"Optimisation of ICCP systems to minimise electric signatures"

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ABSTRACT

Corrosion damage is a major factor in ship maintenance and availability. Paints and ship board impressed current cathodic protection (ICCP) systems are important established tools in the reduction of corrosion damage to ships. The design of cathodic protection systems is of interest to defence organisations not only to protect the integrity of the ship but also because of the electric fields generated in the sea water by the ICCP system.

Recent developments in computer simulation techniques based on the boundary element method have enabled the electric fields generated by the galvanic interaction of the ship metallic structure and the sea water to be predicted. Thus providing a tool to predict changes in the protection level of the ship and the electric field in the seawater caused by modification to the ICCP system.

In this paper an approach to the automatic optimisation of the ICCP system is presented. The objective being to design the system to minimise the electric field while at the same time provide adequate protection. The approach adopted was to couple the BEM model of the corrosion electrode kinetics and sea water electric field with an optimisation algorithm. A user interface has also been developed to enable modelling and optimisation tasks to be performed quickly without the necessity of detailed changes to the BEM model.

Introduction

Corrosion damage is a major factor in ship maintenance and availability. Paints and shipboard impressed current cathodic protection (ICCP) systems are important established tools in the reduction of corrosion damage to ships.

ICCP systems are designed to take advantage of the electrochemical corrosion phenomenon. By applying an external source of current to anodes on the ship hull current passes through the surrounding seawater to the parts of the hull to be protected. The ICCP system is designed to ensure that the current flowing from the anodes is sufficient to maintain the potential on the hull below a certain value of potential that inhibits the electrochemical reaction which causes corrosion.

The design of the cathodic protection system is of interest to defence organisations not only to ensure the integrity of the ship but also because of the electric fields generated in the sea water by the ICCP system. These fields are known as the signature of the ship.

Electromagnetic signatures are playing an important role in the detection of naval vessels and in the fusing of intelligent mines. The static electric signature is the electric field associated with the DC corrosion or cathodic protection current that flows through the seawater around a vessel. This is sometimes referred to as the Underwater Electrical Potential or UEP. The corrosion related magnetic (CRM) field is the coupled magnetic field caused by the corrosion related electric currents flowing in the seawater between the anodes and the ship hull.

It is important to note that UEP and CRM signatures exist even in the absence of a cathodic protection system. They are caused by the galvanic potential differences between the metallic structures in contact with the seawater. For example, the relative position in the electrochemical table of steel and bronze provides a sufficient driving potential to create an electric field.

In order to control the signatures and to preserve the integrity of a vessel it is essential to be able to predict the impact of the design and operation of the ICCP system on the electric fields.

Computational models have been widely used to predict the electromagnetic fields associated with vessels due to on board systems and ferromagnetic aspects. The software BEASY [1] has been widely used to predict the performance of cathodic protection systems by modelling the coupled electric fields and electrochemistry for complete ships and other structures. Other authors have used simple dipole models to make predictions. In this paper an integrated approach is presented to enable the performance of the ICCP system, the corrosion related electric field and the corrosion related magnetic field to be predicted using one detailed model.

Theoretical Aspects

The boundary element method (BEM) has been proved to provide the optimum solution to problems associated with corrosion simulation [2]. The BEM requires the user to only describe the boundary or surface of the ship to be modelled thus simplifying the modelling process. There are also additional benefits that are described in [2]. Figure 1 shows an example of a BEM model.

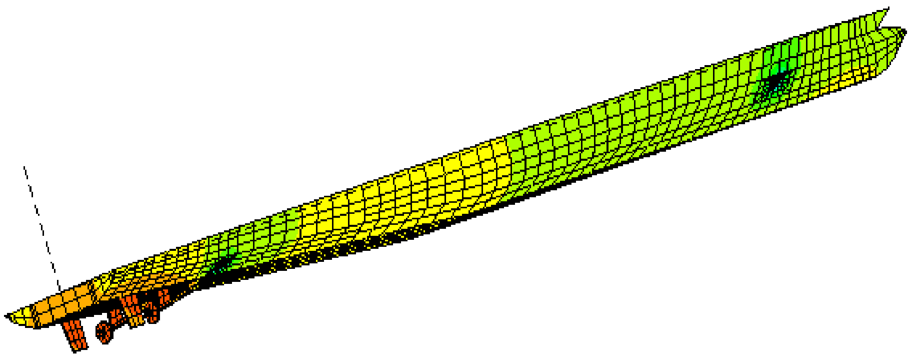

Figure 1 BEM model of a ship (Note: only elements on the wetted surface of the ship)

To model a CP problem the computer model must simulate the IR drop through the electrolyte and the electrochemical electrode kinetics on the metallic surfaces. Therefore, a boat in the sea can be considered as a galvanic system (Figure 2).

