Ocean three components magnetometer for seafloor observatory

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***Abstract*-An ocean magnetometer detecting near seafloor can reveal more information for geologists and geophysics. A new design of Ocean Bottom Magnetometer was proposed in the paper. The sensor error compensation and circuit design was given in detail. The data logger was elaborately designed for data acquisition, data storage and data readout. The first sea trial for this system was described and a data analysis was given as well. Some preliminary conclusions were obtained and some prospects were given for further research.**

I. INTRODUCTION

Observing the Earth's magnetic field and acquiring the geomagnetic data are of great use in some geophysical studies, such as decade-period changes in the length-of-day, or the thermal core-mantle interactions. The main difficulty in running a magnetic observatory is how to acquire the real three components of geomagnetic filed. The orthogonal error of 3-axis of magnetic sensor, the inherent magnetism of ferromagnetic materials of observatory platform, and the lack of orientation of magnetometer, all result in the imprecision of three components acquisition. A new method of three components acquisition is discussed on these three aspects as mentioned above. The calibration of GMR sensor was implemented in a non-magnetism turntable with 6 degree of freedom, which is the foundation of after work. The deviation compensation based on sufficient rotation trial on site was proposed to remove the effect of magnetism from platform materials as possible. The effective methods of initial alignment and autonomous underwater direction judgment were discussed based on the MEMS Strap-down Inertial Navigation System. The Lake trial in QianDao Lake is introduced finally.

II. SYSTEM DESIGN

The system of magnetometer consists of sensor circuit, data logger and power supply. Sensor circuit amplifies the weak signal from sensor, converts it to digital form and transmits it to data logger. The signal should be linearly amplified and noise should be suppressed as possible so as to guarantee the high sensitivity and resolution for whole system. So low noise, low offset and high linearity chips were selected and EMC design of circuit board was given. Data logger receives and stores the data to SD card, which will be read out to host computer via RS-232. The system is due to work under water for several days on self-contain mode, so high energy battery is needed for power supply. The battery package was composed by two groups of cells each of which consist of six 1.5V cells. The system design is described as Figure1.

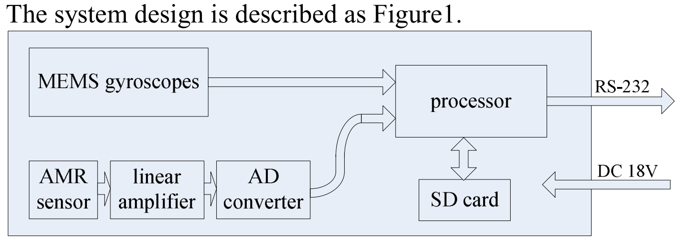

Figure 1. block of whole system

III. AMR SENSORS

Magnetic sensors have been in use for well over 2,000 years. Various technologies can be adopted in earth' field sensing, such as SQUID, optically pumped, nuclear procession, flux-gate and AMR sensors. It is difficult to apply these technologies in ocean bottom except flux-gate and AMR sensors, especially considering the subsea battery power limitation. Flux-gate magnetometers were usually adopted in seafloor observation use. But AMR sensors is a new substitution for higher precision, lower power consumption and smaller size.

The anisotropic magnetoresistive (AMR) sensor is one type that lends itself well to the earth's field sensing range. This sensor is made of a nickel-iron (Permalloy) thin film deposited on a silicon wafer and is patterned as a resistive strip. The reaction of the magnetoresistive effect is very fast and not limited by coils or oscillating frequencies. The key benefit of AMR sensors is they can be bulk manufactured on silicon wafers and mounted in commercial integrated circuit packages. This allows magnetic sensors to be auto-assembled with other circuit and systems components.

A. SENSOR ERROR MODEL

The major errors of magnetoresistive sensors within vector magnetometers are caused by sensor triplet deviations. Both orthogonalized sensors triplets are not always placed in the way that the corresponding axes align together; neither do they align with axes of the casing of the whole device. There are some error models describing sensor triplet deviations to calibrate them in elaborate procedures. A Common error model is described in (1).

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$$\vec{H} = (K \bullet U - O)^T \bullet \begin{bmatrix} \cos\theta_X & 0 & \sin\theta_X \\ \cos\theta_Y \cos\phi_Y & \sin\theta_Y \cos\theta_Y & \sin\theta_X \\ 0 & 0 & 1 \end{bmatrix}^{-1} \quad (1)$$

B. SENSOR CALIBRATION

The magnetoresistant sensor was experimentized for error calibration. Full space rotation test was done. We inserted 10 test points along each axis. The tested data for the triplet is listed out as Table 1.

