



## Research articles

## Electromagnetic trajectory simulation using triaxial cage

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## ARTICLE INFO

## Article history:

Received 10 February 2017

Received in revised form 18 August 2017

Accepted 7 September 2017

Available online 8 September 2017

## Keywords:

IGRF

Earth's magnetic field

Open-loop controller

Trajectory tracking

Signature

Degaussing

## ABSTRACT

This paper implements an open-loop controller for generating earth's magnetic field in vessel's coordinate frame. It also incorporates the rotational movements along the three axes, without physically moving the object. This has potential application in prediction of signature for ferromagnetic marine vessels in changing earth's magnetic field experienced by the vessel due to change in location. It also considers the effect of roll, pitch and heading changes. Uniform magnetic field simulator is designed to generate the required magnetic field in the vessel's coordinate frame. Simulation results are verified using experimental laboratory setup.

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## 1. Introduction

Ships and submarines, have been targeted by underwater and airborne mines and torpedoes. The magnetic presence of these marine vessels cannot be seen or felt unlike of acoustic signatures. The various reasons for magnetic presence of vessels are, firstly, induced magnetism due to presence of earth's magnetic field, secondly, eddy currents due to rotation of electrically conducting vessel in earth's magnetic field [1], thirdly, due to corrosion protection systems [2] and lastly, due to machineries of onboard vessel [3] [4]. The magnetic presence of the vessel is designated as signature of the vessel. In recent decades utilizing earth's magnetic field for mitigating ship's and naval vessel signature has been increasing rapidly. The high permeability of ferromagnetic material, used for construction of marine vessels, as compared to that of air, leads to disturbances in ambient earth's magnetic field [5]. Ferromagnetic materials permit much higher flux values ( $B$ ) for relatively low magnetic field strengths ( $H$ ), and reach a saturation point after which very little additional flux ( $B$ ) can be forced through the material. Thus, the ferromagnetic cylinder provides a channel for magnetic flux, creating chunks of flux convergence and divergence as shown in Fig. 1 near the ferromagnetic cylinder [6].

The main contribution of this paper is to analyze several aspects of electromagnetic signatures related to variation of earth's magnetic field and to propose an open-loop controller to generate the three components of earth's magnetic field. This open-loop controller will be used to develop a degaussing strategy for ferromagnetic body. Degaussing refers to an active system which minimizes the magnetic signature of the ferromagnetic vessel. Ideally, one would install degaussing coils and pump appropriate currents through each of the coils such as to produce a magnetic field which would exactly cancel the distortion in the earth's field created due to the presence of ferromagnetic object. Also the sea vehicle's roll, pitch and heading change during their journey. Unlike ships, submarines also acquire certain depths typically 800m. It is impractical to move a huge ferromagnetic body physically to capture its signature with respect to different rotations and new magnetic field experienced by the body. The implemented open-loop controller will vary the earth's magnetic field at rated speed to observe the variation of magnetic field at any local position. International Geomagnetic Reference Field (IGRF) function [7] based on Legendre polynomial will be used in MATLAB to compute the three components of magnetic field based on latitude, longitude and altitude of any given location in North-East-Down (NED) frame [8].

The paper is organized as follows: Section 2 comprises of triaxial cage modelling, cage as an earth field simulator, and its usage for signature prediction. The magnetic signatures are validated using finite element based simulation software, OPERA. Section 3 models the electromagnetic trajectory utilizing the concept of rigid body motion. Frame transformation using rotational matrix is implemented to obtain the magnetic field in vessel's reference frame.

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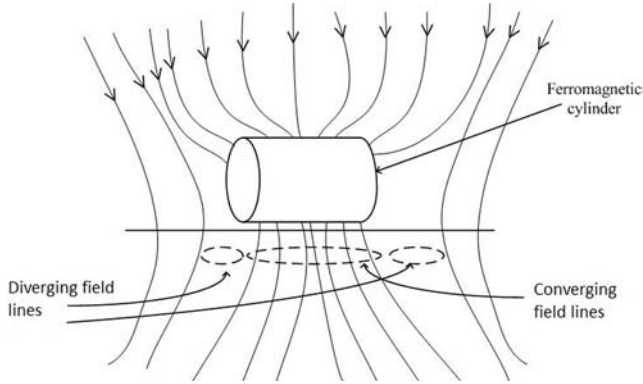


Fig. 1. Ferromagnetic cylinder in ambient magnetic field.

Section 4 discusses the algorithm for signature prediction considering the effects of roll, pitch and heading changes equivalent to a vessel experiencing a new magnetic field. Section 5 explains the hardware setup for conceptual proof. Section 6 discusses the experimental results and finally Section 7 concludes the paper.

