Dynamic Modeling and Control Method of Dual-Body Satellite

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Abstract. For the attitude control problem of dual-body satellite with non-solid connection between payload module and platform module, this paper proposes a dual-body dynamics modeling and control method based on the concept of disturbance-free payload (DFP). The payload module is rotated in orbit with high precision, and its forces can be determined by performing a force analysis on it. The Euler equation is used to calculate the attitude information of the payload module, so that the motion of the payload module can be described more accurately. By designing the control algorithm and the control loop with the idea of DFP, the attitude accuracy of the payload module is better controlled. The simulation results show that the controller can keep the attitude accuracy of the payload module within 1.65°, the results meet the expectation.

1. Introduction
Vibrations in spacecraft can affect the accuracy and stability of spacecraft. The literature [1~2] describes traditional vibration isolation methods. To fundamentally solve the vibration isolation problem of spacecraft payloads, Nelson Pedreiro[3] proposed the DFP control system concept in 2002, which separates the payload module (PM) and the support module (SM), which can protect the PM from the SM and achieve precise control. After this, Trankle et al[4] developed linear and nonlinear simulation models of DFP and analyzed its vibration isolation performance, since then the concepts of ultra-high accuracy and ultra-high stability started to become popular in spacecraft.

Figure 1. DFP system architecture

The PM contains key components that require precise control and high motion stability, such as cameras, telescopes, etc. The SM module contains the main sources of vibration, such as reaction
wheels, thrusters, and large flexible attachments. A non-contact position sensor located between the two modules is used to obtain relative translation and attitude information between the PM and the SM. The non-contact actuator, also located between the PM and SM, applies a force between the two modules to control the motion of the payload.

Due to the special working environment in space, traditional rolling and plain bearings are difficult to meet long life span requirement, so magnetic levitation bearings were born\cite{5}. The non-contact actuator in this paper uses Lorentz force magnetic bearings (LFMB). The magnetic density and flux in LFMB are kept constant, so the output electromagnetic force is proportional to the current of the coil winding.

Facing increasing spacecraft accuracy requirements (The attitude angle error of the three axes of the payload module is within $10^\circ$), in this paper, the dynamics model of LFMB-connected dual-body satellite is established and the controller is designed through the concept of DFP, with the goal of controlling the attitude accuracy of the payload module at a high level and providing a more accurate dynamics model platform for the future development of control algorithms.

2. Materials and Methods

2.1. Dynamics modeling

Firstly, the force situation of the payload module and platform module is analyzed. In the normal levitation process, the payload module and the platform module are not in contact with each other at all, and they can be regarded as rigid bodies respectively, but we should pay attention to the effect of dynamic and static unbalance on the dynamic model. Suppose the static unbalance of the payload module is $u_{st}$ and the dynamic unbalance is $u_{dy}$. Their distribution in the payload module is as follows:

As shown in Figure 2, the LFMB is located between the payload module and platform module, which is divided into two pairs, upper and lower, it exerts radial control forces, thus exerting control forces and moments on the payload module. And due to the distribution of dynamic and static unbalance, $u_{st}$ generates disturbance forces and $u_{dy}$ generates disturbance moments. As the payload module rotates around the x-axis, the disturbance force $f_{ac}$ generated by $u_{st}$ is:

$$
\begin{align*}
 f_{ac} &= u_{stx} \omega_x^2 \cos(\omega_x t + \alpha) \\
 f_{acl} &= u_{stx} \omega_x^2 \sin(\omega_x t + \alpha)
\end{align*}
$$

In the above equation, $\omega_x$ is the rotational angular velocity of the payload module and $\alpha$ is the phase of the static unbalance vector at the zero moment.
The LFMB provides only radial control forces and the forces in the y and z directions are independent of each other. The Lorentz force generated by the upper and lower LFMB can be expressed as:

\[
\begin{align*}
    f_{1y} &= BLi_{1y}; \\
    f_{1z} &= BLi_{1z} \\
    f_{2y} &= BLi_{2y}; \\
    f_{2z} &= BLi_{2z}
\end{align*}
\]  

(2)

where the lower corner mark 1 or 2 represents the upper or lower magnetic bearing, respectively. \( B \) is the magnetic field strength and \( i \) is the current flowing through the magnetic bearing coil.

