

Simulation Research of Interference Magnetic Field Compensation Method on the Underwater Vehicle

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Abstract

It is one of the most difficult issues for underwater vehicle to accurately compensate the interference magnetic field elements in automatic navigation. The theory of geomagnetic navigation on underwater magnetic vehicle is complicated and the development of interference magnetic field compensation system is difficult, so in order to research the compensation method easily and effectively, it is an important way for using the finite element software on the computer to complete the modeling and simulation. In this paper, the space distribution characteristics of magnetic field around the vehicle are analyzed and the vector compensation mathematical model of interference magnetic field is established. At last, the feasibility of compensation method is testified by an united simulation system composed of Comsol Multiphysics and Matlab which is developed using the secondary development technology of software. The results show that the united simulation system can be convenient to complete the modeling and simulation of compensation method, not only accomplishing a magnetic field characteristic analysis and numerical calculation function, but also the simulation precision of compensation results is very high.

Keywords: *underwater vehicle; geomagnetic navigation; secondary development; compensation method; modeling and simulation. this section*

1. Introduction

Geomagnetic navigation technology has the advantage of no source, no radiation, all-weather, the whole region, full-time working, and anti-disturbance, which can offset the shortcomings of the inertial navigation system (INS) which has the problem of error accumulated over time [1]. So that the underwater vehicle does not need a surface position calibration which can improve the stealthiness. Geomagnetic navigation technology for underwater vehicle provides a technical way of high precision and long-endurance independent positioning. Because the strength and direction of magnetic field are the function of position, once when the geomagnetic field vector elements are established, the location information of vehicle can be matched [2-3]. So it is the precondition for getting the geomagnetic field vector value of each point in the path. In addition, the geomagnetic field three-component values include more geophysical information which avoids producing contour line compared with the geomagnetic total field. Due to the underwater vehicle is mostly made of magnetic material, the magnetization effect is going to happen in the geomagnetic environment, which will affect the measurement value of magnetometer. If the real geomagnetic field vector information around the vehicle want to be gotten, the interference magnetic field from the vehicle must be compensated. Compared with air and land, the underwater magnetic field environment is more complex, and the installation of the magnetometer and seal are more

strict. At the same time, it is more inconvenient to control the vehicle attitude. Therefore, it is necessary for the research of interference magnetic field compensation method to depend on the computer simulation firstly, which can be a more efficient way to realize the compensation method study.

Comsol Multiphysics is a large finite element simulation software, which integrates a variety of categories of function module by solving a partial differential equation (single field) or partial differential equations (more fields) to realize the simulation of physical phenomena. At the same time, due to the Matlab has strong ability of data processing, so the software also provides the external interface with the Matlab to conveniently transfer data. Therefore, the united simulation system composed of the both softwares can realize the simulation research of interference magnetic field compensation method.

2. The Compensation Method of Interference Magnetic Field

Now, the compensation of interference magnetic field has two main methods. One is based on the Shipboard Three Component Magnetometer (STCM) [4], the other is based on the Tolles-Lawson equation [5]. But the main interference magnetic field compensation model of these methods has the similar form. In addition to the geomagnetic field, there are many interference magnetic field components in the measuring magnetic field which are gotten by magnetometer. According to the characteristics of the interference magnetic field, they can be roughly divided into the permanent magnetic field, the induced magnetic field and the alternating magnetic field.

The permanent magnetic field is produced because of the vehicle magnetized by the same direction geomagnetic field during the process of building or parking period and whose value will not change in a short period of time. When the sensor and the vehicle have the same vehicle's coordinate system, the each component value of the vector magnetometer for the permanent magnetic field is a constant. It can be described by H_p

$$H_p = [H_{px} \ H_{py} \ H_{pz}]^T \quad (1)$$

Since the geomagnetic field H_G is a weak field, the magnetic moment induced by H_G at each part of the vehicle's body is proportional to H_G . Between the induced magnetic field vector H_R and H_G satisfy following the three-component relations based on the Poisson equation:

$$\begin{bmatrix} H_{Rx} \\ H_{Ry} \\ H_{Rz} \end{bmatrix} = \begin{bmatrix} K_{xx} & K_{xy} & K_{xz} \\ K_{yx} & K_{yy} & K_{yz} \\ K_{zx} & K_{zy} & K_{zz} \end{bmatrix} \cdot A \cdot \begin{bmatrix} H_{Gx} \\ H_{Gy} \\ H_{Gz} \end{bmatrix} \quad (2)$$

