ELECTROMAGNETIC SIGNATURE MODELLING AND REDUCTION

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ABSTRACT: By employing an electrical model of a ship, an a priori prediction of the underwater electromagnetic (UEP and ELF) signature can be made. The model incorporates ship geometry, cathodic protection system current, anode placement, seawater salinity, and seabed conductivity. These parameters can be adjusted, and by trial and error, their effect on the overall signature determined. Thus, the model can be used to design a ship to meet signature constraints, conduct mine engagement scenarios, predict the efficacy of countermeasures, and estimate detection distances. The model is based on a suitable combination of simple current dipoles. Model verification has been performed by measurements on an underwater, electric field sensor range using towed dipoles derived from ship signature measurements.

1 INTRODUCTION

One of the most dangerous and effective threats to naval vessels in marine warfare is the multi-influence ground mine. Many mines are known to localise the target by detecting the acoustic and magnetic influences, but mines can also be developed or modified to exploit the electric fields produced by the vessel. Any non-countermeasured ship is then threatened by its own electric field signature in a manner very similar to its magnetic signature. As a result, increasing importance is being given by many nations to the reduction of the underwater electromagnetic signature. This article describes some of these newer techniques.

Ship electromagnetic signatures arise from several sources, such as corrosion currents, cathodic protection (CP) systems, structural ferromagnetic materials, and onboard equipment. To determine the countermeasure requirements for some of these signatures, W.R. Davis Engineering Ltd. (DAVIS) in conjunction with the Defence Research Establishment Atlantic (DREA) have recently begun modelling existing and proposed naval ships in order to predict, and potentially reduce, the electromagnetic signature. These signature predictions have been verified on an electromagnetic field measurement range.

Section 2 describes some of the sources of the underwater electromagnetic signature and Section 3 presents a generalised discussion of the modelling techniques used for predicting several of the signature classes. Section 4 briefly outlines several countermeasures, including the Active Shaft Grounding System (ASG) system and cathodic protection system filtering, that help eliminate the alternating electric and magnetic components of the signature.

2 SIGNATURE SOURCES

The underwater electromagnetic signature field is commonly separated into four components: two quasi dc terms, the static electric (SE) and the static magnetic (SM), and two ac terms, the alternating electric (AE) and the alternating magnetic (AM). The static terms arise from a constant field configuration that moves with the ship past the mine sensor, whereas the alternating terms arise from sources that are themselves intrinsically time dependent. The normal separation between static and alternating terms is taken to be around 0.1 Hz. Table 1 shows the primary sources and countermeasures for each of these four signature components.

In the present article, we will not discuss contributions from ferromagnetic sources and degaussing systems, but will concentrate on contributions from seawater electric currents. Similar studies have been undertaken in Australia (1) and the UK (2).

2.1 Static Fields

Many vessels are constructed using a variety of dissimilar metals. When these metals are exposed to seawater, the differing electrochemical potentials can cause electrical currents to flow within the seawater. One of the most common of these arises from the use of a steel hull and a bronze propeller. A strong current flows from the hull to the propeller, causing the hull to corrode.

To protect the hull, as well as other underwater components of the vessel from this corrosion, most ships are fitted with either a passive zinc corrosion protection system, or with an active cathodic protection system (ACP) (also known as ICCP or Impressed Current Cathodic Protection). The operation of passive zinc systems is fairly straightforward, with sacrificial zinc anodes being attached to strategic areas of the vessel's underwater structure. The corrosion currents then flow from the zinc anodes to the propeller, and not from the hull.

In a typical ACP system, such as shown in Figure 1, the positive terminal of a high current, low voltage, dc power supply is connected to a platinum (or similar) anode which protrudes through the hull, and the negative terminal is connected directly to the hull. Depending on the complexity of the protection required, there may be several power supplies, each connected to multiple anodes. A reference electrode, which also protrudes through the hull, measures the hull potential and automatically adjusts the level of protection through a feedback system.

