Single-rotor integrating gyroscopic gravimeter

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Abstract. The paper describes the gravity acceleration sensor (GAS) design, the technical characteristics of which provide an increase in the static transfer constant of the GAS, the ability to determine the current static transfer constant of the GAS, reducing the level of noise effects in the output signal of GAS. The acceleration vector components from the side of a moving vehicle add a noise to the gravity vector components. These investigations give an answer how to obtain of GAS’s desired metrological features by the developing of new GAS based on pendulous integrating gyroscopic accelerometer. The presented material can be seen as an example of how to explore a gyro system mechanics and how to develop new gyro systems structure. The presented methods and the sequences of expressions can be used in master’s and bachelor’s disciplines in the field of applied mechanics, instrument development and automatic control.

1. Introduction

Gravity acceleration sensors (GAS) are today the most promising in terms of large-scale study of gravity acceleration anomalies [10], [13]. GAS is considered as a sensitive element of the aviation gravimetric system (AGS). The involving of automation technologies into the system of device functioning, making the computer processing of information signals of the device possible, is relevant. The problem is to design GAS for AGS with the aim of improving measurement accuracy of gravity acceleration anomaly [10]. Accurate knowledge of the Earth gravitation field anomaly is necessary for aviation and space technology, geology, geophysics and geodesy.

Therefore, it is necessary to find solutions to improve the accuracy of gravity sensors.

Nowadays such AGS gravimeters are exploited: quartz, string with liquid damping, magnetic, spring, piezoelectric-type [12]. All of them have almost the same accuracy but different source of measurement errors, which depend on their principle of operation.

The disadvantages of quartz, magnetic, spring, string and piezoelectric-type gravimeters are [1]:

1) instability of static transfer constant;
2) inability to determine the current static transfer constant;
3) presence in the output signal obstacles, due to the fact that the accelerometer is mounted on a movable basis;
4) there is a compulsory need for a sophisticated hardware procedure that filtering the output GAS signal [2].
2. Literature review

Disadvantages of existing GAS can be overcome by using a gyroscopic devices in gravimetry. For these purposes the acceptable gyroscopic devices are: dynamic gyroscope [2] or linear gyro-integrator [1], [4], [5], [9].

Even nowadays, precision gyroscopes are considered the best for use as major sensing elements in inertial navigation and control systems of ballistic rockets. These devices were designed for use in rigid dynamic conditions: 1) axial overload: over 30 g; 2) temperature range: from −60 to +50°C; 3) range of air pressure: 700 to 800 mmHg (near the Earth’s surface) and 10-6 mmHg (at a height of 200 km) [9], [11].

In the gyroscopic gravimetric systems with a dynamic gyroscope [8] a two-level gyroscope is used as a gyroscopic censor of gravity acceleration. The center of rotor mass is shifted in the rotation plane of the rotor, creating pendulum. Rotor itself is attached to the suspension axes with the help of elastomeric rotational springs, the work of which principally depends on twisting and they act as dampers.

Initially, rotor is rotating in the perpendicular to the vertical of a place (normal to the ellipsoid rotation). The rotor deviation from the initial position is measured by an angle sensor with the output signal of a gravity acceleration sensor and with the input signal for the torque sensor. The torque sensor creates an additional torque relative to the rotor suspension axe.

Ideally, a static transfer constant of the gyroscopic GAS (GGAS) as a gravimeter depends only on the pendulum and on the transfer constant of the torque sensor. But in practice the stability of a static transfer constant of GGAS is limited due to the strong dependence of the elastomeric bearings on the temperature and vibration parameters at the installation site causing its weariness [6], [11].

The temperature changes also result in electric parameters changes in the electromechanical system of the torque; and, thus, affect the value of its transfer constant. Instability of the torque transfer constant causes additional instability of the static transfer constant of the gyroscope gravity acceleration sensor.

As mentioned above there are the gyroscopic gravimetric systems based on a linear gyro-integrator or PIGA (Pendulous Integrating Gyroscopic Accelerometer) [4], [5], [9].

PIGA is a three-dimensional gyroscope whose center of gravity is shifted relative to the point of suspension. As a result, PIGA is sensitive to transmitted acceleration of the object, because arising at the moment of inertia forces causes the precession of the gyroscope with an angular velocity proportional to the specified moment, i.e., the magnitude of the acceleration of the object. Then the precession angle will be proportional to the linear velocity of the object, which allows finding the velocity of an object by measuring this angle.

