MECHATRONIC APPROACH TO THE DESIGN OF A TRIAXIAL ANTENNA WITH BACKLASH MINIMIZATION BY THE CONTROL SYSTEM

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Abstract: The features and advantages of the support-rotating platforms design for the antenna systems with three axes are analyzed in the paper. The expediency of using such systems for the satellite tracking without signal losses in the zenith area relative to the coordinate of the antenna system is reasoned. It is necessary in order to expand the antenna system functionality, improve the performance of the antenna device, and increase the control system efficiency and the information reliability from the spacecraft as a whole. The developed design of the 3-axial support-rotating platform is described. The platform is built on a modular principle using of modern autonomous rotary actuators, which are combined by a special design. This approach is proposed in order to ensure backlash sampling using special software algorithms of the support-rotating device control system.

Keywords: *antenna system, 3-axial rotary platform, control system, satellite tracking trajectories, "dead zones", rotary mechanism.*

1. Introduction

The so-called "dead zones" of space object tracking are available for classic azimuth-angular support-rotating devices of antenna systems. In order to increase the reliability of information reception by antenna systems it is important to minimize the dead zones area. To achieve this goal it is necessary to upgrade the design of the antenna system support-rotating devices. The design of a 3-axial antenna, which solves this problem is proposed in the paper.

2. Support-rotating device of the antenna system with three pointing axes

Antenna support devices (platforms) are designed to ensure the reliable exchange of digital information between ground stations and spacecraft (satellites). 2-axial rotary platforms have become predominant in practice. Their advantages are simplicity of a design, rather simple control systems and reasonable cost. They all consist of two electric drives. Guidance of the antenna axis in a given direction is provided by rotating of the antenna mirror relative to the azimuth and angular axis.

Although such 2-axis platforms have different kinematic schemes, but they all have a disadvantage. It is manifested when the trajectory of the accompanying spacecraft intersects the direction of the stationary (first) axis of rotation. Near this point, the speed of rotation relative to the fixed axis increases sharply. At the point of intersection, it reaches infinite value. Since the acceleration and rotation speed of the antenna drives are limited, and so called "dead zones" are formed in these areas. As a result, there are interruptions and loss of information. In addition, the speeds of tracking on one of the axes increase for trajectory tracks that are located near the special points. This leads to an increase in the dynamic guidance errors [1] and requires increased requirements for the dynamic characteristics of the antenna electric drive.

To avoid "dead zones" of satellite support in the areas of the zenith and horizon, it is necessary to use more complex 3-axial rotary platforms and appropriate control systems [2]. This is especially important for antenna systems of satellite tracking. In such systems, loss of communication or untimely issuance of a satellite command can cause significant economic and other losses.

The presence of the third axis is the essence of the 3-axial rotary platform. With this axis, the main vertical axis of the antenna column is inclined at a small angle (about 15^0). This design has three degrees of freedom and allows you to follow the trajectories of satellites through the zenith without "dead zones" [3]. The design of such a 3-axis antenna was developed at the Instruments and Control-measurement Systems Department of the Ternopil National Ivan Puluj Technical University by order of the Kharkiv Research Institute of Radio Engineering Measurements. It is designed to work as part of a ground station for the receiving and transmitting of information to a satellite. The development was carried out in accordance with the participation in the international Egyptian-Ukrainian project on the creation in

Ukraine. This project includes the launch of the satellite "EgyptSat-1" and the creation of ground-based infrastructure for its management.

A certain disadvantage of this 3-base antenna was its higher cost, complexity of design and high requirements for the accuracy of electromechanical drives. Figure 1 shows the developed design of the support-rotating platform of the antenna, in which these shortcomings are absent or minimized. The main technical characteristics of the platform are given in table 1.

The antenna has two azimuth axes E1 and E3. The E1 axis is inclined to the vertical azimuth axis E3 at an angle of 15 degrees. A modular electromechanical drive is used to rotate the antenna mirror relative to the E3 axis. It consists of a cylindrical welded housing on which a sealed rotary mechanism 1 of the company "IMO" (Germany) is fixed.

