A Multi-influence Range with Electromagnetic Modelling

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Abstract

The latest generation of multi-influence ranges which combine static electromagnetic and alternating influence (ELFE, acoustic, seismic) analysis have developed from the traditional degaussing ranges. This paper looks at the analysis and modelling of the alternating electromagnetic influences from both magnetic and electric sources using real and simulated data. The electric environment surrounding the vessel (i.e. the sea-seabed interface) can have a significant impact on a vessel's electromagnetic signature. Using range analysis software the signature of a vessel can be predicted from the range measurements to any other environment. This is achieved using a signature modelling process.

The use of a calibration source to characterise the environmental effects can maximize model accuracy and as such the model can be used to predict signatures at different locations with various sea and seabed characteristics. In previous papers we have shown the theoretical and measured results for the alternating electric signature arising from vessel corrosion and the ICCP system; in this paper we will show results for the alternating magnetic signatures with a magnetic origin (AM) and the alternating corrosion related magnetic (AC CRM) signature.

1. Introduction

Operations in the littoral naval environment can pose a variety of threats to vessels. The corrosion related signatures have a significant impact on both the electric and magnetic signatures of a vessel and this fact has prompted the replacement of degaussing ranges with multi-influence ranges. Multi-influence ranges measure and analyse signatures including static magnetic, static electric, alternating magnetic, alternating electric, pressure, acoustic and seismic signatures ([1], [2], [3]).

The electromagnetic signature modeling process developed over many years ([1],[4],[6]) makes use of the measured signature results to enable prediction of expected static and alternating signatures at other water depths and locations with different environmental parameters e.g. sea water and seabed conductivity.

2. A multi-influence range

Ultra's fixed and portable magnetic range (Transmag) has been enhanced over several years; initially to optimise its magnetic degaussing performance by taking into account the corrosion related magnetic (CRM) component of the magnetic field. The first stage of this was to make electric measurements from which a polarisation distribution is calculated (analogous to the magnetisation distribution) from which the CRM field is calculated. The electric field threat can also be determined and analysed.

In the second stage of development the bandwidth of electric and magnetic sensors has been increased to permit Extremely Low Frequency Electromagnetic (ELFE) data gathering up to 3kHz. Acoustic influence data is available over a bandwidth of up to 100 kHz. Seismic sensors are also available as an option. Multi-influence ranging and signature analysis capability plays an important part in determination of: the mine threat to a vessel or class of vessels, the identity of signature sources onboard the vessel and the presence of anomalous signatures e.g. signals caused by fault conditions.

The data gathering and processing/analysis package runs under the Windows operating system. A user-friendly Graphical User Interface (GUI) is implemented based on Windows™ functionality. For ease of operator use, a common software package is provided for AM, AE, seismic and acoustic data. Several plots of different influence types can be displayed at once to enable correlation of features.

The Transmag*Plus* system and its predecessors have been deployed over 30 times with a 100% record of successful rangings, the multi-influence range itself having had eight deployments ranging surface fleet, Mine CounterMeasure Vessels (MCMVs) and sweeps. Deployment is achieved from a small Zodiac vessel with a three man team with or without the use of divers. The use of lifting equipment is not required. All underwater equipment and analysis office is stored in a single ISO container and runs off a diesel generator.

The standard Transmag*Plus* ranging system can be configured to gather data for the following influences and bandwidths listed in Table 1. Bandwidths and sampling rates can be tuned to meet individual requirements if required.

Influence	**Bandwidth**
Static Magnetic (SM)	0Hz-10Hz
Static Electric (SE)	0Hz-10Hz
Pressure	0Hz-10Hz
Alternating Magnetic (AM)	1Hz-3KHz
Alternating Electric (AE)	1Hz-3KHz
Seismic	1Hz-100Hz
Acoustic	5Hz-100KHz

Table 1 Transmag*Plus* standard influence bandwidths

The small size and low weight of multi-influence sensor has been achieved in part from the use of potential voltage measurements made with a single sensor fitted to an individual sensor housing (Figure 1). Traditionally electric field values have been measured directly with the utilisation of a 3-axis electric field or UEP sensors. The method of calculating the electric and corrosion related magnetic signatures from the potential measurements has been detailed in an earlier paper [2].

