Importance of modelling equipment details and ship motions for magnetic signature predictions

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Synopsis

Investigation of magnetic signatures produced by ships in Earth's magnetic field plays an important role in naval ship design and these signatures need to be kept below safe levels. If the magnetic signature is predicted accurately, then the threat of detection of the ship by sea mines can be avoided by the design of degaussing coils to cancel the magnetic signature. The main source of static magnetic (SM) signature is the ferromagnetic material used for the vessel construction. The vessel could be subjected to severe rolling and pitching motions, depending upon the weather conditions. As a result, eddy currents are generated in the vicinity of the vessel (electrically conducting material) due to such motions, affecting the magnetic signature considerably.

In the present work SM signature and the effect of eddy current on SM signature is investigated for a naval vessel. FE based computational electromagnetic methodology is followed for magnetic signature prediction. In the initial design stage details of critical equipment having considerable ferromagnetic material, e.g. main engine (ME) are normally not available. Thus the effect of modelling such equipment on SM is investigated with suitable approximations.

The study emphasizes the importance of accurate modelling of internal ship structure and the critical equipment. Considering the contribution of deck plating, bulkheads, the orientation and location of certain equipment significantly alters the magnetic signature. A detailed investigation is carried out towards most appropriate prediction of such signature. Vessel is considered fixed for the simulation purpose. Thus in order to simulate eddy currents, earth's magnetic field is varied in accordance with already computed vessel motion. The signature thus computed can be considered for preliminary design of degaussing coils.

Keywords: Static Magnetic Signature; Earth' Magnetic Field; Dipole; FEA;

1. Introduction: Importance of vessel's induced magnetic signature prediction

Vessels reveal magnetic signatures, due to the ferromagnetic steel used in the construction of the hull, internal structure, machinery, and equipment. Due to the high permeability of naval construction steels they offer low reluctance paths for the earth's static magnetic field, distorting it in the process. This anomaly in the earth's field can be detected and exploited by sea mines by magnetic anomaly detection (MAD) equipment. Hence it becomes important to accurately predict the magnetic signatures at the initial design phase. The critical part in the prediction of induced magnetic signature is accurate modelling of internal ship structure, machinery and the equipment items of the naval vessel. The only available ways to assess the magnetic signature is by field measurements or by using numerical tools.

The initial studies were performed to increase the stealth of ships. (Brunotte etal, 1993) presented an overview of their work in the finite-element modelling of ships to predict the induced magnetic signature by using the tool Flux3D a finite-element analysis (FEA) program. Such FEA based tools include surface and line elements, open-boundary modelling using transformation, and the use of the reduced-scalar potential.(Rioux-Damidauetal,1995)have studied the perturbation of a static magnetic field by a massive ferromagnetic material described with the help of magnetic charges, this method has been later applied for computation of the perturbation of the earth's field by steel ships. Later (LeDorze etal, 1995) has predicted ship magnetization by using finite element method.

In the present work the prediction of ship magnetic signature is performed by effectively modelling the internal ship structure along with few machinery items and assuming the ship as static. The aim of the paper is to study the best suitable way of modelling and including the machinery of ferromagnetic equipment used in the vessel.

At sea the vessel is never static; vessel would experience higher sea states with a range of differing wave heights, wave lengths, and periodicities. These will impart significant ship motions like roll and pitch. These motions of the ship in external magnetic field induce eddy currents due to the conducting materials on board, including hull. Flow of those currents is a source of magnetic field around ship.

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International Ship Control Systems Symposium (iSCSS) 2020 https://doi.org/10.24868/issn.2515-818X.2020.043

The effect of eddy currents due to ship motion studies were performed by (Birsan etal,2016) where the validation studies were performed by using Flux 3D tool on a Canadian Forces Auxiliary Vessel with the measurements from Earth's Field Simulator (EFS) in Schirnau, Germany. Later (Polanskietal, 2018) presented simulations and measurements of scaled model and physical scale model made for low magnetic steel. Contribution of eddy current magnetic field in total field in low roll frequencies has been estimated. In the present work the effect of eddy currents developed due roll and pitch motions on ship signature is estimated.

The signature prediction studies are performed using FLUX 3D a computational electromagnetic FE tool.

2. Modelling

A vessel can be magnetized by the earth in each of its three orthogonal directions. Each magnetization state in-turn produces three magnetic signature vectors called the vertical component (positive down), longitudinal component (positive toward the bow), and athwartship component (positive toward the starboard side).When a ship is sailing north at the magnetic equator it receives an induced longitudinal magnetization (ILM) from the earth's magnetic field, which turns into an induced athwartship magnetization (IAM) when the vessel steams west. And the signature induced in the downward direction is its induced vertical magnetization (IVM). Vessel is considered heading Northwards for all simulations.

2.1. Computational Domain

Very large box which can be considered as an infinite box for computational purpose is created around the hull consisting of two regions, Air External and Air Internal to compute far field data (e.g. Signature on Observation Line), Figure 1. The hull is considered as magnetic, electrically non-conducting region and the earth's magnetic field is modelled as an external source field.

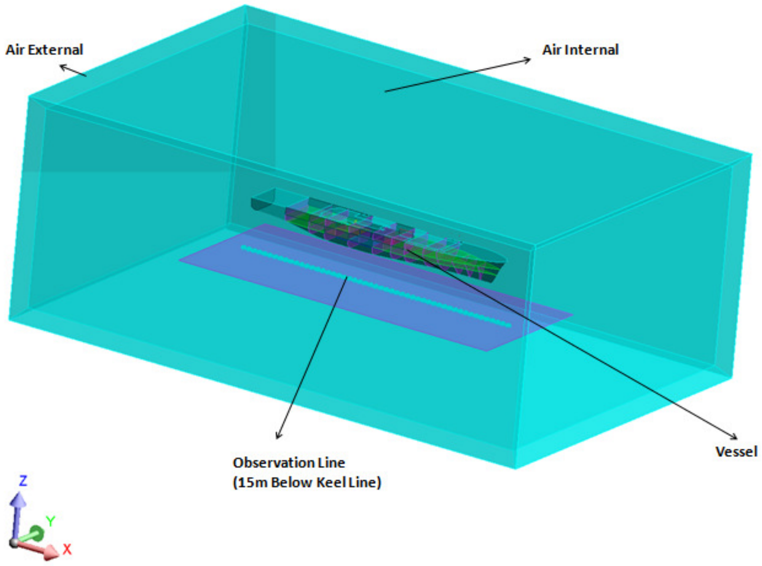


Figure 1: Computational Domain

2.2. Physics Modelling

Earth's Magnetic Field is applied to the FE model as an external boundary condition. The hull and other internal structure are modelled as magnetic non conducting region to predict the magnetic anomaly. The magnetic signature varies for different geographic locations. The earth's field considered in the present work is shown in Table 1.

