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MODERNIZATION OF THE AZIMUTH DRIVE DESIGN FOR THE ANTENNA SYSTEM

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Abstract. *This paper presents the results of modernization an improved design of the azimuth drive, in which reliable and inexpensive asynchronous electric motors with frequency control of rotation speed and planetary gearboxes, which are serially manufactured by domestic enterprises, are used as engines. The use of the developed azimuth drive allows to quickly and relatively inexpensively restore the performance of the antenna system, as well as increase the speed of pointing along the azimuth axis from 4 degrees/s to 15 degrees/s, significantly simplify the design and reduce the weight of the drive.*

Key words: *satellite antenna, azimuth axis, asynchronous electric motor, torque, rotation speed.*

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1. INTRODUCTION

The design of high-precision systems to control massive objects for their pointing at specified coordinates, as well as tracking and following the trajectories of moving objects is an urgent task for many branches of mechanical engineering and defence. The devices for moving the antennas along the azimuthal and angular axes which are intended for fast and accurate pointing of the reflector beam and tracking of space objects by the antenna system are important elements of such systems. Therefore, it is an urgent task to design electromechanical drives using relatively inexpensive domestic mechanisms (frequency-controlled asynchronous electric motors, reduction drives) that can provide fast and accurate pointing of the antenna over a wide range of speeds.

The design and calculation of electric drives for large-diameter antennas are characterised by significant geometric dimensions of the reflectors [1] and, accordingly, large moments of inertia on the shafts of electric drives, wind loads, changes in moments due to the angles of rotation and tilt of the antenna reflector, etc. [2, 3].

During the modernisation of the azimuth drive of the «Crystal-5» antenna system, we analysed a number of papers on improving the design of similar systems. We focused on studies related to improvement of the efficiency of azimuth drives and their adaptation to modern requirements.

A considerable part of the studies focuses on the usage of modern frequency-controlled electric motors to ensure smooth and accurate pointing of the antenna along the azimuth axis. For example, papers [4–6] show that the introduction of frequency-controlled asynchronous motors can not only improve the reliability of the drive but also reduce the cost of its maintenance and operation.

The studies presented in [7, 8] demonstrate the effectiveness of using planetary reduction drives, which provide high torque transmission accuracy with minimal dimensions and weight of the mechanism. In particular, it is indicated that planetary reduction drives have a significantly higher efficiency compared to traditional reduction drives, which reduces energy losses and improves the dynamic characteristics of the drive.

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As for reducing backlash in gearing, several authors [9–11] emphasise the importance of synchronising the operation of two identical drives to minimise the side clearances. This reduces the influence of backlash and improves the accuracy of antenna pointing, which is critical for radio monitoring and space communication systems.

Thus, the analysis of the available research results confirms the feasibility of introducing modern frequency-controlled asynchronous motors and planetary reduction drives into the construction of the azimuth drive [12, 13]. In addition, the synchronous operation of two identical drives is an effective solution for backlash compensation, which makes it possible to simplify the overall design and increase its reliability [14, 15].

The authors have developed a design of the electromechanical drive of the «Crystal-5m» antenna system around the azimuth axis using three-phase frequency-controlled electric motors, which will restore the performance of the regular construction and reduce its cost while increasing the pointing speed along the AZ axis to 15 deg/s.

The «Crystal-5m» antenna systems have been in operation since the late 80s of the last century, and during this period some of their nodes and mechanisms have exhausted their useful life or completely lost their performance. In addition, the development of space communication systems, radio monitoring, etc. has made it necessary to improve some of their technical characteristics. In this case, it is necessary to increase the rotation speed around the AZ axis from 4 deg/s to 15 deg/s and develop a new azimuth drive design, as the standard planetary reduction drive, which was designed specifically for this antenna, has failed and is currently expensive and impractical to restore. The initial data required for the design are given in Table 1.

Table 1

Initial data for design

Maximum rotational speed along the AZ axis	$n_{AZ\ max}$	15 degree/s
Minimum speed along the AZ axis	$n_{AZ\ min}$	4′/s
Pointing limits along the AZ axis		±270 degree
Maximum acceleration along the AZ axis	ε_{AZ}	5 degree/s^2
Gear ratio of the standard spur gear transmission	I_{34}	17,55

2. KINEMATIC CALCULATION OF THE AZIMUTH DRIVE

Figure 1 shows the kinematic diagram of the designed rotation drive for the «Crystal-5m» antenna around the azimuth axis (AZ), further referred to as the «azimuth drive».