Figure 1 The MUWS14 Multi-influence Sensor

3. Signature Prediction Validation

The validity of the theoretical models can be demonstrated by comparing the predicted signatures with those that have been measured at multi-influence sensors positioned on the seabed. The signatures have been generated from sources of known calibrated strength. Figure 2 shows a typical source which comprises a coil capable of generating a static and alternating magnetic fields, an electrode pair capable of generating a static and alternating electric fields (and hence corrosion related magnetic fields) and an acoustic hydrophone which generates acoustic signal at user selectable frequencies. The sources are designed such that the resultant signatures can be measured down to a depth of 50m; their magnitudes are listed in Table 2.

Environmental data such as the sea/seabed conductivity must also be gathered so that any model generated can be used for different environmental parameters. A seabed calibration source can be used to achieve this. Details of the MI range developed by Ultra Electronics can be found in [2]-[4]. A model of the vessel is produced using the modelling techniques described above. The constructed models can then be used to produce the electric and magnetic field signature at any depth and water conductivity.

Figure 2 A catamaran source used for range validation

Influence	Source Strength
Magnetic (SM & AM)	11200 Am^2
Electric (SE & AE)	100 Am
Acoustic	165dB

Table 2 Validation source strengths

4. Overview of ELFE field modeling

The various propulsion and power systems onboard a vessel will generate time dependent, or AC, electromagnetic fields. Such fields emanating from a vessel are referred to as ELFE signatures. The sources of the electromagnetic signature can be both electrical and magnetic and these can be generated at various frequencies. Primary sources of AC electromagnetic signatures are electrical currents generated from the power supplies/subsystems and magnetic fields due to engine/induction motors. Static sources can also be modulated to produce AC electromagnetic fields such as those due to modulated currents caused by the prop and shaft of a vessel.

The understanding of the various electromagnetic signatures is very important since they can propagate for a distance sufficient to be used as a method of detecting a vessel and pose a substantial threat to it. In order to achieve low vessel signatures we must develop a comprehensive understanding of the electromagnetic signatures of a vessel at all frequencies. For this reason the ability to model the vessel's signature and its interaction with it environment is required.

There are two principle methods that can be used to model a vessel signature which have various advantages and disadvantages. At the design stage of a vessel, a model is required in which the effect of different hull constructions and power supplies can be examined. For this a model based on first principles is needed from which an approximate electromagnetic signature of the vessel can be calculated directly from the size and shape of the hull and the type and nature of the systems that are to be fitted on board. Assumptions must be made regarding the regions of damage on the hull which affect the corrosion path for example. However, for the maintenance of vessel signatures, where the model of a ship is usually produced from data gathered on a range a first principle calculation would not be appropriate. The model must be produced in real time so the range operator can use the information while the vessel is being ranged. The model must reflect the current vessel state rather than assumed hull conditions. In this case a fitting algorithm using independent parameters would be more appropriate than an ab initio approach. In this paper we shall describe a method of modelling that is applicable to predicting the AC electromagnetic signature from data gathered on a range.

There is a multitude of methods in which data gathered from a range can be used to predict a vessel signature. Dipole modelling where the vessel is represent by an array of dipoles has been shown to model the static electromagnetic field extremely well, [1]-[4]. This coupled with data gathered from a range has been very effective for obtaining the data of the static fields in order to maintain the signature hygiene of a vessel. In a similar way we can model the AC electromagnetic signatures using time dependent dipoles.

We have previously shown that both measured AC potential and electric fields can be successfully modelled [6]. In this paper we shall demonstrate that the technique of modelling a vessel signature using time dependent electric dipoles can be used to model the alternating corrosion related magnetic signature of a vessel. We shall give in the Theory section a brief discussion of the electromagnetic principles that under lie the technique. We shall then show how we can model the magnetic field signature of a vessel. A brief discussion of ranging and processing methods is given together with a demonstration of the modelling algorithm in the Ranging Results section.

5. The theory of ELFE field modelling

The principle of dipole modelling is to represent an arbitrary current density of the ship by a line or an array of dipoles. The dipole strengths can be found by making field measurements at different spatial positions, [1]-[3], because the source distribution has a direct relation to the magnitude and direction of the field at the measurement points. In order to relate the measured fields to their sources it is necessary to solve Maxwell's equations and cast them into a form appropriate to our problem.

