The Ship Motions Effect on the Position Reference of Telescope's Axis Installed on the Deck of a Ship

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*Abstract:*The existing solutions in control of trajectory measurement telescopes installed on a deck of the ship require a gyro-stabilized platform. However, gyro-stabilized platform has bad dynamic characteristics, which influence on the precision of measurements. Therefore, it is necessary to develop a control system without a stabilizing device, which will compensate the ship's motions by precision electric drive of axis itself. Among others, there is a problem of investigating the influence of ship motions on the control system reference signal.

In current research the mathematical model of position reference signal takes includes models of six kinds of ship motions. As a result,the authors have studied the influence of ship motions on the position reference signal for the variety of trajectories where azimuth and elevation are in range of [0 °; + 90 °].

The proposed mathematical model of ship motions allows determining the range of target coordinate, within which the electric drive can provide the required acceleration. The article may be helpful for developers of precision electric drives of sea-based telescopes.

Key-Words: ship motions, precision electric drive, coordinate conversion, telescope on the deck of the ship.

1 Introduction

When constructing modern telescopes, it is necessary to reduce the mechanical subsystem by using embedded electric motors [1 – 4]. It is also actual for development of telescope on the moving basis to abandon gyro-stabilized platform with low dynamic characteristics and to solve stabilize problem by telescope axis electric drive itself [5 – 8].

The telescope mount is installed on the deck of the ship without gyro-stabilized platform. There areship motions with certain parametersin the area where the telescope is planned to be used. It is assumed that the control system of electric motor drive of telescope should provide the specified accuracy in spite of ship motions.Ship motions compensation is provided by electric motor drivewithout additional device.

The purpose of research is to assess the range of valid coordinates of the object under the action of the six types of ship motions [8].

2 Coordinateconversion

To assess ship motions influence on angular coordinates it is necessary to determine mathematical relation of how angular coordinates, connected with ship's coordinate system, vary from ship motions parameters. To perform this task, the origin of coordinate system should be put to the point of intersection of axes of telescope mount. X-axis is parallel to the keel of the ship, the Y-axis passes from one side to the other and Z-axis is perpendicular to the deck.

Let the target coordinates are determined as *A(x,y,z)* in inertial coordinate system. Then point A has *(x′,y′,z′)* coordinates in moving (non-inertial) coordinate system.Whendeterminingdependencies*x′ = f(x,y,z)*, *y′ = f(x,y,z)*and*z′ = f(x,y,z)*all kinds of ship motions are considered independently.

The scheme of pitch is provided at Fig. 1. Angleθ determines the current value of pitching and therefore, the angle between X-axis andX′-axisandZ-axisandZ′-axis.Rotation occurs about the axis Y, which in this case coincides with the axis Y.

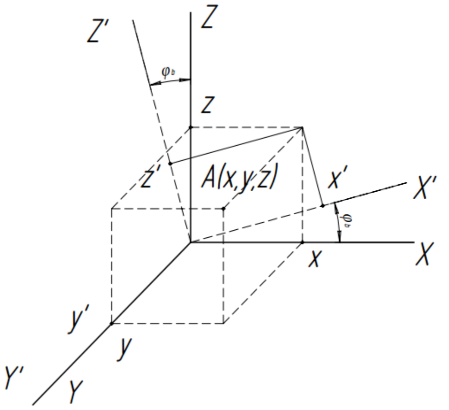

Figure 1. Coordinate conversion at pitching

According to geometric constructions, formulas (1) - (3) were obtained, which transform the inertial coordinate system to the coordinates of the ship (non-inertial).

$x' = x\cos(\psi) + z\sin(\psi)$; (1)

$y' = y$; (2)

$z' = z\cos(\psi) - x\sin(\psi)$; (3)

where $\psi(t) = \Psi\sin(2\pi \cdot t / T_k)$. (4)

Theangle ψ is determined by formula (4), where Ψ ispitching amplitude, T_k ispitching period. The same conversions are valid for roll (5) –(8) andyaw (9) – (12).

$x' = x$; (5)

$y' = y\cos(\theta) + z\sin(\theta)$ (6)

$z' = z\cos(\theta) - y\sin(\theta)$; (7)

where $\theta(t) = \Theta\sin(2\pi \cdot t / T_b)$. (8)

Theangle θ is determined by formula (8), where Θ is roll amplitude, $T_b$is roll period.

$x' = x\cos(\varphi) - y\sin(\varphi)$; (9)

$y' = x\sin(\varphi) + y\cos(\varphi)$; (10)

$z' = z$; (11)

where $\varphi(t) = \Phi\sin(2\pi \cdot t / T_r)$. (12)

Theangle φ is determined by formula (12), where$\Phi$is yaw amplitude, $T_r$is yaw period.

The scheme of heave is provided at Fig. 2. Variable*h* determines the current value of heave and therefore, the Z-axis offset.

