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The component compensation of geomagnetic field vector measurement system

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ABSTRACT

Magnetic field distortion of INS is the major factor influencing the accuracy of geomagnetic field information measurement system. Simulation and experiment results show that traditional scalar compensation methods are disabled for component compensation. A component compensation method is proposed, in which parallelepiped frame and perpendicular platform are used with designed operation process. Comparing with traditional methods, the component compensation method is effective for distortion parameter estimation, and it shows better component compensation performance. Experimental test result demonstrates that distortion field components of INS are suppressed approximately two orders after compensation, and the North, Vertical and East component measurement error of the geomagnetic field are reduced to 2.3%, 3.3% and 4.5% of the former values respectively. Declination error is reduced from 7.074° to 0.331° (4.6% of the former value). This compensation method contributes to the accuracy improvement of geomagnetic field vector measurement system.

1. Introduction

Three axis magnetometers are widely used for earth's information measurement and object detection [1–4]. There has been much progress contributing to geomagnetic field measurement and sensor improvement [5–9]. Vector information of geomagnetic field is of great importance in many applications, such as geological survey, mine detection, underwater navigation and geoscience research [10]. Geomagnetic field vector (the projection of geomagnetic field on geography coordinate) can be measured directly when the attitude of three axis magnetometers is provided by inertial navigation system (INS). One key factor limiting the measurement accuracy is magnetic distortion field, which can reach thousands of nT. Thus, compensation must be considered before application. Especially, magnetic distortion component must be correctly compensated for the measurement of geomagnetic field vector.

Magnetic distortion compensation is not a new problem, and a few techniques have been presented. Tolles–Lawson equation is widely used for magnetic field compensation on aircraft, which can only obtain magnetic intensity compensation result [11,12]. Recently, some researchers used a three axis magnetometer and provided magnetic field intensity to estimate compensation parameters [13–19]. Such kinds of methods are based on scalar approach algorithms, although they can calculate compensated magnetic component. The basic principle is that the calculated magnetic intensity according to three compensated magnetic components should be equal to the known magnetic field intensity. Considering that the same magnetic intensity may be composed of different magnetic components, the compensation is effective for gross amount of magnetic field intensity, but not for magnetic field components. Theoretically, these methods can be called scalar compensations methods.

Li et al. proposed an integrated compensation method to suppress distortion field of underwater vehicles, which was based on nonlinear least square [13]. Wu et al. introduced the stretching particle swarm optimization (PSO) algorithm with good robustness. The performance of this algorithm was evaluated with a series of laboratory experiments and a field experiment of autonomous underwater vehicle [14]. Pang et al. proposed a new compensation model for magnetic vector compensation, which not only includes magnetometer bias, scale factor, non-orthogonality but also considers hard iron, soft iron, eddy-current field and low frequency magnetic field [15]. Gebre-Egziabher et al. proposed a two-step method for compensation based on ellipsoid fitting [16]. Foster et al. presented an extension of the nonlinear two-step estimation algorithm for the compensation of strapdown

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magnetometers [17]. Vasconcelos et al. proposed a maximum likelihood estimator (MLE) algorithm in uninhabited autonomous vehicles to compensate magnetic distortions [18]. Gebre-Egziabher proposed an auto calibration algorithm for compensation of magnetometer triads in small aerial vehicles [19]. As a whole, these mentioned scalar compensation methods can be divided in two categories: (1) Direct scalar compensation, which means that all parameters are estimated directly by scalar approaching algorithm. But, it is hard to obtain all parameters accurately even though distortion field intensity is suppressed. (2) Two-step scalar compensation. Using these methods, middle parameters are calculated in the first step, and soft-iron matrix is transformed into symmetrical matrix or triangular matrix. However, these parameters can not represent distortion field component information even though distortion field intensity can be compensated.

Little work has been done to analyze and evaluate the compensation performance of magnetic distortion field component. In this paper, a component compensation method is proposed to compensate distortion field vector of geomagnetic field information measurement system. Using a parallelepiped frame and perpendicular platform, true values of magnetic field components are provided. All parameters of unsymmetrical soft-iron matrix and hard-iron matrix are calculated accurately, and component compensation performance is evaluated. Comparing with traditional methods, the proposed method shows better component compensation performance.