It is clear that for ships fitted with either passive or active corrosion protection systems, electrical current flows from the CP anode to the bronze of the ship's propeller. These currents give rise to electric fields which are referred to as the SE signature. For vessels with several ACP power supplies, this signature can be quite complex.

In addition to giving rise to this SE signature, the electric currents will also produce a contribution to the vessel's overall SM signature. Particularly in the case of vessels with non-ferrous hulls, this contribution can be significant.

2.2 Alternating Fields

2.2.1 Shaft Rate

As indicated above, the dc electric current in the water generally flows to the bronze propeller. From there, the current completes the circuit by flowing down the shaft and through the shaft bearings to the hull, and then back to either the zinc anodes or the ACP power supply. As the shaft rotates, the electrical resistance of the bearings often changes, and the current is consequently modified. The current is typically modulated at the shaft rotation rate frequency and its harmonics which, in turn, gives rise to alternating field emissions as the current flows through the sea water. These terms form part of the AE and AM signature and are usually referred to as the ELF (extremely low frequency) signature.

2.2.2 ACP Systems

Other sources of AE and AM signatures can arise if poorly filtered power supplies are used in ACP systems. Power frequency ripple can be injected directly into the water, which gives rise to large ac signatures. Re-design of the power supply or appropriate filtering after the supply can remedy this problem.

2.2.3 Blade Rate

If a cathodic protection anode is locate very close to the propeller, ELF signatures can appear at the blade rate due to the electrical current flowing primarily to the closest blade rather than to the centre of the propeller mass.

2.2.4 Strays

Stray sources of electromagnetic radiation typically arise from heavy current equipment such as motors and generators and are usually at 60 or 400 Hz. Fault currents in the power distribution system can also generate transient fields with high frequency components. The fields generated by this equipment can radiate through the hull into the water. With proper design and shielding techniques, these fields can be minimised.

3 MODELLING

As indicated above, the use of dissimilar metals in ship construction, or the use of CP systems, contributes to the SE, SM, AE and AM components of a ship's underwater signature. The static components are due to the inherent nature of corrosion or CP system currents, whereas the alternating components (ACP ripple, shaft rate and (sometimes) blade rate) arise from undesired modulations of these currents.

To determine how best to reduce these contributions to the signature, DAVIS and DREA have begun modelling the various sources of the electrical currents. In this way the SE and ELF signatures can be predicted and the CP system tailored to reduce overall signature while maintaining corrosion protection. At the same time, the ELF signature can be modelled, permitting an assessment of the level of countermeasure required.

3.1 Static Dipoles

Prediction of the SE signature requires modelling of the various electrical currents that flow within the seawater. This is performed by solving Maxwell's equations for the current dipoles around the ship, the principal dipoles usually being formed between the CP system anodes and the bronze propeller. For a twin shaft ship there are two such dipoles, which can often by complemented by a third dipole in the bow region.

The method we use to solve Maxwell's equations was first developed by Weaver (3). It calculates the three complex components of both the electric and magnetic fields at a given point in the water. The model assumes the presence of an air/sea interface, a body of conducting seawater, and a seabed of lesser conductivity. The model calculates the fields arising from either a point or an extended current dipole, and calculates how the fields change as the modelled ship passes by an electric or magnetic field sensor. Its parameters are the geometry, the dipole strength, and the conductivities of the seawater and seabed. Recent work (4) extends this analysis to the case of three or more conducting layers which may be sloped. Since the seawater is a linear medium, the net field resulting from several dipoles may be found by superposition.

The principal dipole of a ship is formed by the positive passive or active CP anode and the negative propeller (for a twin shaft ship there are two such dipoles.) The length of this dipole is the distance between anode and propeller, and the strength of the dipole is the current flowing along the dipole multiplied by its length. If the hull coating is in good condition, the current from all anodes to the hull is small and is generally insignificant in comparison to the propeller dipole. Even with coating degradation, the resulting dipoles are roughly symmetric with respect to any anode, and therefore largely cancel out at distances far from the ship. Experience has shown that the majority of the signature can be modelled with one dipole per propeller.