## 2. Tri-axial cage

### 2.1. Mathematical modelling

As shown in Fig. 2 for a square coil of side  $d$  meters lying in  $x$ - $y$  plane at a distance  $a$  meters along  $z$ -axis from origin, the three components of magnetic field densities at any point  $P(x,y,z)$  is given by Biot-Savart's law [9]. The analytical field components are as depicted in (1),

$$\begin{aligned}
 B(x) &= \frac{\mu_0 I}{4\pi} \sum_{i=1}^4 \frac{(-1)^{i+1} e}{r_i [r_i + f_i]} \\
 B(y) &= \frac{\mu_0 I}{4\pi} \sum_{i=1}^4 \frac{(-1)^{i+1} e}{r_i [r_i + (-1)^{i+1} c_i]} \\
 B(z) &= \frac{\mu_0 I}{4\pi} \sum_{i=1}^4 \left[ \frac{(-1)^i f_i}{r_i [r_i + (-1)^{i+1} c_i]} - \frac{c_i}{r_i [r_i + f_i]} \right]
 \end{aligned} \tag{1}$$

where,  $\mu_0$  is permeability of free space.  $r_1, r_2, r_3$ , and  $r_4$ , are the distance from the vertices of square to the point,  $P$

$$r_1 = (c_1^2 + f_1^2 + e^2)^{\frac{1}{2}} \quad r_2 = (c_2^2 + f_1^2 + e^2)^{\frac{1}{2}}$$

$$r_3 = (c_2^2 + f_3^2 + e^2)^{\frac{1}{2}} \quad r_4 = (c_1^2 + f_3^2 + e^2)^{\frac{1}{2}}$$

$$c_1 = s + x, c_2 = s - x, c_3 = -c_2, c_4 = -c_1,$$

$$f_1 = f_2 = y + s, f_3 = f_4 = y - s, e = z - a, s = d/2$$

This magnetic field components are calculated by evaluating the effect of each side of the square and applying superposition theorem [9].

Consider the four square coil system as shown in Fig. 2. Let  $a$  and  $b$  be the distance of the coils from the origin on either sides such that  $b > a$ . Let  $I$  and  $I'$  be the currents in the inner and outer pair of coils respectively.

Different ways for computation of uniform field for any given coil structures are Tchebychev polynomials [10], Lagrangian multipliers [11], and McLaurian series [12]. In general, homogeneity is the maximum variation in magnetic field with respect to the mean magnetic field value [13], calculated as shown in (2).

$$Homogeneity(a, b, I, I') = 1 - \frac{B_{max} - B_{min}}{B_{mean}} \tag{2}$$

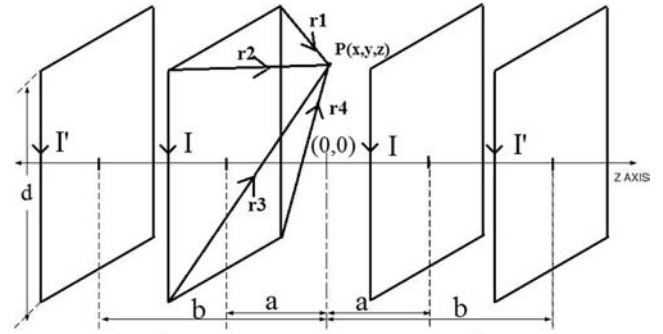


Fig. 2. Four Square coil system.

where,  $B_{max}, B_{min}$  and  $B_{mean}$  are the maximum, minimum and mean magnetic field densities in the desired volume. For sea vehicles the homogeneity requirements are not very strict as for sensor calibration and critical bio-medical applications. Although we formulate an optimization problem such as to obtain 99% homogeneity within 12.5% volume centred at the centre of coil system. The coil system parameters,  $a, b, I$  and  $I'$  are optimized.

The optimization algorithm follows an iterative process to obtain required homogeneity in desired volume. Algorithm consists of following steps, which are implemented in MATLAB,

1. Prompt the user for desired homogeneity,  $H_{desired}$ , side of square, 'd', sampling distance, 'delta', and 'stepsize' for neighbourhood creation.
2. Initial values for  $a, b, I$ , and  $I'$ , will serve as current configuration for that iteration.
3. Generate set of points,  $P$  with the help of delta such that  $x, y$  and  $z$  coordinates vary from  $-d/4$  to  $d/4$  i.e. 50% dimension of cuboid or 12.5% volume as compared to actual space occupied by the entire coil system.
4. For the current configuration in step 2, Calculate Magnetic field density,  $B$  (using Eq. (1)) at all the points,  $P$  and corresponding homogeneity,  $H_{initial}$  (using Eq. (2)).
5. If ( $H_{initial} > H_{desired}$ ) then go to step 9
6. Generate neighbourhood configurations with the help of stepsize by allowing variations in  $a, b, I$  and  $I'$ .
7. For each neighbourhood configuration in step 6, calculate Magnetic field density,  $B$  at all the points,  $P$  and corresponding homogeneity values,  $H$  within the desired volume.
8. If ( $maximum(H) > H_{initial}$ ), replace current configuration with new configuration and  $H_{initial}$  with  $maximum(H)$ . Then go to Step 5.
9. Display the optimum values for  $a, b, I$  and  $I'$  which gives the required homogeneity in desired volume.

A four square coil system, with side of the square, 510 mm is optimized to obtain 99% homogeneity in 12.5% volume. We obtain  $a = 0.06533$  m,  $b = 0.2576$  m, and the ratio of currents  $I'/I = 2.3636$ . This ratio can be best approximated as ratio of integers, in order to drive current using a single power supply for all the four coils. One such approximation is 26/11. The assumed values are  $delta = (d/16)$  and  $stepsize = 0.0001$ . The initial configuration values assumed were  $a = 0.0600$  m,  $b = 0.2500$  m,  $I_1 = 3.9000$  A,  $I_2 = 9.3000$  A. The exact homogeneity achieved is 99.1490%. These design parameters are considered one among the best for large volume applications [14].