PIGA responds to the acceleration of the object that appears, that is, the sum of the absolute acceleration of the object and the gravitational acceleration (acceleration of gravity). As a result, the device output is proportional to the integral of the total acceleration that applied to the object where PIGA is installed.

Both gyro-gravimeters of dynamic and integrating type accept a “useful” moment from the vertical vector component of gravity acceleration, interference moments from the horizontal vector components of gravity acceleration, interference moments from the vertical and horizontal vector components of the movable basis linear acceleration, interference moments from the vertical and horizontal vector components of the angular acceleration of the movable basis and the interference moments from the horizontal vector components of the angular acceleration of the movable basis simultaneously act with the gravimeter relative to the rotor suspension axis.

The moments mentioned above result in the appearance of relevant components in the output signal of gyroscope gravity acceleration sensor – interference moments, but for those, caused by horizontal components of gravity acceleration vector, are explained by the fact that gyroscope gravity acceleration sensor is installed on the movable platform.

In addition, both gravimeters operate by rotating the gyroscopic rotor. This fact mechanically explains the appearance of precession, compensating centrifugal forces, mechanical torques and more. Thus, the rotation of the rotor causes kinetic moment, which fully determines the static transfer constant
for the instruments. When recalculating the output of the gravimeter back to the acceleration value, it is very important to know at all times the current static transfer constant of the gyro-gravimeter. Available data indicate that the described gyro-gravimeters have another drawback – the absence of means for controlling the static transfer constant.

In the integrating gyroscopic gravimeter the property of integrating the applied accelerations allows to reduce the influence of frequency components of obstacles, but to detect the low-frequency component of accelerations – gravity acceleration.

2.1. General problems
The essential disadvantages of the existing gravimeters are:

– Instability of the static transfer constant of GGAS, caused by the changes of rotation spring properties, the changes of gyroscope rotation frequency and the changes of electrical parameters in electromechanical system of the torque;

– Impossibility to define the current static transfer constant of GGAS;

– Presence of interference components in the output signal of GGAS, explained by the GGAS being installed on the movable basis, and interference components from the horizontal vector components of gravity acceleration.

The indicated factors significantly reduce the measuring accuracy of the gyroscope gravity acceleration vertical vector component, performed by such a device from the board of the aircraft.

2.2. Objectives
To suggest GGAS of the new structure with the following criteria:

– It is need to develop GGAS on principles that are in PIGA – integrating properties;

– Increase the stability of the static transfer constant of the GGAS;

– Possibility to measure the current static transfer constant of GGAS;

– Decrease the amount of interferences in the output signal of GGAS leading to a significant increase of accuracy measurement of gravity acceleration vertical vector component from the board of the aircraft.

3. Suggestions and solutions
The targets can be reached by using a new single-rotor integrating GGAS and additional information channels.

On the figure 1 the suggested GGAS is depicted as a part of gravimetric system: GGAS (1); the system of current navigation parameters measurement (velocity, direction and geographic latitude) (2); altimeter (3); board computer (4).

GGAS (1) consists of a gyro-motor (5) attached to the internal gyro-motor suspension axis with spring dampers (7) designed so that the twisting rotation of spring dampers stiffness along the internal gyro-motor suspension longitudinal axis (8) is much less significant than the spring dampers stiffness (7) in bending.

The longitudinal axis (8) of internal gyro-motor suspension axis is shifted relative to the outer plane frame (9) and is found in the perpendicular to the axis plane (10) of the outer frame with the gyro-motor mass center (5) found on the gyro-motor rotor rotation axis that if this axis (11) is perpendicular relative to the outer frame plane (9), then the gyro-motor mass center (5) is placed on outer frame suspension axis installed along the vertical of a place.

The outer frame suspension axis (10) installed along the vertical axis of a place is carried out, for instance, through the gyroscope gravity acceleration sensor installation (1) at the horizontally-stabilized platform. Moreover, the outer frame axis (10) is being installed along the vertical axis ξ of the horizontally-stabilized platform and axis η, ζ – are the horizontal axis of the platform.