The Canadian navy has been successfully modelling signatures based on the Weaver model for many years, with parameters estimated from ship geometry and CP data. This model has been validated most recently as part of a NATO Influence Minesweeping System Feasibility Study. In this study, the signatures of many different classes of ship were measured on an electric field range in Halifax, Canada. The range is composed of 8 electric field sensors spaced at 30m intervals across a 30m deep channel. A simple graphical method was used to correct for offsets between track and sensor, and no correction was performed for track skew which would be small given the sensor positions in the channel. Simultaneous video imagery was used to match the measured signature with a class of ship.

For ships where the hull geometry was unknown, estimates of the current magnitude and dipole length were made. Where the ship geometry was known, only the current magnitude needed to be estimated by matching the measured and modelled signatures. Thus, partly on the basis of measurements, the model parameters could be selected to provide a modelled signature match with the measured data. The basic finding was that a good first approximation to the SE signature could be achieved by using, generally, between one and three dipoles.

For verification, a linear dipole array composed of several copper electrodes, connected to two power supplies, was constructed. By changing the connections, dipoles of different length and strength could be formed. A model of a frigate was implemented on the dipole array and towed over the electric field range. The measured signature from the dipole ship model was then compared with the Weaver model of the ship as shown in Figure 2. Agreement was quite satisfactory considering the sources of error involved.

3.2 Modulated Dipoles

Any modulation of the CP anode current results in AE and AM signature components. Three such modulations are the shaft rate, the ACP power supply ripple, and, less often, the propeller blade rate. All of these sources can be included in the model by adding an equivalent ac current dipole of the same length as the dc dipole and with an appropriate current.

A comparison of the Weaver model and the measured signature of the equivalent linear dipole array is shown in Figure 3.

3.2.1 ACP Ripple

The ACP system can contribute to the AE and AM signature components if it is not well filtered. The conversion from ac input to dc output in the ACP power supply causes ripple on the output voltage. For a single-phase ac input system this ripple is either at 60 or 120 Hz and higher harmonics. For a three-phase ac input system the ripple is either at 180 or 360 Hz and higher harmonics. (The exact ripple frequency depends on the design of the power supply.)

The amount of ac dipole current is easily estimated based on the ripple specification or by direct measurement of the ACP supply.

3.2.2 Blade Rate

Another frequency that can sometimes appear if the CP anode is very close to the propeller is the blade rate, that is (shaft rotation frequency) x (number of blades on the propeller). If the anode is close to the propeller, it no longer appears to be a single mass but a series of masses. The resistance through the water between the anode and blade will then vary as the shaft rotates, which gives rise to a modulation of the shaft current at the blade rate frequency. If this becomes a significant component, the CP anode may have to be located further from the propeller. This, however, has an adverse effect on the static signature.

The amount of ac current can be estimated by finite element modelling the geometry of the anode, seawater, propeller combination, and by determining the change in current flow with shaft angle.

3.2.3 Shaft Rate

Due to the imperfections of the shaft, bearing and seal systems, the resistance from the shaft to the hull is a function of the shaft rotation angle. This variable resistance causes a time modulation of the shaft current from the CP system as the shaft rotates. This alternating current produces alternating electric and magnetic signature components in the one to several hundred Hertz range, with the principal power being in the shaft fundamental and lower harmonics.

To model this AE component, a Fourier transform is performed on the measured signature and appropriate alternating current dipoles are added at the shaft rate frequency and its harmonics.

Predictive modelling is more difficult since the modulation can vary anywhere from 0 to 100%. The strength of the shaft rate dipole can be estimated by analysing an equivalent circuit comprised of shaft current, seawater resistance, bearing resistance, and passive and active shaft grounding resistances. In general, the bearing resistance is unknown and can vary from ship to ship. However, an upper bound on the AE signature can be determined based on 100% modulation. With the addition of ASG the situation becomes easier to predict since the ASG resistance is always much less than the bearing resistance.