A number of mechanical assemblies in the drive remain unchanged as compared to the standard design: 4 – gear wheel with the diameter of d_4=1790 mm; 3 – spur gear with the diameter of d_3=102 mm. However, according to the technical specification, instead of the «DBN-185-16-0.3-2» torque motor, we used a domestic inexpensive and reliable asynchronous electric motor 1 with a speed sensor, electromagnetic brake and frequency control. A planetary gearbox 2 is used to provide the speed range along the AZ axis required by the technical specification.

The side clearance (backlash) in the gearing 3–4 of the azimuth drive is transmitted to the AZ axis and therefore significantly affects the kinematic accuracy of the pointing angles along this axis. To eliminate this backlash, the standard design includes a special backlash-reducing mechanism with a torsion shaft, an electromagnetic friction brake, and two bevel reduction drives. In practice, such a mechanism is not very reliable, it complicates the design of the drive and adds to its cost.

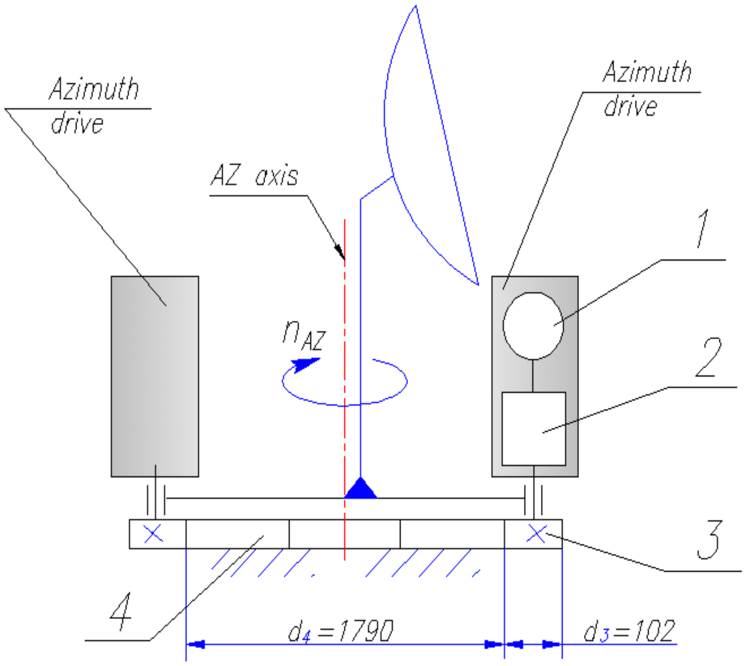

Figure 1. Kinematic scheme of the azimuth drive

In the devised design, two identical drives are used to rotate the antenna rotator along the AZ axis, which operate synchronously and in parallel. However, since there are no identical mechanisms, the friction losses and torques of these drives, in practice, will differ slightly, but not significantly. In this case, the side clearances in the gearing 3–4 between the two gears 3 and the gear wheel 4 will be selected due to the difference in torques on the gears 3 of the two drives. In fact, these two drives operating in parallel, in addition to their main purpose, serve as a backlash-selecting mechanism.

The main kinematic characteristics of the standard gears 3 and 4 used in the designed drive are as follows:

– 3 is a cylindrical gear with a dividing diameter of d_5=102 mm and a module m=6 mm;

– 4 is a cylindrical wheel with a dividing diameter of d_6 = 1790 mm and a module m = 6 mm;

According to the technical specification, the maximum speed along the AZ axis should be increased to $n_{AZ\ max}$ = 15 degree/s = 2.5 rpm. The minimum speed along this axis is $n_{AZ\ min}$ =4′/s = 0,011 rpm.

An asynchronous 6-pole electric motor with a rotational speed of $n_{en.\ nom}$ = 920 rpm at a rotating field frequency of 50 Hz is used as the azimuth drive motor. The speed of rotation of such motors is amenable to frequency control in the range of 2...75 Hz, and with the use of a shaft speed sensor (incremental encoder), these limits can be significantly expanded.

