Vibration control of deployable truss antenna reflector-scanning mechanism

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Abstract. Scanning mechanism and truss reflector are important components of antenna. Aiming at the mechanical system and control system composed of scanning mechanism and truss antenna, the co-simulation technology of hybrid stepping motor and flexible dynamic mechanism is proposed. Through the simulation results of the current and position changes of the antenna system, the various physical characteristics of the system during the co-simulation are studied, and the vibration characteristics of the overall antenna system are analyzed, which verifies the cooperative ability of the antenna mechanism system and the control system.

1. Introduction
The deployable truss antenna consists of a reflector and a scanning mechanism. The deployable truss reflector rotates around the focus, and the multi-stage deployment device of reflector is driven by the scanning mechanism to achieve beam scanning. For the antenna system, the truss reflector is a large mesh antenna, and its structure frequency is low (first-order 0.7 Hz) [1]. The harmonic reducer in the mechanism acts as the connecting part of the mechanism joint, and the rigidity of its flexible wheel is lower, which reduces the stiffness of the antenna system. The structure frequency of the mechanical antenna system is within the frequency band of the antenna control system, and the stepping motor system in the mechanism is non-linear. Therefore, in order to ensure the stability of the natural system, it is necessary to avoid the occurrence of coupling vibration at all times [2,3]. Xu developed a theoretical model of a complete motor-flexible coupling-rotor system which can describe the mechanical vibration resulting from misalignment and unbalance [4]. Lee found that the increase in natural frequency is mostly due to the increase in effective bearing moment stiffness associated with the misalignment direction[5]. Shi proposed a simple solution method for a unified vibration analysis of annular, circular and sector plates with arbitrary boundary conditions [6]. Zhao established the coupling equations of motion of a rotating three-dimensional cantilever beam, and studied the effects of Coriolis term and steady-state axial deformation on coupling vibration [7].

When the antenna is in orbit, the electric energy is converted into mechanical energy by the servo system, which drives the antenna to move. The actual operating position of the antenna is transferred to the servo system through rotation for closed-loop control [8]. If the mechanical system and the control system are modeled separately, because the internal relationship between them is neglected, the goal of vibration analysis cannot be achieved. In this paper, a co-simulation technology of hybrid stepping motor and flexible dynamic mechanism is designed. The vibration characteristics of the
antenna system are obtained, which improves the design efficiency and system performance of the antenna system, and can guide practical application.

2. The route of coupling vibration analysis technology

The structural model of the truss antenna system is shown in Figure 1. The three-axis scanning mechanism of satellite antennas studied is an executive component located at the end of the antenna driving mechanism [9,10], which consists of three rotating units whose axes intersect at one point as shown in Figure 2. The system vibration includes not only the vibration of the antenna or the scanning mechanism itself, but also includes the vibration of the interaction between the reflector and the scanning mechanism during deployment. The coupling vibration is mainly reflected in the connected shafting of the scanning mechanism, as shown in the red section of Figure 1.

![Figure 1. Truss antenna system.](image)

![Figure 2. Three-axis scanning mechanism and structure.](image)

Firstly, considering the characteristics of mechanical system and control system of antenna, the simulation calculation of control system is completed according to the three-axis parameters of scanning mechanism. The calculation results are transmitted to the simulation of mechanical system through common interface. After the simulation analysis of mechanical system, the calculation results are also fed back to the control system, so the iterative calculation is carried out repeatedly. Finally, a stable calculation result is obtained. The technical route diagram is shown in the following Figure 3.
The multi-loop motor model of antenna system is established. The circuit equation of the model is

\[
\begin{bmatrix}
Dl_a \\
Dl_b \\
0
\end{bmatrix} = \begin{bmatrix}
L_{aa} & M_{ab} & M_{ma} \\
M_{ba} & L_{bb} & M_{mb} \\
M_{ma} & M_{mb} & 1
\end{bmatrix} \begin{bmatrix}
u_a \\
u_b \\
0
\end{bmatrix} - \begin{bmatrix}
R_a & 0 & 0 \\
0 & R_b & 0 \\
0 & 0 & 0
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_m
\end{bmatrix} + \begin{bmatrix}
Dl_{aa} & DM_{ab} & DM_{ma} \\
DM_{ba} & DL_{bb} & DM_{mb} \\
DM_{ma} & DM_{mb} & 0
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_m
\end{bmatrix} \omega
\]

where \( I_a \) is the current of permanent magnet excitation winding, \( I_m \) is equal to 1A.; \( DI \) is the derivative of the current with respect to time; \( L_{aa}, L_{bb}, M_{ab}, M_{ab}, M_{ma}, M_{mb} \) is the inductance matrix, \( L_{aa} \) is self-inductance of phase A winding, \( M_{ab} \) is mutual inductance of phase AB winding, \( M_{ma} \) is mutual inductance of phase A winding and permanent magnet excitation winding; \( DL \) is the derivative of inductance with respect to position; \( \omega \) is the speed, in rad/s.