By equivalently translating both the disturbance force \( f_{ac} \) and the control force of the magnetic bearing to the center of mass of the payload module, the total radial force on the center of mass is:

\[
\begin{align*}
    F_{y} &= f_{acy} + f_{1y} + f_{2y} \\
    F_{z} &= f_{acz} + f_{1z} + f_{2z}
\end{align*}
\]  

(3)

Similarly, the disturbance moment \( m_{ac} \) due to the dynamic unbalance can be obtained as:

\[
\begin{align*}
    m_{acy} &= u_{by} \omega_{z}^{c} \cos(\omega_{d} t + \beta) \\
    m_{acz} &= u_{by} \omega_{x}^{c} \sin(\omega_{d} t + \beta)
\end{align*}
\]  

(4)

In the above equation, \( \beta \) is the phase of the dynamic unbalance vector at the zero moment.

The control force generated by the magnetic bearing is multiplied by the corresponding span to obtain the corresponding radial control moment, which is summed with the disturbance moment to obtain the total radial moment \( M \). It is not repeated here.

Consider the dual-body dynamics modeling of the satellite in orbital conditions: firstly, it is necessary to establish the coordinate system, and the rotational angular velocity of the ontological coordinate system \( Oxyz \) with respect to the orbital coordinate system \( Oxyz' \) is \( \omega_{w} \), then the relative position relationship between the two coordinate systems is shown in Figure 3:

![Figure 3. Schematic diagram of coordinate system transformation](image)

Then the transformation matrix from the ontology coordinate system to the orbit coordinate system is:

\[
C_{aba} = \begin{bmatrix}
1 & 0 & 0 \\
0 & \cos(-\omega_{w} t) & \sin(-\omega_{w} t) \\
0 & -\sin(-\omega_{w} t) & \cos(-\omega_{w} t)
\end{bmatrix}
\]  

(5)

Set the rotational inertia matrix of the payload module in the ontology coordinate system as:

\[
I_{a0} = \begin{bmatrix}
I_{xx0} & -I_{xy0} & -I_{xz0} \\
-I_{xy0} & I_{yy0} & -I_{yz0} \\
-I_{xz0} & -I_{yz0} & I_{zz0}
\end{bmatrix}
\]  

(6)

Since the payload is rotating, the inertia matrix of the payload module is always changing with the rotation angle in the orbital coordinate system. Then the rotational inertia matrix is transformed from the ontology coordinate system to the orbital coordinate system as:
\[ I_u = C_{uv}^T J_{uv} C_{uv} \]  

According to the Euler equation, the rotational dynamics model of the payload module can be written as:

\[ M = H + \omega \times H = I_u \frac{d}{dt} \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} + \frac{dI_u}{dt} \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} + \omega' I_u \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} \]  

By mathematical calculation, the above equation can be deformed to:

\[ \frac{d}{dt} \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} = I_u^{-1} \left[ -\frac{dI_u}{dt} \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} + \omega' I_u \begin{bmatrix} \omega_{ux} \\ \omega_{uy} \\ \omega_{uz} \end{bmatrix} \right] \]  

In the above equation:

\[ \frac{dI_u}{dt} = \frac{d(C_{ub} I_u C_{ub})}{dt} = -\omega_{ux0}(I_{u_{y0}} - I_{u_{z0}}) \begin{bmatrix} 0 & 0 & 0 \\ 0 & \sin(2\omega_{ux0}t) & \cos(2\omega_{ux0}t) \\ 0 & \cos(2\omega_{ux0}t) & -\sin(2\omega_{ux0}t) \end{bmatrix} \]  

where \( \omega_{ux0} \) is the rotational angular velocity of the payload module, \( \omega_{uy0} \) is the orbital angular velocity of the satellite, and \( \theta_{ux}, \theta_{uy}, \theta_{uz} \) is the angular error of the three axes. The gyroscopic moment due to the angular velocity of the orbit can be obtained by equation (8).

Afterwards, attitude dynamics modeling is performed for the platform module:

\[ \begin{bmatrix} \dot{\theta}_{dx} \\ \dot{\theta}_{dy} \\ \dot{\theta}_{dz} \end{bmatrix} = \begin{bmatrix} I_{dx0} & I_{dy0} & I_{dz0} \end{bmatrix} \begin{bmatrix} \dot{\theta}_{dx} \\ \dot{\theta}_{dy} \\ \dot{\theta}_{dz} \end{bmatrix} - \begin{bmatrix} M_{dx} \\ M_{dy} \\ M_{dz} \end{bmatrix} \]  

In the above equation, \( I_{dx0}, I_{dy0}, \) and \( I_{dz0} \) are the rotational inertia of the platform module. \( [M_{dx}, M_{dy}, M_{dz}]^T \) is the control torque applied to the platform module by the magnetic bearing. Based on the dynamics model of the payload module and platform module, the attitude variables are output to facilitate subsequent attitude control.

