A Survey of New Electromagnetic Stealth Technologies

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ABSTRACT:

The static and extremely low frequency electric and magnetic signatures of ships are easily detected with modern sensors. Electric fields, and coincident magnetic fields, arise around a ship due to the current flow from active cathodic protection (ACP) systems or from the use of dissimilar metals during construction. Poor filtering of ACP power supplies and the varying resistance in the current path through the rotating shaft causes signature frequencies to be transmitted through the water by electromagnetic fields. This paper provides a broad overview of the sources of, and countermeasures for eliminating, the electromagnetic signature of a vessel, as well as sensors capable of measuring the signature.

Also discussed is an advanced degaussing system for actively controlling the static magnetic signature of a ship. The magnetic signature of a vessel can be better controlled through an increased number of degaussing coils, individual power supplies and the use of a central control computer. This paper outlines the advanced degaussing system hardware.

1. Introduction

One of the most effective weapons against ships in littoral waters is the naval mine. Modern influence mines often sense the static (or dc) magnetic (SM) fields of passing ships to be used as triggers. (Static here means a frequency of less than about 0.01 Hz.) However very little sophistication is required to extend this technology to exploit the alternating magnetic (AM) or static and alternating electric (SE and AE) fields that a ship generates. It is expected that modern mine designers will seek to exploit these influences and use them to improve sweep rejectability of their mines and to target acoustically and magnetically quiet vessels. In fact, SE sensitive mines are already available.

Electromagnetic fields emanate from ships due to the electric currents that are created both through the electrochemical action between dissimilar metals and through the use of either passive or active cathodic protection (ACP) systems. These electromagnetic fields take the form of SE and SM fields arising from the steady flow of current around the hull of the vessel. Modulation of this current leads to AE and AM fields. Modern mines can detect these fields and use them to detect and classify passing ships.

SM fields surrounding a ship also occur as a result of using ferro-magnetic steel as the main construction material. There is an inherent residual permanent magnetism associated with the ship hull and equipment that can be detected by even simple mine sensors. As well, the steel hull interacts with the earth’s magnetic field to produce an induced magnetic field whose strength depends on the ship’s location and heading.

To protect the ships from influence mines exploiting these fields as triggers, both countermeasures and minesweeping methods have been developed. Countermeasures take the form of devices to substantially eliminate the static and alternating components of the electromagnetic signature thereby removing the mine’s ability to classify a ship’s electromagnetic signature. Minesweeping techniques take the form of passing sources that emulate the signature of the target vessel through a mine field to either detonate the mines or indicate safe passage for the vessel.

2. Definition and Origin of Ship Electromagnetic Signatures

2.1 Alternating Magnetic and Static and Alternating Electric Signatures

An electric field over a conduction path gives rise to an electrical current. The amount of current flow depends on the strength of the electric field and the resistance of the path.

The electric current gives rise to a magnetic field proportional to the amount of current flowing. Also a changing electric field generates a changing magnetic field and vice versa. The change can result from either a change in field magnitude or field position. The AE and AM fields occur due to a modulation of the current that causes the amount of current flowing to vary with time.

Electric currents flow around and through the hulls of ships partly because of the use of dissimilar metals during construction. An electric field dipole is set up between the steel hull of the ship and the bronze of the propellor. This dipole causes a current flow along the path including the hull, sea water, propellor, shaft, bearings and seals. This current causes corrosion of the hull of the ship.

In an effort to reduce this corrosion, either passive cathodes or active cathodic protection (ACP) systems are employed. Passive systems place metal anodes, often zinc, on the hull of the vessel to induce currents to flow from the zinc to the propeller and the hull of the ship. The current path through the propeller flows down the shaft and through the shaft bearings to ground out on the hull of the vessel (Figure 1). The ACP system uses a large power supply connected to electrodes placed on the hull of the ship to force large current, up to 50 Amps or more, to flow from the electrode to the hull, propellor, or other exposed parts of the ship. Current to the propellor returns down the shaft and through the shaft bearings and seals back to the hull.