Table 1: Earth's Magnetic Field for the Present Work

Direction	Earth Field(T)
X-Comp	3.91E-05
Y-Comp	-1.60E-06
Z-Comp	1.04E-05

The material properties considered for simulation are the electrical conductivity (5 MS/m) and the relative permeability of 200.

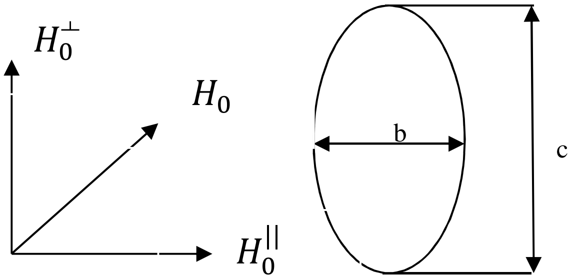
https://doi.org/10.24868/issn.2515-818X.2020.043

3. Methodology

The vessel’s static induced magnetic signature is predicted by accurately modelling the internal ship structure. The static magnetic signature majorly depends on the amount of ferromagnetic material, i.e. steel weight. The dependence of mass of the model on the induced signature is studied by varying the plate thickness. Later the effect of accurately modelling the internal structure and machinery is studied in four different cases. The thickness assignment of hull plating, internal structure, and major plants such as propulsion, auxiliary, etc. is done as per the light ship distribution. Vessel weight for all the cases is maintained same. Following are the investigated cases –

- Case1: The thickness assignment of all major items is assigned to a single plate with the transverse extent along entire breadth and longitudinal extent between two bulkheads near its LCG. Vertical position of the plate kept as close as possible to the VCG of the item.
- Case2: The plate positions of major items are kept similar, however, the bulkheads are also considered as part of the major equipment/plant for assigning the thickness. Thus the entire compartment is considered for checking volumetric effect, if any, on the signature.
- Case3: It is variation of Case1 w.r.t. the equipment weight. For this case, weight of the critical equipment, e.g. ME and AE is separated from the propulsion plant and auxiliary plant respectively and these items are modelled as boxes on port and starboard side.
- Case4: It is same as Case3 except the critical equipment ME and AE are modelled as dipoles, instead of boxes, based on their mass.

The dipole strengths are calculated assuming the machinery items to be of spheroid shape (Gordon, 2000). The formulae for calculating the magnetic field strength for a spheroid of dimension ‘c’ and ‘b’ are given by



$$\eta_0 = \frac{c}{\sqrt{c^2-b^2}} \quad \text{(i)}$$

μ_r=Magnetic permeability of material

V is the volume of spheroid

$$m^{||} = \left[\frac{-(\mu_r-1)}{(\mu_r-1)\eta_0\left[(1-\eta_0^2)\coth^{-1}\eta_0+\eta_0\right]-\mu_r}\right] V H_0^{||} \quad \text{(ii)}$$

$$m^{\perp} = \left[\frac{2(\mu_r-1)}{(\mu_r-1)\eta_0\left[(1-\eta_0^2)\coth^{-1}\eta_0+\eta_0\right]+2}\right] V H_0^{\perp} \quad \text{(iii)}$$

Thus approximating for b and c suitably and knowing mass of the equipment the dipole moments for AE and ME are calculated. (Table 2)

Table 2: Calculated Dipoles Fields for AE and ME

	Dipole Field		
Item	X (A/m)	Y (A/m)	Z (A/m)
AE (P)	15.6	0	5.96
AE(STBD)	15.6	0	5.96
ME(P)	31.26	0	11.94
ME(STBD)	31.26	0	11.94

https://doi.org/10.24868/issn.2515-818X.2020.043

The various cases considered in the present work are given in Table 3 (Mass is in tonnes and thickness of plating is in mm). Thickness is adjusted so as to achieve the weight of particular item. Figure 2 represents the various cases considered. In Figure 2 different colours indicate different plating /items. Bulkheads in red, Decks in blue, Electric Machinery in green, Auxiliary Machinery in yellow, Outfit in Cyan and Propulsion Machinery in Pink.

Table 3: Details of Thickness Assignment and Mass Distribution for Various Cases

			Case1		Case2	
Sl.no	Items		Mass	Thickness	Mass	Thickness
1	Hull Structure		920	12	922	12
2	Electric Plant		150	111	150	111
3	Auxiliary Plant	AE1	0	0	0	0
		AE2	0	0	0	0
		Aux	515	380	514	380
4	Outfitting		308	292	308	292
5	Propulsion Plant	ME1	0	0	0	0
		ME2	0	0	0	0
		Prop	229	169	228	169
	Total		2122		2122	

			Case3		Case4	
Sl.no	Items		Mass	Thickness	Mass	Thickness
1	Hull Structure		920	12	920	12
2	Electric Plant		150	111	151	111
3	Auxillary Plant	AE1	20	23	Dipole	Dipole
		AE2	20	23	Dipole	Dipole
		Aux	476	350	475	350
4	Outfitting		308	292	308	292
5	Propulsion Plant	ME1	40	46	Dipole	Dipole
		ME2	40	46	Dipole	Dipole
		Prop	148	112	148	112
	Total		2122		2002	

