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Research on Three-Component Geomagnetic Field Differential Measurement Method for Underwater Vehicle

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Abstract

The precise measurement of the geomagnetic element is the key to realize navigation and positioning with the development of geomagnetic navigation technology. In this paper, a kind of underwater vehicle three-component geomagnetic field differential measurement method is presented based on the ideas of the difference. The three-component geomagnetic field mathematical model of traditional measurement method is improved and new differential measurement model(DMM) is established. Difference expressions of measurement magnetic field in the DMM obviously reduce the impact of interference magnetic field in the process of geomagnetic field measurement and improve the measuring precision of the three-component geomagnetic field. Finally, the method's effectiveness is validated by simulation. The precision of DMM method is 10±5nT which is about two times that of traditional measurement model (TMM) method under the condition of ±25nT stray outside interference magnetic field. The method effectively improves the geomagnetic field measurement precision and has stronger anti-interference ability. It is of significance for practical application of underwater geomagnetic navigation method.

***Keywords**: navigation and positioning, three-component geomagnetic field, differential measurement model (DMM), traditional measurement model (TMM), underwater geomagnetic*

1. Introduction

Geomagnetic navigation technology has the advantage of no source, no radiation, all-weather, the whole region, full-time working, and anti-disturbance [1]. It also combines with the integrated navigation technology from the other navigation and positioning technology, such as INS/geomagnetic navigation, GPS/geomagnetic navigation, *etc*. [2-4]. These methods can greatly improve the navigation precision of motion carrier or weapons and equipment, to achieve more accurate positioning and attack. Drawing geomagnetic map is one of the key technology of realizing geomagnetic navigation and the source of the magnetic map database mainly has two ways: one way is to build a geomagnetic field model, the other one is the actual measurements of the geomagnetic field. Geomagnetic model data from the satellite and some land scattered geomagnetic observation station can't truly reflect underwater geomagnetic field information of special geographical environment. Therefore, to realize the precise navigation positioning of underwater vehicle, it is necessary for the geomagnetic field of underwater environment to field measure.

As we know, the single total geomagnetic field intensity maybe produce contour line which can't meet one-to-one relationship between the total geomagnetic field intensity and the coordinates of the current position [6]. Therefore, the measurement of the geomagnetic field three-component information become the focus of research content. A shipboard three-component magnetometer (STCM) has been developed since 1977 [7],

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which belongs to the ship borne measurement of the three-component geomagnetic field and builds the TMM with an error of 50 ± 25nT. At present, most methods mainly compensate the induced and permanent magnetic field of vehicle by single sensor according to the TMM [8-10]. For the underwater vehicle, it is pointed out that the description of magnetic field around the vehicle is not enough in the TMM method, which results in measuring magnetic field are easy to be interfered by ambient magnetic field, and the calculating results have great error. The TMM method has carried on the experimental verification, and the results show that the maximum error magnitude of three-component geomagnetic field calculating results is 10^2nt, so it is difficult for TMM method to apply on the accurate navigation.

On the basis of TMM method, Firstly, the article analyzes the magnetic field characteristics of the underwater environment around the vehicle and establishes a new mathematical expression used for magnetic field measurement according to the results of the analysis. Secondly, by the new mathematical expression, the DMM is deduced . Finally, the feasibility of DMM method is verified by simulation. The simulation results show that DMM method can not only enhance anti-interference ability, but also has a high calculating accuracy.

2. Research of DMM

2.1 The TMM and the Existing Problems

Ocean has many characteristics, such as vast area and complex environment, to achieve a wide range of underwater magnetic field measurement, we must rely on ships, underwater robots or other underwater vehicles, and so on. These vehicles are mostly made of ferromagnetic material, so due to the magnetization of the geomagnetic field, it can produce complex interference magnetic field around the vehicle, and the magnetic field vector of superposition together eventually form the measuring magnetic field of sensor getting.