The sensor (12) that measures twisting rotation angle of spring dampers is placed on the internal gyro-motor suspension axis (6) is being connected to the first amplifying element (13) that is connected
to the operating engine (14), stiffly fixed on the outer frame (9), and the operating engine axis (14) is the internal suspension gyro-motor axis (6).

The gyro-motor turning angle sensor (15), installed on the outer frame (9), is connected to the board computer (4) and to the second amplifying element (16) that is connected to the torque sensor (17) being placed on the outer frame suspension axis (10). Connecting the gyro-motor turning angle sensor (15) to the board computer (4) allows controlling the gyro-motor’s rotor rotation axis (11) perpendicularly to the outer frame suspension axis (10).

Figure 1. Single-rotor integrating gyroscope gravity acceleration sensor as an element of a gravimetric system.
The outer frame turning angle sensor (18) is placed on the outer frame suspension axis (10) and connected to the board computer (4). The outer frame turning angle sensor (18) output signal is the main output signal of GGAS (1).

The current power supply frequency sensor (20), connected to the board computer (4), and the gyro-motor (5) are both connected to the frequency-stabilized power supply unit (19).

The power supply frequency sensor output (20) is connected to the board computer (4) in order to measure the current frequency of gyro-motor rotor rotation 5 and the board computer (4), based on the measurements, further defines the static transfer constant of GGAS (1).

Gravimeter does perform in the following way:

The gyro-motor’s rotor (5) is rotating with the velocity \( \gamma \) around gyro-motor rotor rotation axis (11), creating an angular moment \( H \).

The vertical element \( g_\xi \) and horizontal elements \( g_n, g_\zeta \) of gravity acceleration vector together with the vertical element \( W_\zeta \) and horizontal elements \( W_n, W_\zeta \) of the linear acceleration vector of a horizontally-stabilized platform act upon the shifted relative to the longitudinal axis of the gyro-motor internal suspension axis (8) mass center \( C \) of the gyro-motor. At the same time a moment \( M_{g,\eta} \) exists relative to the longitudinal axis (8) of the gyro-motor internal suspension axis. If to address to the general principles of the gyroscope systems description [1], [5], the moment \( M_{g,\eta} \) is defined in the following way:

\[
M_{g,\eta} = -m \cdot l \left[ (W_\zeta - g_\zeta) \cos \beta + (W_n - g_n) \sin \alpha \cdot \sin \beta - (W_\zeta - g_\zeta) \cos \alpha \cdot \sin \beta \right]
\]  (1)

where \( m \cdot l \) – the gyro-motor (5) pendulum; \( \beta \) – the gyro-motor (5) turning angle around the longitudinal axis (8) of the gyro-motor internal suspension axis; \( \alpha \) – the outer frame (9) turning angle around the outer frame suspension axis (10).

With the presence of the vector angle acceleration horizontal elements \( \omega_{\zeta}, \omega_n \) of horizontally-stabilized platform, where the GGAS (1) is actually installed, the inertia moment \( M_{in} \) appears relative to the longitudinal axis (8) of the first gyro-motor internal suspension axis that is calculated as follows:

\[
M_{in} = -B \left( \omega_\eta \cdot \cos \alpha + \omega_\zeta \cdot \sin \alpha \right)
\]  (2)

with \( B \) being a gyro-motor (5) inertia moment relative to the longitudinal axis (8) of the first gyro-motor internal suspension axis.

The vertical element \( \omega_\zeta \) and the horizontal components \( \omega_{\zeta}, \omega_n \) of horizontally-stabilized angular velocity vector, where the GGAS (1) is installed, cause the appearance of compound centrifugal force moment \( M_k \) (gyroscopic moment) from the transmission angular velocity of the horizontally-stabilized platform. The moment \( M_k \) found relative to the longitudinal axis (8) of gyro-motor internal suspension axis is calculated in the following way:

\[
M_k = H \left( \omega_\zeta \cdot \cos \beta + \omega_n \cdot \sin \alpha \cdot \sin \beta - \omega_\zeta \cdot \cos \alpha \cdot \sin \beta \right)
\]  (3)

with \( H \) being a kinetic moment emerging from the gyro-motor rotor rotation 5.

