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A new configuration method for accelerometers in rotating accelerometer-based gravity gradiometer

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Abstract. As a sensor for direct measurement of gravity gradient signals, accelerometer plays an important role in the rotating accelerometer-based gravity gradiometer. Therefore, the way to position the accelerometer has an important influence on the gravity gradient measurement. In this article, we have analysed the principle of gravity gradient measurement, and points out some defects in the configuration of traditional gravity gradients. Finally, we proposed a new way to position the accelerometers in gravity gradiometer, in which, the sensitive axis of the opposite accelerometers are in the same direction. And the results of simulation indicate that the measurement error of the new way to position the accelerometers is about 9.29%, while the traditional configuration is about 39.68%, then the the efficacy of the new configuration method could be proven.

1. Introduction

Gravity gradient reflects the variations of the gravity in space. The gravity gradient is a very weak signal. To detect this weak signal, many kinds of high precision instruments were manufactured, based on different principles, such as cold atomic interferometer-based gravity gradiometer[1-3], the rotating accelerometer-based gravity gradiometer [4, 5], the superconducting gravity gradiometer[6, 7], MEMS gravity gradiometer[8] and some others. Among them, the rotating accelerometer-based gravity gradiometer is the unique one that has passed through the flight test and achieved the desirable sensitivity in the field surveys.

The most important component of the gravity gradiometer is Gravity Gradient Instrument (GGI) [4]. To our knowledge the structure of each GGI is as shown in figure 1.

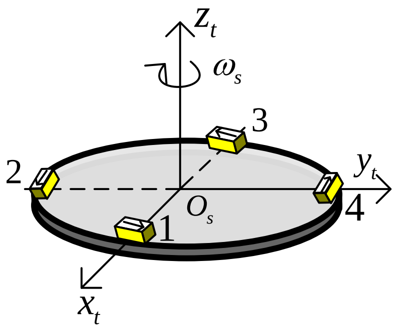

Figure 1. The schematic diagram of GGI. It consists of four accelerometers (1, 2, 3, 4); the arrows represent the direction of the sensitive axis of the accelerometers; and ω_s is the rotation speed of the disc.

The position of accelerometers have an important influence on the measurement. In this paper, we have studied the optimal way to position accelerometers in GGI.

The following is the structure of this article. In the second section, the principle of gravity gradient measurement based on four accelerometers and rotating disk is introduced. In the third section, we have proposed a new way to position accelerometers. In the fourth section, we used simulation data to prove that the new configuration works better than traditional configuration.

2. Measuring principle

As shown in figure 1, the combination of the accelerometers' output signals contains the gravity gradient information. The gravity gradient signal is modulated to the second harmonic of the rotational speed. Thus, the gravity gradient signal can be obtained by demodulating the combined signal.

The relationship between the outputs of accelerometers and the gravitational gradient components is as follows:

$$\frac{f_2 + f_4 - f_1 - f_3}{2r_s} = 2\left(\Gamma_{xy} + N_1\right)\cos\left(2\omega_s t\right) + \left(\Gamma_{xx} - \Gamma_{yy} + N_2\right)\sin\left(2\omega_s t\right) \tag{1}$$

where $\Gamma^t_{xx}, \Gamma^t_{yy}, \Gamma^t_{xy}$ are components of gravity gradient tensor, f_1, f_2, f_3, f_4 are outputs of accelerometers, N_1, N_2 are other known coupling signals.

With the help of equation (1), we can demodulate $f_2 + f_4 - f_1 - f_3$ at $\sin\left(2\omega_s t\right)$ yields $\Gamma_{xx} - \Gamma_{yy}$, and demodulate it at $\cos\left(2\omega_s t\right)$ yields Γ_{xy}.

3. A new configuration of accelerometers

From equation (1) we know that the gravity gradient signals contained in the differences of two paired accelerometers. In other words, when outputs of accelerometers on opposite sides of the table were differenced, we may achieve values of the gravity gradient signals at the midpoint of the accelerometers. To our knowledge, accelerometers on GGI are arranged as shown in figure 1. Actually, accelerometers are not perfectly working, so the position of accelerometers will affect the measurements accuracy.