Where $H_R = [H_{Rx} \ H_{Ry} \ H_{Rz}]^T$ is the three-component vector projections of the induced magnetic field in the vehicle's coordinate system. $K_{3 \times 3}$ is a 3×3 matrix which depends on the distribution of the magnetic susceptibility of the vehicle, the location of the magnetometer, and the shape of the vehicle. When the shape of the vehicle and the location of the sensor installed are determined, each of the elements in the matrix is a constant and the value is less than 1. $H_G = [H_{Gx} \ H_{Gy} \ H_{Gz}]^T$ is the three-component vector projections of the geomagnetic field in the geographic coordinate system. A is the transformation matrix between geographic coordinate system and the vehicle's coordinate system effected by the roll angle α , the pitch angle θ , and yaw angle φ . A is expressed as:

$$A = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos \alpha & \sin \alpha \\ 0 & -\sin \alpha & \cos \alpha \end{bmatrix} \cdot \begin{bmatrix} \cos \theta & 0 & \sin \theta \\ 0 & 1 & 0 \\ -\sin \theta & 0 & \cos \theta \end{bmatrix} \cdot \begin{bmatrix} \cos \varphi & \sin \varphi & 0 \\ -\sin \varphi & \cos \varphi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Vehicle engine, electric equipment, and other institutions will radiate outward low frequency AC magnetic field, and most frequency components of the the magnetic field is high frequency which is more than 10Hz. However, the geomagnetic field is a kind of low frequency changing magnetic field, which usually is lower than 1Hz frequency. So the characteristic of the alternating magnetic field having a difference from frequency with the geomagnetic field can be used to avoid it. The alternating magnetic field can be wiped out by reasonable wiring and be filtered by reasonable designing a filter.

So the magnetic field vector compensation model in vehicle's coordinate system can be expressed as^[6]:

$$H_M = A \cdot H_G + H_R + H_P = (E_{3 \times 3} + K_{3 \times 3}) \cdot A \cdot H_G + H_P \quad (4)$$

Where $E_{3 \times 3}$ is a 3×3 identity matrix. H_M is the observed three-component value on vehicle's coordinate system from the vector sensor. Note that all value gotten on the vehicle's coordinate system ,except that the value of H_G is on the geographic coordinate system.

So H_G is expressed as:

$$H_G = A^{-1} \cdot (E_{3 \times 3} + K_{3 \times 3})^{-1} \cdot (H_M - H_P) \quad (5)$$

In order to get $K_{3 \times 3}$ and H_P ,a 360 degree rotatin of the vehicle at a point where H_G is known is a common way.In equation (5),there are 12 unknown parameter(nine in $K_{3 \times 3}$ and three in H_P),so that one 360 degree rotation of the vehicle may acquire more than 12 linear equations. Therefore, the equations can be solved and get all the values of the unknown parameter.

3. The Theory of Finite Element Modeling and Simulation System

3.1. Mathematical Modeling of Finite Element

After magnetized by the geomagnetic field, the vehicle can produce other magnetic field around it. Due to the limited space in the area there is no continuous current, so the magnetic potential Φ can be used to describe any point of the magnetic field, and then according to the relationship between the gradient with the magnetic field vector, the intensity of magnetic can be obtained. Φ satisfy the following relations:

$$\nabla^2 \Phi = 0 \quad (6)$$

Where ∇ is the vector operator, in the rectangular coordinate system exist that:

$$\nabla = i \frac{\partial}{\partial x} + j \frac{\partial}{\partial y} + k \frac{\partial}{\partial z} \quad (7)$$

Φ is continuous on the boundary surface S of different magnetic materials and according to the condition of magnetic induction normal vector continuous, Φ satisfy:

$$u_1 \left. \frac{\partial \Phi}{\partial n} \right|_{S^-} = u_2 \left. \frac{\partial \Phi}{\partial n} \right|_{S^+} \quad (8)$$

Where n is the normal vector pointing from u_1 to u_2 (that is to say from s^- to s^+).

Induced magnetic field in the model there is another boundary surface at infinity, due to the magnetic field intensity present exponential decay characteristics with the distance, so the magnetic field at infinity has decreased to zero.