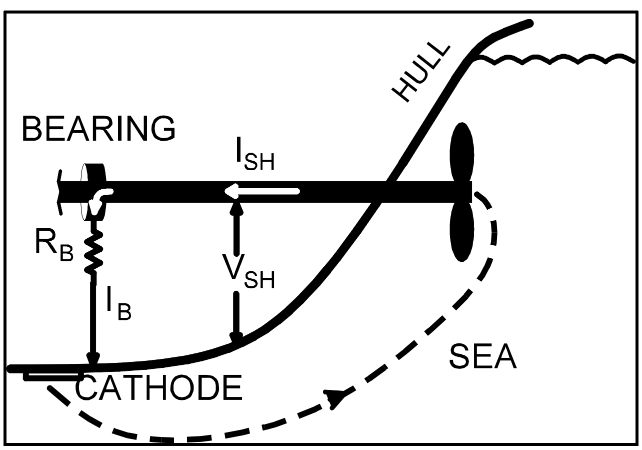

Figure 1: Origin of ELFE Signal

The shaft bearings generally provide for a poor electrical connection between the shaft and the hull. As the shaft turns, the electrical impedance of the connection varies causing a modulation of the electrical current and a corresponding modulation of the electric and magnetic fields surrounding the vessel. AE fields, generated underwater by the ship, can be detected using sensors in the vicinity of the vessel. The resulting electromagnetic signature of the ship contains the fundamental shaft frequency and harmonics.

Another source of AE and AM signals from ships results from the use of improperly filtered power supplies used to power the ACP. Without adequate filtering, the frequency and harmonics of the on-board power supply provide a further modulation of the ACP current, adding to the ship's signature. Mine sensors can make use of this signature to identify a ship.

Additional sources of AM fields include:
- electrical currents flowing in the hull due to equipment faults and/or inadequate electrical equipment design, installation or maintenance;
- inherent magnetic field radiation from rotating electrical machinery in the ship;
- eddy currents generated by ship motions as the conducting hull rolls in the earth's magnetic field.

Generally, for steel-hulled ships these effects are much smaller than those others addressed in this paper.

2.2 Static Magnetic Signatures

All ferrous metals are inherently magnetic, and therefore the ship's steel hull has an inherent permanent magnetic field. This permanent field is reduced by the deperming treatment which many naval ships undergo periodically. However, the permanent field varies over time and depends on many factors including mechanical stresses due to motions in the seaway, impacts, shocks to the ship and the geomagnetic zone where the ship has travelled. This static field is detectable using relatively simple sensors and has long been used as the main trigger for influence mines. The SM signature from the induced magnetic field varies depending upon the ship's orientation and location within the earth's magnetic field.

3. Electromagnetic Surveillance

Performing accurate measurements of electromagnetic signatures is relatively easy using modern sensor arrays. The ability to detect ships electromagnetically allows for the protection of harbours and channels from otherwise undetectable submarines. Magnetic and electric sensor ranges are also useful for measuring the signature of ships for the purposes of quieting their electromagnetic signatures. Most countries have magnetic ranges for the purposes of assessing and controlling the magnetic signatures of ships but electric sensor ranges are still relatively uncommon.

Magnetic sensor ranges typically consist of an array of magnetometers placed on the sea floor and connected to a control computer to be processed and recorded. Electric sensors consist of an array of pairs of silver/silver chloride electrodes laid in a pattern across the path of oncoming vessels and connected to a central computer. Readings from these sensors allows for accurate measurements of ship electromagnetic signatures and by placing the sensors in various orientations the ship signatures can be determined in multiple axes. While a mine is normally limited to about a metre in electrode spacing, the electrodes of an electric sensor array can be placed much further apart. Placing the electrodes far apart (40 metres or more) creates a much more sensitive sensor than the mine is capable of deploying and the range is therefore able to take significantly more sensitive measurements of ship electromagnetic signatures than is possible with mine sensors (Figure 2).

