TRANSPORT SYSTEMS

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TWO-AXIS GIMBALED COURSE SYSTEM FOR MARINE VEHICLES

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Abstract*—*The control features of the small-dimension precision autonomous navigation system for marine vehicle course determination are considered. The list of the studied system operating modes is represented. The expressions for control moments determination are derived. The simulations results proving efficiency of the represented data-ware are given.

Index Terms—Gimbaled system; precision autonomous navigation system; control moments; operating modes.

I. INTRODUCTION

Development of marine vehicles causes rigid requirements to navigation systems, which provide the vehicle attitude and heading determination. Such systems must have improved functional possibilities and decreased mass and dimensions at the same time. There are known two types of systems used for vehicle navigation such as gimbaled and strapdown ones. Systems of both types are based on principles of inertial navigation. Unbounded field of application, high noise-immunity, autonomous determination of navigation parameters, high accuracy in conditions of limited operation time are advantages of such systems.

Nowadays strapdown systems are the most widespread in navigation. The gimbaled systems are used only in the cases, when the main purpose is achievement of the highest accuracy in conditions of autonomous operation.

Disadvantages of gimbaled systems are increasing of errors with time that needs using the correction devices, complexity, the necessity employing the high-precision measuring devices, the high design and maintenance cost, and, at last but not at least, the highly qualified personnel is required to service this equipment.

Although gimbaled navigation systems have some advantages such as relatively simple algorithms for processing the attitude and the linear acceleration data; high accuracy, caused by the comfortable conditions of operation of the measuring devices, since they are mounted at the gyrostabilized platform but not directly at the case of the object [1]. This paper deals with gimbaled inertial navigation systems, which are able to provide autonomous precision determination of the attitude and heading of the marine vehicle.

One of the ways for creating an effective precision autonomous course system is usage of the dynamically tuned gyros, which differ by their low mass, size and power consumption. Therefore, their usage can improve the operation characteristics of the system in comparison with traditional electro-mechanical gyros and reduce the system cost. Taking into account constantly growing requirements to system mass and dimensions reduction, it is convenient to use a platform with two-axes gimbals instead of the traditional three-axes gimbals. Usage of the dynamically tuned gyros and two-axes gimbals for navigation problem solving has some peculiarities relative to control implementation.

II. STATEMENT PROBLEM

The researched system represents a two-axes gimbaled platform with mounted on it navigation sensors such as two dynamically tuned gyros and two accelerometers. These gyros carry out functions of the vertical gyro and directional gyro correspondingly. The principal axis of the vertical gyro is aligned in the direction of the local vertical line by means of accelerometers. The integral correction is used to make the system undisturbed by the external accelerations caused by the vehicle motion. The directional gyro is mounted on a rotary device which is stabilized in the given plane by the signals of the vertical gyro. The directional gyro can be used as a pointer of motion direction if stabilization of a platform is provided in the plane of the meridian. The scheme of the studied system is represented in Fig. 1.

Considerable attention to peculiarities of usage of the dynamically tuned gyros used in systems of such type is given in [1], [2]. Features of two-axis gimbaled system for attitude and heading determination are analyzed in [3]. But peculiarities of control and correction moments forming still need detailed description.

Such peculiarities first of all are represented by separation of control and correction functions. Control by location of the vertical gyro principal axis is implemented by signals of accelerometers. Stabilizing engines provide agreement of position of normal to the stabilized platform with the direction of the dynamically tuned gyro rotor. Such division of

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In the mode of "switch on" the computing device tests are carried out and the signals "norms" are analyzed. If results of these checks are negative, the information about failure is forming.