3.3 Strays

Stray magnetic fields can be modelled as a magnetic dipole located inside the hull at the point of generation. A Weaver-like model can be used to determine the attenuation due to the sea water, and analytical formulae can be used to determine the attenuations between the source and hull, and due to the shielding effect of the steel hull.

4 COUNTERMEASURES

As shown in Table 1, various countermeasure techniques can be applied to reduce the signature associated with certain sources. The following describes three such techniques.

4.1 General Design

Since the majority of the signature components result from the existence of the CP system it might be thought that eliminating it would eliminate the signature. This is only partially true, since eliminating the CP system would reduce the signature at the expense of markedly increased hull corrosion. In addition, a signature would still remain due to the current flow arising from the natural galvanic action of the two dissimilar metals (steel hull and bronze propeller) in an electrolyte (seawater).

Minesweepers and other vessels made from non-ferrous hull materials have much reduced signatures, since either no CP system, or a very small one, is required. Even in this case, however, care must be taken not to introduce dissimilar uncoated metals into the seawater, else galvanic couples and their consequent currents and signatures will be produced.

Since, in general, the CP system cannot be eliminated, the next best procedure would be to reduce the strength of the major current dipole from the anode to the propeller, and to a certain extent this can be done either by reducing its length or its current. Coating the propeller, and all other underwater metal, is an obvious method to reduce the current, but one which is seldom if ever implemented. Moving the anode closer to the propeller reduces the dipole length, but there is a limit. Too small a separation causes the blade rate to become more pronounced and also reduces the corrosion protection for the hull close-by.

By the very nature of a CP system, the SE and SM components cannot be eliminated but only minimised. Modelling is useful in this case to minimise dipole strength while not compromising the corrosion protection.

Design techniques are also useful in reducing the stray fields from onboard equipment by either improved equipment design or shielding.

4.2 ACP Ripple Reduction

A simple and effective method for removing the power frequency harmonics from the seawater dipole current is available by heavy filtering or by system design. Reductions in the ripple content of over 100 dB are easily achieved by low pass filtering of the ACP power supply output.

4.3 Shaft Rate Signature Reduction

Active Shaft Grounding works by effectively shunting the bearing resistance (usually of the order of 10^{-3} to 10^{-1} ohm) with a 10^{-5} ohm active shunt. Thus, the shaft current flows through the fixed resistance ASG unit, bypassing the variable resistance bearing, and therefore eliminating this component of the signature. Some relative performance curves are shown in Figure 4.

As an added benefit, ASG reduces corrosion in the bearings and seals since the shaft to hull potential is kept extremely small.

5 CONCLUSION

We have shown above how the underwater electromagnetic ship signature is produced and how it is modelled for signature prediction and reduction purposes. We have briefly described several countermeasure techniques for reducing or eliminating these signature components. Both the original signature and the signature with countermeasures can be modelled to predict the benefits. Modelling allows the signature to be tailored to the mission and cost of the ship.

6 REFERENCES

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3. J.T. Weaver, *The Quasi-Static Field of an Electric Dipole Embedded in a Two-Layer Conducting Half-Space*, Canadian Journal of Physics, v45, 1967, pp1981-2002.
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Table 1. SOURCES AND COUNTERMEASURES FOR SHIP SIGNATURE

FIELD	SOURCE	COUNTERMEASURE
SE	- CP system	- Optimise anode placement - Eliminate CP system by using similar metals and good coatings
AE	- Fluctuating bearing resistance - ACP power supply harmonic currents - Blade rate	- Shaft grounding - ACP power supply output filter - Anode positioning
SM	- Hull ferromagnetics - CP currents	- Degaussing system or non-ferromagnetic hull - Eliminate CP system
AM	- ACP power supply harmonic currents - Fluctuating bearing resistance - Stray electromagnetic sources inside ship - Eddy currents, ship motion - Blade rate	- ACP power supply output filter - Shaft grounding - improved electromagnetic design and shielding - Degaussing system corrections - Anode positioning