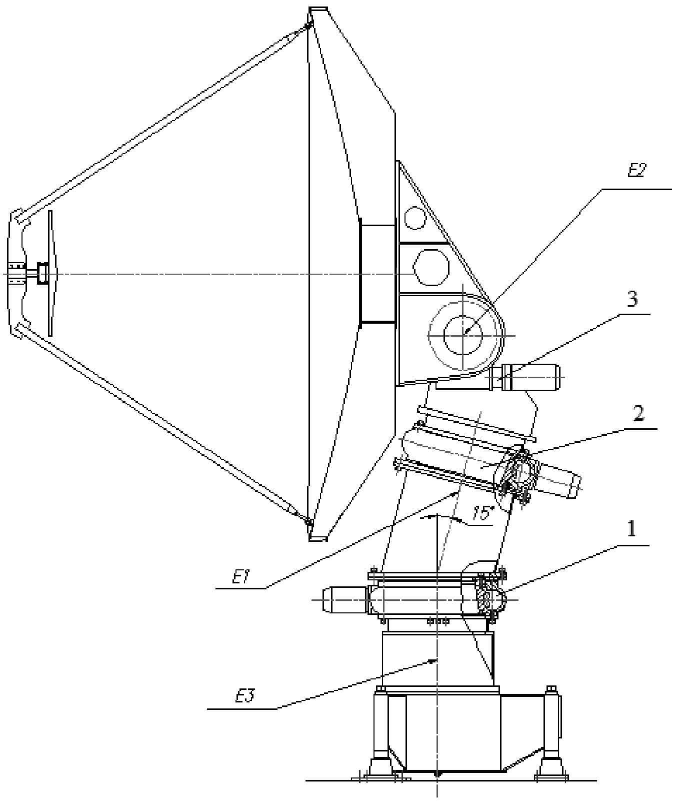

Fig. 1 Design of 3-axis antenna with sealed rotary electromechanical modules

This rotary mechanism is a double worm drive WD-H 0490/3 together with two high-precision planetary-gear reducers of the company "SUMITOMO". This mechanism also includes two asynchronous electric motors with frequency control [4], with electromagnetic brakes, electromagnetic shaft, incremental shaft and stand-alone cooling fans.

Table 1

The main technical characteristics of the antenna rotary platform

Parameter	Nominal value
Antenna mirror diameter, m	3…5
Number of control coordinates, pcs.	3
Limit angles of rotation, deg. on the axis E1 on the axis E2 on the axis E3	 ±170 120 ±170
Maximum speed, deg/s on the axis E1 on the axis E2 on the axis E3	 8 4 8
Maximum antenna acceleration, deg/s^2 on the axis E1 on the axis E2 on the axis E3	 1 0.3 1
Drive power on each axis, kW	1.1

"IMO" rotary mechanisms are delivered as a ready-to-install sealed module in order to replace a number of individual elements and components of the structure. This feature simplifies the construction and reduces the time for installation and dismantling of the device [5,6]. According to this design, it is possible significantly reduce the cost of the drive compared to the individual manufacture of such components.

Such universal modules have a fairly wide range of torques on the output shaft. This allows them to be successfully used in various components and mechanisms, including in the drives of antenna systems [7,8]. With the use of electric motors of the different power, the same rotary device can be used for drives with small and very large torques. For example, the torque on the azimuth axis E3 of the developed antenna, required for its guidance on this axis with the specified parameters (speed, acceleration), is equal to the moment of resistance of all opposing forces of the drive. It can be calculated by the formula:

$$T_{E3} = T_{dyn} + T_G + T_{wind} \tag{1}$$

where T_{dyn} – dynamic moment; T_G weight moment (from weight loads); T_{wind} – aerodynamic moment (from wind loads).

Dynamic load moment T_{dyn} is manifested by the rotation of the antenna with acceleration ε_{E3}. As this moment is reduced to the E3 axis, so it is calculated by the formula:

$$T_{E3} = T_{dyn} + T_G + T_{wind} \tag{2}$$

where I_Σ – the total moment of inertia of all moving masses relative to the axis E3.

The calculation is performed for the antenna diameter $D = 5\,m$ and weight of the antenna mirror $G_{mir} = 9700\,N$ Assume in the first approximation that the mass of the mirror is concentrated at one point in the distance $L_1 = 1.44\,m$ from the azimuth axis of rotation E3 (fig. 2).

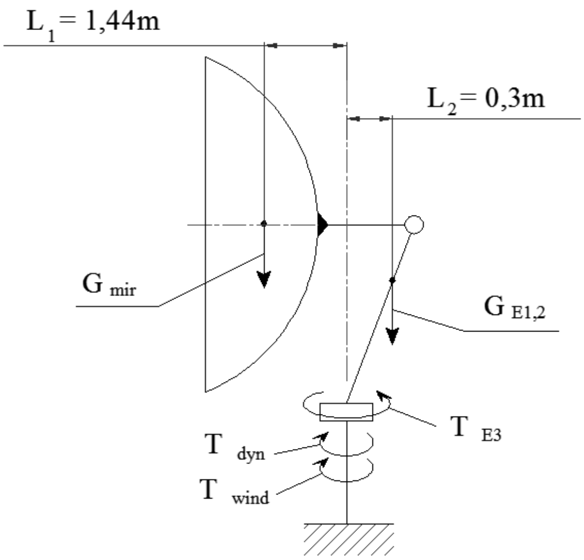

Fig. 2 Calculation scheme for determining of the torque on the azimuth axis E3

Then the moment of inertia of the antenna mirror

$$I_{mir} = \frac{G_{mir}}{g} \cdot (L_1)^2 = \frac{9700}{10} \cdot 1,44^2 = 2011\,kg \cdot m^2 \tag{3}$$