https://doi.org/10.24868/issn.2515-818X.2020.043

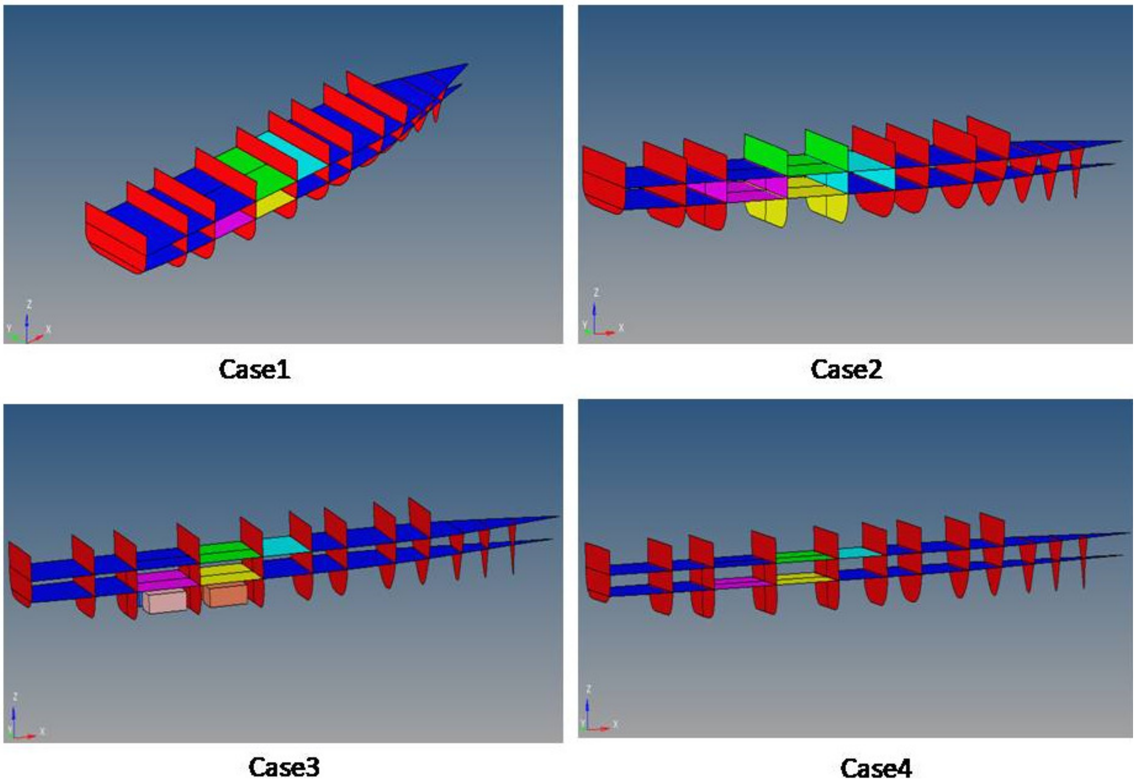


Figure 2: Configuration of Various Cases

4. Mesh and Thickness Sensitivity Studies on Ship Static Signatures

4.1. Mesh Sensitivity Studies

A study was carried out to evaluate the effect of mesh on the predicted magnetic signature. Few meshes ranging from coarse to very fine were considered for predicting the IVM signature on the observation line. The details of mesh count for various cases are tabulated in Table 4.

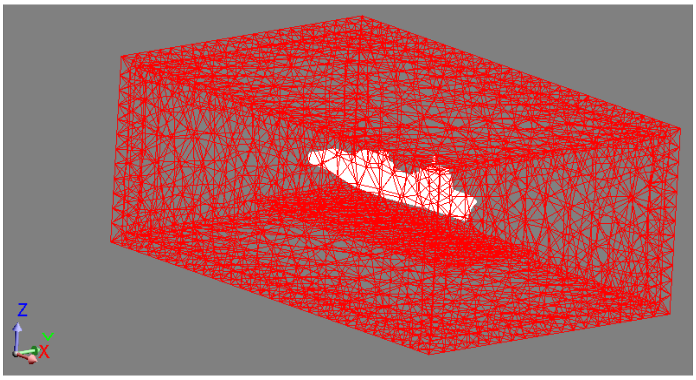


Figure 3 Sample Mesh for a Coarse mesh Case

Table 4: Mesh Count for Refinement Sensitivity Studies

Mesh Refinement	Mesh Count
Coarse	1367329
Medium	1469853
Fine	1795390
Very Fine	2672563

The results of signature in all three directions are shown below (Fig. 4 – 6)