In the mode of previous leveling the platform is set in the plane of the local horizon by signals of accelerometers, taking into consideration known values of the temperatures drifts and systematical errors

$$\begin{aligned} A_x^{'} &= A_x - |a_{sysx}|\,\mathrm{sign}a_{sysx} - |a_{xt}|\,\mathrm{sign}a_{xt}; \\ A_y^{'} &= A_y - |a_{sysy}|\,\mathrm{sign}a_{sysy} - |a_{yt}|\,\mathrm{sign}a_{yt}, \end{aligned} \tag{1}$$

where A_x, A_y are accelerometers signals; a_{sysx}, a_{sysy} are values of the systematical errors (drifts); a_{xt}, a_{yt} are values of the temperature drifts.

Forming of the control moments applied to the platform torque motors by the axis x, y is implemented based on (1) in the following way

$$\begin{aligned} M_x &= k_1 A_y^{'} + k_{g1}\dot{\theta}; \\ M_y &= k_2 A_y^{'} + k_{g2}\dot{\gamma}, \end{aligned} \tag{2}$$

where k_1, k_2 are gains; $\dot{\theta} = \theta / \Delta t$, $\dot{\gamma} = \gamma / \Delta t$ are angular rates of turns by the longitudinal and lateral axes of the platform and of the marine vehicle correspondingly (such mutual location of the vehicle and of the course system platform is provided before system operation); Δt is time of the platform turn.

Finally, control currents are defined based on the expressions (2)

$$\begin{aligned} I_x &= M_x / k_{tm}; \\ I_y &= M_y / k_{tm}, \end{aligned} \tag{3}$$

where k_{tm} is a gain slope of the torque motor characteristic.

The mode of calibration of the vertical gyro is carried out against a background of the previous leveling mode. Calibration is based on turns of the rotary unit, on which the vertical gyro is mounted, under action of the control moments forming in the computing device. These moments provide rotation of the platform with the angular rate $\dot{\psi}_{giv}$ = 2deg/s. During this rotation measurements of the Earth angular rate projections onto the measuring axes of the vertical gyro (ω_x, ω_y) are carried out at instants of time corresponding to turns of the platform at angles $0°, 10°, ..., 360°$. Calculation of the vertical gyro drifts $\dot{\alpha}_{dr}$, $\dot{\beta}_{dr}$ during calibration is carried out by the following algorithm

$$\begin{aligned} \Delta x_i &= \frac{\omega_{xi} + \omega_{x(i+18)}}{2}; \qquad \Delta x_i = \frac{\omega_{yi} + \omega_{y(i+18)}}{2}; \\ \Delta x_i &= \frac{\omega_{yi} + \omega_{y(i+18)}}{2}; \qquad S_y = \sum_{i=1}^{18} \Delta y_i; \\ \dot{\alpha}_{dr} &= S_x / 18; \qquad \dot{\beta}_{dr} = S_y / 18. \end{aligned} \tag{4}$$

After stopping the vertical gyro calibration against a background of the previous leveling mode the calibration of the directional gyro is implemented. In this mode the platform is rotated with the angular rate 1 deg/s under action of the control moment forming in the computing device. At the fixed instants of time (90 s, 180 s, 270 s correspondingly) the values of the angles ψ are measured and appropriate values of the drifts and errors of the angles ψ measurement are calculated.

After termination of calibration the directional gyro begins to carry out the mode of the initial alignment. In this mode the turn of the directional gyro sensitivity axis in the direction of the meridian plane is implemented.

Calculation of the angle of misalignment between the directional gyro sensitivity axis and the meridian plane is carried out by the components of the Earth angular rates, measured by the vertical gyro. As in this course system the dynamically tuned gyro as a vertical gyro is used, such measurements require to switch this device in the mode of the angular rate measurement. In this case location of the platform relative to the geographical reference frame will be estimated by values of projections of the vector of the Earth angular rate Ω onto the horizontal plane

$$\mathrm{tg}k_p = \omega_x / \omega_y . \tag{5}$$

As a rule, for course systems of such type, ten measurements are carried out during three minutes and average values of angular rate ω_x, ω_y and angle k_p using (5) are calculated.