Solving the equation of Φ can be equivalent transformed to:

$$F = \int_{\Omega} \frac{1}{2} u \left[\left(\frac{\partial \Phi}{\partial x} \right)^2 + \left(\frac{\partial \Phi}{\partial y} \right)^2 + \left(\frac{\partial \Phi}{\partial z} \right)^2 \right] dx dy dz = \min \quad (9)$$

Where F is functional whose integral range is the whole field. u has the different permeability value for the different materials^[7]. When functional F is minimum the unit nodes magnetic can be worked out, and the magnetic field value is:

$$H_i = -grad\Phi_i \quad (10)$$

3.2. Establish the Simulation System

Comsol Multiphysics is a modeling and simulation software based on the finite element theory, which realizes the simulation by solving a partial differential equation (single) or partial differential equations and using mathematical method to solve the physical phenomena of real world. The software not only inserts many professional module for user to apply it conveniently, but also provides a lot of external interface with other software, which is convenient for model import and data output. Including the external interface of Solidworks and Matlab and so on, through the special channel of Comsol with Matlab the function of commands calls and data transmission can be implemented. This article mainly uses the transfer instructions function of Matlab GUI toolbox to call Comsol Multiphysics to achieve the function of modeling and simulation for underwater vehicle, and then to pass back the simulation data of magnetic field to the Matlab for data processed. Matlab calculates the related parameters (including $K_{3 \times 3}$ and H_p) and the geomagnetic field vector based on the compensation mathematical model (4) by the way of the least square algorithm under ellipse restriction, and then the geomagnetic field compensation results are displayed on the GUI interface. It is so convenient and quick to finish the real-time simulation of the vector compensation of interference magnetic field^[8]. Detailed implementation is shown in Figure 1.

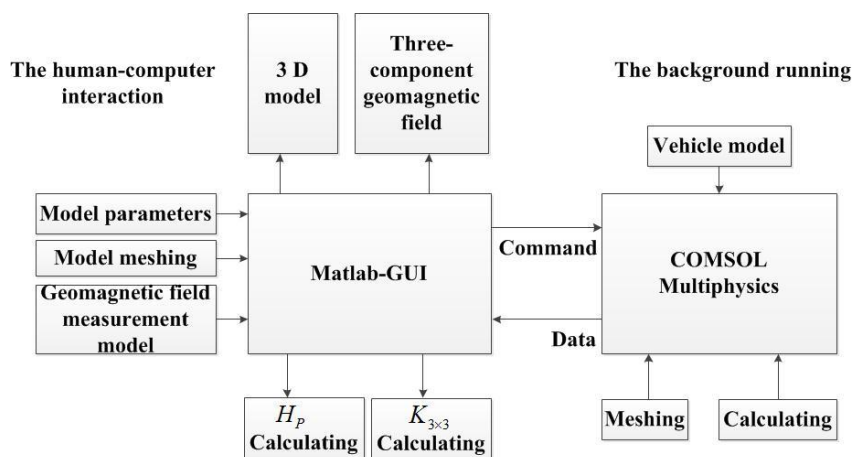


Figure 1. The Simulation System Structure Diagram

4. Simulation of Interference Magnetic field Compensation Method

4.1. Establishing the Vehicle's Coordinate System

The x axis of pointing toward the vehicle forward is positive on left and right sides symmetrical longitudinal profile. Right side of the y axis on the center plane of the vehicle is positive. The down z axis is positive and it is perpendicular to the x and y plane. The vehicle's coordinate system is shown in Figure 2.

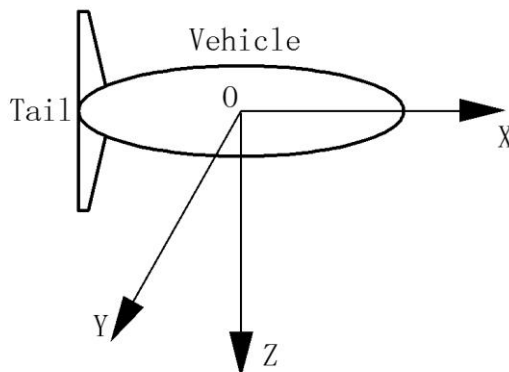


Figure 2. The Vehicle's Coordinate System

4.2 System Simulation

Using a single ellipsoidal to construct the model^[9-10], 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. 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^[11]. According to the International Geomagnetic Reference Field (IGRF-11/2010), a point is selected in north latitude 5 ° 110 ° east longitude coordinates and the background three-component geomagnetic field are set to 40863.1nT, 162.1nT and -3909.1 nT.