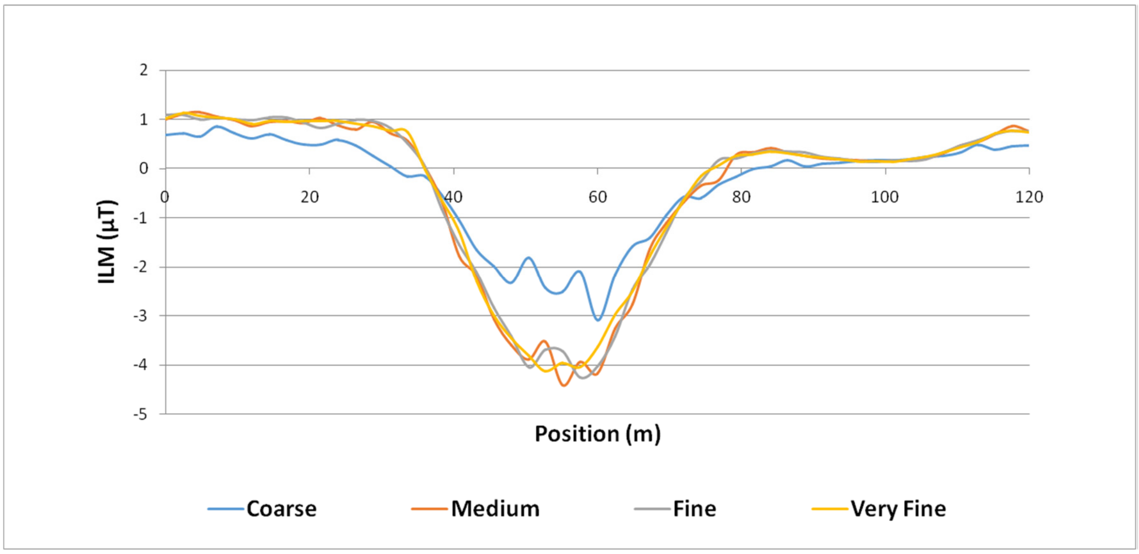


Figure 4: ILM for Various Mesh’s on Observation Line

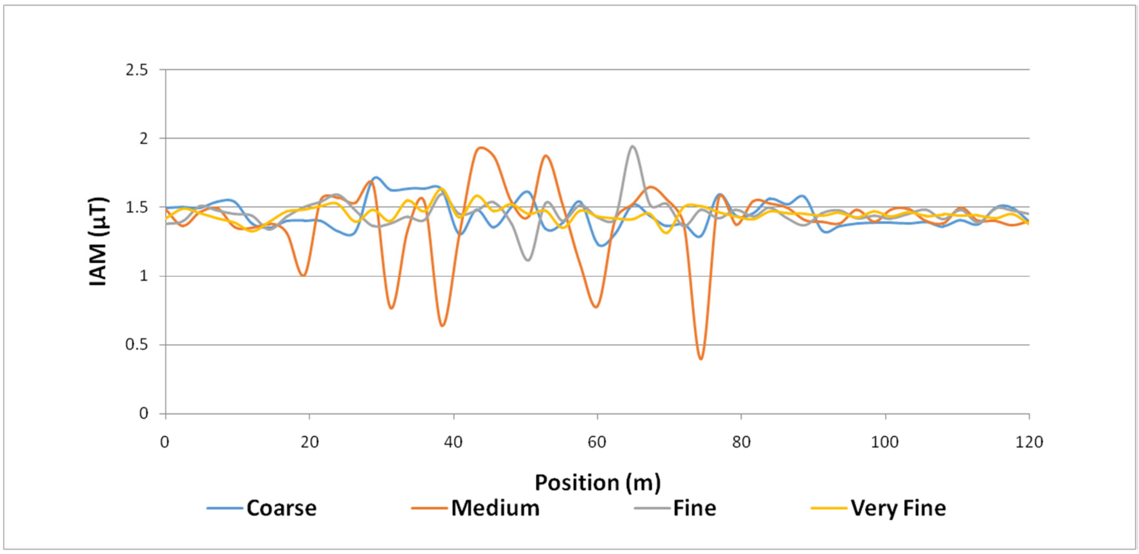


Figure 5: IAM for Various Mesh’s on Observation Line

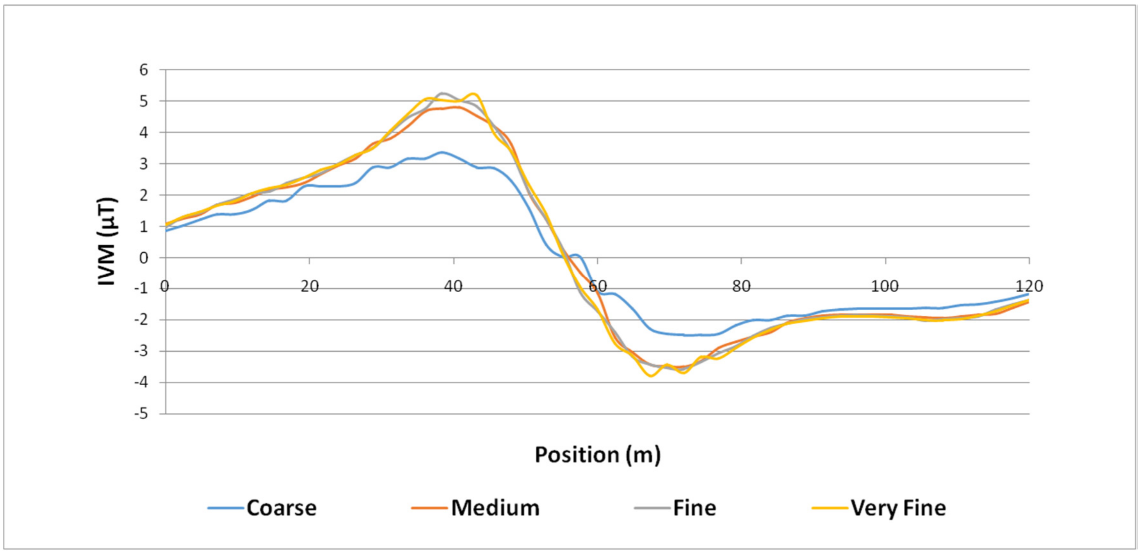


Figure 6: IVM for Various Mesh's on Observation Line

It is observed that the magnetic signatures trend in all directions remains the same for various meshes. There is a deviation in signatures for coarse mesh. But as the refinement levels are increased no further significant change in the predicted signatures is observed. The results of fine mesh and very fine mesh are very close to each other and the IVM signature of fine mesh is smooth, but it was observed that the other two signatures ILM and IAM are fluctuating for this case. For a very fine mesh case the signatures are smooth for ILM and IAM. Considering this fact, further studies are performed with very fine mesh.

4.2. Plate Thickness Variation Studies

Initially the magnetic signature study was performed to study the effect of plate thickness variation on the induced signature. The hull plating thickness is varied from 0.01 to 0.025m, and the Induced Vertical Magnetization (IVM) is predicted on an Observation Line 15m below the keel line of the vessel. The results are given below,

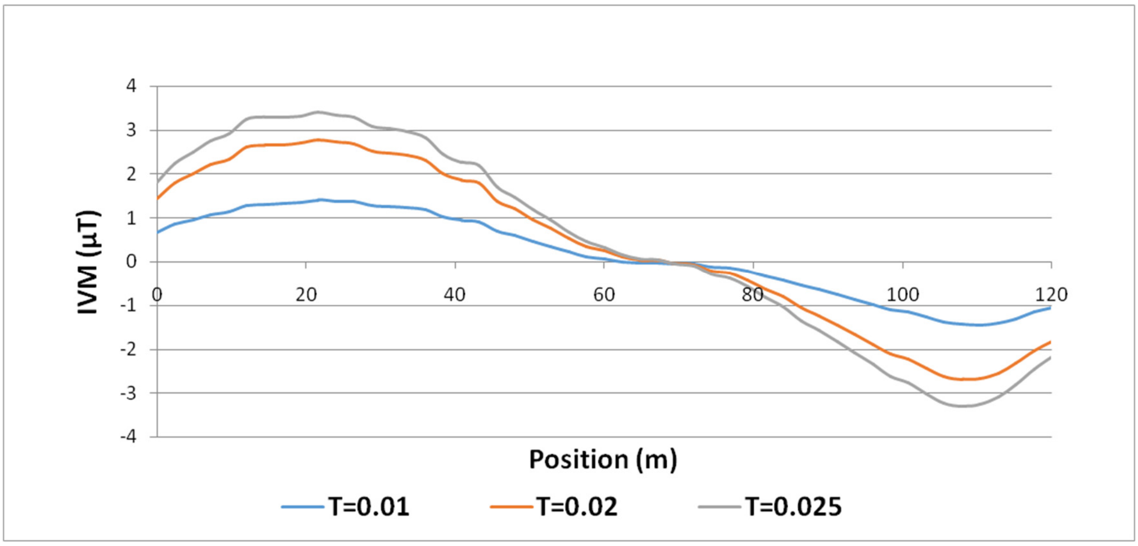


Figure 7: IVM for Various Plate Thicknesses on Observation Line

It is observed that the induced magnetic field varies significantly with the plate thickness and it is inferred that accurate modelling of internal structure is necessary for estimating the magnetic signature.