The moments \( M_g, W_r, M_k, M_m \) cause the gyro-motor’s (5) rotation around the longitudinal axis (8) of gyro-motor internal suspension axis and that is why:

\[
\beta \neq 0
\]  (4)

The gyro-motor (5), rotating around the longitudinal axis (8) of gyro-motor internal suspension axis, twist the spring dampers up (7). In this way there appear moments, caused by the spring dampers (7) force, relative to the mentioned axis and are calculated in the following way:

\[
M_{spr} = C \cdot \Delta \beta_{spr}
\]  (5)

\[
\Delta \beta_{spr} = \beta - \beta_{rot}
\]  (6)

with \( C \) being spring dampers (7) stiffness constant of twisting along the longitudinal axis (8) of gyro-motor internal suspension axis; \( \Delta \beta_{spr} \) being the angle of spring dampers (7) twisting rotation; \( \beta_{rot} \) – the rotation angle of the gyro-motor internal suspension axis (6) around the longitudinal axis (8) of gyro-motor internal suspension axis performed by the drive engine (14).

In the presence of the spring dampers twisting rotation angle \( \Delta \beta_{spr} \) in the output of the sensor there is the proportional to the angle \( \Delta \beta_{spr} \) signal that is transmitted to the first amplifying element (13) with its output being connected to the drive engine (14). The drive engine will rotate the gyro-motor internal
suspension axis (6) around the longitudinal axis (8) of gyro-motor internal suspension axis till the condition is being performed:

\[ \Delta \beta_{spr} \neq 0 \]  

(7)

Thus, the direction of the gyro-motor internal suspension axis (6) rotation around the longitudinal axis (8) of gyro-motor internal suspension axis is always the one providing the decrease of the current angle \( \Delta \beta_{spr} \) value measured by the sensor (12) of spring dampers twisting rotation angle. In the result, the following condition is possible to be performed: the steady angle value \( \Delta \beta_{spr \ std} \) is approaching the zero (\( \Delta \beta_{spr \ std} \to 0 \)). It also means:

\[ M_{spr \ std} \to 0 \]  

(8)

Even if \( \Delta \beta_{spr \ std} \to 0 \) during sensor operation:

\[ \beta = \beta_{init} + \Delta \beta_{spr} \neq 0 \]  

(9)

here the correction circuit between the longitudinal axis (8) of gyro-motor internal suspension axis and the outer frame suspension axis (10) starts acting.

The gyro-motor turning angle sensor (15), installed on the outer frame (9), measures the \( \beta \) angle and transmits the signal proportional to the \( \beta \) angle to the other amplifying element (16), the output of which is connected to the torque sensor (17).

The torque sensor (17), in relation to the input signal, causes the correction moment \( M_{corr} \):

\[ M_{corr} = -K_k \cdot \beta \]  

(10)

with \( K_k \) being the general transfer constant of the described channel.

The torque sensor (17) applies \( M_{corr} \) to the outer frame suspension axis (10). The outer frame (9) affected by \( M_{corr} \) acquires \( \alpha \) angle velocity that is enough to compensate the total moment relative to the longitudinal axis (8) of gyro-motor internal suspension axis and, as a result, provide the smallness of \( \beta \) angle that \( \cos \beta \) meaning is as close as possible to the unit: \( \beta \to 0 \).

The \( \beta \) angle smallness signifies the directly proportional smallness of the following moments: \( M_g \), \( W \), \( M_k \), \( M_{spr} \) depending on \( \sin \beta \) value. In this way it becomes possible to insure the minimum dependence of the output signal of GGAS (1) on the interferences components, caused by \( W_n \), \( W_\xi \) horizontal components of the linear acceleration vector and \( \omega_n \), \( \omega_\xi \) – horizontal components of the angular velocity vector of the horizontally-stabilized platform on which the GGAS (1) is actually installed; and also caused by the horizontal \( g_\xi \), \( g_n \) components of the gravity vector acceleration.