Direction of rotation of the directional gyro on the angle k_p is defined by the relationships

$$\begin{aligned} k_p &= k_p^a - 180° \ \text{ for } \ \omega_x^a \le 0, \omega_y^a \le 0; \\ k_p &= 180° - k_p^a \ \text{ for } \ \omega_x^a > 0, \omega_y^a \le 0; \\ k_p &= -k_p^a \ \text{ for } \ \omega_x^a \le 0, \omega_y^a > 0; \\ k_p &= k_p^a \ \text{ for } \ \omega_x^a > 0, \omega_y^a > 0. \end{aligned} \tag{6}$$

Turn at the angle k_p is implemented by the rotary unit, on which the directional gyro is mounted. Ter-

mination of the turn may be determined using relationships

$$\psi \le |k_p| \quad \text{for} \quad \omega_y^a \ge 0; \qquad \psi \le 180^\circ - k_p \quad \text{for} \quad \omega_y^a < 0. \tag{7}$$

After termination of the initial alignment the mode of the precise leveling of the platform becomes functioning. In this mode the vertical gyro based on the dynamically tuned gyro is switched on in the mode of the angle measuring instrument.

Precise leveling of the platform is implemented by the algorithm of the non-disturbed inertial vertical with the integral correction. The control moments, which are applied to the platform stabilizing engines, are determined by the following expressions

$$M_x = k_{st1}\theta_g + k_{r1}\dot{\theta}_g; \quad M_y = k_{st2}\gamma_g + k_{r2}\dot{\gamma}_g, \tag{8}$$

where $k_{st1}, k_{st2}, k_{r1}, k_{r2}$ are transfer constants, θ_g, γ_g are angles of the pitch and roll entering from the vertical gyro; $\dot{\theta}_g = \dfrac{\theta_{g_k} - \theta_{g_{k-1}}}{\Delta t}$; $\dot{\gamma}_g = \dfrac{\gamma_{g_k} - \gamma_{g_{k-1}}}{\Delta t}$; Δt is time of the control cycle.

The correction moments in the precise leveling mode are defined by the necessity to carry out the integral correction, which provides non-disturbance of the vertical. The moments of the integral correction are described by the following formulas

$$M_{x1} = \frac{H_1}{R_2}\int_0^{\Delta t} \dot{v}_x dt; \quad M_{y1} = \frac{H_1}{R_1}\int_0^{\Delta t} \dot{v}_y dt, \tag{9}$$

where H_1 is the kinetic moment of the vertical gyro; R_2, R_1 are the principal radiuses of the Earth ellipsoid curvature in the meridian plane and perpendicular to it plane;

$$\dot{v}_x = A_x^{'} - \Delta W_1^x - \Delta W_2^x; \quad \dot{v}_y = A_y^{'} - \Delta W_1^y - \Delta W_2^y, \tag{10}$$

where $A_x^{'}, A_y^{'}$ are phantom accelerations of the platform, $\Delta W_1^x, \Delta W_2^x, \Delta W_1^y, \Delta W_2^y$ are corrections due to action of the acceleration of translation and the Coriolis acceleration calculated in the computing device.

The correction moments due to the Earth rotation may be determined by the expressions

$$M_{x2} = H_1\Omega\cos\varphi\cos\theta_g; \qquad M_{y2} = H_1\Omega\cos\varphi\sin\theta. \tag{11}$$

The correction moments compensating the systematical components of the vertical gyro drift are calculated in the computing device by the formulas

$$M_{x3} = k_{dr1}\dot{\alpha}_{dr}; \quad M_{y3} = k_{dr2}\dot{\beta}_{dr}, \tag{12}$$

where $k_{dr1} = k_{dr2} = H_1$.

The moments of correction by the external information (from the log) may be determined using the relationships

$$M_{x4} = k_{l1}\int_0^{\Delta t} \frac{v_{lx} - v_x}{R_2} dt; \qquad M_{y4} = k_{l2}\int_0^{\Delta t} \frac{v_{ly} - v_y}{R_1} dt, \tag{13}$$

where k_{l1}, k_{l2} are the transfer constants by the log information.