The proposed measurement system and its compensation method have a wide application in geoscience. DI-flux were widely used in geomagnetic observatories to determine the geomagnetic field vector, which must be deployed at a flat and stable place, and it is time-consuming to adjust the DI-flux carefully [20,21]. As for airborne geomagnetic field vector measurement, bulky inertial navigation platform or gravity gradiometer system should be used, and it should follow a designed routine or keep levelly stable. Even 1° orientation measurement error will lead to about one thousand nT of geomagnetic field vector measurement error. Thus, it is difficult and costly to operate [22]. The proposed system can be a better way for earth's surface and airborne geomagnetic field vector measurement, because geomagnetic field vector can be measured quickly in application and the system deployment attitude is not required. On aircraft, even slight change of magnetometer attitude can be measured immediately due to its high angle measurement resolution, thus the aircraft wobble problem influencing airborne geomagnetic field vector measurement accuracy can be solved. Also, the proposed system can be used for geomagnetic field vector measurement where traditional methods are unfeasible, for example, under water. In addition, the proposed compensation method is a better way for distortion field component compensation comparing with traditional methods, which can be a better way to improve the measurement accuracy of magnetic compass.

Exploration geophysicists usually measure only the magnitude of magnetic field (TMI measurement). The disadvantages of measuring only the TMI are unimportant in many resource exploration situations [22]. Moreover, this practice is incorrect because it fails to allow for the fact that the magnetic field is a vector field [23]. If the magnetic anomaly sources are strongly magnetized, in a direction different from the main Earth field, then the TMI does not truly represent the strength or direction of the magnetization of those sources [22,23]. Vector measurement can overcome the problem of TMI measurement because the magnetic intensity is calculated from the measured vector magnetic field, thus providing reliable magnetic anomaly information. Also, it can be used for mine detection or geological structure analysis when the compensated instrument is used for magnetic field measurement in a large area.

This paper reports an effective way for magnetic field component compensation, which can be used for: (1) Geomagnetic field information measurement. (2) Magnetic field component compensation. (3) Magnetic object detection. (4) Geological structure analysis.

2. Component compensation theory

The distortion field model can be expressed by [19]:

$$\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix} \begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} + \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} + \begin{bmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \end{bmatrix}. \tag{1}$$

where H_x, H_y, H_z are true values of magnetic field components. B_x, B_y, B_z are measured components of the three-axis magnetometer. r_{xx}, ⋯, r_{zz} are soft-iron parameters [19]. b_x, b_y, b_z are hard-iron parameters. ε_x, ε_y, ε_z are measurement noise of X axis, Y axis, and Z axis, respectively.

Thus, the component compensation model can be expressed as:

$$\begin{bmatrix} H_x \\ H_y \\ H_z \end{bmatrix} = \begin{bmatrix} r_{xx} & r_{xy} & r_{xz} \\ r_{yx} & r_{yy} & r_{yz} \\ r_{zx} & r_{zy} & r_{zz} \end{bmatrix}^{-1} \left[\begin{bmatrix} B_x \\ B_y \\ B_z \end{bmatrix} - \begin{bmatrix} b_x \\ b_y \\ b_z \end{bmatrix} \right] \tag{2}$$

Fig. 1 shows the structure of compensation system, which mainly contains parallelepiped frame and perpendicular platform. Firstly, the three axis magnetometer is fixed in the parallelepiped frame to obtain the true value of geomagnetic field component (Fig. 1(a)). As shown in (1), there are 12 unknown parameters, thus at least 4 attitudes should be deployed. Theoretically, there are in total 24 attitudes because parallelepiped frame has 6 sides. The deployment attitudes are recorded in sequence.

After the deployment of parallelepiped frame fixed with magnetometer, the INS is fixed together with magnetometer (Fig. 1(b)).

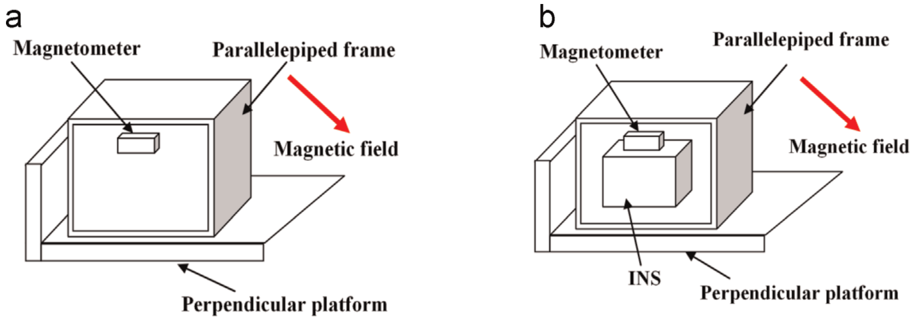

Fig. 1. (a) True value measurement of magnetic field component. (b) Component measurement with INS magnetic distortion field.