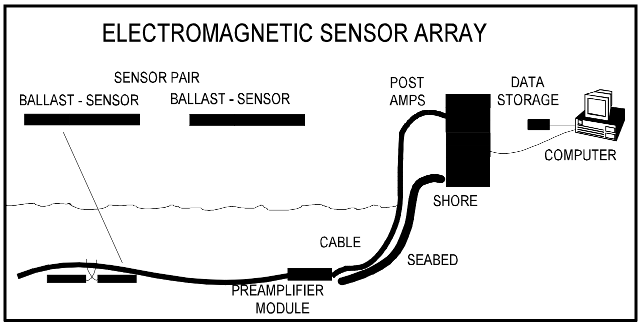

Figure 2: Schematic Diagram of Electric Sensor Array

Using filters, the electromagnetic signature can then be parsed into the SE signature and AE signature. Computer analysis may subsequently be performed on the signature data to identify characteristics of the passing vessel such as shaft rotation rate, on-board power supply frequencies, placement of electrodes, and other features that may be used to classify the vessel.

4. Mine Sensors

Simple influence mines use induction coils to sense the static magnetic field of an oncoming vessel. Their ability to process logic is limited and therefore their ability to target specific ship classes or avoid minesweeping measures is also very limited.

Modern mines have greatly improved on the capabilities of these early mines with the introduction of thin-film and fluxgate magnetometers. Modern magnetic sensors are more reliable and have a greater dynamic range (Castles, 1997). Microprocessors have also enhanced the effectiveness of influence mines allowing them to utilize the sensors in combination with more sophisticated logic. This combination enhances their ability to identify and ignore minesweeping vessels while targeting vessels based on certain signature characteristics.

Detection of AM signals by these modern mines is relatively easy. With the addition of microprocessor logic to implement Fast Fourier Transform (FFT) or other efficient signal analysis algorithms, frequency analysis of the ship signature in real time is possible. This type of mine would then be able to exploit frequency information and other signature characteristics to identify vessel classes and avoid minesweepers.

Very little additional effort is required to convert the existing magnetic field mine technology to detect the electric signature of vessels. Replacement of the induction coil with electrodes allows the modern mine to measure and analyse the electric field of an oncoming ship and apply similar frequency analysis techniques to classify the target based on the electric signature. Mines which exploit the SE signature of ships are known to exist and modifying those mines to sense and analyse the AE signature of vessel is relatively easy.

5. Electromagnetic Countermeasures

A number of techniques exist that are designed to eliminate or reduce the electromagnetic signatures of ships. They are useful for reducing the electromagnetic signature of the vessel to avoid detection or to avoid triggering a mine.

5.1 Shaft Grounding

The presence of the underwater static and alternating electric (SE and AE) fields has been known for some time and it has been standard practice in many countries to fit their ships with passive grounding systems. The system generally consists of a brush and slip ring assembly that connects the shaft directly to the hull of the ship.. The system provides for a lower resistance to ground for the current passing through the shaft and thus tends to eliminate some of the variations in resistance as the shaft turns.

These passive systems do not however eliminate all of the variations in the signal. The brush and slip ring assemblies tend to degrade greatly over time, particularly if maintenance is poor, and as a result the benefits are lost.

A more effective approach to managing the current flow through the shaft of a ship is through the use of an Active Shaft Grounding (ASG) device. This device uses electronics to compensate for changes in shaft-to-hull resistance, thereby eliminating the modulation of the shaft current. The ASG system operates by using slip-ring sensors to measure the shaft-to-hull potential of the ship as shown in Figure 3. By determining the variations in the current on the shaft, electronics in the ASG make use of a high current power supply to draw a proportional current through a second slip-ring assembly. The ASG device therefore acts as a current bypass for the shaft bearings and seals. The fluctuations in the shaft current are therefore eliminated and the AE and AM portions of the electromagnetic signature due to shaft current modulation disappear as demonstrated in the signature measurements shown in Figure 4.