5. Results of Various Modelling Techniques for Internal ship structure and Machinery on Ship Static Signatures

The results of Induced magnetic signature for various components are predicted for various considered cases (Case1-Case4) of internal ship structure and machinery items is given in Figure 8, Figure 9 and Figure 10.

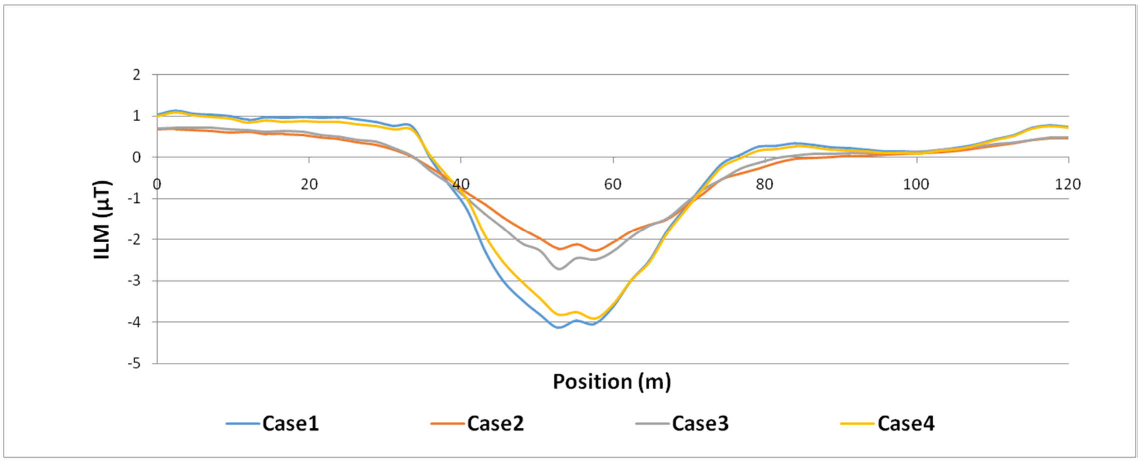


Figure 8: ILM Results for Various Cases on Observation Line

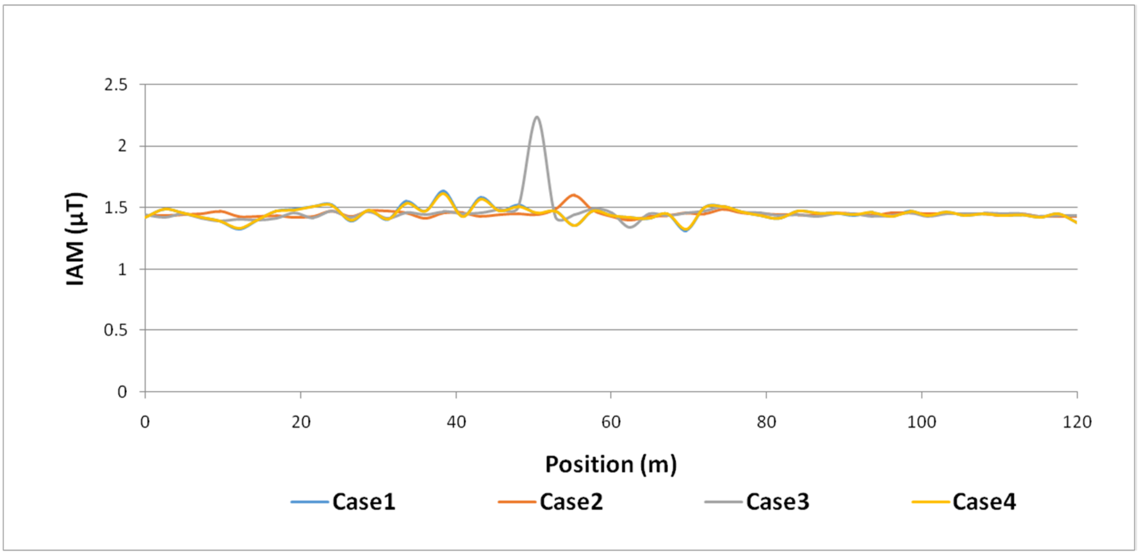


Figure 9: IAM Results for Various Cases on Observation Line

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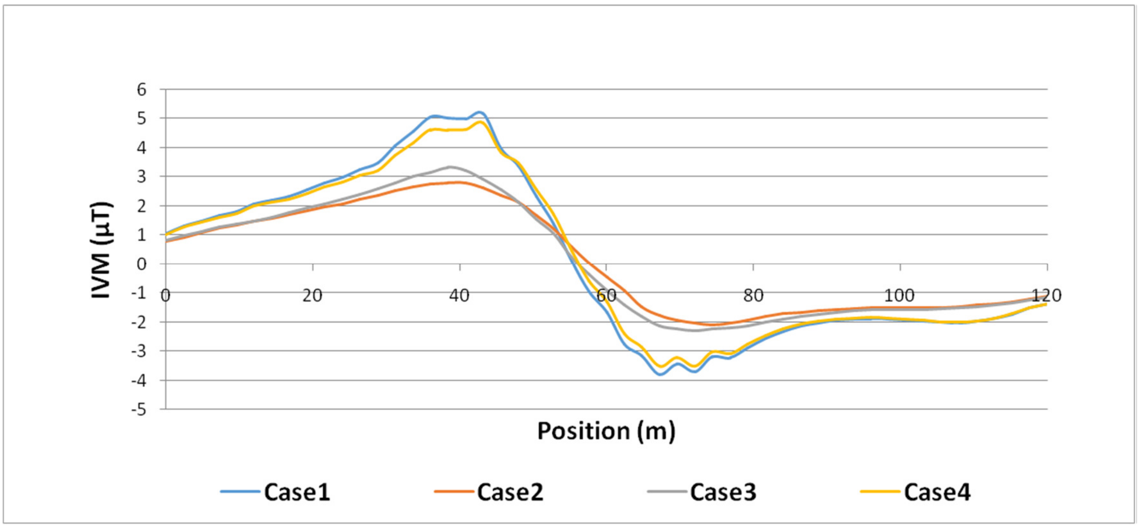