Figure 3 shows the X component magnetic field distribution on the 7m surface (Z=7) under the vehicle after running. Because of the initial setup of X component of the geomagnetic field is a constant, if the vehicle has not been magnetized, the X component of the horizontal magnetic field on the surface should be the same value. That is mean that only there is one colour on the surface^[12-13]. But the colour illustration table on the right side of the picture can be seen that there is a variety of colors on the surface, which confirms that the vehicle has been magnetized by the background magnetic field and produced a complex magnetic field distribution around the vehicle. The maximum change of magnetic field reaches 2441.2nT compared with the initial value for the X component.

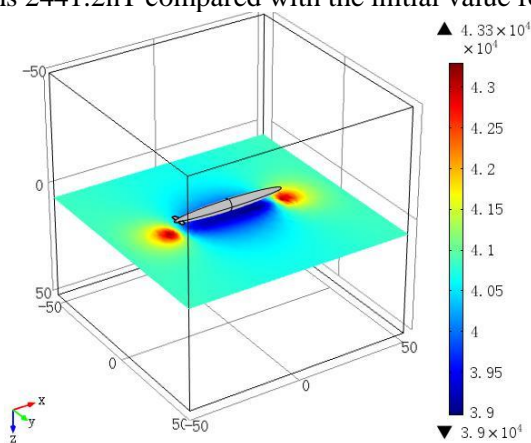


Figure 3. Magnetic Field Distribution of X Component on the Seven Meter Plane Under the Vehicle

After that the model has a 360 ° horizontal rotating accompanied by pitch and rolling activity around a point P, and the angle error is less than 0.001 °. The measurement noise of the sensor is the gaussian white noise assumed that the mean is zero and the variance is 2nT .The rotation schematic diagram as shown in Figure 4.

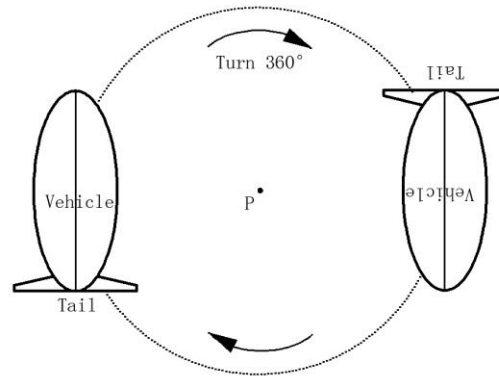


Figure 4. 360 Degrees Rotation Method of the Vehicle for the Unknown Parameters

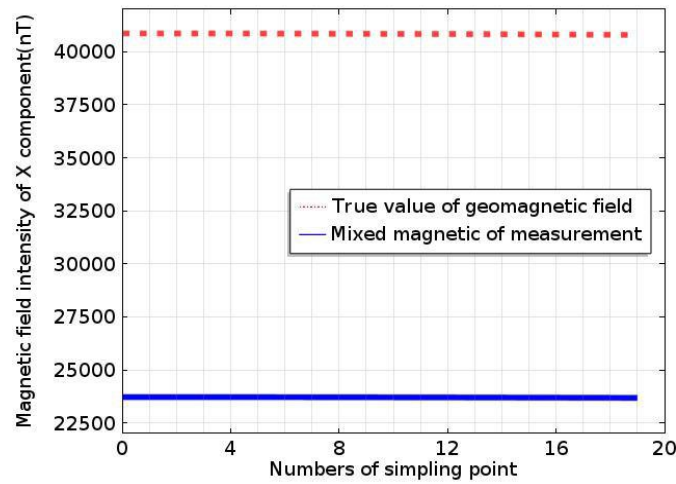
By pressing the button of $K_{3 \times 3}$ Calculating and H_s Calculating in the simulation system as Figure 1, all the unknown related parameters can be calculated. The result is shown as the Table 1. According to the Table 1, the effect of simulation system can be identified by compared the true value with the simulation value. The simulation system of Comsol Multiphysics and Matlab united can achieve a high precision value by a reasonable estimation method running in the background. The maximum error of induction coefficient matrix $K_{3 \times 3}$ within 0.6%. the maximum error of permanent magnetic field H_p within 0.08%.

