Analysis of indirect stabilization system errors in a sea gravimeter

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Abstract. A system of sea gravimeter indirect stabilization is presented. Mathematical modeling is carried out, and the main errors of the indirect stabilization system are studied, using strapdown inertial navigation system output data.

Introduction

A number of research and applied problems can only be solved with known highly precise gravity data. In water areas, gravity is measured with mobile gravimeters installed on research vessels. The main challenge in such measurements is that the inertial accelerations caused by the vessel motion are a few orders greater than the desired signal, i.e., the gravity anomalies being sought. The effects of vertical accelerations are compensated for by means of filtering techniques during processing the gravimeter data; and the effects of horizontal accelerations on the gravimeter measurement system are removed at the physical level by installing a gravity sensor into a gyrostabilizer which maintains its sensitive axis in the vertical direction on a moving vehicle. In this case, the required accuracy of vertical stabilization of the gravimeter sensitive axis should not be worse than one arcminute [1]. Although some experimental prototypes of gimballess gravimeters have appeared recently [2, 3, 4], all production models of sea gravimeters comprise gyroscopic stabilizers [5].

Concern CSRI Elektropribor has designed and is manufacturing off-the-shelf mobile gravimeters Chekan-AM which are widely used all over the world in gravimetric surveys performed from sea and air vehicles to search for oil and gas bearing deposits and to study the gravitational field of the Earth [6, 7]. The sensitive element of the Chekan-AM gravimeter is mounted in a two-axis gyrostabilizer on floated gyroscopes. One of the ways to improve this type of gravimeter in order to enhance its reliability, reduce its cost, and minimize the size is to make the design of its gyrostabilizer simpler by implementing the indirect stabilization system based on strapdown inertial navigation system (SINS) which is installed on board the vehicle for navigation and orientation tasks decision. The purpose of this paper is to study the errors of a sea gravimeter indirect stabilization system using SINS output data.

1. Design of the gravimeter with an indirect stabilization system

It is proposed to use a gravity sensor of Chekan-AM unit as a sensitive element of the gravimeter with an indirect stabilization system [8], without making any design and technological changes.

The gravity sensor is based on a double quartz elastic system of torsional type, placed in damping fluid. The elastic system consists of two torsional systems from especially pure silica glass, contained in a common casing. The systems are turned by 180° relative to each other in the horizontal plane, which virtually fully prevents the effect of orbital motion on the gravimeter readings. Variation in the
gravity results in changing angle of pendulums torsion. Data on the pendulums angular position are read out using the mirrors welded onto them, and the readings are registered by means of an optical-electronic converter. The gravity sensor has an integrated digital system of thermal stabilization. The range of gravity increment measurement lies within ±5 Gal, which makes it possible to take measurements at any point of the globe.

The proposed design of the gravimeter with an indirect stabilization system is shown in Fig. 1.

![Fig. 1. Design of the gravimeter](image)

The gravity sensor is mounted in the stabilizer which is a two-axis gimbal; on each of its axes there are two stabilizing motors (M) and two angle sensors (AS). Vehicle’s pitching is traced on the internal gimbal ring axis, while its rolling – on the external gimbal ring axis.

To implement the indirect stabilization system, SINS is installed on a common mounting plate with the gravimeter.

Control of the stabilizing motors (M) is formed by the stabilizer microcontroller MC-IS as the difference between the readings of the stabilizer AS for pitch $\Psi_g$ and roll $\theta_g$, and the angles of pitch $\Psi$ and roll $\theta$, generated by the SINS.

For the indirect stabilization system we use SINS [9]; its error of rolling angles does not exceed one arcminute.

The main specific feature of the SINS is the possibility to trace the angular velocities of the base on which the SINS is installed. This allows using the angular velocities for damping the oscillations of the indirect stabilization system. To obtain additional data for damping, namely, the angular velocity of gimbal motion, it is proposed to install two micromechanical gyros (MMG) on its axis.

2. Analysis of stabilization errors

The operation of the gravimeter indirect stabilization system is described by the following differential equations [10]:

$$\ddot{\bar{\alpha}} = \frac{1}{J}(M_{FR} - M_M)$$

$$U = (\ddot{\bar{\alpha}} - \ddot{\theta})W_1 + (\alpha - \theta)W_2$$

$$M_M = k_M U$$

where

- $M_{FR}$ is moment of friction;
- $M_M$ is torque of stabilizing motor;
\( \theta \) is rolling angle generated by SINS;
\( \dot{\theta} \) is angular velocity of rolling angle variation generated by SINS;
\( \alpha \) is stabilization error;
\( \ddot{\alpha} \) is angular velocity of gimbal ring motion generated by MMG;
\( W_1 \) is transfer function of the compensating element which ensures the stabilization system damping, and compensating signal generation;
\( W_2 \) is transfer function of misalignment control channel;
\( k_M \) is motor-specific coefficient;
\( U \) is control voltage supplied to motor input;
\( J \) is moment of inertia of the gimbal ring.

Fig. 2 shows a block diagram of the gravimeter indirect stabilization system.

\[ \text{Simulated error Value} \]

\begin{array}{|l|l|}
\hline
\text{FOG noise, } \circ/h/\sqrt{\text{Hz}} & 0.02 \\
\text{Random drift, } \circ/h & 0.01 \\
\text{FOG nonlinearity, } \% & 0.005 \\
\text{Asymmetry of FOG scaling factors, } \% & 0.00005 \\
\text{Misalignment of FOG sensitive axes, } " & 15 \\
\text{Delays of FOG signals, } \mu\text{s} & 10 \\
\text{Noise of accelerometers, } \text{m/s}^2/\sqrt{\text{Hz}} & 0.0003 \\
\text{Random accelerometer bias, } \text{m/s}^2 & 0.001 \\
\text{Accelerometer scale factor of, } \% & 0.03 \\
\text{Accelerometer misalignment angles , } " & 1 \\
\text{Delays of accelerometer signals, } \text{ms} & 1 \\
\hline
\end{array}

Indirect stabilization errors were simulated in MATLAB (Simulink). During the research, we used the model of SINS errors [11]. The components of simulated error model for SINS inertial sensors are summarized in Table 1 below.
Simulation was carried out for two operation modes; in the first mode there were no instrumental errors of SINS in order to study the effect of time delay in signal transmission on the magnitude of stabilization errors; the second mode took into account the SINS instrumental errors. The simulation results are shown in Fig. 3.

![Fig. 3. Results of stabilization errors simulation at \( \theta_{\text{mod}} = 3^\circ, T = 6s \)](image)

For all modes, the settings were as follows: roll \( \theta_{\text{mod}} = 3^\circ \), period \( T = 6s \). As can be seen from the diagrams, the main factor affecting the magnitude of stabilization error is the frequency of exchange between the SINS and the gravimeter.

Conclusions

Design of a gravimeter with an indirect stabilization system has been considered. The errors of indirect stabilization system of gravimeter under rolling conditions have been studied. The results of simulation at 300 Hz taking into account instrumental errors of SINS sensitive elements prove that it is possible to develop an indirect stabilization system with an error of no more than one arcminute, providing a SINS is used.

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