Maxwell's equations for a magnetic field $\mathbf{B}(\mathbf{r})$ and current distribution, $\mathbf{j}(\mathbf{r})$ in a conducting media are given by the following equations where $\mathbf{E}(\mathbf{r})$ is the electric field and σ is the conductivity.

$$\nabla\cdot\mathbf{B}(\mathbf{r})=0,\ \nabla\times\mathbf{E}(\mathbf{r})=-\frac{\partial B(\mathbf{r})}{\partial t}\ \text{and}\ \nabla\times B(\mathbf{r})=\mu_0\mathbf{j}(\mathbf{r})+\mu_0\sigma\mathbf{E}(\mathbf{r})+\varepsilon_0\varepsilon_r\mu_0\frac{\partial\mathbf{E}(\mathbf{r})}{\partial t} \quad (1,2,3)$$

We are free to write $\mathbf{B}(\mathbf{r})$ in terms of a vector potential, $\mathbf{A}(\mathbf{r})$, such that equation (1) is satisfied,

$$\mathbf{B}(\mathbf{r})=\nabla\times\mathbf{A}(\mathbf{r}) \quad (4)$$

The electric field may be represented by a scalar function, $V(\mathbf{r})$, ensuring that equation (2) is satisfied.

$$\mathbf{E}(\mathbf{r})=-\nabla V(\mathbf{r})-\frac{\partial\mathbf{A}(\mathbf{r})}{\partial t} \quad (5)$$

Maxwell's equations do not specify the vector and scalar potentials uniquely, we must specify the divergence of the vector potential. We choose a gauge for the vector potential, or connection between the vector and scalar potentials such that,

$$\nabla\cdot\mathbf{A}(\mathbf{r})=-\mu_0\sigma V(\mathbf{r})-\varepsilon_0\varepsilon_r\mu_0\frac{\partial V(\mathbf{r})}{\partial t} \quad (6)$$

with no loss in generality and this relation effectively de-couples the vector and scalar potentials. $\mathbf{A}(\mathbf{r})$ is seen to obey the vector differential equation,

$$\nabla^2\mathbf{A}(\mathbf{r})-\mu_0\sigma\frac{\partial\mathbf{A}(\mathbf{r})}{\partial t}-\varepsilon_0\varepsilon_r\mu_0\frac{\partial^2\mathbf{A}(\mathbf{r})}{\partial t^2}=-\mu_0\mathbf{j}(\mathbf{r}) \quad (7)$$

If we assume harmonic field then the vector potential can be written as, $\mathbf{A}(\mathbf{r},t)=\mathbf{A}(\mathbf{r},t)\exp(i\omega t)$ where ω is the angular frequency on substitution into equation (7) we find that

$$\nabla^2\mathbf{A}(\mathbf{r})+k^2\mathbf{A}(\mathbf{r})=-\mu_0\mathbf{j}(\mathbf{r}) \quad (8)$$

where k the wavevector is given by $k^2=\frac{\omega^2}{c^2}-i\alpha^2$, $\alpha^2=\mu_0\sigma\omega$ and c is the speed of light.

For low ELFE frequencies in a conductor the general equation for the vector field for an arbitrary current distribution in a conducting media when the displacement currents are neglected is:

$$\nabla^2\mathbf{A}(\mathbf{r})-i\alpha^2\mathbf{A}(\mathbf{r})=-\mu_0\mathbf{j}(\mathbf{r}) \quad (9)$$

6. Three layer Model

In order to obtain a dipole representation of the AC electromagnetic field of a ship in its environment we must solve Maxwell's equations for a dipole in a stratified media, figure (2). In this system the air, sea and seabed are assumed to be parallel layers with the air assumed non-conducting.