Table 1. The Results of Parameter Estimating

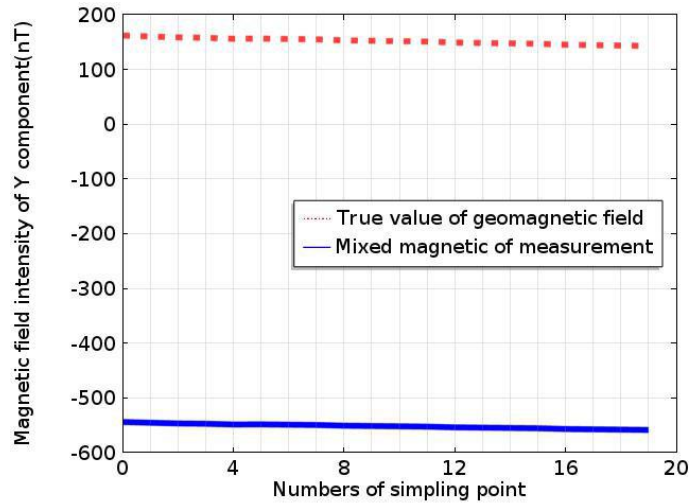
Contrast	\hat{K}			\hat{H}_{PX} (nT)	\hat{H}_{PY} (nT)	\hat{H}_{PZ} (nT)
True value	-0.0241	-0.0053	0.0144	1000.0	1700.0	1350.0
	-0.0233	-0.0613	-0.1340			
	0.0333	-0.1453	0.0522			
Simulation value	-0.0241	-0.0052	0.0143	1000.8	1698.5	1351.2
	-0.0234	-0.0613	-0.1341			
	0.0335	-0.1454	0.0522			

The position of sensor installed is about 2m distance above the vehicle surface, so a 3d coordinate point (5, 0, -5) is chosen to read the measurement value of the magnetic field. After that, it is necessary to test whether the method of geomagnetic field separated from the mixed magnetic field is right or not. Twenty three-component data of geomagnetic field are selected from the sea region of 5°N to 6°N and 110°E to 111°E as the background field .

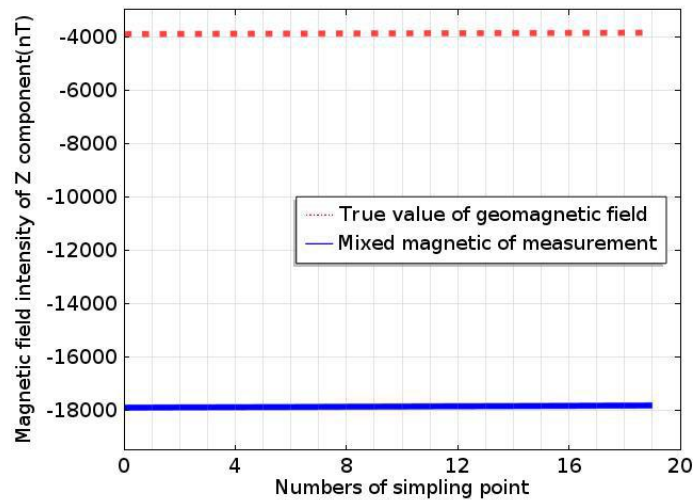
Figure 5 shows the three-component intensity of mixed magnetic field before compensation. The red dotted line represents the true value of geomagnetic field added in the background. The blue lines represents the value of mixed magnetic field of sensor measuring. Some of the absolute value of measuring magnetic field is larger than the true value of the geomagnetic field, and some is smaller than the true value. That is because the direction of the induced magnetic field is influenced by the direction of the three-component geomagnetic field. The maximum change of magnetic field is 17113.1nT compared with the geomagnetic field for the X component.



(a) Magnetic Field Intensity of X Component



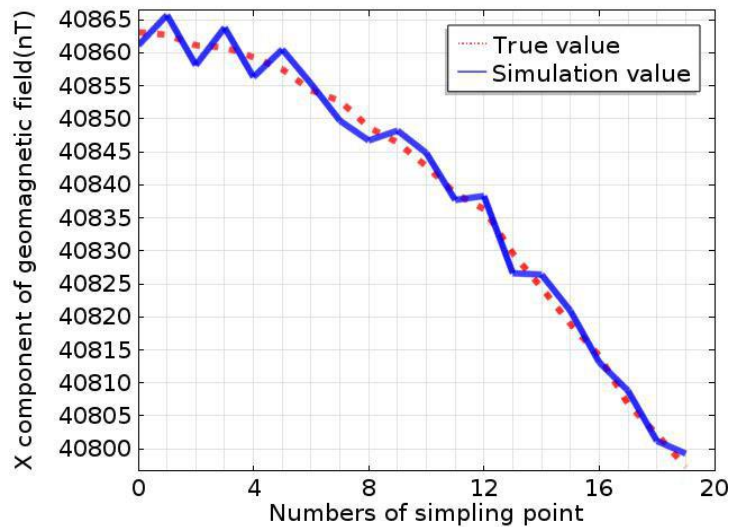
(b)Magnetic Field Intensity of Y Component