The magnetic field around the vehicle mainly is divided into geomagnetic field and magnetized field according to TMM, and the magnetized field includes the induced magnetic field and the permanent magnetic field. Size and direction of the geomagnetic field and vehicle attitude determines the size and direction of the induced magnetic field. The vehicle is magnetized by the same direction geomagnetic field in the process of building or parking period and then produce the permanent magnetic field whose value in a short period of time will not change. Therefore, the TMM is expressed as

$$H_G = D^{-1} \cdot \left(H_M - H_R - H_S \right) \quad (1)$$

Where H_G is the three-component geomagnetic field value on geographical coordinate system. D is the transformation matrix between geographic coordinate system with the measuring coordinate system due to the roll, pitch, and yaw of the vehicle. H_M is the observed three-component value on measuring coordinate system from magnetic vector sensor. H_R and H_S are the three component value of the induced and the permanent magnetic field on measuring coordinate system.

In the actual underwater environment, eddy current magnetic field is produced due to the vehicle movement in the geomagnetic field producing induced current. Vehicle engine, electric equipment, and other institutions will radiate outward low-frequency AC magnetic field. Underwater shipwrecks, surface ships and other motor vehicle around all can produce some stray interference magnetic field. These magnetic field components will affect magnetic vector sensor measurement. Therefore, vehicle magnetic vector sensor measurement model is expressed as:

$$H_M = D \cdot H_G + H_R + H_S + H_E + \sum H_A + \sum H_N \quad (2)$$

Where H_E is the three-component value of eddy current magnetic field on measuring coordinate system. Due to the magnetic field gradient vector itself is small and the underwater vehicle actual speed is relatively low, the eddy current magnetic field in general can be ignored; ΣH_A is the three-component value on measuring coordinate system of all sorts of electric equipment producing low frequency AC magnetic field, which can be filtered by reasonable designed filter. ΣH_N is the three-component value on measuring coordinate system from other surrounding source of interference magnetic field which is the source of one or more of the unknown outside stray interference magnetic field. ΣH_N has a strong uncertainty, so it can't be estimated the size and direction. It is more difficult to remove and compensate the stray magnetic field. In the TMM method ,due to the single sensor measurement can't remove the ΣH_N and it have to ignore this component. Therefore, after filtering and deformation ,the new magnetic vector sensor measurement model is:

$$H_M = D \cdot H_G + H_R + H_S + \sum H_N \quad (3)$$

Although ΣH_N is uncertain, it is one of essential components in the complex environment magnetic field of underwater. It will be added to the measured values of magnetic sensor, and the equation (1) of TMM consider only a part of the influencing factors. Therefore, ignoring ΣH_N will affect the geomagnetic field measurement precision of the TMM method.

2.2 Establish the DMM

Aiming at the shortcomings of the TMM method, this paper puts forward the space DMM method based on multi-sensor, and DMM is established by solving the equations of geomagnetic field vector expression.

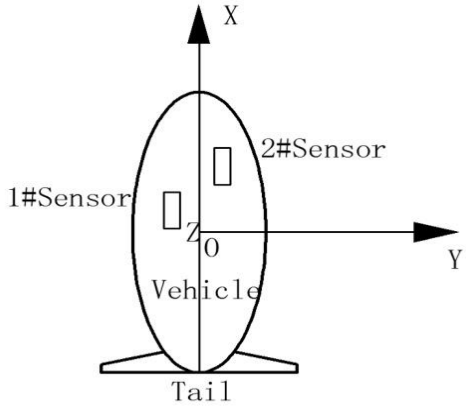
Between the induced field generated from the induction magnetic moment and the geomagnetic field has a linear relationship, so the induction magnetic moment of each part of the vehicle is proportional to H_G .As a result, the induced magnetic field three-component and the geomagnetic field three-component in matrix form meet the following relationship:

$$\begin{bmatrix} H_{R_X} \\ H_{R_Y} \\ H_{R_Z} \end{bmatrix} = K \cdot D \cdot H_G = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot D \cdot \begin{bmatrix} H_{G_X} \\ H_{G_Y} \\ H_{G_Z} \end{bmatrix} \quad (4)$$