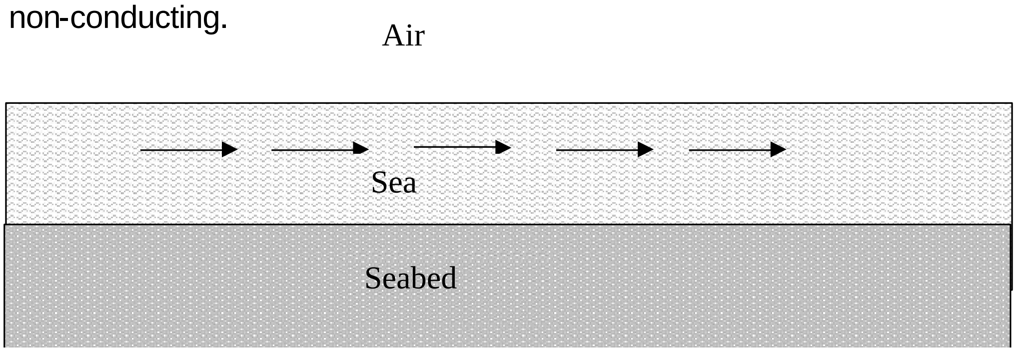

Figure 3 A simple vessel represented as a line of dipoles in a three layer medium

Considering figure (2) we can write equation (9) for a three layer system as,

$$\nabla^2 \mathbf{A}_1 = 0 \qquad 0 < z$$
$$\nabla^2 \mathbf{A}_2 - i a_2{}^2 \mathbf{A}_2 = -m_0 \mathbf{j} d(z+a) \qquad 0 < z < -b \qquad (10)$$
$$\nabla^2 \mathbf{A}_3(\mathbf{r}) - i a_3{}^2 \mathbf{A}_3(\mathbf{r}) = 0 \qquad z < -b$$

subject to boundary conditions.

The boundary conditions require that the magnetic field and the tangential component of the electric field must be continuous across the boundaries. If k is a vector perpendicular to the surface then we have that $\mathbf{k} \cdot \mathbf{H}$, $\mathbf{k} \times \mathbf{H}$, $\mathbf{k} \times \mathbf{E}$ are , continuous such that,

$$\mathbf{k} \cdot \nabla \times (\mathbf{A}_n - \mathbf{A}_{n+1}) = 0 \qquad (11)$$
$$\mathbf{k} \times \nabla \times (\mathbf{A}_n - \mathbf{A}_{n+1}) = 0 \qquad (12)$$
$$\mathbf{k} \times \nabla\nabla \cdot \left(\frac{\mathbf{A}_n}{s_n} - \frac{\mathbf{A}_{n+1}}{s_{n+1}} \right) = 0 \qquad (13)$$

In order to solve equation (10) subject to the boundary conditions it is helpful although not necessary to treat vertical and horizontal dipoles separately. We shall show the horizontal case only here, although the solution will use an array of 3-axis dipoles.

Horizontal Dipole

In order to satisfy the boundary conditions in equations (11)-(13) it is necessary for the vector potential to have the form, $\mathbf{A}_n = \mathbf{i} A_{nx} + \mathbf{k} A_{nz}$. The general solution to equation (10) for a horizontal dipole is,

$$A_{0x} = \int_0^\infty dl J_0(rl) \{ f_{0x} \exp(-zl) + g_{0x} \exp(zl) \} \qquad (20)$$

$$A_{1x} = \int_0^\infty dl \frac{l}{\sqrt{l^2 + ia_1^2}} J_0(rl) \left\{ \frac{m_0 j_x}{4p} \exp\left(-|z+a| \sqrt{l^2 + ia_1^2} \right) + f_{1x} \exp\left(-z\sqrt{l^2 + ia_1^2} \right) + g_{1x} \exp\left(z\sqrt{l^2 + ia_1^2} \right) \right\} \qquad (21)$$

$$A_{2x} = \int_0^\infty dl \frac{l}{\sqrt{l^2 + ia_1^2}} J_0(rl) f_{2x} \exp\left(-z\sqrt{l^2 + ia_2^2} \right) + g_{2x} \exp\left(z\sqrt{l^2 + ia_2^2} \right) \qquad (22)$$