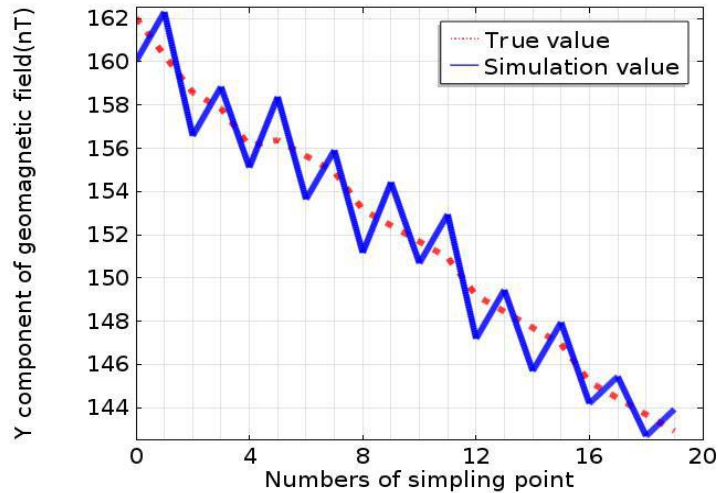
(c) Magnetic Field Intensity of Z Component

Figure 5. Three-Component Intensity of Mixed Magnetic Field

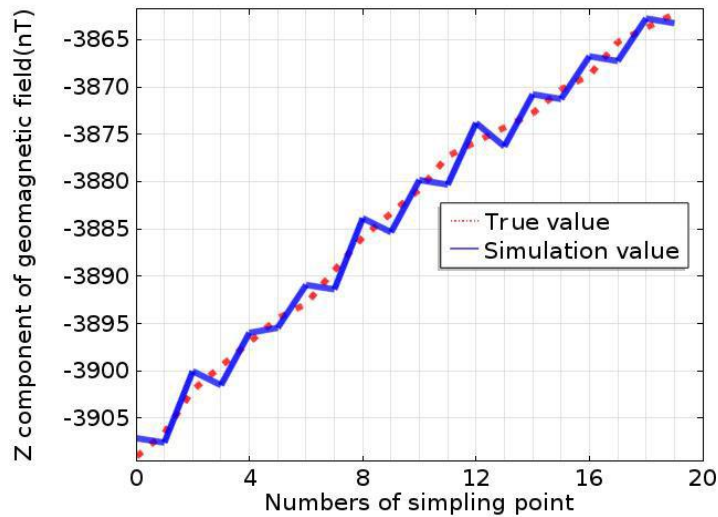
Assuming that the coordinates of the vehicle is the same as the geographic coordinates during the simulation. Regardless of the measurement error introduced by others. After the parameters in Table 1 are transferred directly to the Matlab, the compensation results of three-component geomagnetic field will be calculated through the geomagnetic field compensation subroutine. The results in vehicle coordinate system are shown in Figure 5.



(a) Magnetic Field Intensity of X Component



(b)Magnetic Field Intensity of Y Component



(c) Magnetic Field Intensity of Z Component

Figure 6. The Field Compensation Value Compared with the Real Value of Three-Component Geomagnetic Field

Figure 6 shows that the united simulation system achieve the compensation of three-component geomagnetic field from the mixed magnetic field, and the residual error basically within 2.0nT, compared with before compensation, which reduces about 0.02% of the interference magnetic field. The calculation shows the maximum average compensation error is 0.1nT in the X component, the standard deviation is 3.2 nT. So the united simulation system in this article realizes the modeling and simulation of geomagnetic field vector compensation for the underwater vehicle, and the simulation results of geomagnetic field separated from the united magnetic field has a high precision.

5. Conclusions

It is difficult for the motion vehicle in the underwater environment to compensate the interference geomagnetic field from the mixed magnetic field. To the problem this paper proposes a research method based on Comsol Multiphysics and Matlab which are united

to achieve modeling and simulation together. The system combines the advantages of two software, so vehicle's rapid modeling and simulation can be conveniently accomplished through the program running in the background and friendly man-machine interface. Simulation results show that the united simulation system has the characteristic of flexibility for data exchanged and processed, and the simulation results have a high precision compared with the true value of the three-component geomagnetic field. Therefore, it is convenient to research the vehicle in modeling, and the sensor installation location according to the simulation result. The united simulation system not only provides an effective way of compensation method research for underwater motion vehicle, but also it can be more convenient and effective to explore new method in geomagnetic aided navigation, to shorten the development time and to reduce development costs.

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