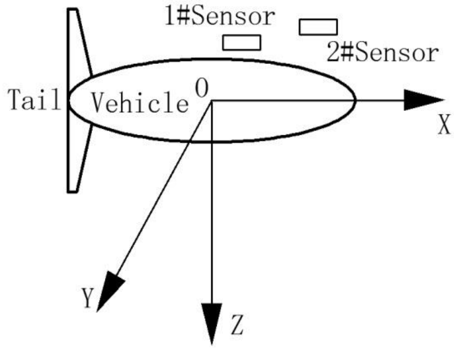
Where K is called induction coefficient matrix which is a 3×3 matrix and its elements value depends on the distribution of the magnetic susceptibility of the vehicle ,the location of the sensors and the shape of the vehicle and so on. It is generally believed that if the installation location of sensor is permanent, the value of the induction coefficient matrix will not change. Equation (3) is transformed into:

$$H_M = (E + K) \cdot D \cdot H_G + H_S + \sum H_N \quad (5)$$

Where E is an identity matrix. How to remove H_S and ΣH_N in the equation (5) has become a major problem. In order to better reflect the advantage of spatial DMM method, improve the measurement precision of the three-component geomagnetic field, the vector sensor installation location on the vehicle must satisfy some special requirements.



(a) Vertical View



(b) Right View

Figure 1. Measurement Coordinate System of Underwater Vehicle and Sensor Installation Drawing

Measurement coordinate system and sensor installation position as shown in Figure 1, (a) is the vertical view and (b) is the right view of underwater vehicle. The x axis of pointing toward the vehicle forward on left and right sides symmetrical longitudinal profile is positive. The y axis pointing toward the right on the center plane of the vehicle is positive. A positive z axis is perpendicular to the x and y plane. According to the actual size, it is necessary for two or more three-component magnetic sensor to install obeyed the principle of strap down and away from the position of the engine on vehicle. In order not to get the singularity matrix appeared by difference calculation of K , sensors are installed on both sides along the central axis on the vehicle surface, and we design the sensor installation location to make them keep a certain distance in space x, y, z direction displacement. Figure 1 (a) shows the x, y axis direction keep a certain displacement, Figure 1 (b) shows the z axis direction keep a certain distance, but also by shortening the distance between two sensor line makes the stray magnetic field the two sensors measured have the same value as far as possible. Therefore, the component of the stray magnetic field may be subtracted when solving the differential equations, so that the interference magnetic field from unknown magnetic source radiation is the greatest extent reduced the influence to the geomagnetic field measurement results.

According to the equation (5) to build the following equations:

$$\begin{cases} H_{1M} = \left(E+K_1\right)\cdot D\cdot H_{1G} + H_{1S} + \sum H_{1N} \\ H_{2M} = \left(E+K_2\right)\cdot D\cdot H_{2G} + H_{2S} + \sum H_{2N} \end{cases} \tag{6}$$

Because each component of the geomagnetic field gradient itself is very small and the geomagnetic field strength of horizontal component from south to north in China mainly change with latitude whose the maximum change of 1 latitude is 10nT and vertical component strength biggest change of 1 latitude is 27nT [14]. According to the vehicle actual size, the distance two sensors installed is relatively close. Therefore, on geographical coordinate system ,the three-component geomagnetic field value on two sensors location and the three-component geomagnetic field on the vehicle location is the same, and satisfy the following relations:

$$H_{1G} \approx H_{2G} \approx H_G \tag{7}$$

Because of various interference magnetic field being generated by the magnetic body outward radiation, it satisfies the experience formula of magnetic source producing the magnetic field intensity attenuation in the water [15] :

$$H = 1.5\frac{M}{R^3} \tag{8}$$

Where H is the magnetic field intensity of the magnetic body outward radiation, M is the equivalent magnetic moment of the magnetic body, R is the distance of leaving the magnetic body. Through the equation (8) we know the magnetic field intensity is inversely proportional to the distance, and then the first and second derivatives of distance show that magnetized magnetic field has the characteristics of the attenuation and gradient decreasing with the distance. When measuring position and the magnetic body distance is close, the vehicle itself as a magnetic body, magnetic field intensity gradient is bigger around the vehicle, which makes the inductive magnetic field of the two sensor location has great different, namely the K_1 and K_2 existing obviously differences.