Let’s find the gear ratio of reduction drive 2 to provide a maximum speed along the axis AZ $n_{AZ\max}$ =2,5 rpm. Let’s assume that the motor will be supplied with a maximum supply frequency of 75 Hz, which will result in a speed of $i_{en(75)} = 920\frac{75}{50} = 1380$ rpm. Then the total gear ratio of the azimuth drive is

$$i_{AZ.\Sigma} = \frac{n_{\text{en}\,(75)}}{n_{AZ\max}} = i_{34} \cdot i_2. \qquad (1)$$

Hence the gear ratio of the reduction drive 2 is

$$i_2 = \frac{n_{\text{en}\,(75)}}{n_{AZ\,\max} \cdot i_{34}} = \frac{1380}{2,5 \cdot 17,55} = 31,45. \tag{2}$$

Let's take a domestically produced two-stage planetary reduction drive 3MPM-50 with a gear ratio of $i_2 = 31,5$. The total gear ratio of the azimuth drive with such a reduction drive is

$$i_{AZ.\Sigma} = i_{34} \cdot i_2 = 17,55 \cdot 31,5 = 552,8. \tag{3}$$

The minimum speed along the AZ axis $n_{AZ\ min} = 4^{/} / \text{s} = 0,011\ \text{rpm}$ will be achieved at the electric motor speed of $n_{en.\,min} = 0,011 \cdot 552,8 = 6,08\ \text{rpm}$. It will achieve this speed at the control frequency of the rotating field:

$$f_{\min} = \frac{6,08 \cdot 50}{920} = 0,33\ \text{Hz}\,. \tag{4}$$

The rotational speeds of the upgraded azimuth drive of the «Crystal-5m» AS at different control frequencies of the rotating field of the induction motor are given in Table 2.

Table 2

Rotational speeds along the AZ axis of the modernized drive at different rotating field control frequencies

The frequency of the rotating field in Hz	75	50	25	1	0,33
Motor rotational speed in rpm	1380	920	460	18,4	6,08
Rotational speed along the AZ axis in rpm	2,49 (14,99 degree/s)	1,66	0,83	0,033	0,011 (4′/s)

3. POWER CALCULATION OF THE AZIMUTH DRIVE

Fig. 2 shows the design scheme of the power calculation of the azimuth drive. The minimum calculated torque on the motor shaft $M_{en.min.cal}$ that is required to point the antenna along the AZ axis with the specified parameters (speed, acceleration) is equal to the sum of all resistance moments (counteracting moments) applied to the motor shaft $M_{resist\ given}$: static moments (in this case, friction forces in the supports) $M_{static\ given}$; dynamic moments (inertia forces) $M_{dyn.\,given}$; moments from weight loads $M_{weigt\ given}$; aerodynamic moments (from wind loads) $M_{aer.given}$.

$$M_{en.min.cal} = M_{resist\ given} = M_{static\ given} + M_{dyn.\,given} + M_{weigt\ given} + M_{aer.given}. \tag{5}$$

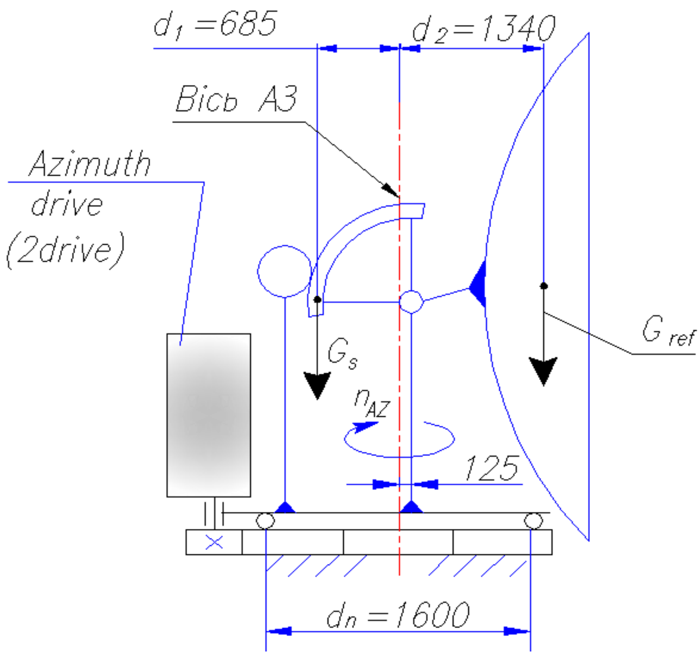

Figure 2. Scheme for power calculation of the azimuth drive

The static moment equal to the frictional moment $M_{fric.bearing}$ in a roller bearing with a diameter of $d_n = 1{,}6\ \text{m}$, is calculated by the formula:

$$M_{fric.bearing} = F_a \cdot f_A \cdot \frac{d_n}{2} = 20000 \cdot 0{,}03 \cdot \frac{1{,}6}{2} = 480\ \text{Hm}, \tag{6}$$

where F_a is the axial load on the bearing, according to the technical specification, the weight of the rotating antenna components is F_a=20000 N; f_A=0.03 is the rolling friction coefficient of the bearing.

