin model. Based on the Modelica standard library of basic components, in particular multi-body dynamics library whose physical theory have been described very well, it is helpful to save the modeling engineer the time spent in formula derivation. According to the actual physical topology of the satellite, the model of the satellite cabin is built by building blocks, and the information of the position of the solar arrays and the antennas is also defined. This model mainly considers the mass and inertia of the cabin.

| Frame | Description |
|-------|-------------|
| Left_SolarWing | Solar array wings |
| Right_SolarWing | Solar array wings |
| Cabin_Mass_Center | Satellite cabin |
| Left_SAR | Solar array wings |
| Right_SAR | Solar array wings |

Figure 1. The satellite cabin model.

2.2.2. Solar array wings. Since the solar array in the unfoldment process of satellite attitude a great impact, it is necessary to consider the flexibility of the wings when modeling. The main process is as follows: Firstly, the three-dimensional geometric model is processed into the modal neutral file using the finite element tool, then it is imported into the flexible body library based on MWorks. Finally, the related parameters are set. The main equations of the flexible body are:

\[ M\ddot{s} + C\dot{s} + Ks = Fu \]  

(1)
In this equation, $M$ is the mass matrix, $C$ is the damping matrix, and $K$ is the stiffness matrix. The $n_u$-component vector $u$ represents the nontrivial force inputs to the system, while the $n_s \times n_u$ matrix $F$ maps these nontrivial inputs to the corresponding degrees of freedom.

2.2.3. Antenna. Figure 2 shows the antenna model. The model mainly considers the rigid dynamic characteristics of the antenna during its unfoldment. The drive is driven by a DC motor. Since the antenna unfoldment process takes a long time, it does not need to consider the effect of its flexibility.

![Antenna model](image)

**Figure 2.** The antenna model.

2.2.4. Thruster model. Thruster model uses a simplified model, without considering the propellant combustion process, the thrust value as constant. The model mainly considers the influence of the number of thruster, installation positions and installation angles on satellite attitudes. The switch of the thruster is determined by the attitude control and management unit.

![Thruster model](image)

**Figure 3.** Thruster model.

2.2.5. Earth sensor. Earth sensor model uses an infrared earth sensor. The principle of the model is to obtain the angle between the geocentric vector and the scanning spin axis and the angle between the geocentric vector and the projected X-axis on the plane of the coordinate system by solving the attitude angle information of the input satellite. The angle between the geocentric vector and the scanning spin axis.

$$\eta = \arccos \left( z_{se} \left( x_{se}^2 + y_{se}^2 + z_{se}^2 \right)^{1/2} \right)$$

(2)

The angle between the geocentric vector and the projected X-axis on the plane of the coordinate system:

$$\lambda = \arccos \left( z_{se} \left( x_{se}^2 + y_{se}^2 \right)^{1/2} \right)$$

(3)

Where: $x_{se}$, $y_{se}$, $z_{se}$, respectively, is the earth vector in the measurement coordinate system representation.

2.2.6. Sun sensor. The principle of the sun sensor model is to compute the angle between the projection of the solar vector in the XOZ plane and the Y-axis, and the angle between the projection of the sun vector in the measurement coordinate system YOZ plane and the Y axis by inputting the right ascension and declination and the attitude angle of the satellite relative orbital system. The angle between the projection of the sun vector in the measurement coordinate system XOZ plane and the Y axis:

$$\xi = \arccos \left( z_s \left( x_s^2 + z_s^2 \right)^{1/2} \right)$$

(4)

The angle between the projection of the sun vector in the measurement coordinate system YOZ plane and the Y axis:

$$\eta = \arccos \left( z_s \left( y_s^2 + z_s^2 \right)^{1/2} \right)$$

(5)

Where: $x_s$, $y_s$, $z_s$, respectively, is the sun vector in the measurement coordinate system representation.
2.2.7. **Gyroscope.** The model principle of the gyroscope is to input the angular velocity of the satellite on the rotation axis of the gyro, and output the satellite attitude angular velocities considering the constant drift and zero mean white noise.

2.2.8. **Attitude and orbit control computer (AOCC).** AOCC is the core component of satellite attitude control. It mainly consists of PID controller, control signal conversion, jet time control and control strategy. AOCC calculates the control voltage signal by inputting the attitude angles and attitude angular velocities of the satellite and the control modes.

2.3. **System model construction**

Figure 4 shows the dynamics system model. Including satellite cabin, solar array wings, antennas, earth sensor, gyroscope and integrated drive controller and other stand-alone components. The main function of the integrated drive controller is to transmit commands according to the flight program, including solar arrays unfolding and driving and unfolding unwinding commands. The earth sensor is used to measure the attitude angles of the satellite. The gyroscope is used to measure the attitude angular velocities of the satellite. The system model is mainly used to simulate the change of the attitudes during the development of moving parts.