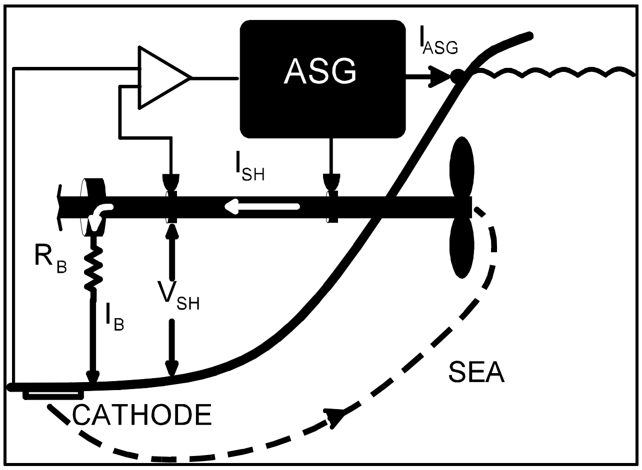

Figure 3: Schematic Diagram of ASG Layout

5.2 ACP Filtering

The ACP system typically provides hull and propellor corrosion protection by mounting anode plates on the hull of the ship and using a high current power supply to bias the potential of the steel hull and propeller. Often the supply is poorly filtered and the fundamental and harmonic frequencies of the ship's power system are introduced into the cathodic protection current. This variation can be detected by mine or surveillance sensors becoming part of the ship's signature.

These frequencies can be eliminated from the signature with a passive filter connected to the power supply output.

5.3 ACP Design

Cathodic protection systems are required by all ships for the purposes of protecting the hull and appendages from damaging corrosion. There is therefore a continued need for the current to flow through the shaft to protect the ship. As a result it is not feasible to completely eliminate the SE component of the ships electromagnetic signature. Methods are however available for reducing the SE signature of vessels.

Techniques can be applied during ship design and construction that minimize the size of the electric dipoles and thus reducing the intensity of the electric field. By carefully determining the optimum placement of the electrode plates on the hull of the ship the electric field can be minimized without compromising the corrosion protection of the cathodic protection system. It has also been proposed that by constructing the ship propeller and other major components solely of electro-chemically equivalent materials, the naturally occurring currents that flow between dissimilar metals could be virtually eliminated and there would be no need for an ACP system. Modern metal coatings for steel also help in preventing hull corrosion.

5.4 Degaussing

All modern vessels, being constructed largely of steel, have a permanent magnetic field surrounding the vessel. Both the simple induction coils found in older mines and the magnetometers found in modern mines are equipped to detect the magnetic field surrounding large vessels. Techniques exist to reduce the permanent magnetism of ships through deperming.

Most countries typically perform deperming of their vessels by passing large currents through coils temporarily rigged over the exterior of the hull when alongside or docked. This technique serves to reduce the overall permanent magnetism of the vessel. However the magnetism of the ship can not be completely eliminated by deperming, and furthermore, the permanent magnetism of a vessel changes over time. On-board degaussing coils have been installed on naval ships to counteract the residual permanent magnetism and also to counteract the affects of the induced magnetic field.

Advanced degaussing methods take the process one step further by increasing the number of on-board degaussing coils and using sensors to measure the magnetic field of the vessel and actively eliminate it. Computer technology can therefore correct for the changes that occur over time to the magnetism of the vessel.