Table 1. data of sensor rotation test

		±180	+144	+108	+72	+36	0	-36	-72	-108	-144
Rotate on X-axis	X	47.86	48.06	47.52	47.32	47.98	48.10	47.36	47.85	47.96	47.77
	Y	-96.36	-64.20	-18.26	17.34	54.68	92.31	60.36	15.85	-13.96	-57.77
	Z	0.36	20.16	36.03	37.07	25.64	-0.32	-29.55	-36.85	-39.11	-30.21
Rotate on Y-axis	X	49.35	34.63	15.75	15.36	-5.12	43.56	34.55	16.37	13.58	39.44
	Y	-96.02	-95.34	-96.27	-96.06	-96.99	-95.86	-96.23	-96.01	-96.77	-96.56
	Z	1.30	-19.66	-35.36	-32.66	-18.36	0.36	16.39	39.15	34.56	18.33
Rotate on Z-axis	X	48.54	95.65	109.55	78.89	21.56	-45.88	-94.21	-108.54	-81.47	-21.83
	Y	-99.35	-55.33	14.11	74.69	107.50	101.23	54.22	-14.36	-73.17	-106.23
	Z	0.30	0.13	0.85	-0.30	-0.18	0.26	-0.75	0.12	0.30	0.05

Here we use the quasi-newton iterative method, and use the Broyden algorithm to realize it into codes. The flowchart of Broyden procedure is drawn in Figure 2. The programming environment is Visual C++ 6.0. The results of program running are listed in Table 2.

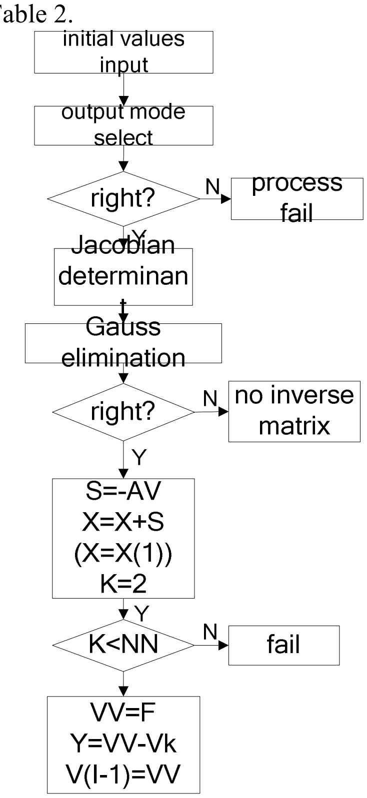

Figure 2. flowchart of Broyden procedure

We can derive the relative changes of sensing data toward rotate angles from table 1, and draw it in Figure 3. After running calibration program, we can get the estimate errors and compensate them. The new relation between sensing data and rotate angles after calibration is drawn in Figure 4.

Table 2. data before and after calibration

parameter	K_x	K_y	K_z	O_x	O_y	O_z	θ_x	θ_y	φ_y	H
before calibration	300	300	300	0	0	0	0	0	0	30000
after calibration	266.34	265.36	267.83	2.36	1.89	2.13	0.09	0.59	0.43	29375.48

Notes：N（equation dimensions）=10；TOL（accuracy of iteration）= 1.0×10-6；NN（maximum iteration number）= 10000；actual iteration number is 182；actual computing time is 2.8s

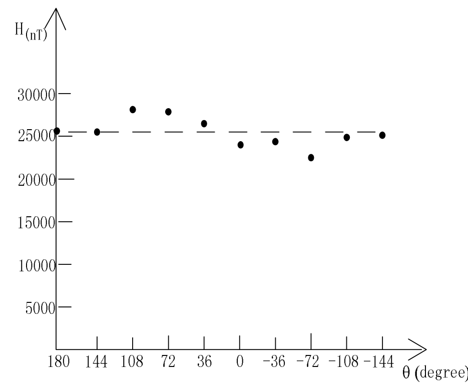

Figure 3. relation between total fields and rotating angles before correction

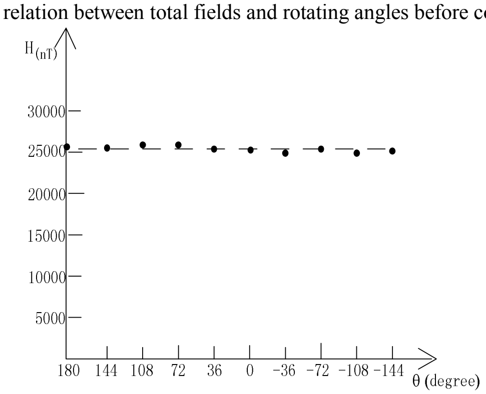

Figure 4. relation between total fields and rotating angles after correction

IV. SYSTEM CALIBRATION

The experiment data should be analyzed carefully to find out the reason of big fluctuation of total field. The 3D view of magnetic field vector is shown as Figure 5. It is obvious that the distribution of data is not random. The profile of figure seems a ball which centre departs from zero point. We can call it magnetic deviation ball. The inherent magnetism of towed body was the main reason, which could be calibrated by data fitting.