The static load moment applied to the motor shaft is

$$M_{static\ given} = \frac{M_{fric.bearing}}{i_{AZ.\Sigma}} = \frac{480}{552{,}8} = 0{,}868\ \text{Hm} \tag{7}$$

When the antenna rotates with acceleration of $\varepsilon_{AZ} = 5\ \text{degree/s}^2 = 0{,}087\ \text{rad/s}^2$, a dynamic load torque M_{dyn} is generated. This moment, applied to the motor shaft, is calculated by the formula $M_{dyn.given} = I_{\Sigma\ given} \cdot \varepsilon_{en}$. Here ε_{en} is the acceleration of the electric motor; $I_{\Sigma\ given}$ is the moment of inertia of the moving masses of the antenna, applied to the motor shaft.

$$I_{\Sigma\ given} = 1{,}5 \cdot I_{rot.en} + \frac{I_{ref} + I_s + I_0}{i_{AZ.\Sigma}^2} = 1{,}5 \cdot 35 \cdot 10^{-4} + \frac{781 + 82{,}1 + 390}{552{,}8^2} = 0{,}0093\ \text{Hm}. \tag{8}$$

In this formula, $I_{rot.en}$ is the moment of inertia of the rotor of the electric motor. Since a particular electric motor has not yet been selected, we take the average value of the rotor moments of inertia for this series of induction motors with a power of 1 to 1.5 kW $I_{rot.en} \approx 35 \cdot 10^{-4}$ кg·m^2.

I_{ref} is the moment of inertia of the antenna mirror relative to the AZ axis. We assume that the mass of the antenna mirror that weighs $G_{ref} = 8700$ H is centered at a point located at a distance of d_2 = 1340 mm from the AZ axis (see Fig. 2). Then $I_{ref} = \frac{1}{2} \cdot \frac{G_{ref}}{g} \cdot (l_2)^2 = \frac{1}{2} \cdot \frac{8700}{10} \cdot 1{,}34^2 = 781\, k\,\text{g} \cdot \text{m}^2$.

I_s is the moment of inertia of the gear section and the angular drive relative to the AZ axis. We assume that the mass of the sector that weighs $G_s = 3500$ H is centered at a point located at a distance of d_1=685 mm from the AZ axis. Then the moment of inertia is $I_s = \frac{1}{2} \cdot \frac{G_s}{g} \cdot (l_1)^2 = \frac{1}{2} \cdot \frac{3500}{10} \cdot 0{,}685^2 = 82{,}1\, k\,\text{g} \cdot \text{m}^2$.

I_0 is the moment of inertia of the other moving parts of the antenna that rotate in relation to the AZ axis. We take them in the form of a disc that weighs $G_0 = G_a - G_s - G_{ref} = 20000 - 3500 - 8700 = 7800$ H and has the diameter of d=2m. The moment of inertia of such a disc is $I_0 = \frac{1}{2} \cdot \frac{G_0}{g} \cdot \left(\frac{2}{2}\right)^2 = \frac{1}{2} \cdot \frac{7800}{10} \cdot \left(\frac{2}{2}\right)^2 = 390\, k\,\text{g} \cdot \text{m}^2$.

Dynamic moment applied to the motor shaft is

$$M_{dyn.given} = 0{,}0093 \cdot 0{,}087 \cdot 552{,}8 = 0{,}447 \text{ Hm}. \quad (9)$$

For this design scheme, the weight moment $M_{weigt\ given}$ will be equal to $M_{weigt\ given} = 0$.

As for the wind loads, since no changes to the design of the mirror of the modernized antenna were made, we assume the maximum moment from wind loads is the same as that used in the design of the «Crystal-5m»: $M_{aer.} = 3100$ Hm at the maximum wind speed of $V = 20$ m/s. Then the torque from the aerodynamic load applied to the motor shaft is

$$M_{aer.given} = \frac{M_{aer}}{i_{AZ.\Sigma}} = \frac{3100}{552{,}8} = 5{,}6 \text{ Hm}. \quad (10)$$

The torque of resistance of all the listed opposing forces applied to the motor shaft is

$$M_{resist\ given} = 0{,}868 + 0{,}447 + 5{,}6 = 6{,}9 \text{ Hm}. \quad (11)$$

The minimum calculated power of the electric motor is

$$M_{en.min.cal} = \frac{M_{resist\ given} \cdot \omega_{en}}{\eta_{AZ.\Sigma}} = \frac{6{,}9 \cdot 96{,}3}{0{,}388} = 1712{,}5 \text{ Watt} \quad (12)$$