The correction moments, which are forming in the computing device and entering to the torque motors of the vertical gyro based on expressions (9) – (13), are determined in the following way

$$M_{tmx} = \sum_{i=1}^{4} M_{xi}; \qquad M_{tmy} = \sum_{i=1}^{4} M_{yi}. \tag{14}$$

Setting of the directional gyro sensitivity axis in the direction of the meridian is implemented by the turn under action of the control moment

$$M_A = k_1\psi + k_2\dot{\psi}, \tag{15}$$

where k_1, k_2 are transfer constants.

The correction moments for the directional gyro are formed in the computing device in the following way

$$M_x = \sum_{i=1}^{3} M_{xi}; \qquad M_z = \sum_{i=1}^{3} M_{zi}, \tag{16}$$

where $M_{x1} = -k_{10}\theta_A$; $M_{z1} = -k_{11}\theta_A$ are components of the pendulum and damping moments based on information about deviation of the directional gyro from the platform; $M_{x2} = k_{12}A_y / g$; $M_{z2} = k_{13}A_y / g$ are components of the pendulum and damping moments based on accelerometers signals;

$$M_{x3} = H_1\left(\frac{v_x\sin\psi + v_x\cos\psi}{R_1}\right)\mathrm{tg}\varphi + \Omega\sin\varphi;$$

$$M_{z3} = H_1\left(\frac{v_y\sin\psi + v_x\cos\psi}{R_1} - \frac{v_y\cos\psi - v_x\sin\psi}{R_2}\right)$$

are moments correcting influence of the Earth rotation and the vehicle motion.

Decrease of the time of the directional gyro setting to the meridian plane may be ensured due to change of the transfer constant of the damping moment.

The studied course system may operate in the modes of the gyro compass, gyro azimuth and short-time precision gyro azimuth depending on the given control command, which enters from the computing device. The main task of the course system operation in all these modes is ensuring of the platform angular rates corresponding to the angular rates of the geographical reference system turns taking into consideration the Earth diurnal rotation and the vehicle motion [7]

$$\omega_{xg} = -\frac{v_N}{R_2} = -\dot{\varphi};$$

$$\omega_{yg} = \Omega\cos\varphi + \frac{v_E}{R_1}; \qquad (17)$$

$$\omega_{zg} = \Omega\sin\varphi + \frac{v_E}{R_1}\mathrm{tg}\varphi.$$

Solving of this task provides comfortable conditions for operation of the vertical gyro and the directional gyro.

Taking into consideration that in the studied course system the platform is oriented relative to the vehicle trajectory reference frame and correspondingly is turned with the vehicle course change, the projections of the platform onto its own axes taking into consideration (17) may be defined by the following expressions

$$\omega_x = \omega_{xg}\cos\psi + \omega_{yg}\sin\psi;$$

$$\omega_y = -\omega_{xg}\sin\psi + \omega_{yg}\cos\psi;$$

$$\omega_z = \omega_{zg}.$$

The vehicle object linear speeds v_N, v_E in the geographical reference frame may be described by the following formulas

$$v_N = v_x\sin\psi + v_y\cos\psi;$$

$$v_E = v_x\cos\psi - v_y\sin\psi.$$

IV. SIMULATION RESULTS

Results of studied system simulation are shown in Figs 3 – 5 [8].

Above stated relationships (3), (4), (6) – (8), (14) – (16) are used for forming of the moments by control the vertical gyro and directional gyros that provides non-disturbance and damping of the system.

