Design and Research of Servo Mechanism of Airborne Full Polarization Microwave Radiometer

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Abstract. According to the requirements of the servo mechanism of airborne full polarization microwave radiometer, the structure was designed and divided into two parts: the azimuth mechanism and the pinch mechanism, which can scan the ground 360° continuously without dead angle. Three-dimensional model of airborne full polarization microwave radiometer was designed using CATIA in this paper. The static analysis, modal analysis and vibration analysis of the servo mechanism of airborne full polarization microwave radiometer were performed using ANSYS. The analysis results showed that the structure of the device satisfied the strength and stiffness requirements. This thesis theoretically studied the position and posture of the servo mechanism. According to the Euler coordinate transformation theory, the velocity equation, acceleration equation and transmitting torque equation were derived. By simulating the physical model of the device using ADMAS, the variation law of displacement, velocity, and acceleration over time was obtained, which provided the foundation for actual motion and control system design.

1. Introduction
Airborne full polarization microwave radiometer is a new kind of microwave remote sensor mounted on an aircraft for observing the atmosphere, ocean, topography and military detection. In the 1980s, a full polarization microwave radiometer capable of measuring three stocks vectors was successfully manufactured, and anisotropic brightness-temperature curves of microwave radiation with different wind velocities were plotted\textsuperscript{[1]}. In the 1990s, the National Oceanic and Atmospheric Administration successfully developed a full polarization microwave radiometer that can measure four stokes parameters in cooperation with the Georgia Institute of Technology. At the same time, the Massachusetts campus had also successfully developed a polarized microwave radiometer and studied the modulation of sea surface brightness and sea surface wind direction\textsuperscript{[2-3]}. In 2001, the world's first airborne full polarization microwave imager (APMIR) was developed and airborne flight experiments were performed\textsuperscript{[4,5]}. At present, the research on the full polarization microwave radiometer is mainly focused on the theoretical research of microwave radiation, and the structural design of the device is less. Combined with the requirements of light weight, high stiffness and wide measurement range of the device, the design of the servo mechanism is of great significance.
microwave radiometer, the design and analysis of airborne full polarization microwave radiometer were carried out in this paper.

2. Design and Analysis of Airborne Full Polarization Microwave Radiometer

2.1. Structure design

As a kind of airborne equipment, the airborne full polarization microwave radiometer is supposed to have a structure capable of satisfying continuous rotation of 360° and full coverage of space electromagnetic wave frequency, phase, and amplitude information under complex working conditions. The structure of airborne full polarization microwave radiometer designed in this paper was divided into azimuth mechanism and pitch mechanism, as shown in Fig. 1. The azimuth mechanism can rotate 360° continuously in the azimuth direction, as shown in Fig. 2. The pitching mechanism realized 360° continuous rotation in the pitching direction, as shown in Fig. 3.

Fig. 1 Airborne full polarization microwave radiometer

Fig. 2 The azimuth mechanism

Fig. 3 The pitch mechanism

2.2 Static analysis

The airborne full polarization microwave radiometer is installed at the opening of the aircraft. It will withstand up to 6g of inertial load during the aircraft taking-off and landing. Therefore, it is necessary to check whether the structure meets the strength requirement under the 6g acceleration load. Using the ANSYS to mesh the 3D model, a total of 423,845 nodes and 113,313 meshes were obtained. The acceleration load and static load of 6g were applied in each of the X, Y, and Z directions, respectively. The corresponding simulation results are 41.945MPa, 20.899MPa, 9.797MPa, 48.447MPa, and the above data are less than the minimum allowable stress of material 260MPa. The results showed that the overall structure meets the strength requirement.
2.3 Modal analysis

For the modal analysis, the modal analysis module was added to the ANSYS analysis project, and the frequency range was selected from 0 to 2000 Hz. The natural frequency of the main bearing structure is 51.02 Hz, which is greater than the fundamental frequency of the aircraft by 15 Hz, which can avoid resonance with the aircraft. The first six modes of the main bearing structure were extracted and the vibration mode was analyzed. It was found that the pitch motor, the azimuth motor and the pitch turret are weak links. These three parts should be properly reinforced during manufacturing and assembly.