The boundary conditions for the x components of the vector potential is,

$$A_{0x} - A_{1x}\big|_{z=0} = 0, \quad A_{1x} - A_{2x}\big|_{z=-b} = 0 \qquad (23)$$

$$\left. \frac{\partial A_{0x}}{\partial z} - \frac{\partial A_{1x}}{\partial z} \right|_{z=0} = 0, \quad \left. \frac{\partial A_{1x}}{\partial z} - \frac{\partial A_{2x}}{\partial z} \right|_{z=-b} = 0 \qquad (24)$$

$$A_{iz} \to 0 \quad r \to \infty \quad i = 0,1,2 \qquad (25)$$

The z components of the vector potential have the form,

$$A_{0z} = \int_0^\infty dl J_1(rl) \{ f_{0z} \exp(-zl) + g_{0z} \exp(zl) \} \qquad (26)$$

$$A_{1z} = \int_0^\infty dl J_0(rl) \left\{ f_{1x} \exp\left(-z\sqrt{l^2 + ia_1^2} \right) + g_{1x} \exp\left(z\sqrt{l^2 + ia_1^2} \right) \right\} \qquad (27)$$

$$A_{2z} = \int_0^\infty dl J_1(rl)\left\{f_{2x}\exp\left(-z\sqrt{l^2+ia_2^2}\right)+g_{2x}\exp\left(z\sqrt{l^2+ia_2^2}\right)\right\} \qquad (28)$$

The coefficients in equation (26)-(28) can be solved from the boundary conditions which have the form,

$$A_{0z} - A_{1z}\big|_{z=0} = 0, \quad A_{1z} - A_{2z}\big|_{z=-b} = 0 \qquad (29)$$

$$\left(\frac{\partial A_{1x}}{\partial x} + \frac{\partial A_{1z}}{\partial z}\right)\Bigg|_{z=0} = 0, \quad \frac{1}{s_1}\left(\frac{\partial A_{1x}}{\partial x} + \frac{\partial A_{1z}}{\partial z}\right) - \frac{1}{s_2}\left(\frac{\partial A_{2x}}{\partial x} + \frac{\partial A_{2z}}{\partial z}\right)\Bigg|_{z=-b} = 0 \qquad (30)$$

$$A_{iz} \to 0 \quad r \to \infty \quad i = 0,1,2 \qquad (31)$$

From the boundary conditions we see immediately that the coefficients $g_{0x} = g_{0z} = f_{0x} = f_{0z} = 0$. The other coefficients are readily derived from (20)-(22) and (26)-(28) and explicit expression can be found in [5].

7. Modelling of corrosion related magnetic signature measurements

In the previous section we have shown how we can obtain analytical expressions for the vector potential for an arbitrary orientated dipole in a three layer system. From these expressions we can derive the scalar potential, electric field and the magnetic fields using equations (4)-(6). By representing a vessel as a line of dipoles with different strengths we can model the vessel's electric and magnetic signatures once the amplitude of the individual dipoles have been determined. The aim of the fitting algorithm is to produce a set of dipoles for a particular frequency. We can then use these dipoles to predict the vessel's electric and magnetic signatures at the measurement frequency.

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As with the potential modelling [6] the dipole set may be used to predict the potential, electric and magnetic signatures of the vessel at any depth and sea/seabed conductivity. Here we shall show that it is possible to determine an electric dipole model from propeller shaft frequency magnetic measurements.

8. Alternating corrosion related dipole ranging results

A vessel's electromagnetic signature is usually determined by open sea ranging. A ship ranging typically involves collecting electrical potential, electric field and magnetic field data as the ship passes over an array of sensors; there are five sensors used in the data analysis below. The ship is tracked using GPS while the data of the vessel's signatures is being gathered.

In general the corrosion currents flow along the length of the ship from regions of damage or passive or active cathodic protection anodes along the length of the ship and up the propeller shaft. The corresponding magnetic fields are generated in a circular form about the direction of current flow. Thus for a longitudinal current flow the Corrosion Related Magnetic field appears at right angles to it in the athwartships direction.

The magnetic data obtained from the range is sub-sampled, filtered and a Fast Fourier Transform (FFT) applied. The Fourier transform is performed for fixed time intervals generally less then a second. The FFT will produce measured magnetic spectra at discrete frequency and fixed intervals. The FFT data can then be used to construct dipole model of the vessel at any of the discrete frequencies.

The support vessel was ranged at a speed of 6.4 ms^{-1}. The gathered data is decimated and low pass filtered to enable to enable a high resolution FFT analysis to be performed. The plot data is displayed in the 0-40Hz bandwidth in order that the low frequency shaft rate signatures arising from the propeller can be clearly seen. The results are shown in Figure 4 which indicates that the predominant frequency is 5.7Hz in the ship’s athwartships axis; its higher harmonics occur at 11.4Hz etc. A second run was made at 5.3ms^{-1}.The predominant frequency for this run corresponds to 4.7Hz and its higher harmonics occur at 9.4Hz etc. It can be seen that the frequency varies linearly with speed indicating together with the athwartships field direction that this is shaft related effect.