In this formula, ω_{en} is the nominal angular speed of the electric motor $\omega_{en} = \frac{\pi \cdot n_{en}}{30} = \frac{\pi \cdot 920}{30} = 96,3 \text{ rad/ s}$; $\eta_{AZ.\Sigma}$ is the energy conversion efficiency of the developed azimuthal drive and it is calculated by the formula

$$\eta_{AZ.\Sigma} = \frac{1}{k_t}\left(\eta_2 \cdot \eta_{34}\right) = \frac{1}{2}\left(0,97 \cdot 0,8\right) = 0,388, \tag{13}$$

where $k_t = 2$ is the temperature coefficient that takes into account the thickening of lubricants in bearings and gears at subzero temperatures; $\eta_2 = 0,8$ is the energy conversion efficiency of the planetary gearbox; $\eta_{34} = 0,97$ is the energy conversion efficiency of the spur gear.

We take an asynchronous 6-pole electric motor «АИР90L6ЕУ3» with flange mounting, with a power of 1.5 kW, with a rated speed of n_{en}=920 rpm and an electromagnetic brake as an electric motor of the developed azimuthal drive. Given that the rotation of the antenna along the AZ axis is realized by two identical drives and, accordingly, two motors operating in parallel (see Fig. 1), we obtain a significant power reserve.

For reliable operation at low speeds (provided by frequency control), the electric motor is additionally equipped with a speed sensor.

4. CONCLUSIONS

The design of the azimuthal drive of the «Crystal-5m» antenna system has been developed using a reliable and inexpensive asynchronous frequency-controlled asynchronous motor and a planetary reduction drive, which are serially manufactured by domestic enterprises. The application of the developed azimuthal drive allows to quickly and relatively inexpensively restore the performance of the «Crystal-5m» antenna system, which has been in operation for more than 30 years, as well as to improve some of its technical characteristics: to increase the pointing speed along the AZ axis from 4 degree/s to 15 degree/s, to significantly simplify the design and reduce the weight of the drive.

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УДК 621.326

МОДЕРНІЗАЦІЯ КОНСТРУКЦІЇ АЗИМУТАЛЬНОГО ПРИВОДА АНТЕННОЇ СИСТЕМИ

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Резюме. *Наведено результати удосконалення конструкції азимутального приводу антенної системи «Кристал-5м», який призначений для наведення рефлектора антени по азимутальній осі. Антенні системи «Кристал-5м» експлуатуються з кінця 80-х років минулого століття і за цей період деякі їх вузли та механізми виробили свій ресурс або повністю втратили працездатність. Крім цього, з розвитком систем космічного зв'язку, радіомоніторингу та ін. виникає необхідність у покращенні деяких їх технічних характеристик. Наведено результати проєктування удосконаленої конструкції азимутального приводу, в якому в якості двигунів застосовані надійні й недорогі асинхронні електродвигуни з частотним керуванням швидкості обертання й планетарні редуктори, які серійно виготовляють вітчизняні підприємства. Застосування розробленого азимутального приводу дозволяє швидко й відносно недорого відновити працездатність антенної системи «Кристал-5м», а також збільшити швидкість наведення по осі AZ з 4 град/с до 15 град/с, суттєво спростити конструкцію та зменшити вагу приводу. В розробленій конструкції застосовано два абсолютно ідентичних приводи, що обертають опорно-поворотний пристрій антени навколо азимутальної осі. Ці приводи працюють синхронно й паралельно. Оскільки абсолютно однакових механізмів не буває, то втрати на тертя й крутні моменти цих приводів, як свідчить практика, будуть, хоч незначно, але відрізнятися. Тоді бокові зазори в зубчастому зачепленні, що обертає антену по осі AZ, будуть вибиратися через різницю крутних моментів на шестірнях обох приводів. Фактично ці два приводи, що працюють паралельно, крім основного призначення виконують ще й функцію люфтовибираючого механізму. Отже, застосування розробленого азимутального приводу дає можливість відмовитися від штатного спеціального люфтовибираючого торсіонного механізму з електромагнітним гальмом і двома конічними редукторами. Це дало змогу суттєво спростити конструкцію приводу, зменшити його вартість і підвищити надійність.*

Ключові слова: *супутникова антена, азимутальна вісь, асинхронний електродвигун, крутний момент, швидкість обертання.*

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