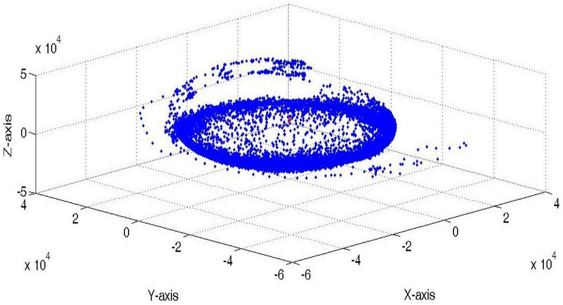

Figure 5. 3D view of magnetic filed data of sea trial

Theoretically, data fitting should be done in lab with a full space rotation of whole system. But the actual situation did not allow the 'special system' after calibration occupy a special ship time. So the OBM boarded ST6000 from STU with other underwater sensors. The ST6000 and other sensors had unknown magnetism, so data fitting have to be made in real on-site field without adequate full space rotation.

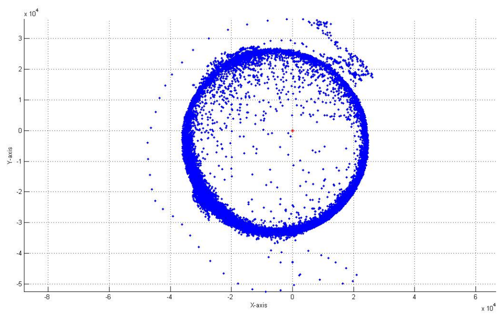

Figure 6. XOY plane of magnetic filed data of sea trial

Figure 6 shows a projection of XOY plane from Figure 9. Although data is not sufficient, the circle deviating from zero point seems significantly, because the towed body rotated around the cable more over than other way. Although applying an method of data fitting on figure 9 may be difficult, an easy way to find out the centre of circle of Figure 10 seems feasible. The concrete flow using MATLAB is given below.

A. Intercept the data during towing under the deep water, remove the data at the beginning or end while the towed body beneath water, so as to the exclude the magnetic interruption of ship body.

B. Average the maximum and minimum on each axis, calculate the initial centre of circle for searching, and then derive the variance of each data point to this initial centre.

C. beginning with this initial centre, search the next potential centre on a shell with radius of 10nT, calculate out the variance for every potential centre.

D. End of searching. Find out the point with minimum variance. Memorize the radius of shell on which this point existed.

The result of searching algorithm is given below.

$$\text{centre} = 1.0e{+}003 * [-5.5391 \quad -3.9192 \quad 0.7265 \quad 0.6400] \qquad (2)$$

That is, the real centre of circle by this method was:

$$(x, y, z) = (-5539.1 \quad -3919.2 \quad 726.5)\ \text{nT} \qquad (3)$$

Substituted by this new centre, the total magnetic field had been calculated again was shown as the yellow curve of Figure 7. Compared by the black curve of original data, the effect of this easy way of calibration is obvious.

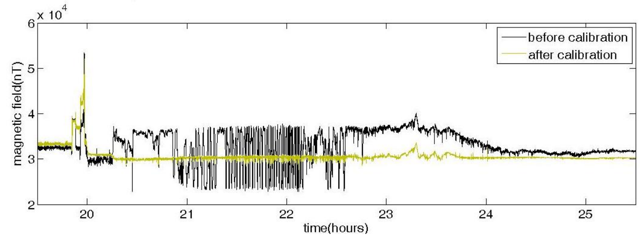

Figure 7. comparison of data curve of sea trial before and after calibration.

V. NON-MAGNETIC ORIENTATION

High-resolution non-magnetic orientation is the most important technology for acquiring the 3 components of total field accurately. Since its high precision and not being interfered with the geomagnetic field, Strapdown Inertial Navigation System(SINS) has become the best substitution of electronic compass. The H∞ filtering optimization method is adapted to the initial alignment of SINS, which is critical to achieve high-resolution non-magnetic underwater direction judgment. Compared with the standard Kalman filter, H∞ filtering filter is more robustness and also improves the accuracy. The application of observability analysis can solve the contradiction between the misalignment angles's convergence speed and alignment accuracy effectively. The simulation results show that, H∞ robust filtering is a very effective estimation method and can become a reference plan for deep-sea accurate positioning.

VI. LAKE TEST

Finally, a lake test is done in Qiandao Lake. The deepest area is up to 50m and the duration up to 40 hours. It takes about 20 minutes to launching the observatory and the deviation of Euler angle is not more than 0.5 degree. The difference of each component between above and beneath the water was given. The seafloor geomagnetic observatory was shown as Figure 8.

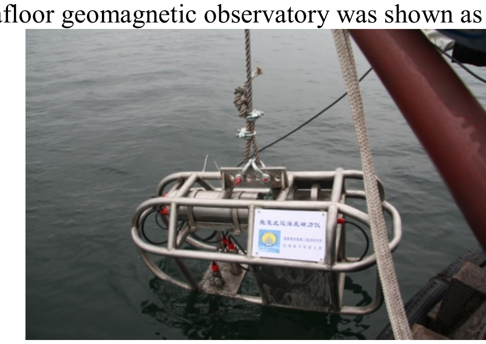

Figure 8. lake trial of seafloor 3 components geomagnetic observatory

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