### 2.2. Earth field simulator

To generate magnetic field of any location across the globe, we basically need to generate a controlled field environment capable

**Table 1**  
12 coil system design parameters for 99% homogeneity in 12.5% volume.

Axis	B( $\mu$ T)	d(m)	a(m)	b(m)	I(A)	I'(A)
x	33	0.510	0.0653	0.2576	3.9666	9.3756
y	15	0.460	0.0589	0.2323	1.6258	3.8428
z	19	0.410	0.0525	0.2070	1.8360	4.3398

$\mu$ T = microtesla, m = meters, A = Amperes

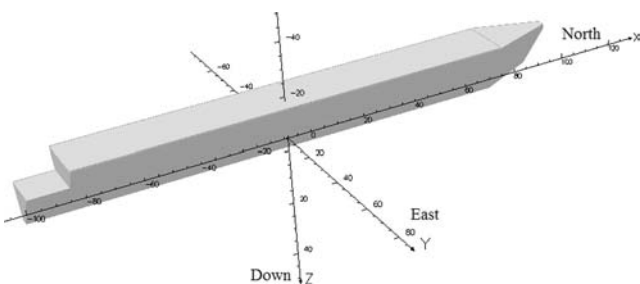
of generating each of the three components of the magnetic field. One way this can be achieved is by replicating this four coil structure along all the three axes. By pumping appropriate amount of currents along each directions, the magnetic field inside the coil structure can be varied. The uniformity for the tri-axial simulator cage is simulated in OPERA and also verified experimentally. The volume homogeneity is justified by simulating a cage of dimension 510 mm\*460 mm\*410 mm. Current pumped in each directional coil are such as to generate  $B_x = 33 \mu$ T,  $B_y = 15 \mu$ T,  $B_z = 19 \mu$ T at the centre of the coil system. Hence the resultant  $B$  at the center of coil system is 40.8485  $\mu$ T.

For the proposed 12 coil system Table 1 gives the details of coil parameters and dimensions for generating homogeneous field of  $B_x = 33 \mu$ T,  $B_y = 15 \mu$ T,  $B_z = 19 \mu$ T in 12.5% volume around the centre of the coil system.

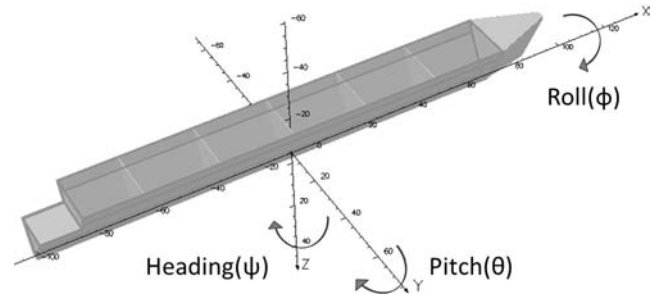
### 2.3. Signature prediction

The magnetic signature of ferromagnetic body is nullified by injecting proper currents in degaussing coils, so that magnetic field equal in magnitude and opposite in direction of the signature is generated. The accuracy of the degaussing currents estimation depends on how well is the signature predicted. A controlled magnetic environment needs to be generated with precise uniformity to avoid major prediction errors. A ferromagnetic ship, 200 mm long, 20 mm width and 22 mm height as shown in Fig. 3 is modelled in OPERA. The dimensions are chosen such as to fit in the maximum uniformity region. The internal structure consists of ferromagnetic bulkheads and deck as shown in Fig. 4. The relative permeability of the modelled ship material is assumed to be 200, typical value of steel by which vessels are made. Sea vehicles follow North, East, Down, (NED) as axes coordinate for reference frame.

The ship is assumed to be present in ambient earth's field,  $B_x = 33 \mu$ T,  $B_y = 15 \mu$ T,  $B_z = 19 \mu$ T. The induced magnetic field anomaly due to the presence of permeable ship in earth's magnetic field is compared with and without the cage. In practicality permanent magnetism also contributes to the signature. The ship is meshed with tetrahedral 74670 nodes and corresponding 391840 elements. The signature patch is obtained at a distance equal to beamwidth from the base of the ship. Following two cases are simulated.



**Fig. 3.** Ferromagnetic ship model with axes convention.



**Fig. 4.** Open ship model with visible internal structures and angular rotations.

Case 1: Ambient field generated using magnetostatic(TOSCA) solver: The ship is placed directly in an ambient field of  $B_x = 33 \mu$ T,  $B_y = 15 \mu$ T,  $B_z = 19 \mu$ T. There are no cage coils and the signature is as shown in Fig. 5.

Case 2: Ambient field generated by using tri-axial cage: The ship is placed in an environment whose external field is  $B_x = 10 \mu$ T,  $B_y = -20 \mu$ T,  $B_z = 30 \mu$ T. However, we are interested in obtaining ship's signature in an ambient field of  $B_x = 33 \mu$ T,  $B_y = 15 \mu$ T,  $B_z = 19 \mu$ T. Before simulating the required earth's magnetic field, the magnetic field of the location where the triaxial cage is placed is nullified. This can be done by pumping currents in coils in opposite direction so as to have zero field inside the cage. Later currents can be adjusted in the cage coils so as to generate the required ambient field.

Fig. 5 and Fig. 6 concludes that the ferromagnetic vessel's signature for any desired location can very well be calculated by pumping appropriate currents in the cage coils no matter what is the external field.