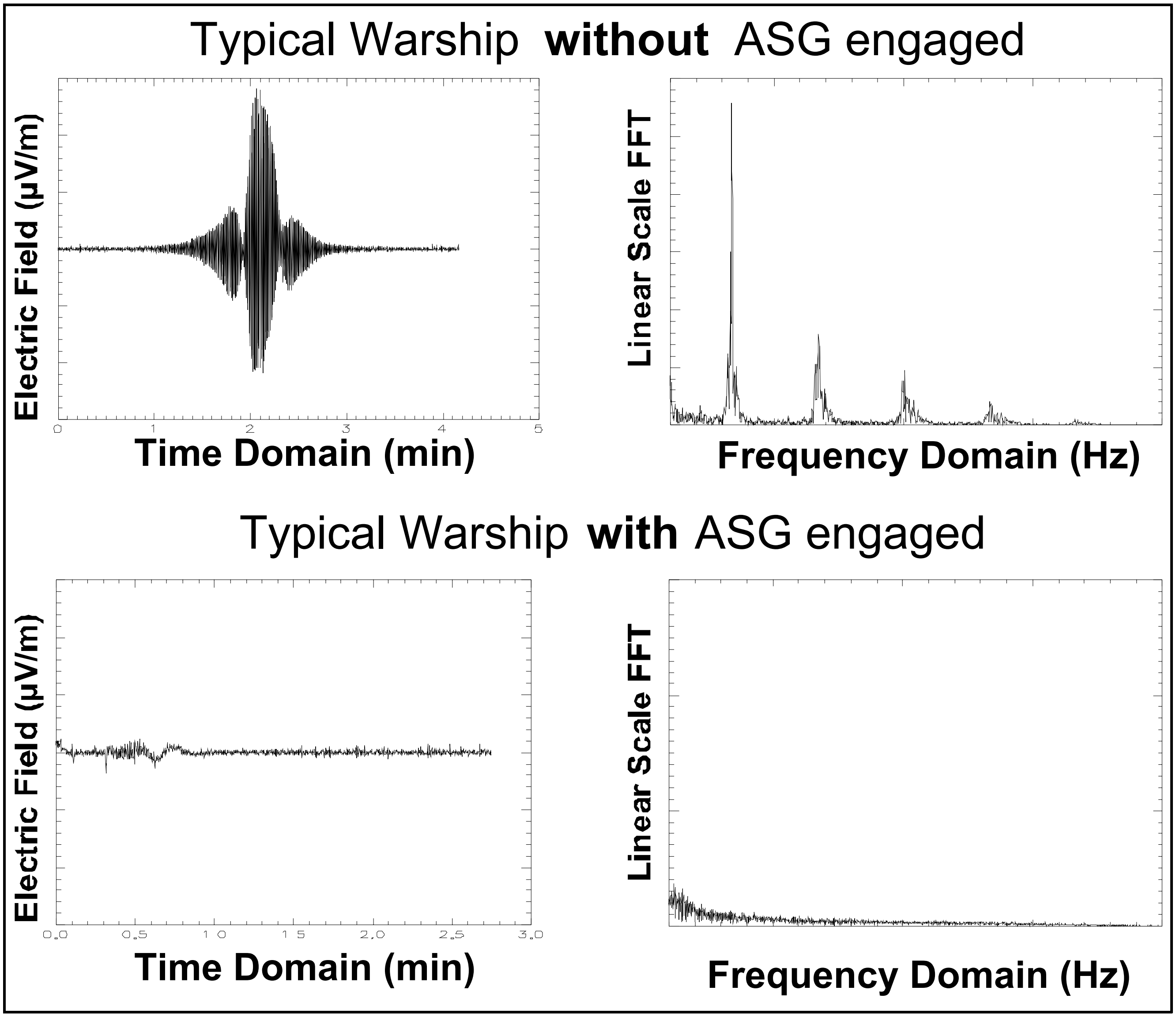

Figure 4 ASG Suppressed Electric Signature of Warship on Longitudinal Axis in Time and Frequency Domains

6. Emulation Minesweeping

To combat influence mines one of two methods of eliminating the mine threat must be employed. Either a minehunting type of operation is needed to detect the mine followed subsequently by classification and clearance activities, or a minesweeping operation is used to sweep an area potentially containing influence mines and either cause them to detonate or prove the waters safe for the passage of the target vessels.

Traditionally influence minesweeping operations have relied upon a "brute force" approach to activating the mine sensors. Large magnetic and acoustic sources are used to subject the mines to much higher magnetic and acoustic influences as large or larger than would normally emanate from a target ship.

With the sensors and logic employed on naval mines becoming more and more sophisticated, more accurate emulation of the influence signatures of ships is required.

6.1 Electric Field Emulation Minesweeping

The electromagnetic field that surrounds a ship can be emulated by a minesweeping system in much the same manner as it is originally created on the target ships. By towing a sweep array that contains a number of electrodes, electric field sensing mines may be swept by passing large currents through the electrodes to create electric dipoles of the same size and intensity as the ships being emulated.

Computers would be used to control the electronics and the electric current would be modulated to match the frequencies typically measured on the type of ship that is being emulated. Because the sweep system generates the electric field in essentially the same manner as the ship being emulated, the mine would not be able to distinguish between the electric field of the sweep and the targeted ship. By placing a library of ship signatures on the computer and allowing for a variety of physical electrode configurations, any of a large number of ships can be emulated in a minefield. By passing the emulation system through the minefield a sufficient number of times, safe passage for the emulated ships can be established.