The mechanical equation of the model is

\[
Te = \begin{bmatrix}
I_a & I_b & I_m
\end{bmatrix} \begin{bmatrix}
DL_{aa} & DM_{ab} & DM_{ma} \\
DM_{ba} & DL_{bb} & DM_{mb} \\
DM_{ma} & DM_{mb} & 0
\end{bmatrix} \begin{bmatrix}
I_a \\
I_b \\
I_m
\end{bmatrix} + T_d
\]

where \( Te \) is the electromagnetic torque of the motor, \( T_d \) is the positioning torque (cogging torque). The load torque \( T_l \) of the motor consists of three parts: load, friction torque and damping torque,

\[
T_l = T_r + B_1 \omega + T_f \times \omega / |\omega|
\]

where \( T_r \) is the load, \( B_1 \) is the damping coefficient, \( T_f \) is the friction moment.

The net output torque of the motor is

\[
T_o = T_e - T_l
\]

3. Vibration control analysis

The antenna controller is the rotational control terminal of the antenna. It is generally composed of the following modules: control module, drive module, angle/position acquisition module, as shown in Figure 4.
The simulation of antenna controller needs to complete the modeling of control module, drive module, angular displacement acquisition module and motor [11], so as to realize the electromechanical simulation of control system model.

3.1. Modeling and simulation of single-axis control system

According to the technical route of antenna system modeling, the model of single-axis control system is established as shown in Figure 5.

Its basic principle is to control the speed of the motor by proportional amplification of the position error. The speed of the motor is converted from mechanical frequency to electrical frequency to obtain the frequency of the current of the control machine. At the same time, the sinusoidal voltage (frequency is converted frequency) is subdivided into 8 subdivisions as a given voltage. After comparing with the collected feedback voltage, the H-bridge control signal is used to control the phase and frequency of the current. The current amplitude remains unchanged.

Tracking the slope condition with a slope of 145 degrees/sec. The current and position simulation results are shown in Figure 6 and Figure 7 respectively.
From the simulation curves, it can be seen that the amplitude of current waveform is 0.85A, the effective value is 0.6A, and the maximum frequency is 20.83Hz (150 degrees/sec). Because the red and green current curve changes basically the same, when the position error is less than 1 degree, the current frequency becomes 0Hz, which meets the control strategy requirements.

If the 100-degree step condition is tracked, the simulation results are shown in the following Figure 8 and Figure 9.

From the simulation curves, it can be seen that the amplitude of the current waveform is 0.85A and the effective value is 0.6A. The motor moves at the maximum speed of 150 degrees/sec (current frequency is 20.83Hz). Because the red and green current curve changes basically the same, when the position error is less than 1 degree, the current frequency becomes 0 Hz, and the position remains unchanged, which meets the control strategy requirements.

3.2. Modeling and Simulation of three-axis control system

After verifying the different working conditions of the single-axis control system model, the model of the single-axis control system is reliable. Therefore, the model of single-axis control system can be extended to three axes, and the model of three axes control system can be established like Figure 9.

The simulation results of the third axis are shown in the Figure 10 and Figure 11.
The simulation results show that the current waveform has an amplitude of 0.85A, an effective value of 0.6A, and a maximum frequency of 20.83Hz (150 degrees/sec). When it reaches the target position, the current frequency becomes 0 Hz. In the initial stage and the stable stage when the antenna system reaches the target position, the position fluctuates with the frequency of 14.49 Hz, which is not in the range of the mechanical resonance frequency of the antenna and will not cause resonance.

The simulation results of the other two axes are similar. From the simulation results, it can be seen that the three axes can track the trajectory in orbit, which proves that the model of the three axes control system is reliable.

4. Conclusions
In this paper, the driving frequency is solved by controlling and utilizing the current characteristics, so as to judge whether resonance occurs. A co-simulation technology of hybrid stepping motor and flexible dynamic mechanism is designed. The mechanical system and motor control system composed of scanning mechanism and frame antenna are simulated. Through simulation control of both single-axis and three-axis, it is verified that the designed deployable antenna system has no resonance and has a good application type.

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