## 3. Electromagnetic trajectory

For laboratory validation of degaussing algorithm, precise controlled magnetic environment needs to be generated. First of all, the intensity and the direction of the earth's magnetic field have to be obtained. There are various ways to simulate the earth magnetic field and among these ways the most accurate and preferred one is to obtain earth's magnetic field's mathematical model using IGRF coefficients. A typical trajectory is simulated, considering all the movements of vessel. The earth's magnetic field based on the IGRF coefficients is modelled and the results are verified with experimental setup.

### 3.1. Modelling

Maneuvering of sea vessel is simulated by using polynomial trajectory [15]. Hence to visualize the earth magnetic field in triaxial cage considering roll, pitch and heading variations, we model a 3rd order non-linear trajectory with six degrees of freedom. The position of the vessel at any instant of time along its traversal through this trajectory can be defined by the position vector,  $P(t)$  as shown in (3).

$$P(t) = m * t^3 + n * t^2 + l * t + p \quad (3)$$

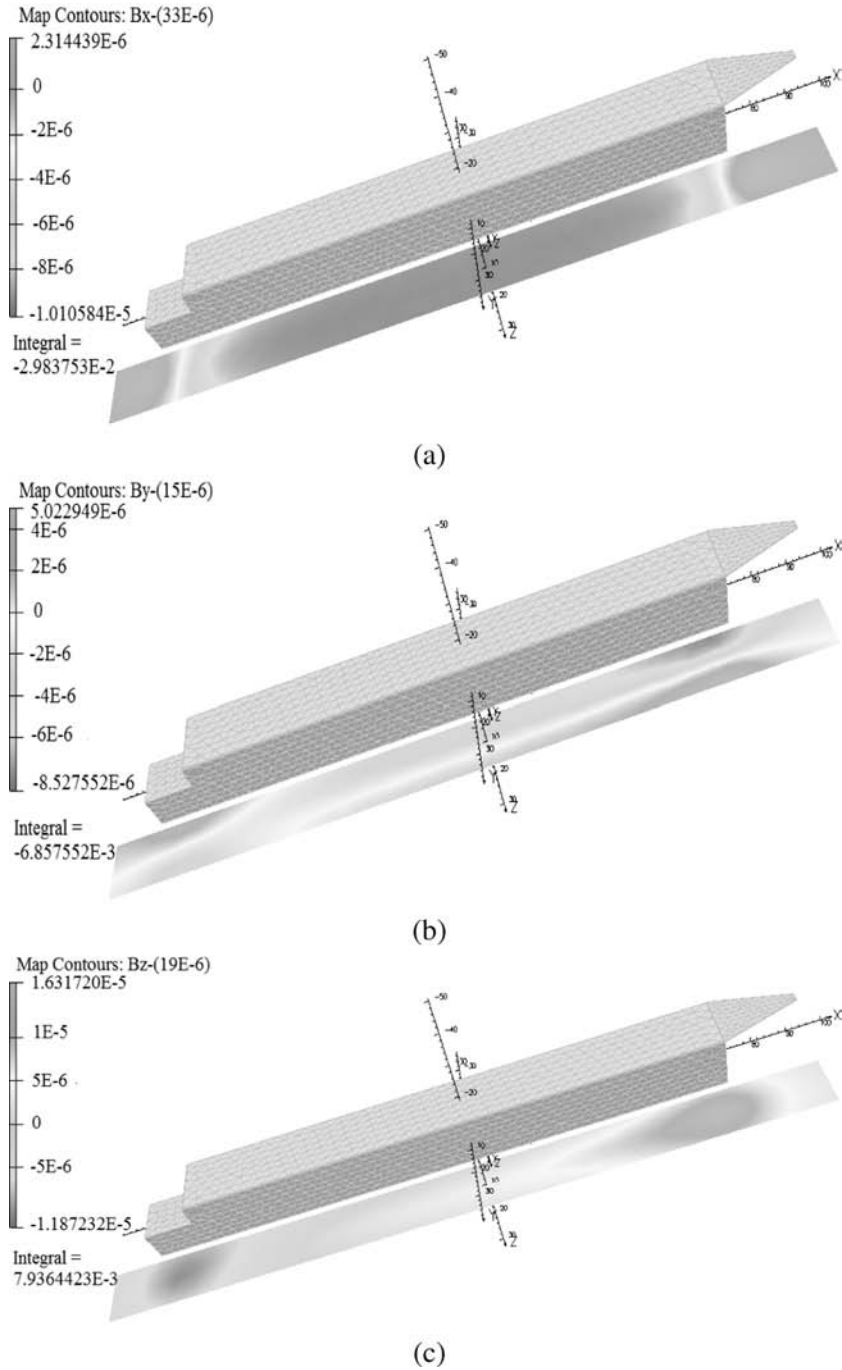


Fig. 5. Ship signature due to external field  $B_x = 33 \mu\text{T}$ ,  $B_y = 15 \mu\text{T}$ ,  $B_z = 19 \mu\text{T}$  (a)  $B_x$  component (b)  $B_y$  component and (c)  $B_z$  component.

where,  $m, n, l, p$  are column vectors. Each row for these columns contributes to latitude, longitude and altitude information. we assume constant velocity of the vessel, the corresponding velocity,  $V(t)$  is as shown in (4).