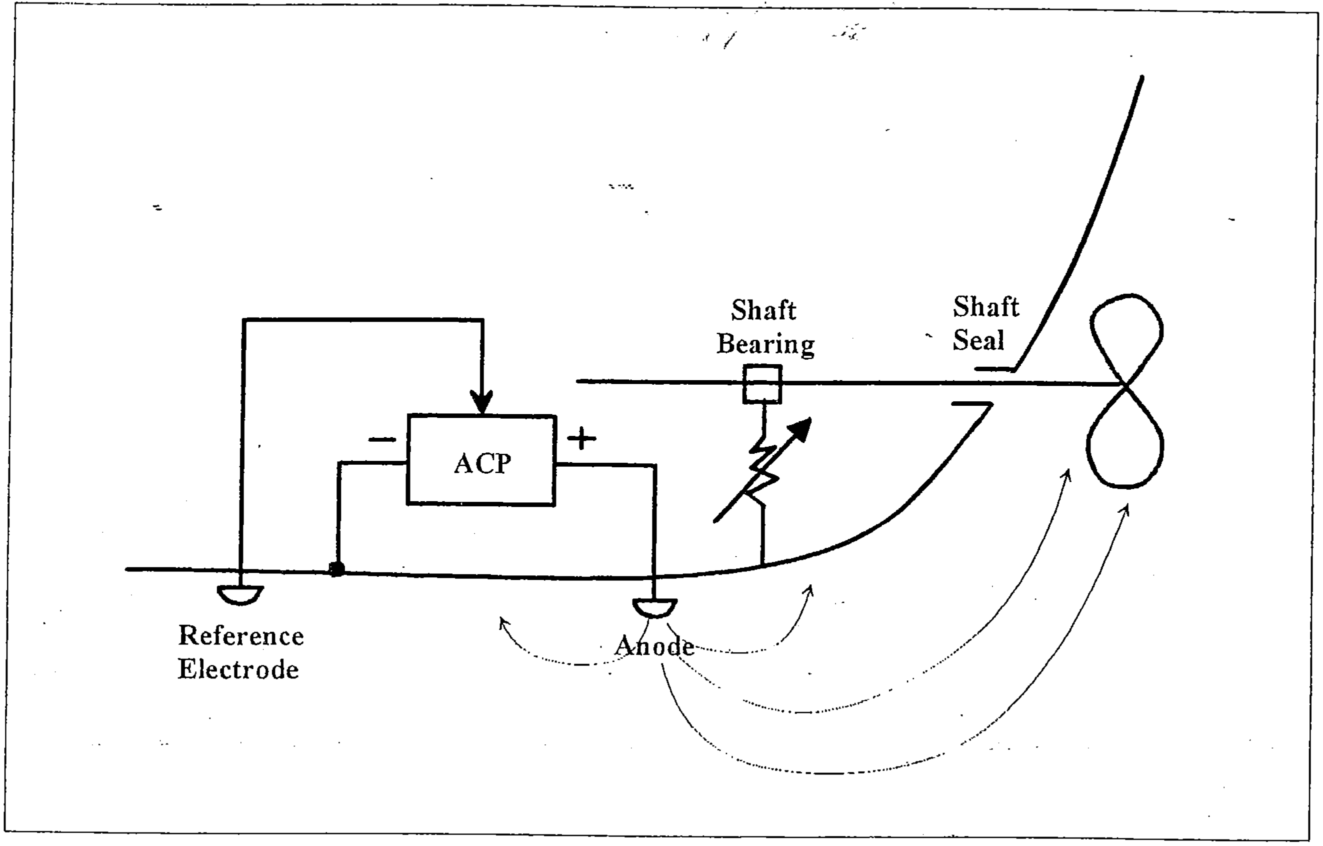

Figure 1 Active Cathodic Protection System

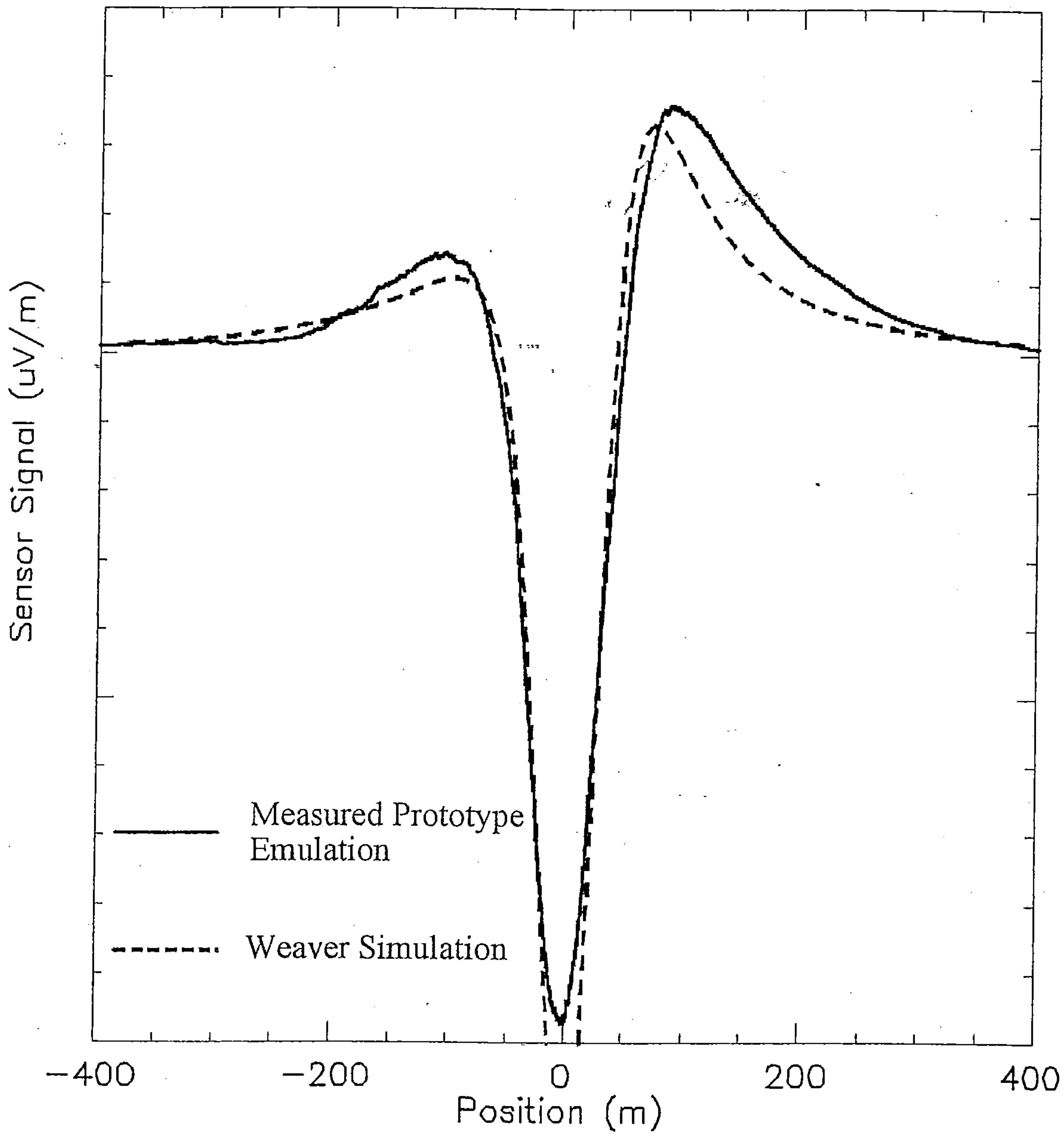

Figure 2 Comparison of Prototype SE Sweep with Weaver Simulation Prediction for 2000 ton Warship