When the distance between measuring position and the magnetic body is far, the outside unknown magnetic source as a magnetic body, gradient of magnetic field intensity is smaller around the vehicle, so you can see this part of the magnetic field as a uniform magnetic field, and meet the following formula:

$$\sum H_{1N} \approx \sum H_{2N} \tag{9}$$

Through the analysis of the above, difference equation （10） is derived by difference of two equations in equation （6）:

$$H_G = D^{-1}\cdot\left(K_1 - K_2\right)^{-1}\cdot\left[\left(H_{1M} - H_{2M}\right) - \left(H_{1S} - H_{2S}\right)\right] \tag{10}$$

The equation (10) is called the DMM. K_1 、 K_2 and H_{1S} 、 H_{2S} exist obvious difference in different location on the vehicle, and they can be gotten by a series of changing attitude measurement. H_{1M} and H_{2M} can be directly measured by magnetic vector sensor. D can be directly measured by posture sensor. Therefore, H_G on geographical coordinate system was calculated.

2.3 Description of the Coefficient Matrix and the Permanent Magnetic Field

The inductance matrix and permanent magnetic field in the DMM can be obtained through the measurement of rotating 360° . Before the vehicle leaving, a non-magnetic anomaly point P which is recorded by the GPS is selected at a certain depth below water, and there isn't other interference magnetic source near the point P. Therefor, the ΣH_N can be ignored and the H_G can be measured when the vehicle does not exist. Then a vehicle equipped with magnetic vector sensors circles around the point P with its own length as the radius and keeps slight roll and pitch. The sensors data of vehicle's different poses are recorded by the real-time data acquisition system, including the roll angle α 、 pitch angle θ 、 heading angle φ and the $H_{1M}(\alpha,\theta,\varphi)$ and $H_{2M}(\alpha,\theta,\varphi)$ measured by magnetic vector sensor in the corresponding pose . The expression of coordinates transformation matrix[16] is :

$$D = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & \sin\alpha \\ 0 & -\sin\alpha & \cos\alpha \end{bmatrix}\cdot\begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix}\cdot\begin{bmatrix} \cos\varphi & \sin\varphi & 0 \\ -\sin\varphi & \cos\varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{11}$$

There are a total of 12 unknown parameters in the K and H_S, so in order to solve the all parameters each sensor needs n($n \geq 4$) sets of all attitude three-component survey data at least, and then the known geomagnetic field and the measured magnetic field are plugged into the DMM. The equations are shown below:

$$H_{1M}\left(\alpha_i,\theta_i,\varphi_i\right)=\left(E+K_1\right)\cdot D_i\cdot H_G+H_{1S}\ \left(i=1,2,\cdots n\right) \tag{12}$$

$$H_{2M}\left(\alpha_i,\theta_i,\varphi_i\right)=\left(E+K_2\right)\cdot D_i\cdot H_G+H_{2S}\ \left(i=1,2,\cdots n\right) \tag{13}$$

Through the above equations K and H_S are estimated. There are many commonly used estimation methods including the elliptic constraint method, Kalman filtering method and nonlinear least squares method [17].After adding the value of H_{1M} 、 H_{2M} and D into the equation（10）， the H_G from a certain point or a measured strip line can be calculated .

3. Computer Simulation Study

Due to the fact the experiment of underwater vehicles has to overcome many technical difficulties, we can use the computer to construct experimental environment and solve relevant parameters to realize the simulation study of spatial differential measurement method.

3.1 Set the Vehicle Simulation Model

A large-scale finite element simulation software is applied to verify and simulate this method. Using a single ellipsoidal vehicle to construct the model [18-19], which is a ellipsoidal cavity with 50m long and 5m in width and height. The cavity's thickness is 0.05m.There is a tail in the back and the relative magnetic permeability of the material is 100. Two sensors strap down are installed on the both sides of surface axis in an asymmetrical position. The sensor of the left side is 0.2m higher than the vehicle's surface, and the sensor of the right side is 1.2m higher than the vehicle's surface. The straight line distance between the two sensors is 1.73m.