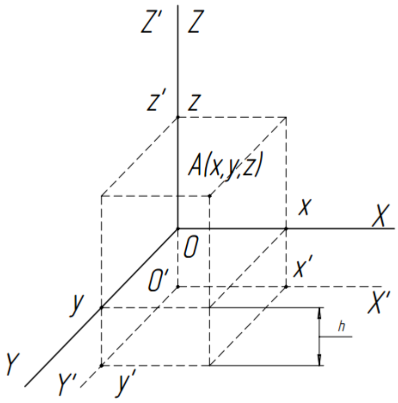

Figure 2.Coordinate conversion at heave

According to geometric constructions, target coordinates in moving coordinate system are determined by formulas (13) - (15)

$x' = x$; (13)

$y' = y$; (14)

$z' = z + h$; (15)

где $h(t) = H\sin(2\pi \cdot t / T_h)$. (16)

The value *h*is determined by formula (16), where *H*is heave amplitude, T_h is heave period. Thesameconversionsarevalidforsurge (17)–(20) andsway (21)–(24).

$x' = x + l_k$; (17)

$y' = y$; (18)

$z' = z$; (19)

где $l_k(t) = L_k\sin(2\pi \cdot t / T_{lk})$. (20)

The value $l_k$is determined by formula (20), where L_k is surge amplitude, T_{lk} is surge period.

$x' = x$; (21)

$y' = y + l_b$; (22)

$z' = z$; (23)

где $l_b(t) = L_b\sin(2\pi \cdot t / T_{lb})$. (24)

The value $l_b$is determined by formula (24), where L_b is surge amplitude, T_{lb} is surge period.

The telescope mount has two rotativeaxis and, therefore, two angular coordinates – azimuth and elevation, which are shown on the Fig. 3. Azimuth is an angle between XOY-plane and Y-axis.

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Elevationisananglebetweentarget radius vector and its projection on XOY-plane.

According to geometric constructions shown at Fig. 3, azimuth and elevation are determined by formulas (25) and (26) respectively.

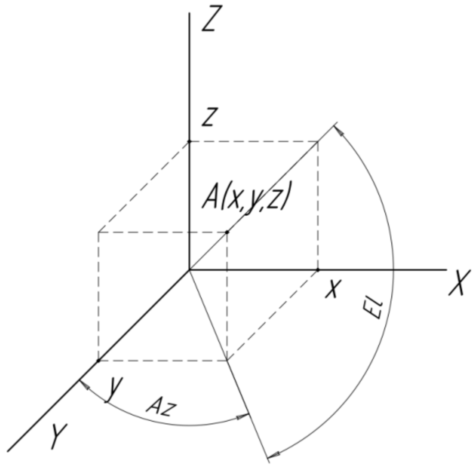

Figure 3. Azimuth (Az) and Elevation (El)

$$Az(x,y)_n = \begin{cases} arctg(\frac{y}{x}), \quad x \geq 0 \\ arctg(\frac{y}{x}) + 180°, x < 0, Az_{n-1} > 0 \\ arctg(\frac{y}{x}) - 180°, \quad x < 0, \quad Az_{n-1} \leq 0 \end{cases} \quad (25)$$

$$El(x,y)_n = arctg(\frac{z}{\sqrt{x^2 + y^2}}) \quad (26)$$

In formula (25) Az_n and Az_{n-1} are current and previous position of azimuth axis respectively. According to formulas (25) and (26),*Az* is a function of *x* and *y*target coordinates. *El* is a function of three target coordinates.

The telescope azimuth axis has rotation range of ±270 ° and the angle sign depends on the previous angle value.

Thus at the positive x-coordinate azimuth axis is located in the zone of unambiguity (first and fourth quadrants), since it is possible to get there only one way. The telescope elevation axis has rotation range of (0 °; +90 °) [6 – 10].

If target elevation is greater than 90 °, then telescope azimuth axis must make a 180 ° turn. That involves a large acceleration and speed of azimuth axis.

3 Ship motions modeling

In the general case, ship motions are a random process with a known spectral density. However, at the first approximation it is possible to describe them as the main harmonic component of each type of ship motions.

When target coordinates are near to zenith an acceleration of azimuth axis increases significantly. That is why it is important to define under which maximum possible values of target elevationthe electric drive of azimuth axiscould provide continuous tracking. The described system has maximum feasible acceleration 15 °/sec^2 and maximum feasible speed 30 °/sec. Acceleration limit is caused by power subsystem capabilities, and speed limit is caused by peculiarities of optical encoders [11].

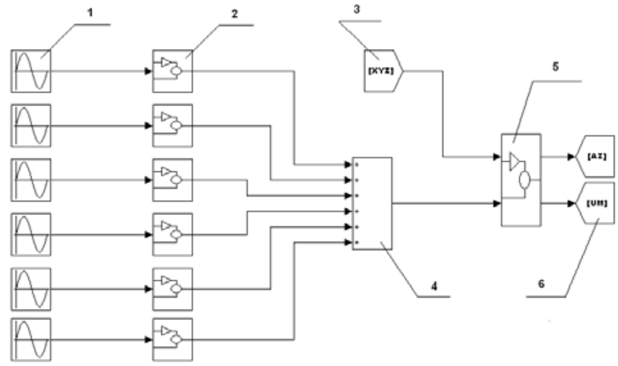

Figure 4.Themodelofshipmotions. 1 – ablockofconcretemotionkind, 2 – ablockofcoordinateconversion, 3 – target coordinates, 4 – a summer of ship motions corrections , 5 – a block of XYZ conversion to angular coordinates, 6 – model output, azimuth and elevation references.