The Lorentz force of LFMB on the payload module and platform module is an interaction force, which can be used as the basis for modeling the displacement dynamics of the dual-body of the satellite with multiple degrees of freedom. Modeling for the displacement of the platform module:

\[ \begin{bmatrix} m_d \\ m_d \\ m_d \end{bmatrix} \begin{bmatrix} \dot{x}_d \\ \dot{y}_d \\ \dot{z}_d \end{bmatrix} = \begin{bmatrix} F_{dx} \\ F_{dy} \\ F_{dz} \end{bmatrix} \]  

where \( m_d \) is the mass of the platform module and \( [F_{dx}, F_{dy}, F_{dz}]^T \) is the control force exerted by LFMB on the platform module.

Assume that the only internal force on the satellite is the Lorentz force of LFMB, with no damping force. So the whole satellite composed of the payload module and the platform module satisfies the conservation of mass:

\[ \begin{align*}
  m_u x_u + m_d x_d &= (m_u + m_d) x_c = 0 \\
  m_u y_u + m_d y_d &= (m_u + m_d) y_c = 0 \\
  m_u z_u + m_d z_d &= (m_u + m_d) z_c = 0
\]  

Then the displacement of the center of mass of the payload module satisfies the following equation:
(13)

Through the establishment of the above dynamics model, the position and attitude information of the payload module and platform module can be obtained, which can be controlled by the controller.

2.2. Controller design

The dynamics model of the dual-body satellite uses PID controller, which is a very classical controller in the field of control, with the advantages of simple control algorithm, good robustness, adaptability, stability, reliable operation, easy debugging and have a clear physical meaning. The structure of the PID controller is shown in Figure 4:

To prevent excessive current, limiting links is established. PID controller exists three specific links:

(1) Proportional link, the error of the present $e(t)$, can help the system to reduce the regulation time $t_s$, enhance the rapidity of the system. However, it may lead to an increase in the overshoot of the system due to the excessive growth.

(2) The integral link, the accumulation of errors $\int_0^t e(\tau)d\tau$, whose main role is to eliminate the static error of the system, is also helpful in reducing the amount of overshoot of the system.

(3) Differential link, the rate of change of the error $de(t)/dt$, which can determine the trend of the transformation of the system error, generating an overrun control signal, can also play a role in reducing the amount of system overshoot and shortening the regulation time $t_s$.

PID controller superimposes three links, proportional, integral and differential, in the form of a linear superposition to form the final control signal:

$u(t) = K_p e(t) + K_i \int_0^t e(\tau)d\tau + K_d \frac{de(t)}{dt}$

The dynamics model can be used to obtain the position and attitude information of the payload module and platform module, and the system error $e$ is obtained by making the difference between these information and the expected value. $e$ is used as the input of the controller, and the control quantity $u$ is obtained after the PID controller.

3. Results & Discussion

The target values of the position and attitude errors of the payload module and platform module are set to zero. After the controller outputs the control signal, LFMB outputs the control force and moment acting on the dynamics model. The output of the system is shown below:
Figure 5. Three-axis attitude angle error of the payload module

It can be seen from the simulation results that the three-axis attitude angle of the payload module is kept within $8 \times 10^{-6}$ rad, which is about 1.65". It can be seen that by setting the control parameters of the PID controller reasonably, it can make the payload module have high attitude accuracy.

Figure 6. Displacement of the center of mass of the payload module

It can be seen from Fig.6 that the center of mass of the payload module will fluctuate due to disturbance of static unbalance, and its displacement is kept within 0.1mm. The control effect is more satisfactory. In the actual control, we should pay attention to the gap between the payload module and the platform module to avoid the collision between the two bays.

4. Conclusions

In this paper, the dynamics of the dual-body satellite is modeled, and the more accurate attitude information of the payload module is obtained by Euler's equation. The control of position and attitude is carried out by PID controller with good control effect, so that the payload module achieves high attitude accuracy. Because the disturbance force is not applied in the x-axis direction, the displacement of the center of mass of the payload module in the x-direction is zero. However, the actual in-orbit situation is very complex, and the disturbance force and moment on the payload module will be more, which can be further studied subsequently to improve the dynamics model of the dual-body satellite and provide a better R&D platform for the study of the control algorithm of the satellite.

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