6.2 All Influence Minesweeping

Acoustic and static magnetic influence sweep systems have been used for a long time, and traditionally influence minesweeping has been limited to these two types of simultaneous influences. Mines are now able to incorporate many more types of sensors and use logic to attempt to reject undesirable targets and minesweeping systems. The best way to sweep these mines is to attempt to accurately emulate all of the influence signatures of the target ship in a single system. This is typically called an "all influence" minesweeping system and attempts to emulate as many of the ship's influences as possible. By emulating all aspects of a ship's influence within the discernable accuracy of modern mine sensors, unsafe waters can be swept by a minesweeping platform that is hardened against the shock of a mine detonation. Any mines in the waters capable of detecting the ship of interest will be detonated and the ship may subsequently pass safely through the area.

A group of four NATO countries are currently engaged in research in this area under a project called the NATO Influence Minesweeping Study (NIMS). A consortium from Canada, France, Norway and the United States is studying means of emulating the acoustic, magnetic, electric, and pressure signatures. There are already several commercial multi-influence systems available (Germany, Australia) but none that yet incorporate all the major signature components.

7. Advanced Degaussing System

The common degaussing system design today uses a masthead magnetometer to sense the ambient field in the vicinity of the ship. A control algorithm in the degaussing control computer adjusts the coil currents in all the degaussing coils so that the field resulting from the presence of the ship is the same as the measured ambient field. This system can minimize the ship's magnetic signature in the presence of changing ambient fields and compensate for ship orientation within that geomagnetic field. A variant of this design is the replacement of the masthead magnetometer with a geomagnetic field prediction algorithm using the GPS location of the ship and gyro attitude inputs to control the degaussing compensation system in an open loop mode. The objective of design activity is to develop a closed loop degaussing system that would use an array of magnetometers strategically located about the ship to provide direct feedback of the magnetic state of the ship allowing control based on not only the induced magnetic field but on the changing permanent field residuals, something which is not now accomplished other than on an experimental basis.

The present generation of military vessels is equipped with several on-board degaussing coils to counteract the effects of the ship's residual permanent magnetism and the induced magnetism due to the earth's field. While this has been adequate in the past when mines had simple firing algorithms, such degaussing systems are no longer adequate in the presence of intelligent mines.

Future generation ships will require a much larger number of degaussing coils in order to achieve better control over the magnetic signature. By fitting each of these degaussing coils with its own power supply, separately controlled from a central computer, a more complete cancellation of the ship's magnetic signature can be obtained. This reduces the ship's detectability by magnetic surveillance systems and its vulnerability to magnetic mines.

Such an Advanced Degaussing System is comprised of a large number of degaussing coils (20-80), individual power amplifiers for each coil, a computer running the control algorithm, magnetic sensors, and a digital communication network to connect these components together. At least two ship classes have already been designed using this philosophy - the Canadian Patrol Frigate (CPF) and the LPD-17. The CPF has 23 coils and the LPD-17 is proposed to have 63. While the LPD-17 is still in the design phase, six CPFs have been built with the additional coils and next a ship will be trialed with a subset of this advanced degaussing system.

Although there are more coils, each draws less power. A new type of degaussing coil power supply is therefore required to exploit the advantages of better control. This supply is located next to the coil it drives and connects to the control computer, from which it receives its commands, by an Ethernet or similar network. The control computer sends coil current commands to the power supply and the supply in turn, reports back its status to the computer. While technically this is a simple architecture, it will be a challenge to keep power supply costs down as a result of the larger number of power supplies required for the whole system.

Another new aspect of this system is the control algorithm. With many more coils contributing to the magnetic field, the inverse mapping problem of determining the required coil currents to produce a desired magnetic field distribution becomes more challenging.

The bandwidth of the control system must cover dc to perhaps several Hz to compensate for the components arising from the pitch and roll of the ship.

8. Conclusions

As naval mines become more sophisticated and incorporate more modern technology, more attention must be paid to all of the ship's influences of which the mine makers may take advantage. The electromagnetic field of ships is easily exploited by modern mines and steps must be taken to minimize electromagnetic signatures. The use of systems such as Active Shaft Grounding and Advanced Degaussing allows for more complete control of the electromagnetic signature of a ship in order to substantially eliminate their associated mine liability.

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