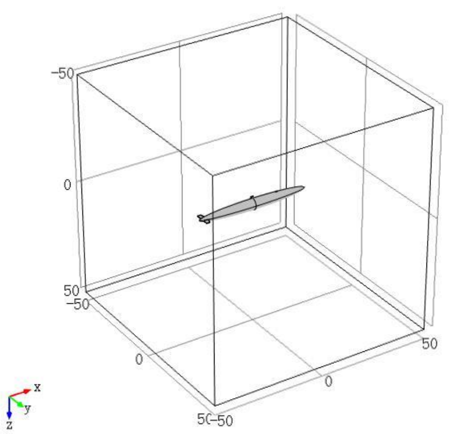


Figure 2. Vehicle Simulation Model

The three-dimensional size of the solving cube field is 100m*100m*100m and three-direction vector data are provided as the background geomagnetic field. Adding the initial magnetic field vector to offer the vehicle's own three-direction permanent magnetic field in the software. The simulation model is shown in Figure 2.

3.2 The Simulation and Solution of K and H_S

The K and H_S are Simulated and solved in an ideal environment (the magnetic environment of $\Sigma H_N = 0$). Firstly, in the condition of no background magnetic field , the initial magnetic vector is controlled to generate respectively the permanent magnetic K_1 and K_2 with 169.0nT, 106.0nT, 136.0nT and 125.0nT, 185.0nT ,155nT. Then adding the three-component magnetic field data to background, according to the IGRF-11/2010 model, the point of China's South Sea (5 ° N, 110 ° E) is chose with the three-component geomagnetic field 40858.8nT, 161.8nT, -3908.8nT. At last, the model is rotated 360 ° horizontally, accompanied with roll and pitch motion. The roll and pitch angle is no more than 5 degrees, the maximum measurement error of angle is 0.001 degree .Each sensor records 100 three-component measurement data . Then the data are taken into the DMM equations and used the least squares method to solve the equations. The K and H_S which are get from calculating are shown in Table 1.

In the Table 1, $\hat{K}$ 、 $\hat{H}_{SX}$ 、 $\hat{H}_{SY}$ and $\hat{H}_{SZ}$ represent the fitting values of each Parameter. δ indicates the relative error whose maximum value is 0.4% between the true and fitting values of the permanent magnetic field . By installation layout with a certain height difference of the two sensors, most of the effective number difference in the internal inductance matrix elements keep a minimum magnitude of 10-2, which ensure that it may not produce a singular matrix during the difference calculation and the solvability of the DMM mathematical expression .

Table 1. Coefficient Matrix and Permanent Magnetic Field Fitting Results

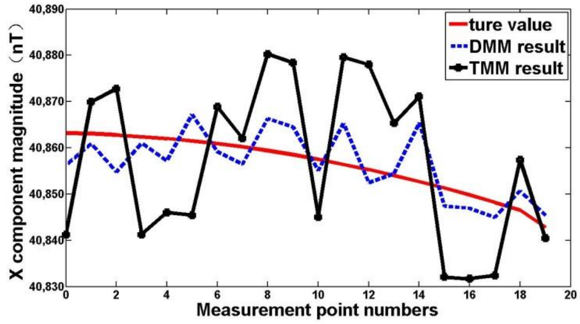
序号	$\hat{K}$	$\hat{H}_{SX}$ (nT)	δ_{SX} (nT)	$\hat{H}_{SY}$ (nT)	δ_{SY} (nT)	$\hat{H}_{SZ}$ (nT)	δ_{SZ} (nT)
1	$\begin{matrix} -0.0241 & -0.0053 & 0.0144 \\ -0.0233 & -0.0613 & -0.1340 \\ 0.0333 & -0.1453 & 0.0522 \end{matrix}$	105.8	0.2%	168.3	0.4%	135.4	0.4%
2	$\begin{matrix} 0.0020 & 0.0228 & 0.0234 \\ 0.0236 & -0.0751 & 0.0923 \\ 0.0214 & 0.0862 & 0.0354 \end{matrix}$	124.6	0.3%	185.6	0.3%	154.6	0.3%