The main cause of failure of airborne full polarization microwave radiometer is the variable load caused by random vibration. The random vibration is mainly caused by the noise emitted from the engine and the turbulence of the airflow on the surface of the aircraft. The performance of the device under variable load was verified by random vibration analysis of the main bearing structure. Referring to the standard GJB150.16-86[6] and the standard HB5830.5-96[7]. The power spectral density of the random vibration environment of the device was finally determined, as shown in Table 1. The data was brought into the acceleration power spectral density function (1). The acceleration power spectral density curve was plotted, as shown in Fig. 4. The deformation and equivalent stress of the output structure in the X, Y and Z directions under the excitation are calculated, and then the scale parameter is set as $\sigma$, finally Table 2 is obtained. According to the data in Table 2, the maximum equivalent stress is 84.922MPa, which occurs in the Y direction. Under the stress of 3$\sigma$, the maximum stress is 254.8MPa, which is smaller than the minimum allowable stress of 260MPa. The results show the device meets the requirements of random vibration testing.

### Table 1 Power spectral density table for random vibration environments

| Frequency Range(Hz) | 20–178 | 178–300 | 300–1000 | 1000–2000 |
|---------------------|--------|---------|----------|-----------|
| Power Spectral Density | 0.04g² | +4dB/octave | 0.08g² | -6dB/octave |
| Test direction | X, Y, Z (0.02 g²) |

Where: $N$ is the slope (dB/oct); $n$ is the octave (w); $w_a, w_b$ are the power spectral density values at the frequencies $f_a, f_b$.

$$N = \frac{10}{n} \log \frac{w_a}{w_b}, \quad n = \frac{1}{\log 2} \log \frac{f_a}{f_b}$$ (1)

![Fig. 4](attachment:acceleration_power_spectral_density_curve.png)

### Table 2 Maximum deformation and equivalent stress in X, Y, and Z directions

| Test content | Maximum deformation | Maximum equivalent stress |
|--------------|---------------------|---------------------------|
| X direction  | 1.357               | 83.092                    |
| Y direction  | 0.525               | 84.922                    |
| Z direction  | 0.261               | 59.996                    |
3. Motion analysis of airborne full polarization microwave radiometer

3.1 Coordinate transformation

The motion of the airborne full polarization microwave radiometer mainly includes the rotation of the azimuth turntable around the vertical axis and the rotation of the pitch turntable about the horizontal axis, respectively establishing coordinate systems O-x1y1z1 and O-x2y2z2. In order to facilitate the derivation of the motion equation, two coordinate systems were transferred to the same coordinate system O-x0y0z0 by coordinate transformation. The coordinate conversion formula can be expressed as:

$$
\begin{bmatrix}
\omega_x \\
\omega_y \\
\omega_z
\end{bmatrix} = T_{xy} \begin{bmatrix}
\dot{\alpha} \\
\dot{\beta}
\end{bmatrix} = \begin{bmatrix}
\cos \alpha & \sin \alpha \sin \beta & -\sin \alpha \sin \beta \\
\sin \alpha & \cos \alpha \cos \beta & \cos \alpha \sin \beta \\
0 & -\cos \alpha & \sin \alpha
\end{bmatrix} \begin{bmatrix}
\dot{\alpha} \\
\dot{\beta}
\end{bmatrix}
$$

(2)

Where: Coordinate system O-x0y0z0 rotates $\alpha$ angle around $y_0$ axis to get O-x1y1z1; Coordinate system O-x1y1z1 rotates $\beta$ angle around x1 axis to get O-x2y2z2.