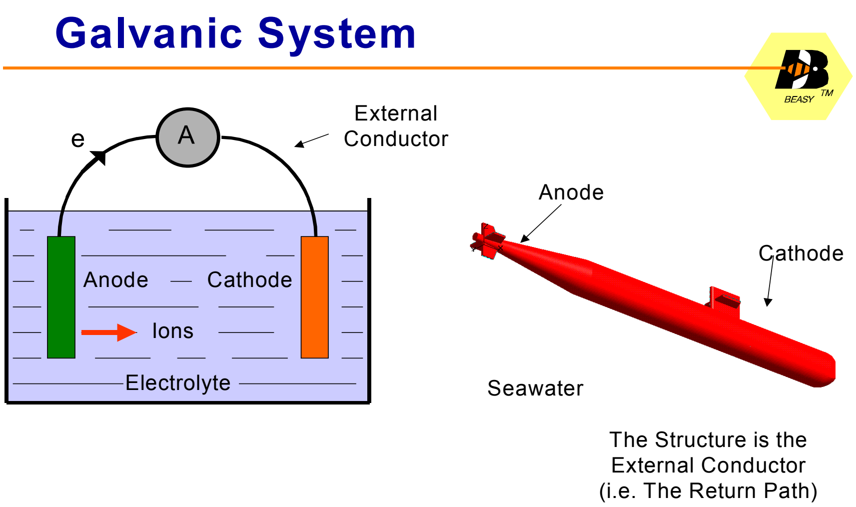

Figure 2 The CP model is a simple galvanic system

BEM solution of the Laplacian in the sea water, combined with representation of the electrode kinetics associated with different surface types, has been shown to provide accurate results for the complex current fields in the sea water and hence the UEP signature

The CRM signature generated by the currents flowing in the seawater can be found by solving the vector potential.

Equation $\nabla^2 \underline{A} = -\mu \underline{J}$

Where $\underline{A}$ = vector potential

$\underline{J}$ = Vector of current density components

Control of the complete sequence of steps is simplified by use of a “wizard” which allows the user to very easily perform all operations. If all steps are to be performed the user actions simply involve selection of the data file and assignment of magnetic properties. The solution sequence is then triggered and proceeds fully automatically

Corrosion Optimisation

The design of cathodic protection systems requires the engineer to define the number of anodes, their shape and size and location. Successful and durable designs often take significant time and require the engineer to have a great deal of knowledge and experience. Not only must the type of anode be selected, but also its position and output current, all in order to ensure the correct distribution of voltage over the surface of the structure.

The use of modern software systems which can predict the performance of cathodic protection systems (e.g. BEASY) substantially improves the design process but does not essentially change the 'trial and error' method of obtaining the "optimum" design. While this approach can give a good design it is unlikely to give the best design. Furthermore, to reach a point where all design constraints are satisfied can take a considerable time, much more than normally available.

A better approach would be to allow the engineer to define the simulation model in terms of the objectives to be achieved, for example:-

- Find the minimum anode currents required to protect the structure;
- Find the anode positions required to give a uniform level of protection potential on the structure;
- Find the anode currents required to reduce the electric field to minimum;
- Find which anodes will achieve a specific signature.

In this approach the engineer describes the structure (ship, boat etc) with the positions of the candidate anodes, the metallic surfaces and associated surface material properties, the initial currents for the impressed anodes, etc. The software will then automatically search for the optimum solution.

While the objective function describes the goals to be achieved the user must also define the constraints to be satisfied. For example a constraint may be that the potential on part of the structure should be between –800mv and –950mv.

In order to simplify the optimisation process a visual interface has been developed (referred to as the "Wizard" from here on) which guides the user through the steps required to specify the model, select the material (polarisation data), define the environmental conditions (resistivity etc), specify the constraints, select the objective function and finally identify the design variables. The Wizard automatically runs all the required software and provides a visual display of the progress of the optimisation.

Flow diagram of the optimisation process

The components of the optimisation software are the following:-

- Modelling system (to define the geometry and mesh)
- Polarization Database
- Java Visual Interface
- Interface Boundary Elements Software – Optimisation Software
- Optimisation Software
- Boundary Elements Software (BEASY)
- Result Visualization

The starting point for the process is a model defined in a data file ("dat" file) suitable for the BEM software. This model describes all the geometric characteristics of the problem, including all metallic surfaces that are to be protected, and all candidate anodes.