$$V(t) = \frac{dP(t)}{dt} = 3 * m * t^2 + 2 * n * t + l \quad (4)$$

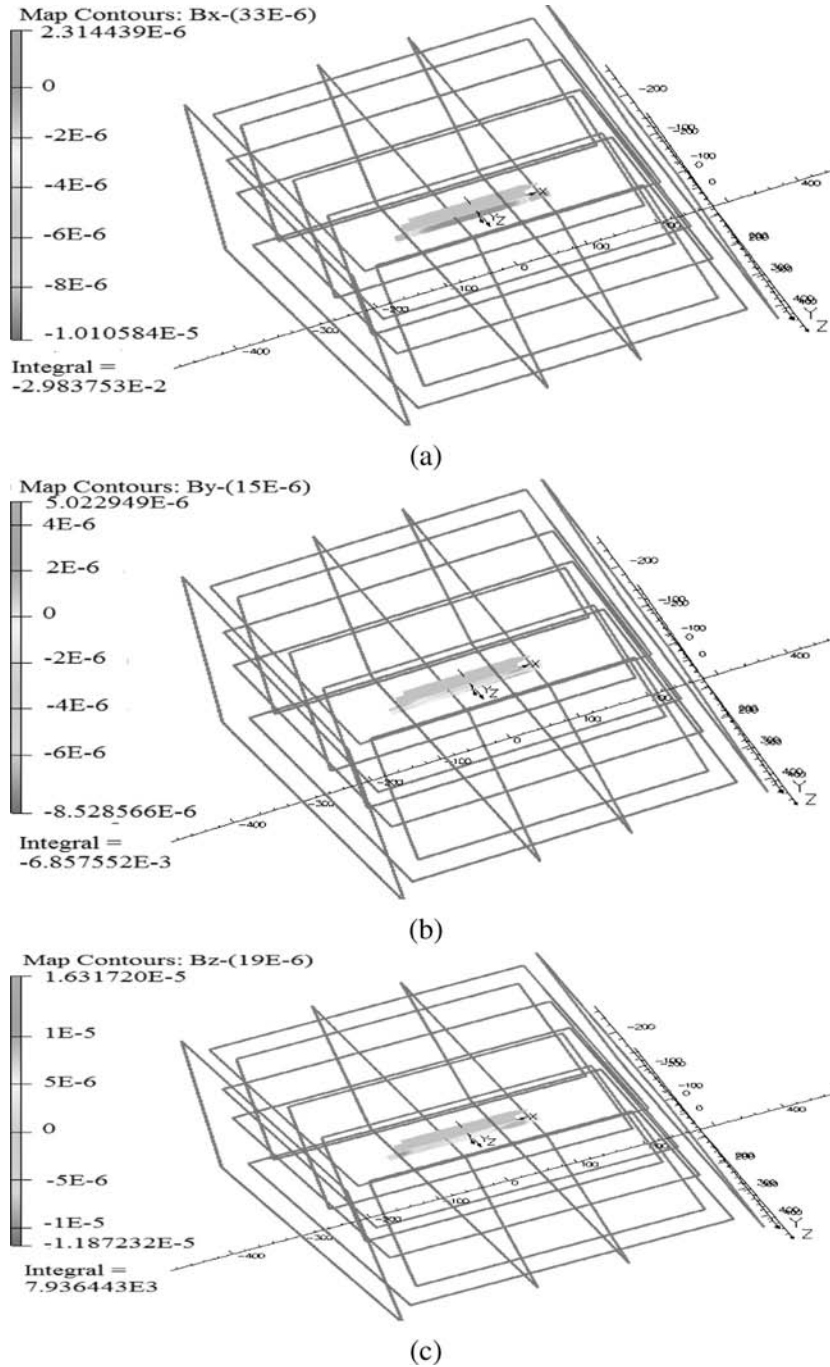
The trajectory coefficients  $m, n, l, p$  are computed by applying initial and final boundary conditions for the position and velocity of vessel to (3) and (4). The simulated trajectory is as shown in Fig. 7. The position vector at any point can be calculated based on speed and time of ferromagnetic body. Once the trajectory is modelled as per the given position vector, then IGRF function is

applied on each of the sampled value for the simulated trajectory to compute the magnetic field at those position vectors in North-East-Down [NED] frame.

### 3.2. Frame transformation

The transformation of earth's magnetic field in NED frame to vessel's reference frame is done by using Euler angle method [16], a basic concept of rigid body motion. This works on the fact that, the distance between any two particles of the rigid body remains constant irrespective of the motion of particle along any axes. Which also holds true for the ferromagnetic vessel under consideration.





**Fig. 6.** Ship signature due to field  $B_x = 33 \mu\text{T}$ ,  $B_y = 15 \mu\text{T}$ ,  $B_z = 19 \mu\text{T}$  generated with Tri-axial cage in the presence of external field  $B_x = 10 \mu\text{T}$ ,  $B_y = -20 \mu\text{T}$ ,  $B_z = 30 \mu\text{T}$  (a) Bx component (b) By component and (c) Bz component.