Establishment of the equation of motion

Dynamic analysis of the main motion parameters of the airborne full polarization microwave radiometer, combined with the coordinate conversion formula, the motion equations of speed(3), acceleration(4), and torque(5) were obtained.

$$
\begin{bmatrix}
\omega_{x1} \\
\omega_{y1} \\
\omega_{z1}
\end{bmatrix} = \begin{bmatrix} 0 \\
0 \\
0 \end{bmatrix}, \quad \begin{bmatrix}
\omega_{x2} \\
\omega_{y2} \\
\omega_{z2}
\end{bmatrix} = \begin{bmatrix}
\dot{\beta} \\
\dot{\alpha} \cos \beta \\
-\dot{\alpha} \sin \beta
\end{bmatrix}
$$

(3)

$$
\begin{bmatrix}
\dot{\omega}_{x2} \\
\dot{\omega}_{y2} \\
\dot{\omega}_{z2}
\end{bmatrix} = \begin{bmatrix}
\dot{\beta} \\
\dot{\alpha} \cos \beta - \dot{\alpha} \sin \beta \\
-\dot{\alpha} \sin \beta - \dot{\alpha} \cos \beta
\end{bmatrix}
$$

(4)

$$
\begin{align*}
M_1 &= J_{x2} \ddot{\beta} + (J_{y2} - J_{z2}) \alpha \sin \beta \cos \beta \\
M_2 &= J_{x1} \ddot{\alpha} + J_{y2} \cos \beta (\ddot{\alpha} \cos \beta - \ddot{\alpha} \sin \beta - \dot{\alpha} \dot{\beta} \sin \beta) + J_{z2} \sin \beta (\dot{\alpha} \dot{\beta} \cos \beta + \ddot{\alpha} \sin \beta + \ddot{\alpha} \cos \beta)
\end{align*}
$$

(5)

Where: $\omega$ is the angular velocity, $\omega$ is the angular acceleration, $M$ is the torque, $J$ is the moment of inertia; the angle 1 corresponds to the pitch mechanism, and the angle 2 corresponds to the azimuth mechanism.

3.2 Motion Simulation

In order to visually study the motion law of the airborne full polarization microwave radiometer device, the model of the device structure was designed and appropriately simplified using CATIA. After setting the corresponding constraints, the model was imported into ADAMS for kinematic simulation. Finally, the physical prototype model of the airborne full polarization microwave radiometer device was obtained as shown in Fig. 5. Rotary pair was applied to the azimuth turntable and the pitch turntable to accelerate the rotation speed from 0 to 12r/min within 10 seconds. The input curve is shown in Fig. 6.
The main purpose of the motion simulation is to observe the displacement, velocity and acceleration of the antenna horn. This article selected the 10.7GHz antenna horn feed and marks MARKER 37 at its center, as shown in Fig. 7. The changes in the displacement, point velocity, and point acceleration of point MARKER 37 with the movement of the turntable mechanism and the pitch mechanism over time were recorded, as shown in Fig. 8, 9 and 10.

4. Conclusions
The mechanical structure of airborne full polarization microwave radiometer was designed in this paper, which can realize 360° continuous scanning in azimuth and pitch direction. In this paper, CATIA is used to build a three-dimensional model of airborne full polarization microwave radiometer, and ANSYS is used for static analysis and modal analysis. The results of static analysis show that the maximum equivalent stress is 41.945MPa, which is smaller than the minimum allowable stress of 260MPa. The results of modal analysis show that the first-order natural frequency is 51.02 Hz, which is 15 Hz higher than the aircraft basic frequency. Random vibration analysis shows that the 3σ stress of the device is 254.8MPa, which is smaller than the minimum allowable stress of the material of 260MPa. The results show that the structural design meets the requirements of strength and stiffness. In this paper, ADAMS is used to simulate the movement, and the curve of displacement, velocity and acceleration of
the marked points with time is obtained, which provides a reliable basis for the actual movement and control design of the device.

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