Figure 10: IVM Results for Various Cases on Observation Line

It is observed that the results for case1 are in line with case4 whereas the results of case2 and case3 are close. For case2 the plate thickness is assigned to the nearby plates covering the entire compartment which was identical to modelling as box in the compartments of propulsion plant as well as auxiliary plant. The modelling approach is similar for both; hence the signature results were close for case2 and case3. The interesting finding is the concept of modelling the machinery items Main Engine (ME) and Auxiliary Engine (AE) as dipoles leads to the similar result of assigning thickness to plates according to the weight distribution. Hence this method of modelling machinery and equipment as dipoles can be used for signature prediction. The advantage of this method is, if there are any design changes like the orientation/location of the machinery and equipment are changed in the design iteration process the entire FE model need not be regenerated. The details of field strengths of modified machinery/equipment can be recalculated and used for signature prediction.

6. Eddy Currents Due to Ship Motions

Eddy current magnetic signature acts along with the static induced magnetic signature for ferromagnetic hull. Due to roll and pitch motion of the ship in external magnetic field, eddy currents are induced in conducting materials on board ship, mainly in conducting hull. Flow of those currents is a source of magnetic field around a ship. In the present work the extreme ship motions for rolling and pitching based on empirical relations are considered. Magnetic signature simulations for the roll motion were performed with an extreme roll angle of 35° and three different frequencies 1/8, 1/12 and 1/16 Hz. Similarly the pitch motion was studied with an extreme pitch angle 15°. The ship is kept static in the simulation, where the ship motions are modelled as varying earth's magnetic field as a function of cosine.

The earth's variable magnetic field in roll motion is given by

$$H'_Y = H_Y * \phi * \cos(\omega_r t) \tag{iv}$$

$$H'_Z = H_Z * \phi * \cos(\omega_r t) \tag{v}$$

Where,

$H'_Y$is the fluctuating earths field in Y-component due to roll motion
$H_Y$is the static earth's field in Y-component
$H'_Z$is the fluctuating earths field in Z-component due to roll motion
$H_Z$is the static earth's field in Z-component
$\phi$is the roll amplitude = 0.623 rad
$\omega_r$is the roll frequency

The earth's variable magnetic field in pitch motion is given by

$$H'_X = H_X * \theta * \cos(\omega_p t) \tag{vi}$$

$$H'_Z = H_Z * \theta * \cos(\omega_p t) \tag{vii}$$

Where,

$H'_X$is the fluctuating earths field in X-component due to pitch motion
$H_X$is the static earth's field in X-component
$H'_Z$is the fluctuating earth's field in Z-component due to pitch motion
$H_Z$is the static earth's field in Z-component

θ is the pitch amplitude= 0.266 rad
ω_p is the pitch frequency

The eddy currents induced due to roll motion in athwart ship direction and vertical direction are predicted for Case1 and the signature plots are given in Figure 11 and Figure 12. Similarly the eddy currents induced due to pitch motion in longitudinal direction and vertical direction are given in Figure 13 and Figure 14. These signatures are only due to the electrical conductivity of the material and are independent of the ferromagnetic property of the material. Eq. iv –vii suggest the fluctuating components of earth's field are dependent on ship motion amplitude and frequency. Effect of varying ship motion frequency (or period) is shown in Fig 11 – 14. The peak of induced magnetic field gets shifted (although insignificantly) along the vessel length with vessel's roll and pitch period. The peak amplitude of induced magnetic signature in vertical direction is noted to be sensitive to the roll and pitch periods. The amplitude of motions considered is very high (extreme life time motions). For operational sea state the motion amplitudes and periods would be different and results would vary.

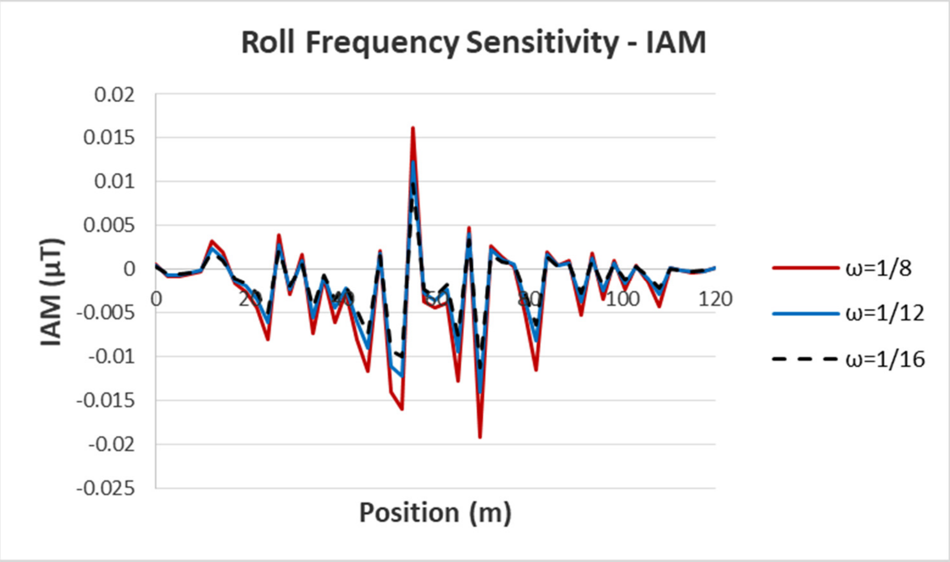

Figure 11: Athwart ship eddy current induced magnetic field on an observation line for applied field of H_Y'