### 3.2.1. Euler angles

The Euler angles are three angles introduced by Euler to describe the orientation of a rigid body. Orientation between any two cartesian frames can be described by Euler angles. More specifically, the Euler angles move the reference frame to the referred frame, following a Z-Y-X (or the so-called 321) rotation sequence. These three Euler angles are also known as the heading, pitch, and roll angles. For frame transformation ZYX Euler angle method [15] as shown in (5) is used.

$$R = R_z(\psi) * R_y(\theta) * R_x(\phi) \tag{5}$$

where, the Euler angles  $\phi$ ,  $\theta$ , and  $\psi$  are roll, pitch and heading angles respectively.  $R_x$ ,  $R_y$ , and  $R_z$  are corresponding transformation matrices

in x, y, and z directions. The generalized elementary rotational matrix is given as shown in (6).

$$R = \begin{bmatrix} 1 - v_x(\omega_2^2 + \omega_3^2) & \omega_1\omega_2v_x - \omega_3s_x & \omega_1\omega_3v_x - \omega_2s_x \\ \omega_1\omega_2v_x - \omega_3s_x & 1 - v_x(\omega_1^2 + \omega_3^2) & \omega_2\omega_3v_x - \omega_1s_x \\ \omega_1\omega_3v_x - \omega_2s_x & \omega_2\omega_3v_x - \omega_1s_x & 1 - v_x(\omega_1^2 + \omega_2^2) \end{bmatrix} \tag{6}$$

where,  $\omega \in R^3$ ,  $\alpha \in R$ ,  $v_x = 1 - \cos\alpha$ ,  $s_x = \sin\alpha$ ,  $c_x = \cos\alpha$ .

This matrix can be thought of as a sequence of three rotations, one about each principle axis,  $\omega = [1, 0, 0]^T$ ,  $\omega = [0, 1, 0]^T$  and  $\omega = [0, 0, 1]^T$ . Since matrix multiplication does not commute, the order of the axes which one rotates about will affect the result.

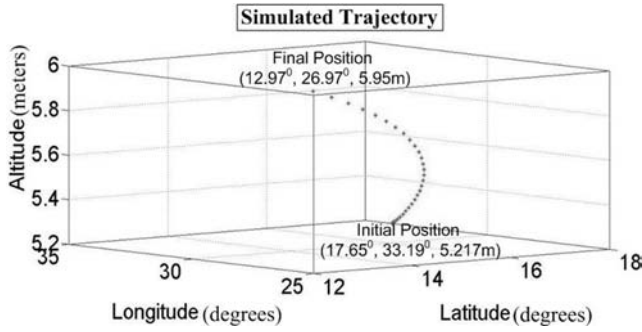


Fig. 7. Modelled trajectory for simulating Earth’s magnetic field.

For this analysis, we will rotate first about the z-axis ( $\alpha = \psi$ ), then the y-axis ( $\alpha = \theta$ ), and finally about the x-axis ( $\alpha = \phi$ ). Such a sequence of rotations can be represented as the matrix product and the rotational matrix is as,

$$R = \begin{bmatrix} C_\psi C_\theta & -S_\psi C_\theta + C_\psi S_\theta S_\phi & S_\psi S_\theta + C_\psi C_\theta S_\phi \\ S_\psi C_\theta & C_\psi C_\theta + S_\psi S_\theta S_\phi & -C_\psi S_\theta + S_\psi C_\theta S_\phi \\ -S_\theta & C_\theta S_\phi & C_\theta C_\phi \end{bmatrix} \quad (7)$$

A rotation matrix  $R \in SO(3)$  satisfies,

$$R * R^T = I, \det R = 1$$

which implies that  $R$  is orthogonal. Consequently, the inverse rotation matrix is given by,

$$R^{-1} = R^T$$

Thus using this transformation, we can get the frame orientation between the two reference frames.

$$[B_x, B_y, B_z]_{vessel} = R * [B_x, B_y, B_z]_{NED} \quad (8)$$

#### 4. Algorithm

The proposed algorithm is capable of providing the net magnetic field components which the marine vessel would interact with assuming its presence in earth’s magnetic field and all the rotational variations. The flowchart as shown in Fig. 8 describes the sequence of steps in detail.

This algorithm mainly consist of eight stages to simulate earth’s magnetic field along the trajectory,

1. Set the initial conditions:
  - (a) Initial position and final position of the marine vessel.
  - (b) Modelled trajectory,  $P(t)$  which defines the actual path the vessel would traverse. Details are discussed in Section 3.
  - (c) Sampling time,  $\Delta T$ .
  - (d) Total time,  $T$  taken by the vessel to go from initial position to final position.
  - (e) Initial instantaneous time  $T_{inst} = 0$ .
2. Calculate position vector,  $P(t)$  for  $t = T_{inst}$ .
3. Using IGRF function obtain magnetic field, components  $B_x, B_y,$  and  $B_z$  in NED form.
4. Apply rotational matrix  $R$  to transform field from local plane to vessel’s frame,  $B_{vessel}$ . Include the effect of roll, pitch and heading angle changes also.
5. Compute the gain of open-loop controller for each of the three axes,  $x, y,$  and  $z$  based on geometrical structure of triaxial cage.
6. Compute the required currents to be given to triaxial cage to generate the actual new field components which the vessel experiences in its own body frame.