The model of ship motions is shown at Fig. 4. This model isused to investigate the reference input signal at the telescope work mode “standing point”. Using this model, output references could be obtained for each motion separately and for sum of all six ship motions.

To summarize output information, it is necessary to get and save mean values of speed, acceleration and maximum difference of azimuth and elevation references at different target coordinates.

Table 1 contents parameters of ship motions of the sea area, the telescope is planned to be used.

Table 1. Ship motions parameters

№	Kind of motion	Amplitude	Period, sec
1	Roll	10 °	12
2	Pitch	3 °	7
3	Yaw	5 °	15
4	Heave	4 m	9
5	Surge	3.5 m	10
6	Sway	3.5 m	13

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The influence of ship motions is not equal at various target coordinates, because of different amplitude and period of each kind of motion.In other words, ship motions influence depends oncourse of a ship. To get a full picture of ship motions influence on telescope axis reference modeling is provided in azimuth range from 0 ° to + 90 °. For each azimuth angle a moving trajectory is built with defined radius and elevation is in range from 0 ° to + 90 °, passing zenith point.

The surface of maximum accelerations of azimuth axis position referenceis shown on the Fig. 5. When target elevation increases, then accelerations increase too. By the way, when target azimuth is near 0 °, or in other words, is directly ahead of the ship, this increase is the greatest. The given maximum possible accelerations of axis limits the elevation coordinate range at level 75 ° because of telescope power subsystem capabilities.

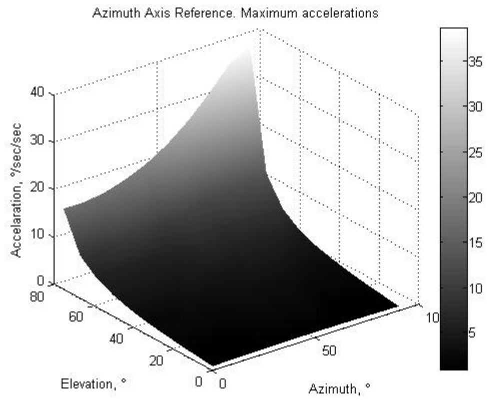

Figure 5. Maximum accelerations of azimuth axis reference

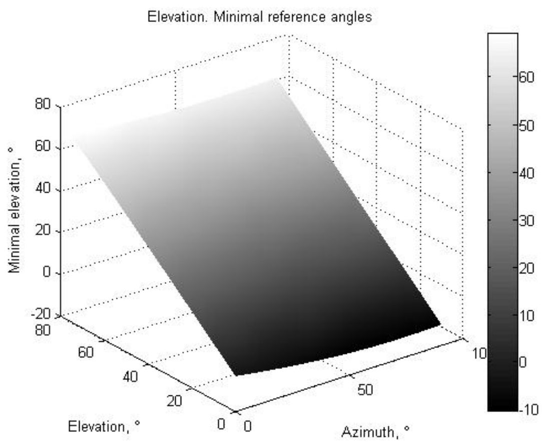

Figure 6. Minimal angles of elevation axis

The surface of minimal reference angles for elevation telescope axisdepending on various target coordinates is shown on Fig. 6. If target elevation is 10 ° and lower in inertial coordinate system, then telescope's elevation axis should rotate on negative angle at some periods of time. That is constructively impossible because of telescope's elevation axis rotation range is limited from 0 ° to 90 °, so that causes the lower limit of elevation reference angle. The lower limit of target elevation angle should be 10 °, because in other way, telescope could not continuously observe a target.

4 Conclusion

Summarizing the analysis of the graphs, it can be concluded that ship motions with specified parameters limit the allowable range of possible positions of the object of observation at range from 10 ° to 75 °. At first, limitation is due to the fact that, when target elevation coordinate is close to the zenith, then velocity and acceleration of position reference of the azimuth axis increases tenfold. The power subsystem cannot fulfill the required acceleration, and so, the entire system becomes inoperable at all.Secondly, when the target elevation is near 0 °the telescope's elevation axis must turnto a negative angle, that is constructively impossible.

The modeling was performed for the variety of target trajectories in the range from 0 ° to + 90 ° in azimuth and elevation. Mode "standing point" has been worked out at each point of the trajectory to determine the maximum and mean of dynamic parameters of telescope's axes.

The proposed mathematical model of ship motions could be used to determine the reduction of range of coordinates of the observed object, in which the electric drive can provide the required acceleration and movement of telescopes axes and, as a consequence, provide continuous tracking.

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