Figure 5 show the time progression of the alternating magnetic 5.7Hz frequency (dotted lines). This data is modelled using alternating electric dipoles as discussed above. The alternating magnetic signatures predicted from the electric dipole model at the sensor locations are shown as solid lines. The agreement between the measured and predicted signatures is good indicating that the source of the magnetic field is predominantly corrosion related for this vessel.

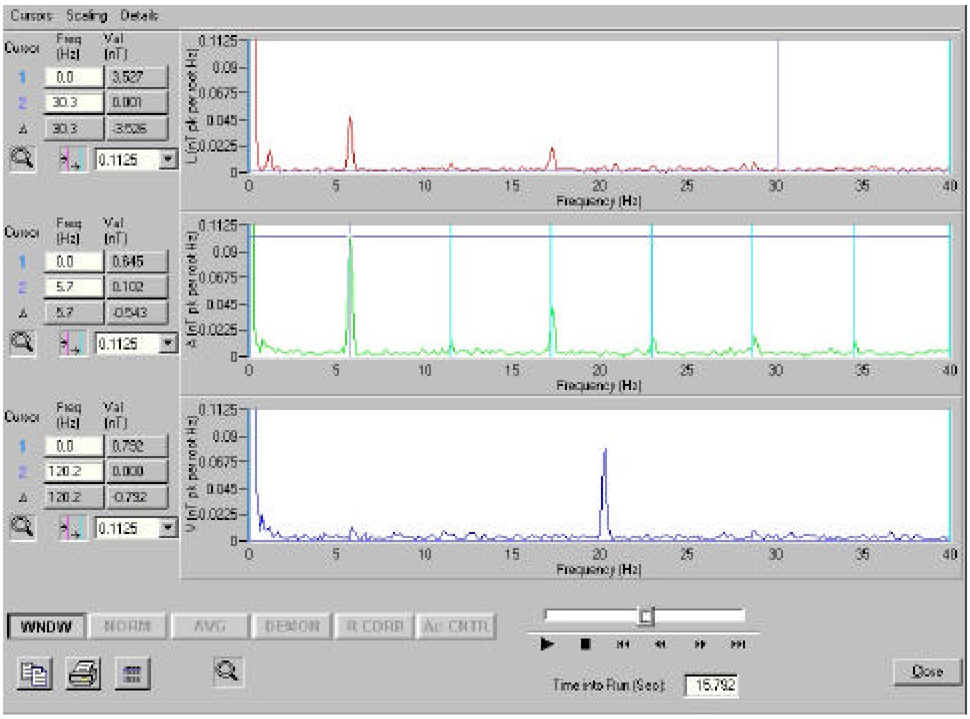
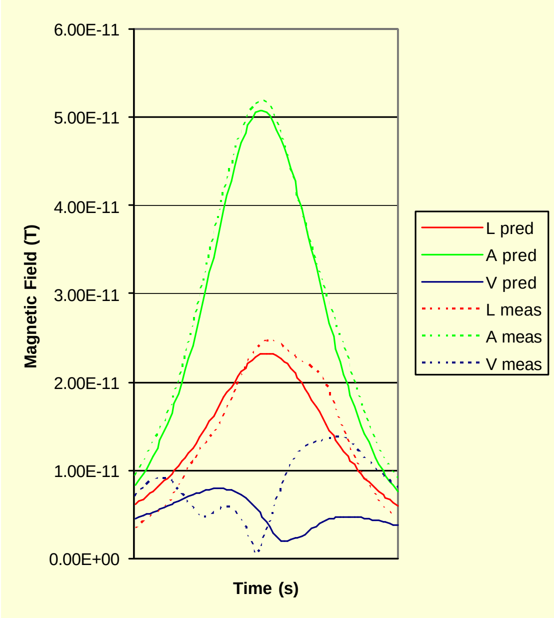


Figure 4 The three axes magnetic field in ship’s co-ordinate frame. The corrosion related magnetic frequencies can be seen as harmonics of 5.7Hz in the longitudinal and athwartships directions as highlighted on the athwartships axes by the harmonic cursor. The vessel speed in this case was 6.4 ms^{-1}

Figure 5 The time progression of the 5.7Hz magnetic signal. The dotted lines represent the measured signature in the longitudinal (L), athwartships (A) and vertical(V) directions, whereas the solid lines represent the signature predicted from the electric dipoles modelling process in the same co-ordinate frame. It can be seen that a good fit is found to the main Athwartships signature component. The other two components are affected by background magnetic noise which is of order 1e-11T (0.01nT).