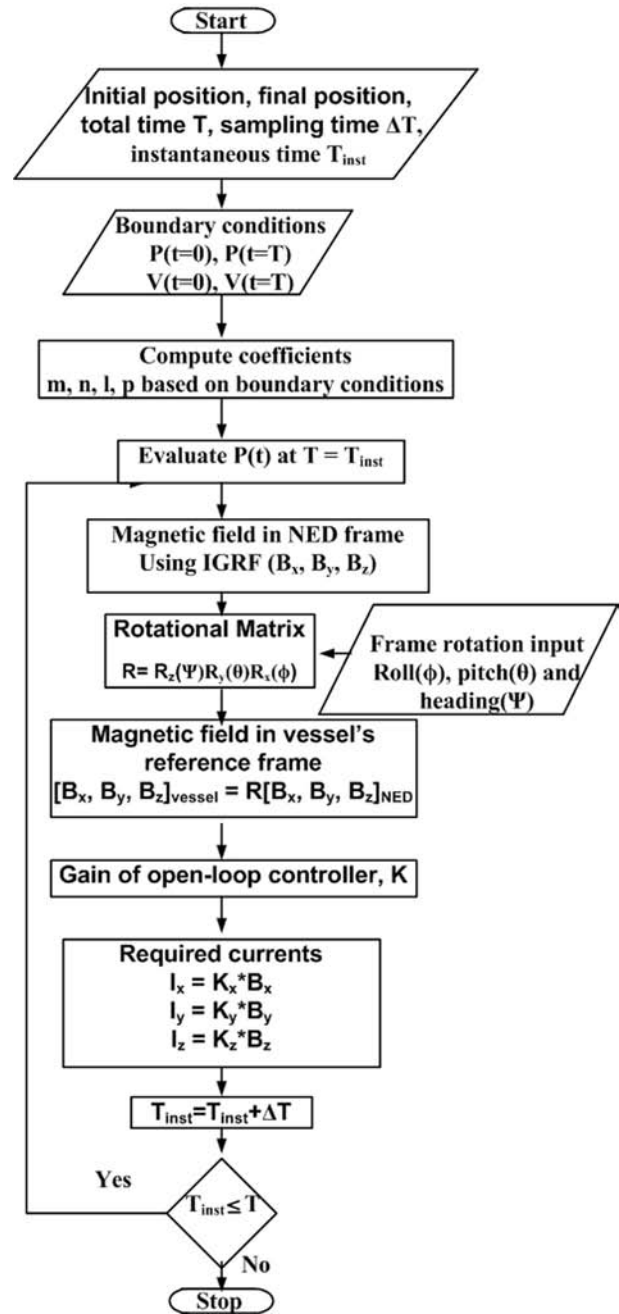


Fig. 8. Open-loop controller algorithm.

7. Increment  $T_{inst}$  by  $\Delta T$ .
8. Verify if  $T_{inst}$  is less than the total time for traversal. If so, go to step 2 otherwise stop.

Based on total time,  $T$  and sampling time  $\Delta T$ , the algorithm will generate set of latitude, longitude and altitude at specified  $\Delta T$  intervals.

#### 5. Hardware setup

IGRF function in MATLAB will generate the earth’s magnetic field based on reference position, this magnetic field components are input to open-loop controller to compute corresponding currents for each direction. These currents are fed to programmable

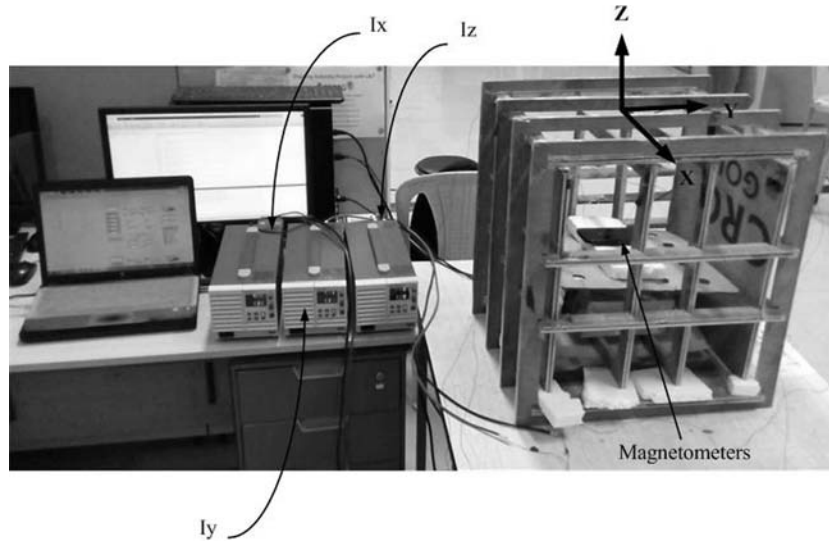


Fig. 9. Hardware set-up.

DC power supply interfaced through LABVIEW to generate current signals for the triaxial cage. Hence, the triaxial cage will generate earth’s magnetic field of sampled instantaneous position. Magnetometers are used to capture magnetic field components of triaxial cage.

Before simulating the required earth’s magnetic field, the magnetic field of the location where the triaxial cage is placed needs to be nullified. This can be done by measuring the intensity and direction of magnetic field in triaxial cage and pumping currents in coils in opposite direction so as to have zero field inside the cage. The dimensions of the modelled cage are 510 mm \* 460 mm \* 410 mm. The magnetic field inside the triaxial cage, without the cage coils being energized, is found to be 5  $\mu\text{T}$ , -37.8  $\mu\text{T}$ , -22.3  $\mu\text{T}$  in x, y, and z directions respectively. The equivalent currents to be injected in triaxial coils are calculated as -0.054 A, 0.265 A and 0.31 A to create zero field zone.

Hardware set-up of the proposed open-loop controller mainly consists of programmable DC power supply, triaxial cage and magnetometer for magnetic field measurements.