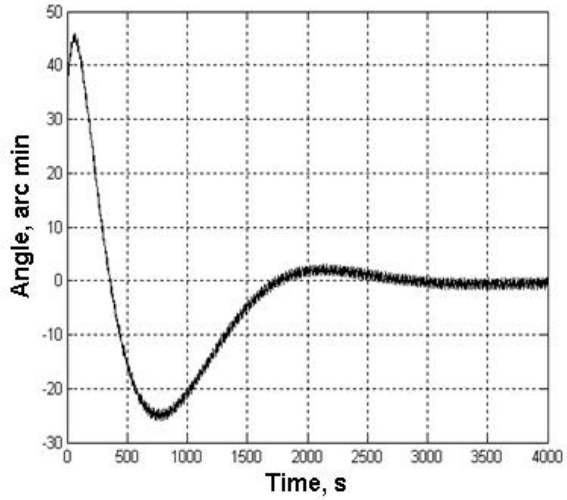

Fig. 3. Stabilization of the platform under influence of sea regularities

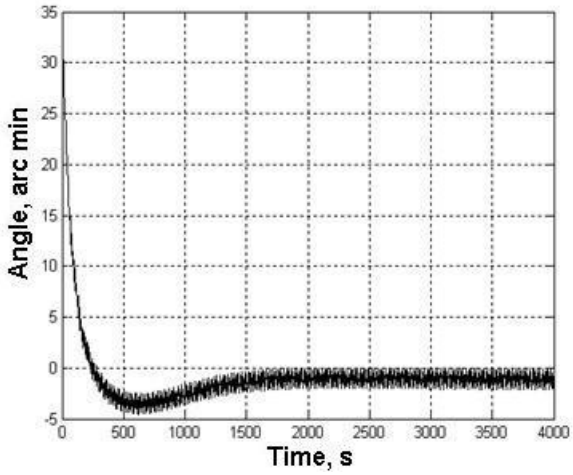

Fig. 4. Stabilization of the platform under influence of sea regularities(amplitude is 12 deg/s)

The possibilities of integral correction are characterized by Fig. 5.

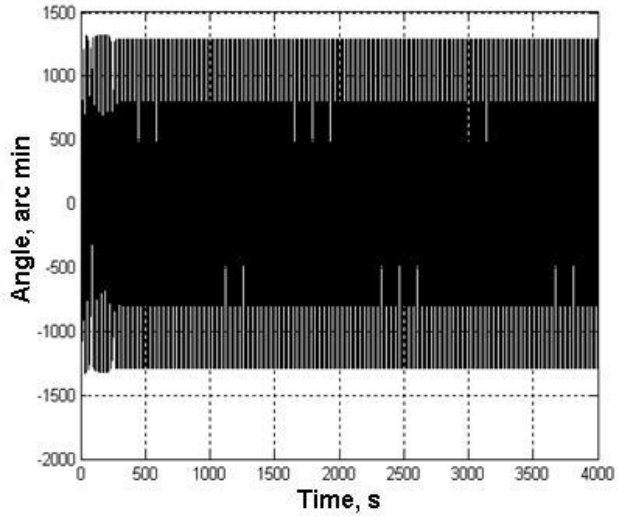

Fig. 5. Operation of the system without integral correction under action of the vehicle accelerations

CONCLUSIONS

As result of carried out researches the basic peculiarities of control by the two-axes course system were considered. The basic operating modes of the system were described. The control and correction moments for every operating mode were derived. The simulation results proving efficiency of the derived expressions were represented.

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О. А. Сущенко. Двовісна платформна курсова система для морських рухомих об'єктів

Розглянуто особливості керування малогабаритною високоточною автономною навігаційною системою для визначення курсу морських рухомих об'єктів. Представлено перелік робочих режимів системи, що досліджується. Отримано вирази для визначення моментів керування. Надано результати моделювання, що підтверджують ефективність запропонованих алгоритмів функціонування.

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О. А. Сущенко. Двухосная платформенная курсовая система для морских подвижных объектов

Рассмотрены особенности управления малогабаритной высокоточной автономной навигационной системой для определения курса морских подвижных объектов. Представлен перечень рабочих режимов исследуемой системы. Получены выражения для определения моментов управления. Приведены результаты моделирования, которые подтверждают эффективность предложенных алгоритмов функционирования.

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