![Figure 4. Dynamical system model.](image)

The satellite attitude dynamics and control integrated model is shown as Figure 5. Including antenna, integrated drive controller, attitude control and management unit, earth sensor, solar sensor, star sensor, gyroscope and environment model. The model is mainly used to simulate control strategy validation.

![Figure 5. Attitude dynamics and control model.](image)

3. **Simulations and Analysis**

3.1. **Dynamic model validation**
In order to verify the correctness of the model with Modelica/MWorks software, the satellite dynamics model based on ADAMS software was compared, which has been a lot of test validation in satellite’s designs. Based on the agreement between the model parameters and given the same flight control command, both the results were compared.

![Figure 6. Comparison of yaw angles.](image)

![Figure 7. Comparison of roll angles.](image)

![Figure 8. Comparison of pitch angles.](image)

The attitude angles obtained by MWorks/Modelica agrees well with that of ADAMS shown in Figure 6, Figure 7 and Figure 8, the maximum relative error is 0.1%, and the average relative error is 0.05%, thus confirming that it is feasible for Modelica multi-domain unified modelling technology to simulate process in the satellite system.

3.2. Effect of flexible solar wings

Since the separation of the satellites and the rocket into the states of the solar arrays completely unfolds will cause the inertia to vary widely, it is very difficult to plan the satellite attitude control algorithm and the flight program. Therefore, in this section, the effects of the presence of rigid solar wings and flexible solar wings on simulation results were compared. The results were shown in Figure 9. It could be seen that replacing rigid solar wings with flexible wings has little effect on the overall attitude variation of the satellite, but it could be seen from the simulation result curves and the deformation cloud that there is obvious vibration when the moving parts start to expand and stop.
Figure 9. Deformation cloud.

After separated from the rocket, the satellite was to complete the following actions, as shown in Figure 10. The model of the satellite attitude dynamics and control system constructed in section 2.3 was set up parameters according to the flight program, and the whole flight process simulation was carried out. The simulation process was mainly concerned with the effect of the control and whether the design requirements were met about the satellite attitude changes to verify the correctness of the control strategy.

The satellite attitude and attitude angular velocity curves are shown in Figure 11 and Figure 12, respectively. As can be seen from the figures, in 0~100 s the satellite worked in eliminating the initial deviation mode, and at 150 s in the yaw-capture mode, when attitude angle and attitude angular velocity have a great change, the attitude angle and attitude angular velocity satisfy the design requirements at the end of the yaw acquisition. at 700 s the antenna begins to expand when control program is in the standby mode, the maximum attitude angle deviation caused by 0.01 rad within the design specifications. Figure 14 shows the thrust switch control signal, it can be seen from the working state of the thruster during the control implementation. Through the above analysis, it is convenient to provide reference and basis for the development of attitude control strategy.

Figure 14 shows a three-dimensional animation display of the satellite. It is very intuitive to reflect the satellite attitude changes.

Figure 10. Flight procedure.
4. Satellite multi-system modelling and coupling analysis

Based on the model of satellite dynamics and control model and the multi-professional features of the single device taken into account, six model libraries including power supply, propulsion, measurement...
and control, communication, data management and transmission, and integrated electronics were extended and constructed.

Based on the construction of the six professional model library, the integrated satellite System Model is built. The coupling of dynamics and control subsystem, power subsystem, propulsion subsystem, measurement and control subsystem, data management and transmission sub-system and integrated electronic subsystem is considered to obtain satellite attitude changes with different control modes, the dynamic balances among the solar array, the battery and the device loads, the real-time output characteristics of the thruster under different control modes and the propellant remaining amount, satellite uplink and downlink calculation, information storage Balance characteristics as well as sending and receiving characteristics of flight procedures in the program instructions and remote control. Through the coupling analysis of satellite multi-system, it can provide reference for the designer to design the satellite system and verify the index in the stage of the plan.

5. Satellite multi-system modelling and coupling analysis
Through analysis of satellite dynamics and control system, the following conclusions are drawn:

- It is helpful to verify the correctness of the control strategy by comparing the satellite attitude dynamics and control simulation results with the design indexes;
- After replacing the rigid solar wings with the flexible wings, although the influence on the attitude of the satellite is not significant, both the simulation results and the Deformation cloud show that the satellite has a significant vibration in the process of solar wings and antennas unfolding.
- Modelica technology solves the coupling problem of satellite attitude dynamics and control system. The system of satellite dynamics and control is modelled on the same platform based on the unified physical modelling standard, and the natural coupling integration helps to validate the control strategy.
- On this basis, the satellite state changes under the coupling of the dynamic subsystem, the attitude control subsystem, the power subsystem, the propulsion subsystem and the integrated electronic subsystem are obtained synthetically, which provides an effective way of system-level multi-disciplinary collaborative simulation and verification for the whole department. It also lays the foundation for the satellite system-wide digitalization and multidisciplinary optimization.

6. References
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