In this article, we have proposed a new configuration, as shown in figure 2.

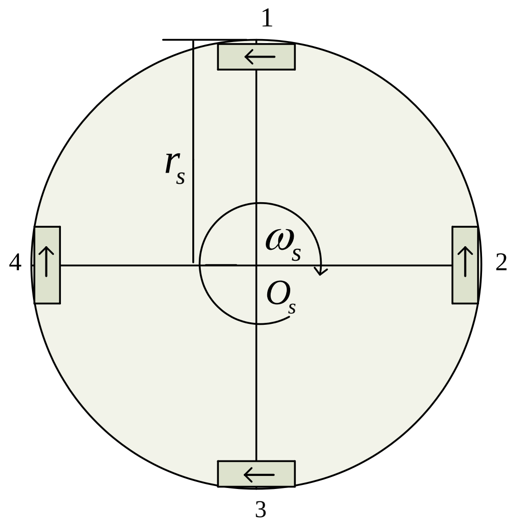

Figure 2. A new configuration of accelerometers in GGI.

The difference between figure 2 and figure 1 is that the direction of the sensitive axes of accelerometer 3 and 4 are different.

3.1. Measuring model of accelerometer

Ideally, the specific force measuring model of the accelerometer is generally represented by the following formula:

$$N_a = kf_{in} \tag{2}$$

where N_a is the output of the accelerometer, k is the scale factor of the accelerometer, and f_{in} is the specific force as input of the accelerometer.

But in fact, due to the interference of the external environment, the limitation of the processing technology and the differences of device's performance, the actual measurement model is different from equation (2). In inertial navigation system, equation (3) is often used as the mathematical model of the accelerometer:

$$N_n = k_0 + k_1 f_{in} + \varepsilon \tag{3}$$

where N_n is the output of the accelerometer, k_0 is bias of the accelerometer, k_1 is the scale factor of the accelerometer, f_{in} is the input of the accelerometer, and ε is the measurement noise.

The accuracy of the model of equation (3) is sufficient to meet the accuracy requirements of inertial navigation. However, for gravity gradient measurement, this model is still too rough. Next, we use equation (4) as the mathematical model of the accelerometer:

$$N_g = k_0 + k_1 f_{in} + k_2 f_{in}^2 + \varepsilon \tag{4}$$

in which k_2 represents the parameter factor associated with the quadratic term.

Because the main purpose of this paper is to analyze the effect of the accelerometers configuration on the gravity gradient measurement, the influence of the installation error is not considered in the following analysis.

3.2. Comparison of two configurations

As previously mentioned, the gravity gradient signals are implied in the difference of accelerometers' outputs.

Next, we have analyzed the accuracy of measurement for difference specific force under the two configurations.

It is assumed that the accelerometers in the accelerometer group are symmetrically mounted on both ends of the turntable diameter (as shown in figure 3), the mounting points are denoted as A and B. The specific force at A and B are denoted as f and $f + \Delta f$, respectively.

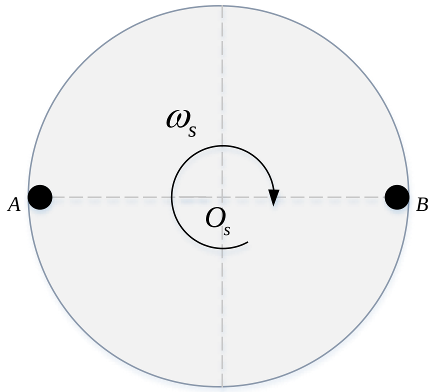

Figure 3. The position of the accelerometers on the disc.