Programmable DC power supply are rated at 80 volts, 27 Amp maximum with LABVIEW interface. Such three power supplies are used to control the magnetic field of all three directions independently.

Triaxial cage structure as shown in Fig. 9, mainly consist of three dimensional coils placed in wooden structure to produce

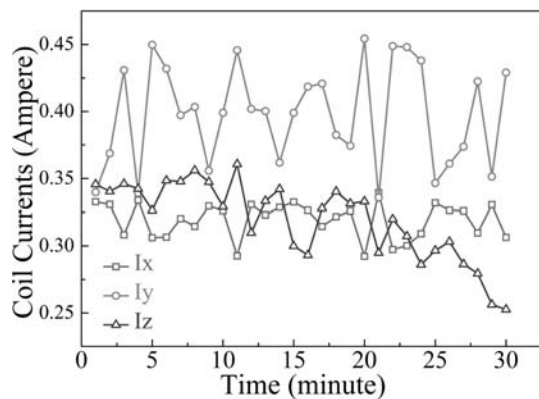
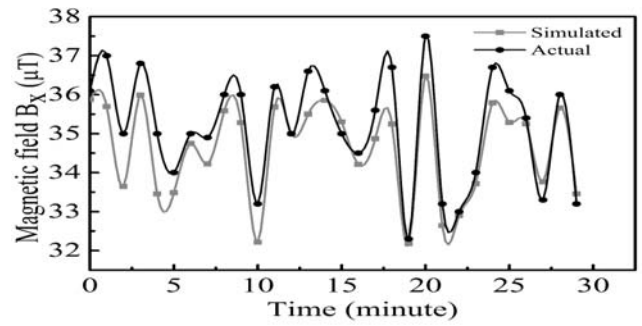
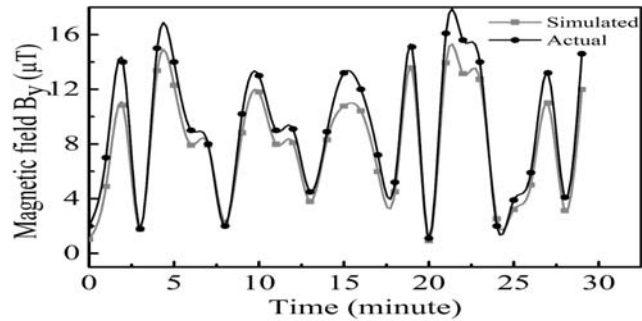


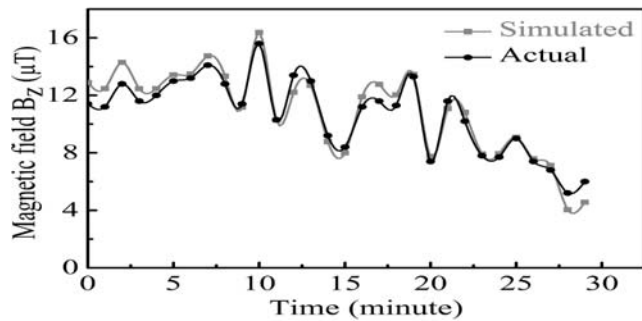
Fig. 10. Time varying current pumped in each axis of triaxial cage.



(a)



(b)



(c)

Fig. 11. Simulated and actual earths magnetic field along the defined trajectory (a) x- component (b) y-component (c) z-component.

earth's magnetic field. These coils are energized with proper currents obtained using open-loop controller algorithm.

Flux gate magnetometers of Bartington make, rated at 10 Volts, 100 mA, three axis, measuring range of  $\pm 524 \mu\text{T}$ , resolution 62.5 pT/bit and data speed of 100 samples/sec are used for measurements.

Thirty sample points are taken to simulate earth's magnetic field. Sampling time of 60 s is assumed. The gain  $k_x$ ,  $k_y$  and  $k_z$  of the controller can be obtained as in (9) and is discussed in Section 2.

$$k_i = \frac{d_i}{46.67} \quad \text{where, } i = x, y, z \quad (9)$$

where,  $d_i$  is in meters and signifies the side length of the cage in that particular direction used to generate uniform magnetic field component.

## 6. Experimental results

With reference to the modelled trajectory, as shown in Fig. 7 for simulating earth's magnetic field, the time varying applied currents for each axis of the triaxial cage is as shown in Fig. 10. The simulated and actual magnetic field,  $B$  along  $x$ ,  $y$  and  $z$  direction for the assumed trajectory are plotted as shown in Fig. 11. It is observed that the simulated magnetic field is in agreement with the actual experimentally generated values.

## 7. Conclusion and future scope

In this paper we have presented an open-loop controller based on IGRF coefficient to generate earth's magnetic field. A non-linear equation is chosen to model the required trajectory based on some initial and final boundary conditions. To observe the effect of roll, pitch, and heading variation on earth's magnetic field, fields are transformed from NED form to body frame by using Euler angle method. Simulation results of generated earth's magnetic field by the proposed open-loop controller algorithm are compared with practical lab set-up and are found in agreement. The generated time varying controlled magnetic environment is very well suited for prediction of magnetic signatures of ferromagnetic vessels. Further, it can be used to validate the degaussing strategy for minimization of signatures and hence save the vessel against mines.

## Acknowledgment

Research supported by TEQIP-II (subcomponent 1.2.1) through Centre of Excellence in Complex and Nonlinear Dynamical Systems (CoE-CNDS), VJTI, Mumbai, India.

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