The flow diagram shown in Figure 3 describes the software components which form the system, and the data flow through each component.

The Polarisation Database is used to select appropriate polarisation data for the metallic surface materials, and write the data to a file (the "mat" file).

The "mat" file and the "dat" file are inputs to the wizard, which is used to define initial current for the anodes, and to relate the polarisation properties to the metallic surfaces. The extra data is added to the "dat" file, which is later accessed both by the BEM Software and the Optimisation Software.

The wizard is also used to select the objectives, the values of constraints, the minimum and maximum possible values of the variables, the optimisation method to be used and the parameters of the optimisation software. All this data is written to a file (the "opt" file) accessed by the optimiser.

Once the parameters, constraints and objectives of the optimisation are set up, a launch signal is sent to start the optimisation. EXCEL can be used to display the progress of the optimisation process.

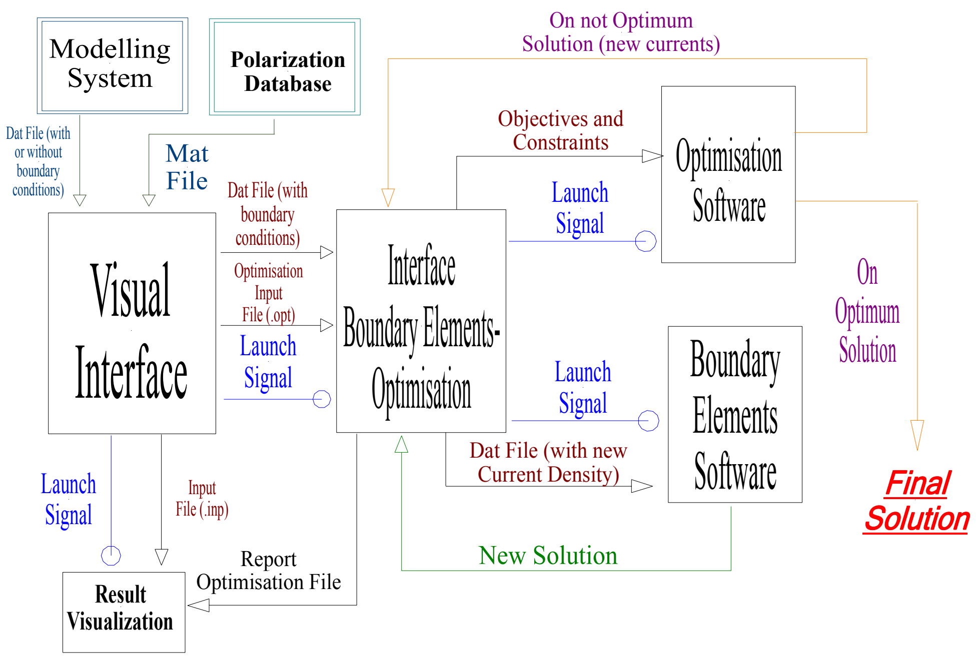

Figure 3 **Flow diagram of the process**

Visual Interface

Developed using Java, the wizard manages all the tasks involved in setting up a corrosion model. Java was chosen as the programming language as it is object-oriented, distributed, interpreted, robust, secure, architecture neutral, portable, high- performance, multithreaded, and dynamic. A view of the wizard is shown in Figure 4.

The wizard currently has two modes of operation. It can be used to set up and control the optimisation process, and it can be used as a high level tool to make design changes without the need to involve the model building software. For example all environmental parameters, construction materials and anodes can be modified and new predictions made directly from the wizard. This makes it possible to quickly assess the impact of design changes.