The output of accelerometer 1 at *A* is recorded as:

$$N_{Ay} = k_0 + k_1 f + k_2 f^2 + \varepsilon_{A1} \tag{5}$$

The output of the accelerometer 2 at B, which has the same sensitive axis direction with the accelerometer 1, is:

$$N_{By'} = k_0' + k_1'\left(f + \Delta f\right) + k_2'\left(f + \Delta f\right)^2 + \varepsilon_{B2} \tag{6}$$

The output of the accelerometer 3 at *B*, which has the opposite sensitive axis direction with the accelerometer 1, is:

$$N_{By''} = k_0'' - k_1''\left(f + \Delta f\right) + k_2''\left(f + \Delta f\right)^2 + \varepsilon_{B3} \tag{7}$$

In order to obtain the difference of specific force Δf between A and B, N_{Ay} and $N_{By'}$ are differentiated:

$$\begin{aligned} N_{By'} - N_{Ay} &= \left(k_0' - k_0\right) + \left(k_1' - k_1\right) f + \left(k_2' - k_2\right) f^2 + k_1'\Delta f + 2k_2' f \Delta f + k_2' \Delta f^2 + \varepsilon_m \\ &= \Delta k_0 + \Delta k_1 f + \Delta k_2 f^2 + k_1' \Delta f + 2k_2' f \Delta f + k_2' \Delta f^2 + \varepsilon_m \end{aligned} \tag{8}$$

where $\varepsilon_m = \varepsilon_{B2} - \varepsilon_{A2}$.

Similarly, to obtain the difference of specific force Δf , N_{Ay} and $N_{By'}$ are summed:

$$\begin{aligned} N_{By''} + N_{Ay} &= \left(k_0'' + k_0\right) - \left(k_1'' - k_1\right) f + \left(k_2'' + k_2\right) f^2 - k_1'' \Delta f + 2k_2'' f \Delta f + k_2'' \Delta f^2 + \varepsilon_a \\ &= 2k_0 + 2k_2 f^2 + \delta k_0 - \delta k_1 f + \delta k_2 f^2 - k_1'' \Delta f + 2k_2'' f \Delta f + k_2'' \Delta f^2 + \varepsilon_a \end{aligned} \tag{9}$$

where $\varepsilon_a = \varepsilon_{B3} + \varepsilon_{A1}$.

Since $k_0, k_0', k_0'', k_1, k_1', k_1'', k_2, k_2'$ and k_2'' are the results of calibration, they are known quantity. Therefore terms $\Delta k_0 + \Delta k_1 f + \Delta k_2 f^2$ and $2k_0 + 2k_2 f^2 + \delta k_0 - \delta k_1 f + \delta k_2 f^2$ can also be calculated. Finally, by equation (8) and equation (9), we can achieve Δf .

Compare equation (8) and equation (9), we can find that equation (9) requires more compensation. This means that when the parameter factor of the accelerometer drifts, using the configuration shown in figure 1 will result in a greater error.

Next, we will use simulation results to prove this conclusion.

4. Simulation

On the basis of the hypothesis that scale factors of accelerometers drift in the same trend, the accuracy and the robustness of the proposed configuration method are verified by the simulation test.

The simulation is carried out according to the following steps: first, setting up the simulation environment; second, using outputs of the accelerometers to calculate Δf ; third, compare the results of above two configurations, and determine which configuration is better.

The steps of the simulation are shown in figure 4.

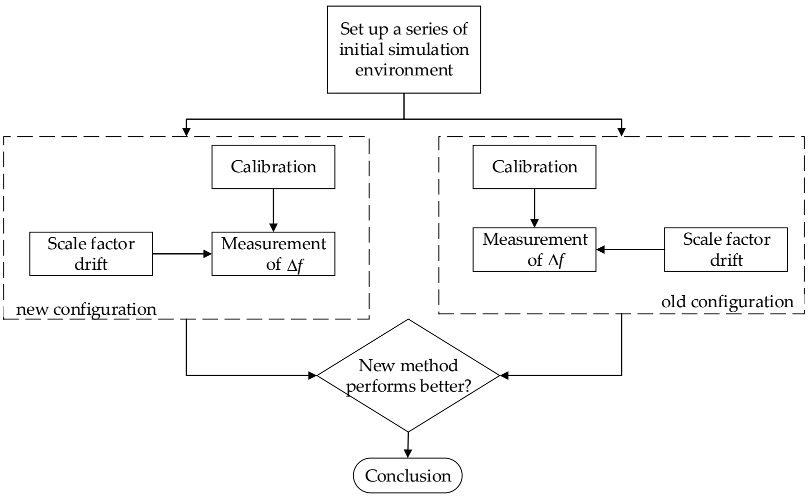

Figure 4. Simulation steps.