To simplify the calculations, we also assume that the weight of all parts and rotary actuators on the E1 axis and the angular axis of the E2 is equal to $G_{E1,2} = 17000\,N$. This weight is concentrated at one point in the distance $L_2 = 0.3\,m$ from axis E3. Then the moment of inertia of these moving masses of the antenna is

$$I_{E1,2} = \frac{G_{E1,2}}{g} \cdot (L_2)^2 = \frac{17000}{10} \cdot 0,3^2 = 153\,kg \cdot m^2 \tag{4}$$

Total moment of inertia is

$$I_{\Sigma} = I_{mir} + I_{E1,2} = 2011 + 153 = 2164\ kg \cdot m^2 \quad (5)$$

Dynamic moment on the E3 axis during its rotation with acceleration $\varepsilon_{E3} = 1\text{deg}/s^2 = 0.017 s^{-2}$ will be equal to

$$T_{dyn} = I_{\Sigma} \cdot \varepsilon_{E3} = 2164 \cdot 0,017 = 36,8\ Nm \quad (6)$$

Weight moments T_G depend on the weight of individual antenna components and can reach fairly large values in large systems. However, during azimuth mounting, the weight loads are directed parallel to the azimuth axis. For this calculation, this is the E3 axis. In this case, the weight moment is $T_G = 0$

The wind load on the working surface of the antenna mirror from the wind flow is calculated by the formula:

$$F_{wind} = \alpha \frac{\rho \cdot V^2}{2} S \quad (7)$$

where α – coefficient of the aerodynamic resistance; ρ – wind flow density; V – wind speed; S – antenna mirror area. For mirror diameter $D = 5\ m$ at maximum wind speed $V = 25\ m/s$ the wind load is $F_{wind} = 11000\ N$.

It is known that the maximum moment from the wind load relative to the azimuth axis E3 will act when the tilt of the focal axis to the air flow at an angle of 60^0. The lateral wind load in this position is equal to half of the full wind load F_{wind}, and the point of application is the central point of the half of the mirror. Then the aerodynamic moment from the wind loads is

$$T_{wind} = \frac{F_{wind}}{2} \cdot \frac{D}{4} = \frac{11000 \cdot 5}{8} = 6875\ Nm \quad (8)$$

Total torque on the azimuth axis E3 is

$$T_{E3} = T_{dyn} + T_G + T_{wind} = 36,8 + 0 + 6875 = 6912\ Nm \quad (9)$$

To implement such torque on the E3 axis, a rotary mechanism WD-H 0490/3 from "IMO" company is used. The torque on the output shaft of this mechanism can reach 49.5 *kNm*. When we use a double drive with two electric motors, the torque is doubled. Gear ratio of the mechanism is $i_{WD} = 40$.

The choice of this standard size with the increased torque is explained by convenience of its installation on a bearing column of a basic and rotary platform. The diameter of the cylindrical column is 630 mm, which coincides with the diameter of the centres of the mounting holes of the drive. This allows you to simplify its installation on the column without additional components and devices.

To ensure a given speed of rotation along the axis E3, it is necessary to perform a kinematic calculation of the drive shown in fig. 3.

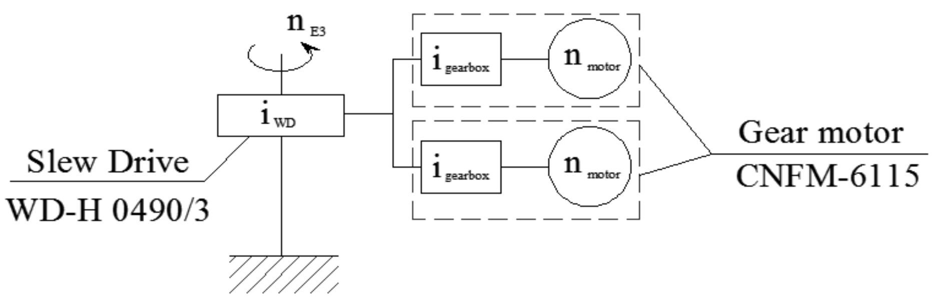

Fig. 3 Rotary drive with two motors

The calculation is based on the average speed $n_{E3} = 5\frac{\text{deg}}{s} = 0.83\ rpm.$ Maximum speed $n_{E3\ max} = 8\frac{\text{deg}}{s} = 1.33\ rpm$ will be provided with frequency control of the rotational speed of the selected induction motor. As such motor we accept the 4-pole asynchronous electric motor with speed of rotation $n_{motor} = 1400\ rpm$. Such electric motors are well usable to frequency control of speed. Then the required gear ratio of the intermediate gearbox is equal to

$$i_{gearbox} = \frac{n_{motor}}{i_{WD} \cdot n_{E3}} = \frac{1400}{40 \cdot 0,83} = 42,2 \tag{10}$$