9. Alternating magnetic dipole ranging results

Following on from the development of the static magnetic dipole model, an alternating model has been also been developed. Typical sources onboard a vessel could include rotating machinery. In order to verify the model an alternating magnetic field was generated at a 75Hz frequency using the validation source shown in Figure 6. The validation source in this case was towed across a 5 sensor array comprising MUWS14 sensors as described above. The field is predicted from a three layer alternating dipole model of the source coil using the same current strength and dimensions as the source coil. The theoretical model is derived from the vector potential for a point current source and integrating the Somerfield integral over a current loop (Note that for brevity the theoretical basis of the model is not shown here). Figure 6 shows that there is good agreement between the measured and predicted signatures verifying the theoretical model for the signature gathered at the keel line sensor. The dotted lines indicate the upper and lower bounds of the theoretically predicted signature given the experimental errors determined by the worst case sea state (Sea State 3), tracking and sensor positioning errors and source current stability.

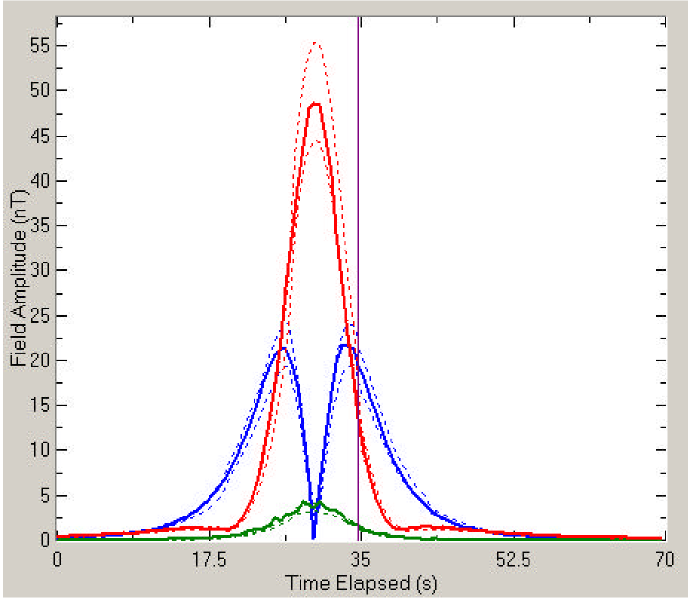


Figure 6 The time progression of the 75Hz alternating magnetic signal. The solid lines represent the measured signature in the longitudinal (L), athwartships (A) and vertical(V) directions, whereas the dotted lines represent the upper and lower bounds of the predicted signature predicted by the model in the same co-ordinate frame.

10. Conclusions

In this paper we have given a description of how time dependent electromagnetic signatures can be modelled using dipoles. We have demonstrated how modelling AC magnetic data can be used to predict the shaft related electric field signature of a vessel and produce a good fit to the data indicating that corrosion related currents are the primary signature source at propeller shaft frequency for these vessels. The signature predicted from the model compares with the actual measured signature of an vessel by 4-7%. The models generated by this technique are valid for a particular frequency and may be used to predict the electric field at any depth and sea/seabed conductivity and hence may be used to determine a vessel's signature in the majority of locations across the globe.

In addition the validation of the theoretical models for alternating magnetic dipole have been shown. The signatures have been generated from sources of known calibrated strength deployed from a towed catamaran and gathered on a multi-influence range. The theoretically validated equations are used as the basis for the modelling process as previously described.

The catamaran source can also be used to periodically verify range system functionality. This validation process can be achieved by towing the catamaran across the range with its sources energised and using the validation software to compare the measured and theoretically predicted signatures at the sensor locations. The measured signatures will only match the theoretical signatures if all aspects of the range system (sensor, tracking, timing) are functioning within their specification.

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