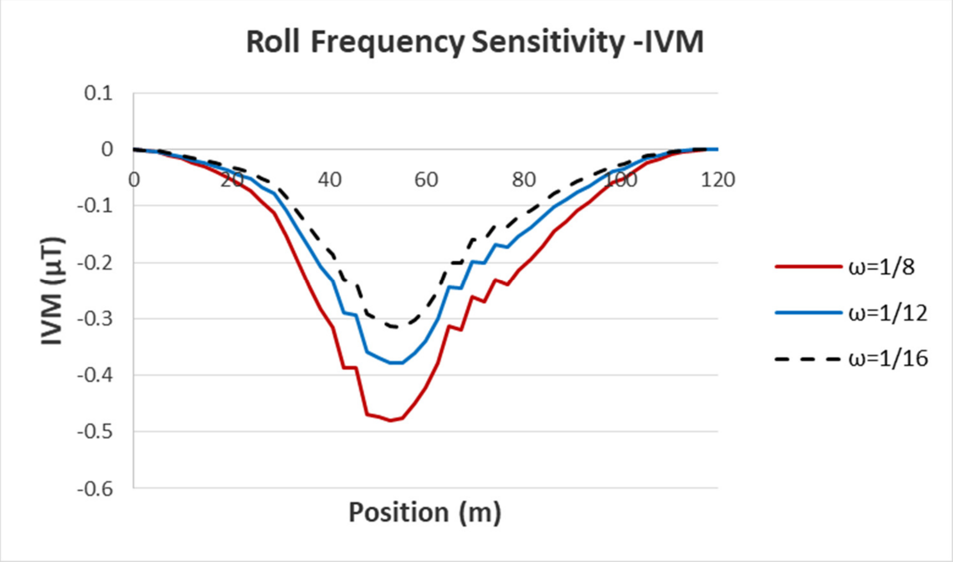

Figure 12: Vertical eddy current induced magnetic field on observation line for applied field of H_Z'

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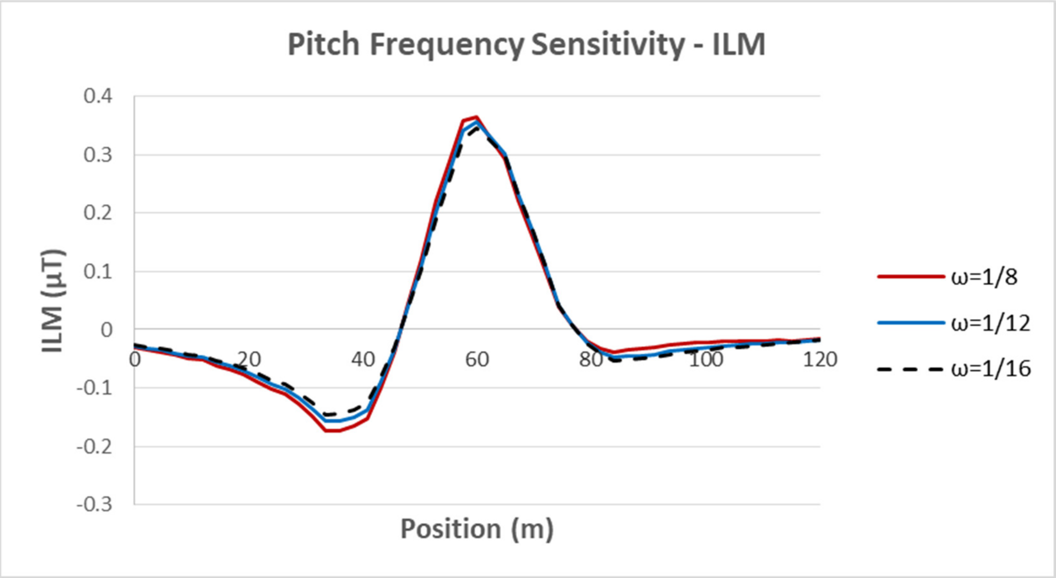

Figure 13: Longitudinal eddy current induced magnetic field on observation line for applied field of H'_X

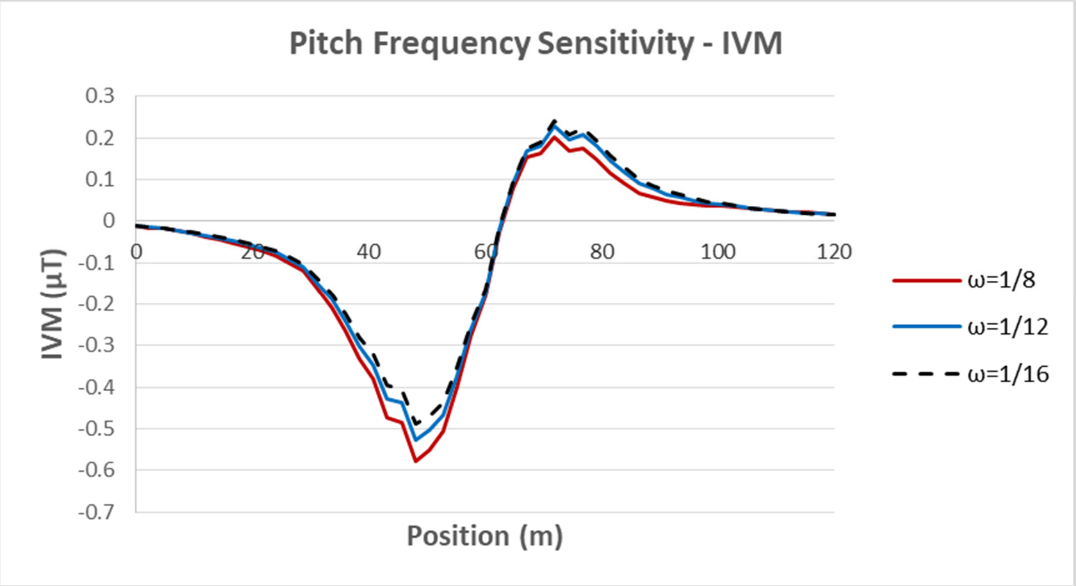

Figure 14: Vertical eddy current induced magnetic field on observation line for applied field of H'_Z

The iso-lines of magnetic field variation for ship rolling case and pitching case on a plane 20 m below keel are shown in Figure 15 and Figure 16 respectively.