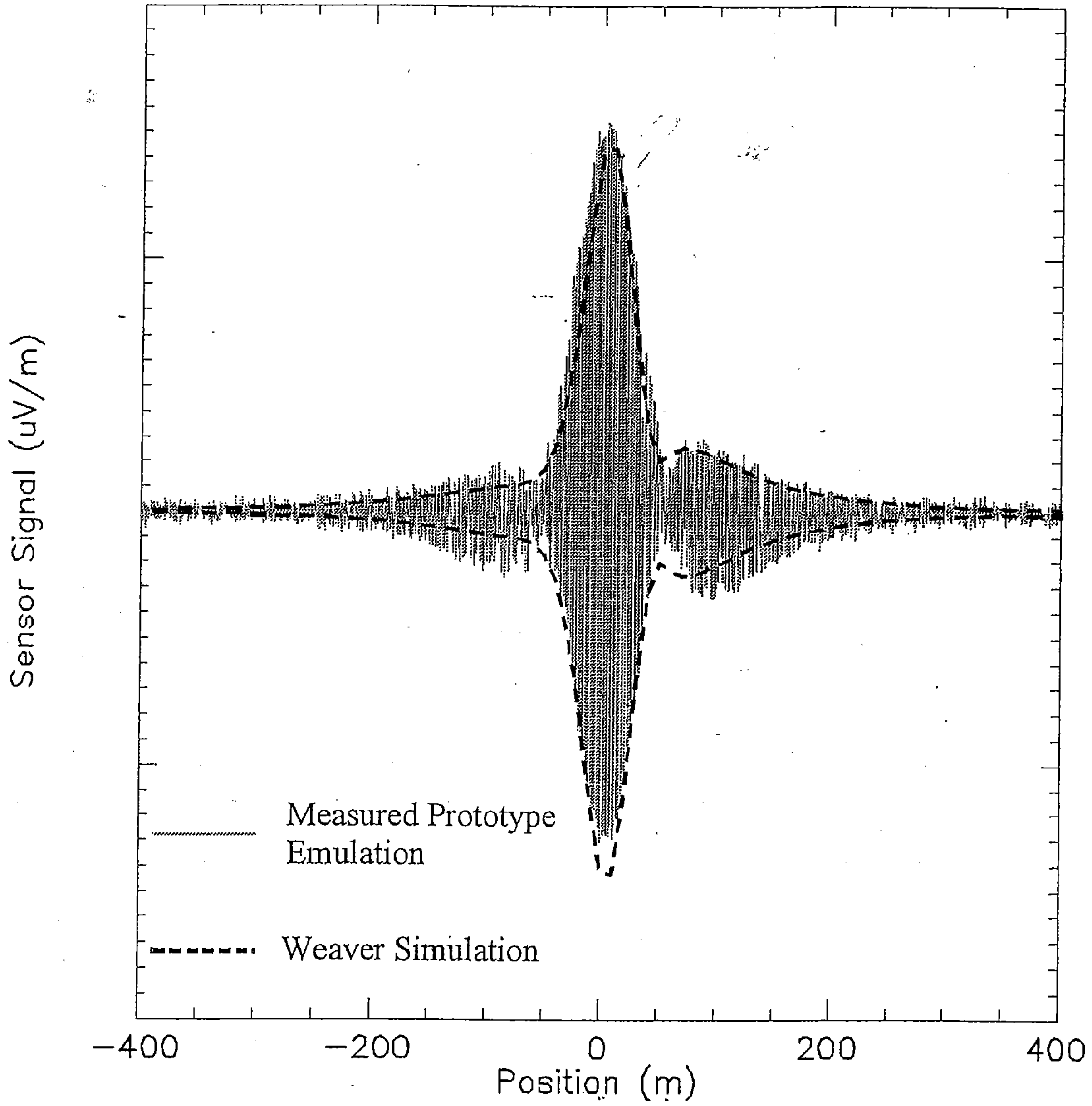

Figure 3 Comparison of Prototype AE Sweep with Weaver Simulation Prediction for 500 ton MCMV