Referring to the general principles of the gyroscope systems dynamic description [3], [7], and taking into consideration \( \beta \to 0 \), \( M_{spr} \to 0 \) conditions, \( \alpha(t) \) – turning angle of the outer frame (9) in the steady mode:

\[
\alpha_{std}(t) = -\frac{1}{H} \left\{ \left( M_{g,v} + M_{in} + M_k + M_{spr} \right) t - \left( \frac{m l^2}{H} \right) \frac{\gamma}{\zeta} \right\} t - \left( \frac{\omega}{\zeta} \right) t + \frac{B}{H} \left( \dot{\omega}_{\xi} \cos \alpha + \dot{\omega}_{\xi} \sin \alpha \right) \right\} t 
\]  

(11)

with \( t \) being the time between the starting data sample time moment \( t_0 \) and the ending data sample time moment.

In this case, a “useful” signal component is:

\[
\alpha_{usf \ std}(t) = -\frac{m l^2}{H} \left( \frac{\gamma}{\zeta} \right) t 
\]  

(12)

Other components are the interference (error) signals:

\[
\alpha_{int \ err \ std}(t) = \frac{m l^2}{H} \left( \frac{\gamma}{\zeta} \right) t - \left( \frac{\omega}{\zeta} \right) t + \frac{B}{H} \left( \dot{\omega}_{\xi} \cos \alpha + \dot{\omega}_{\xi} \sin \alpha \right) \right\} t 
\]  

(13)

\( \alpha (t) \) signal is detected by the outer frame turning angle sensor (18), installed on the outer frame suspension axis (10) and is the main output signal of the GGAS (1). From the outer frame turning angle sensor (18) output this signal gets into the board computer (4) for its further processing.

To calculate the average value \( \dot{g}_\xi \) of the vertical component of the gravity acceleration vector, the board computer chooses the intervals of the already measured signal values \( \alpha (t) \) according to the data stability in these intervals of the gyro-motor kinetic moment \( (5) \) \( H \) and according to the angle \( \beta \) value.
data in these intervals. For this the board computer (4) during the whole time while the measurements are taking place, reads the gyro-motor power supply (5) frequency \( y' \) data coming from the output of the current frequency supply (20) data and from the output of the gyro-motor turning angle (15) sensor – the \( \beta \) angle data. The board computer (4), according to the gyro-motor power supply (5) frequency \( y' \), defines the appropriate gyro-motor rotor rotation frequency value. This can be achieved by simple measuring of gyro-motor’s rotor frequency by embedding appropriate sensor.

Based on the received data, the board computer (4) chooses the intervals, for which the indicated below conditions are carried out.

The first is the stability of gyro-motor rotor rotation (5) frequency:

\[
\gamma_i = \text{const} \pm A\gamma_i
\]

with \( \gamma_i \) being the corresponding to \( i \) interval of the gyro-motor rotor rotation frequency \( \gamma' \) value (5); \( A\gamma_i \) – module of the difference between the gyro-motor rotor rotation frequency \( \gamma' \) value (5) and the average gyro-motor rotor (5) frequency \( \gamma_i \) value, meanwhile \( A\gamma_i \) can be omitted and considered as the one equal to zero.

The second is the angle \( \beta \) smallness condition:

\[
\beta_i = 0 \pm A\beta_i
\]

with \( \beta_i \) being the corresponding to \( i \) interval of the gyro-motor turning angle \( \beta \) value around the longitudinal axis (8) of gyro-motor internal suspension axis; \( A\beta_i \) – the module of the angle \( \beta_i \) deviations from zero that can be omitted and considered as the one equal to zero.

For every \( i \)-type interval chosen by the board computer (4) performs a calculating operation of the current static transfer constant \( R_{st,i} \) of the GGAS (1) taking into account the corresponding to each of the interval \( \gamma_i \) value:

\[
R_{st,i} = \frac{ml}{H_i} = \frac{ml}{J \cdot \gamma_i}
\]

with \( J \) being the gyro-motor rotor (5) inertia moment relatively to the gyro-motor rotor rotation axis (11).

At the same time while reading the main \( \alpha \) (i) signal and the additional \( \beta \), \( \gamma' \) signals, the board computer (4) reads the data from the connected to it devices: the current navigation parameters measurement system (2) and the current altitude measurement. According to the received data, the board computer (4) calculates the values for each of the \( i \)-type chosen interval:

\[
\begin{align*}
\int_{t_{\text{start},i}}^{t_{\text{end},i}} W_{\xi,i} dt + \int_{t_{\text{start},i}}^{t_{\text{end},i}} \omega_{\xi,i} dt
\end{align*}
\]

with \( t_{\text{start},i} \) is the start and \( t_{\text{end},i} \) is the end time moments of the \( i \)-type data interval; \( W_{\xi,i}, \omega_{\xi,i} \) – are the current \( i \)-type interval values according to the vertical component \( W_{\xi} \) of the linear acceleration vector and the vertical component \( \omega_{\xi} \) of the angular velocity vector of the horizontally-stabilized platform.