The minimum power of the electric motor is calculated by the formula:

$$N_{monor\ \min} = \frac{T_{E3} \cdot \omega_{E3}}{\eta_{WD} \cdot \eta_{gearbox}} = \frac{6912 \cdot 0,83 \cdot 2 \cdot \pi}{60 \cdot 0,6 \cdot 0,8} = 2085\,W \tag{11}$$

Since the used rotary mechanism WD-H 0490/3 is double (it has two motors), and we accept two 4-pole asynchronous motors with a capacity of 1.1 kW. For such scheme the motor-reducer CNFM-6115 of the «SUMITOMO» company with a power of 1.1 kW, with the planetary reducer of the increased accuracy and with a gear ratio is optimally suitable $i_{gearbox} = 32.8$. The maximum torque on the output shaft is $T_{gearbox} = 304\ Nm$.

Maximum speed on the axis $n_{E3max} = 1.33\ rpm$ E3 is achieved by increasing the speed of the motor

$$n_{motor\ \max} = n_{E3\max} \cdot i_{WD} \cdot i_{gearbox} = 1,33 \cdot 40 \cdot 32,8 = 1745\ rpm \tag{12}$$

For this speed, the motor is accelerated by increasing of the current frequency to 62.3 Hz using a frequency control device.

It should be noted that the used rotary devices, among other things, also perform the function of the backlash mechanism [9-11] . In these devices, one worm wheel 1 is driven by two worms 2 and 3. So these worms are driven by two motors 4 and 5 (with gearboxes 6 and 7), as it is shown in fig. 4.

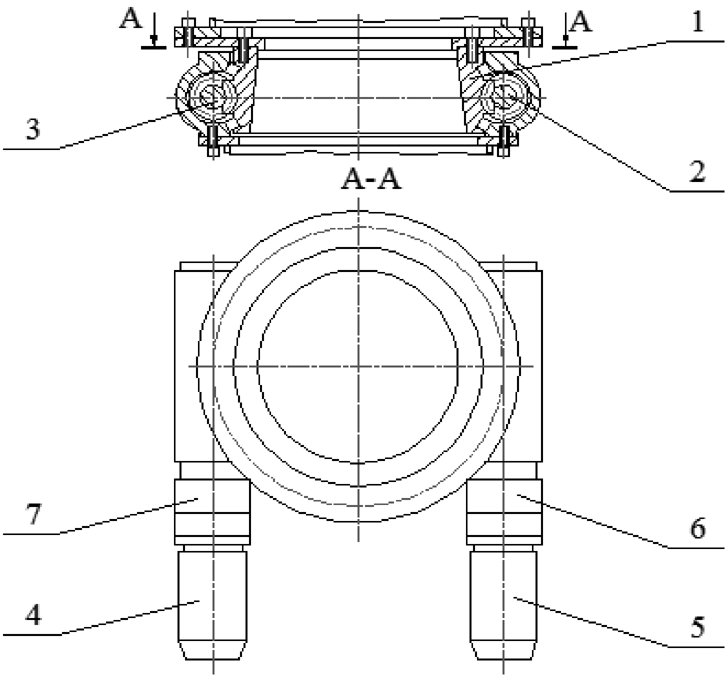

Fig. 4 Modular sealed rotary mechanism with double drive

They are identical and can work in parallel and synchronously. However, as we know, there are no absolutely identical mechanisms. As practice shows, the torques and friction losses (efficiency) of both drives, although slightly, will be different. Then, due to the difference in torques on the drive worms of both drives, the lateral clearances (dead travel) in the engagement between the turns of the worm wheel 1 and two worms 2 will be selected. These clearances are directly transmitted to the antenna axis. Therefore, their elimination significantly increases the accuracy of working of the aiming angles along this axis.

To modulate the antenna mirror relative to the other two axes E1 and E2, the similar modular rotary actuators 2 and 3 of the company "IMO" are used (fig. 1).

3. Conclusions

The presence of the third axis in the support-rotating platform of the antenna system makes it possible to follow the trajectory of the satellite, which passes through the zenith, relative to the coordinates of the antenna without "dead zones". At the same time communication with the satellite for any directions of its movement is not lost.

The use of modern sealed modular rotary mechanisms, which is ready for installation, in the construction of the support-rotating platform allows to simplify the design of the platform. There is no need to install a number of elements and mechanisms that are already present in these drive mechanisms, such as angle sensors, manual drive, and backlash sampling. As a result, the cost of the structure was reduced. The installation and repair process was simplified.

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