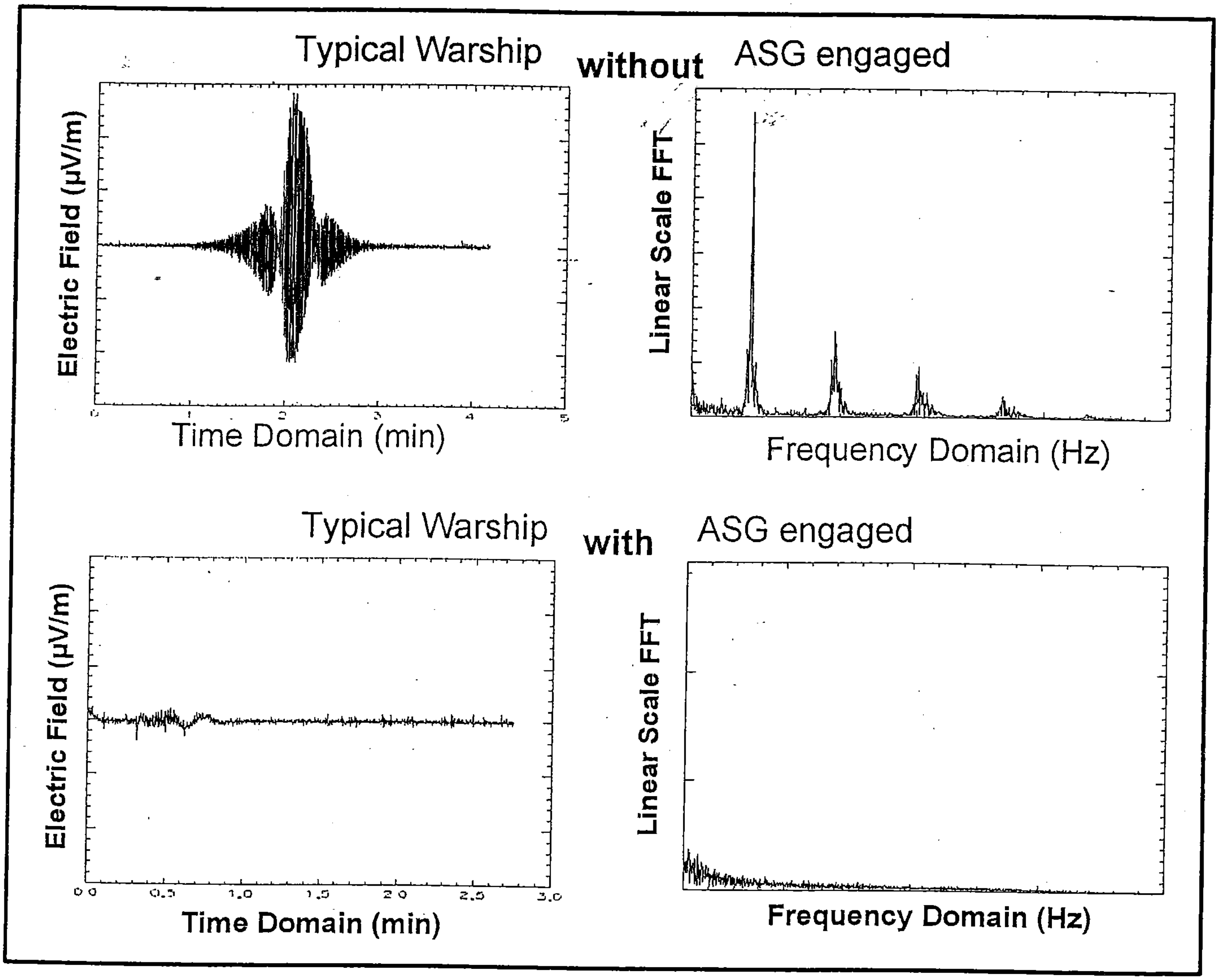

Figure 4 ASG Suppressed Electric siganture of Warship on Longitudinal Axis in Time and Frequency Domains