4.1. Initial Simulation Parameter

The initial parameters of the simulation are as follows:

Noise intensity of each accelerometer: $1\mu g / \sqrt{Hz}\,(1\sigma)$

Specific force at A: $f = 35 m / s^2$

Specific force at B: $f+\Delta f=(35+0.00001)m/s^2$

The parameter factors of each accelerometer are shown in table 1.

Table 1. Parameter factors of each accelerometer

Parameter Factors	k_0	k_1	k_2	k_0'	k_1'	k_2'	k_0''	k_1''	k_2''
Values	96	4800	0.0960	49	4900	0.0490	49	4900	0.0490

The parameter factors' drift of the accelerometers are shown in figure 5.

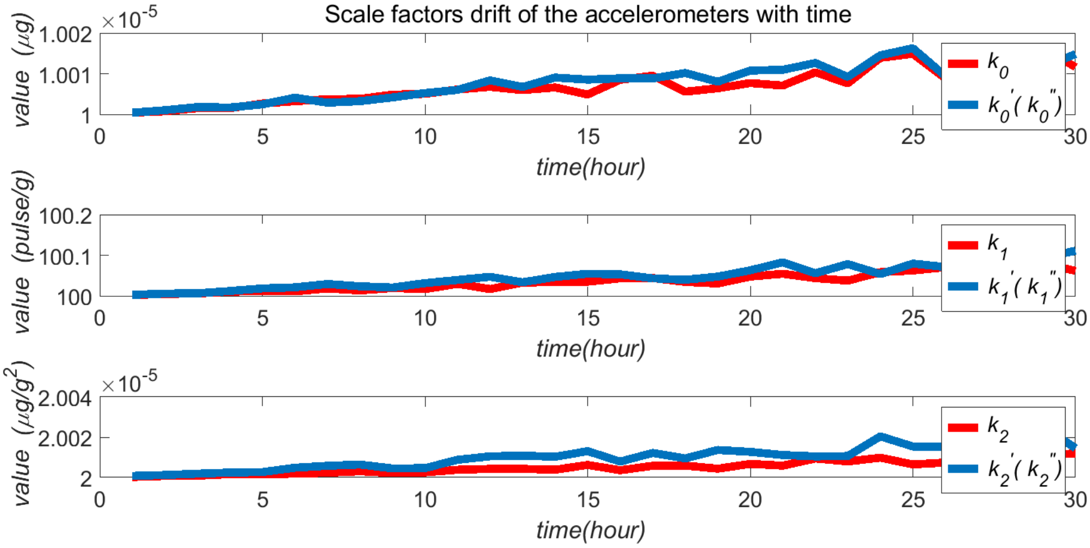

Figure 5. Parameter factors' drift of the accelerometers with time.

4.2. Simulation Results

In the two configurations, the accuracy of the measured Δf are shown in table 2 and table 3.

Table 2. Δf , measured using the old configuration

True value	Measured value	Relative measurement error
0.0001	0. 000138685	39.68%

Table 3. Δf , measured using the new configuration

True value	Measured value	Relative measurement error
0.0001	0. 000090713	9.29%

It is clear from table 2 and table 3 that the measurement error of the new configuration method is about 9.29%, while the old configuration is about 39.68%.

5. Conclusion

In this paper, we proposed a new accelerometer configuration method in gravity gradiometer, which helps to improve the accuracy of gravity gradient measurement. The improved configuration has the following advantages:

1) When there is a large drift in the parameter factors of the two accelerometers, as the change of accelerometer parameters have the same trend, the difference between the two accelerometers' parameter factors is relatively stable. Therefore, the performance of the new configuration is relatively stable.

2) The coefficient of Δf in equation (9) is $2k_2''f-k_1''$, less than $k_1'+2k_2'f$ in equation (8), this makes the resolution and anti-interference ability decrease when using the old configuration to measure Δf .

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