3.3 The Verification of DMM Simulation

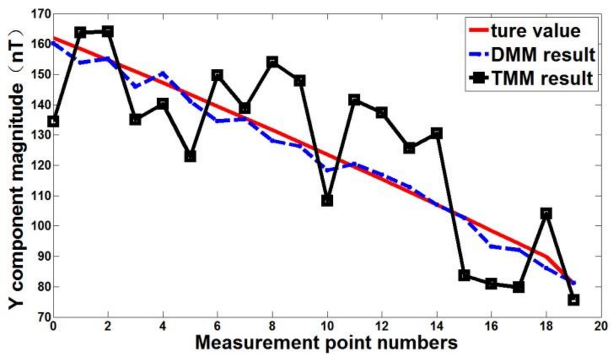
According to the IGRF-11/2010 model, 20 three-component of geomagnetic field data from the sea region of 5°N to 6°N and 110°E to 111°E are selected as the background field . Assuming that the coordinates of the vehicle are the same as the geographic coordinates during the simulation.

Underwater magnetic field around the vehicle is very complex. In addition to the vehicles' self-generated interference magnetic field , many of the external unknown interference sources can produce some stray magnetic fields, which will response on the sensor. Therefore, in order to be more approaching to the real underwater magnetic environment around the vehicle, to verify the validity of the DMM, random interference will be added into the data of the simulation measurement as the external stray magnetic field （$\Sigma H_N \neq 0$） in the real environment. Assuming that the maximum amplitude of the stray interference is ± 25nT on the 1# sensor, and the x, y, z direction gradient is 1nT/m, due to the straight-line distance between the two sensors is 1.7m, so the changing value of interference value on the 2# sensor is less than 2nT.

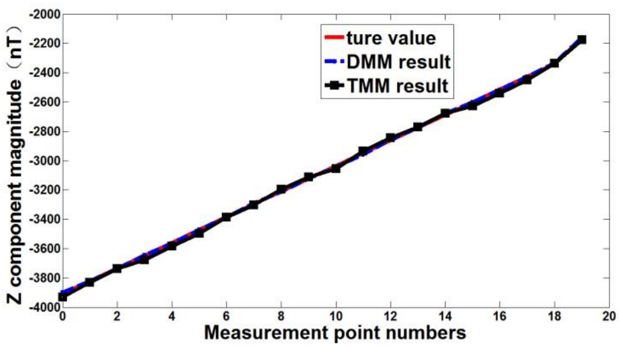
In the Figure 3 , red solid line is the true value of three-component geomagnetic field, and the blue dotted line is the DMM result and black square solid line is the TMM result. The data shown in (a-c) can be clearly seen by comparing when added the external stray magnetic interference whose maximum amplitude value of ±25nT. Both methods can separate the geomagnetic field from the measurement magnetic, but the results of the TMM increasing calculation error after adding external stray magnetic interference. The maximum absolute error is 30.0nT and the maximum relative error is 19.1%. While the effect of stray magnetic field for DMM is weaker, so the absolute maximum error is only 10.0nT, and the maximum relative error is 4.0%. The results not only illustrate the correctness of each estimation parameter ,but also demonstrate the calculation in DMM method wons higher precision than that of TMM. The DMM has a strong ability of anti-interference to remove the external stray which makes the measured results more close to the true value of geomagnetic field, and improves the accuracy and reliability of measurement.



(a) X Component of the Geomagnetic Field



(b) Y Component of the Geomagnetic Field



(c) Z Component of the Geomagnetic Field

Figure 3. The Vehicle Interference Magnetic Field Before and After Compensation of each Component of the Magnetic Field Intensity

4. Conclusions

In view of the TMM , a single magnetic sensor is used in the underwater vehicle geomagnetic field measurements ,which has poor anti-interference ability and low precision. The paper not only proposes a measurement method based on multi-sensor but also derives a DMM through the differential processing of the sensor array. The differential expression in the model pays more attention to the relative amount of change, which effectively removes the influence of vehicles' own magnetic interference and the external anomalies. Besides, it enhances the ability of resistance to the external interference in the measurement process. The simulation results show that DMM can measure at a accuracy 10 ± 5nT when external magnetic interference existing and the maximum amplitude of the stray interference is ±25nT, and that the relative error is reduced by 15.0% compared with TMM. Thus it improves the foundation of research for the underwater geomagnetic field measurement.

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