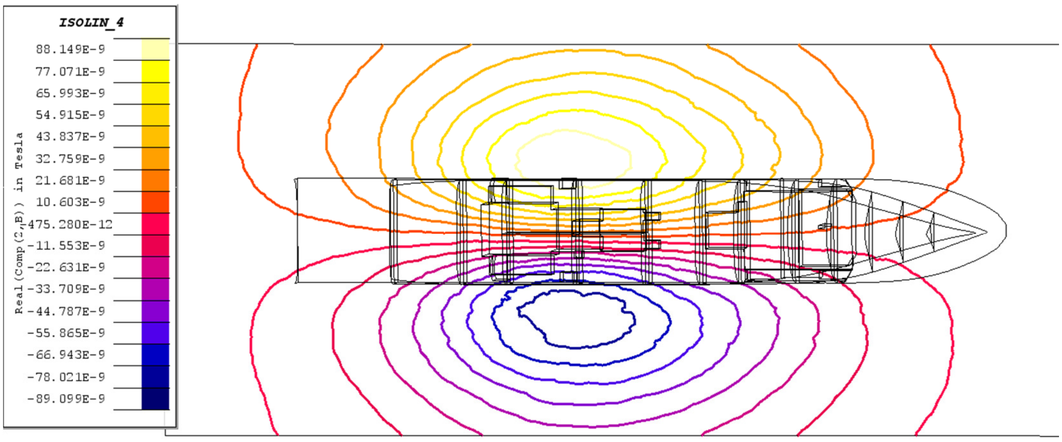

Figure 15 IAM Plot for Roll motion

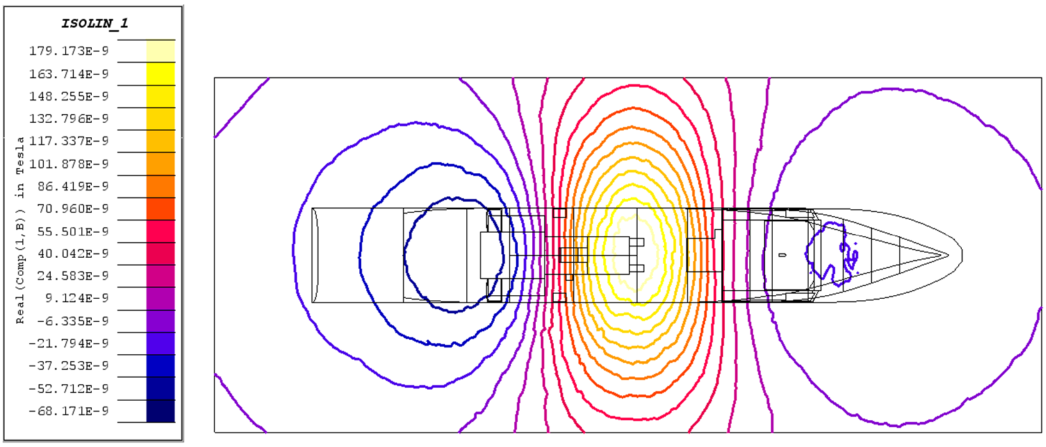

Figure 16 ILM Plot for Pitch motion

The induced signatures in the vertical direction are shown for a static case1, roll and pitch motions are given in Figure 17.

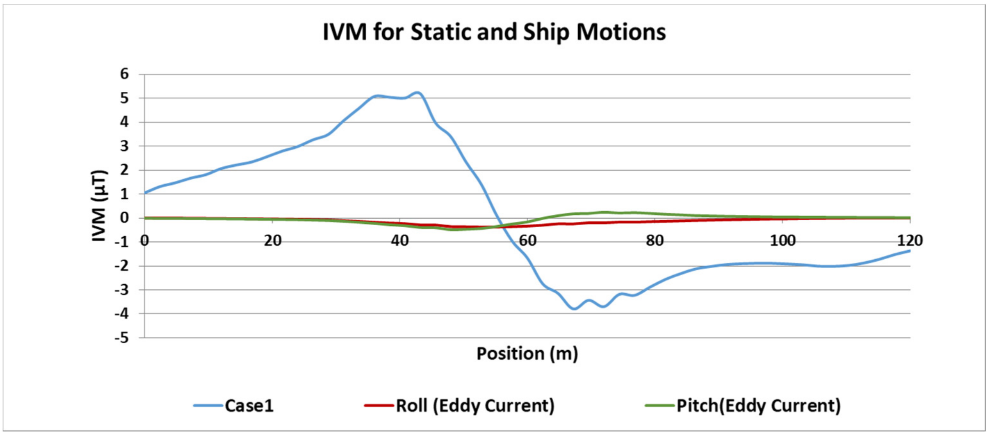

Figure 17: IVM Signatures for Static Case1 and Ship Motions

The eddy current signatures are generally less in magnitude as compared to ship static signatures. But in some cases peak of both signatures may coincide giving rise to the total magnetic signature of the vessel, especially when the vessel is degaussed. Hence these signatures should be considered in the design of degaussing coils.

https://doi.org/10.24868/issn.2515-818X.2020.043

7. Conclusions

The induced magnetic signature for a vessel is predicted based on computational electromagnetic method. Different configurations of thickness assignment representing the overall weight distribution of hull were considered. For all the cases the overall weight was maintained same. Based on the results following can be concluded

- Modelling of the entire hull with internal structural details which forms the part of ferromagnetic material is important for SM signature prediction
- Overall weight of the major items such as propulsion plant, auxiliary plant, etc. need to be accounted exactly. The distribution of weight of these items is important, however, bifurcating the weight of the components of these items (Case2 and 3) does not result in any advantage or accuracy in prediction
- Rather, the critical equipment can be modelled as dipoles based on its weight, size and the position. Dipoles can be modelled (Case4) considering the equipment as ellipsoidal with suitable approximations. This is the most easiest, reliable and flexible modelling for magnetic signature prediction.
- Thus in the initial design phase when the least details of critical equipment are available, modelling dipoles can be followed for quick predictions of SM for various combinations in terms of weight and position of the equipment.

The signature induced due to ship motions is predicted. Although eddy current induced signatures are comparatively lesser than SM signature the effective magnetic signature is calculated by addition of two signatures (static and dynamic). Static magnetic signature is due to the ferromagnetic property of the material whereas eddy current induced (dynamic) signature is due to the electrical conductivity of the material used for the construction of the vessel. Also the dynamic signature is dependent on the inherent seakeeping characteristics, i.e. the motion behaviour of the vessel in the operational conditions. Thus these effects need to be studied at the initial design stage to arrive at design of degaussing system to cancel both the ferromagnetic and the eddy current contribution to the magnetic signature simultaneously for reducing the susceptibility to sea mines.

Acknowledgements

The authors express their earnest gratitude to the Indian Register of Shipping, Mumbai for supporting the reported work. The authors would also like to thank Altair (FLUX 3D) for their valuable guidance and support.

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