The board computer (4), having performed the calculations, defines the average value of the vertical vector gravity acceleration \( g_{\xi,i} \) for each of the \( i \)-type chosen interval:

\[
g_{\xi,i} = \frac{1}{R_{st,i}} \left( \alpha(t_{\text{end},i}) - \alpha(t_{\text{start},i}) \right) - R_{st,i} \left( \int_{t_{\text{start},i}}^{t_{\text{end},i}} W_{\xi,i} dt \right) + \left( \int_{t_{\text{start},i}}^{t_{\text{end},i}} \omega_{\xi,i} dt \right)
\]

In general case, the board computer (4) performs an additional reduction of the received vertical component value of the gravity acceleration vector.

4. Conclusions

The suggested implementation of the single-rotor integrating gyroscopic sensor as the GGAS allows improve the stability of the static transfer constant of the indicated sensor. It is possible because in this case the static transfer constant is measured only by the pendulum value, the axial inertia moment and the gyro-motor rotor rotation frequency. As soon as it is possible to stabilize the pendulum, the axial inertia moment and the gyro-motor rotor rotation with the help of low heat growth and to reach the
stability of gyro-motor rotor rotation frequency value using a high-quality precision synchronic gyro-motor together with the power unit of the stabilize frequency, the stable static transfer constant of the GGAS is received.

It is a significant advantage as the stability of this constant is one of the key points defining the output accuracy of the single-rotor integrating gyroscopic gravimeter with the controlled parameters and, therefore, the gravity acceleration vertical component measurement accuracy from the board of the moving vehicle with the help of such equipment.

The system with the current frequency supply sensor, connected to the board computer, takes control of the gyro-motor power supply frequency and the gyro-motor rotor frequency, creates an additional information channel and allows, chose out the intervals with the necessary, for the required accuracy, stability of the gyro-motor frequency. It also defines the current mean value of the static transfer constant of the GGAS with accordance to the gyro-motor rotor rotation frequency value. Then it is possible to calculate the proper value of correction and remove some kind of obstacle from the gravimeter output signal.

High-frequency interference components cause the need to average the output signal of the GGAS, involving the integration procedure. The suggested single-rotor integrating gyroscopic gravity acceleration sensor has a significant advantage in this way, since it is an ideal integrator from the precession theory point of view [7].

The gyro-motor arrangement, as well as the arrangement of the gyro-motor internal suspension axis is that the center of the gyro-motor mass is as close as possible to the outer frame suspension axis, allows get rid of the interference’s components in the output signal of the GGAS caused by the centrifugal acceleration affecting the gyro-motor mass center during the outer frame rotation together with gyro-motor around the outer frame suspension axis

Fixing the gyro-motor on the gyro-motor internal suspension axis with spring dampers, mainly working on twisting, initiates that in the operating mode in relation to the longitudinal axis of gyro-motor internal suspension axis, the moments, caused by the dry friction forces are not applied and simultaneously provides the absence of the GGAS threshold.

The correction circuit consisting of the gyro-motor rotation angle sensor, which is connected to the torque sensor installed on the outer frame suspension axis, allowing ensure the minimum deviation angle of the gyro-motor rotor rotation axis, from the perpendicularity to the outer frame plane, and, therefore, from the perpendicularity to the outer frame suspension axis. Thus, the “zero-point” stability and maximum sensitivity of the proposed gyroscopic gravity acceleration sensor are provided being a standard requirement for such devices [7].

All of these increase the accuracy in measurements of the gravity acceleration vertical component from the board of the movable vehicle.

The presented materials are related to general methods and sequences of mathematical description of gyro-systems. All this can be part of fundamental research, as well as an educational aspect for such areas as applied mechanics, instrument development and automatic control. Analysis of existing gyros can be used by bachelors, but masters can explore new forms of gyro structures.

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