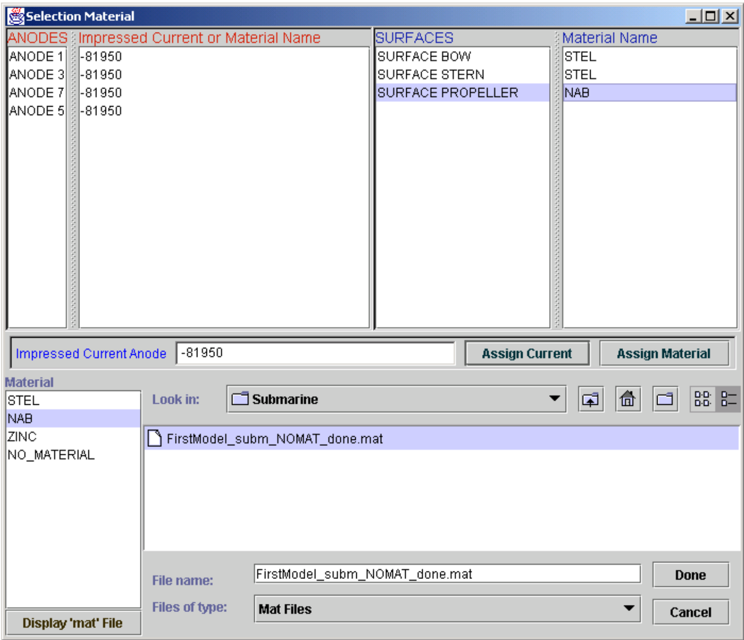

Figure 4 View of the design visual user interface where the properties of the anodes and the construction materials can be selected and quickly changed

Types of Objectives

Currently four types of objective have been implemented but it is possible to define additional objectives as necessary.

For example:-

Minimise the total anode current

With this objective, the optimisation searches for the minimum anode currents that satisfy the constraints.

$$\mathrm{Obj1} = \sum_{1}^{n} I_1 + I_2 + I_3 + \ldots . I_n$$

Where:

n= number of anodes

It can be applied either to specific anodes or to all the anodes.

Uniform protection of the surfaces (Least Squares).
With this objective, the optimisation searches for the optimum anode currents, which satisfy the constraints and attain as smooth a distribution of potential over the surfaces as possible.

$$\text{Obj2}= \sum_{k=1}^{m}\sum_{j=1}^{n}\left(V_{kj} - V_{target_k}\right)^2 \tag{1}$$

Where:

m= number of surfaces

n= number of the elements for each surface

Minimise the magnitude of the signature

With this objective, the optimisation searches for the optimum anode currents, which satisfy the constraints and attain the smallest maximum electric field at selected positions.

$$\text{Obj4}= \text{Max}\left(\sqrt{I_{x_i}^2 + I_{y_i}^2 + I_{z_i}^2}\right)$$

Where:

I is the current density at selected positions in the sea adjacent to the vessel

Magnetic Fields

The CRM signature generated by the currents flowing in the sea water can be found by solving the vector potential.

Equation $\nabla^2 \underline{A} = -\mu \underline{J}$

Where $\underline{A}$ = vector potential

$\underline{J}$ = vector of current density components

The magnetic field is then simply $\underline{B}$ = curl $\underline{A}$.

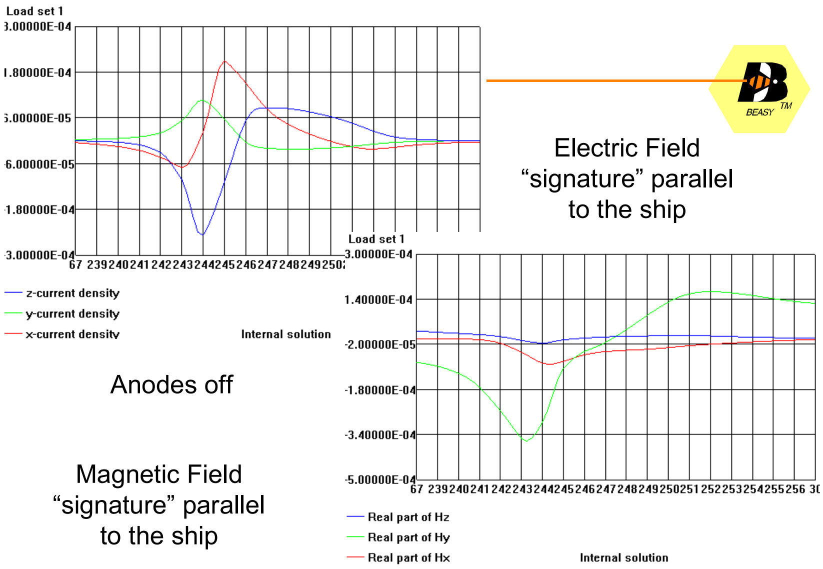

Figure 5 UEP and CRM example signatures computed using the same model

Applications

Vessel model

A model of a vessel with the features shown below was developed in order to investigate the optimum position and current outputs of the anodes. As the model is symmetric only half of it need be meshed. The model has the following characteristics:

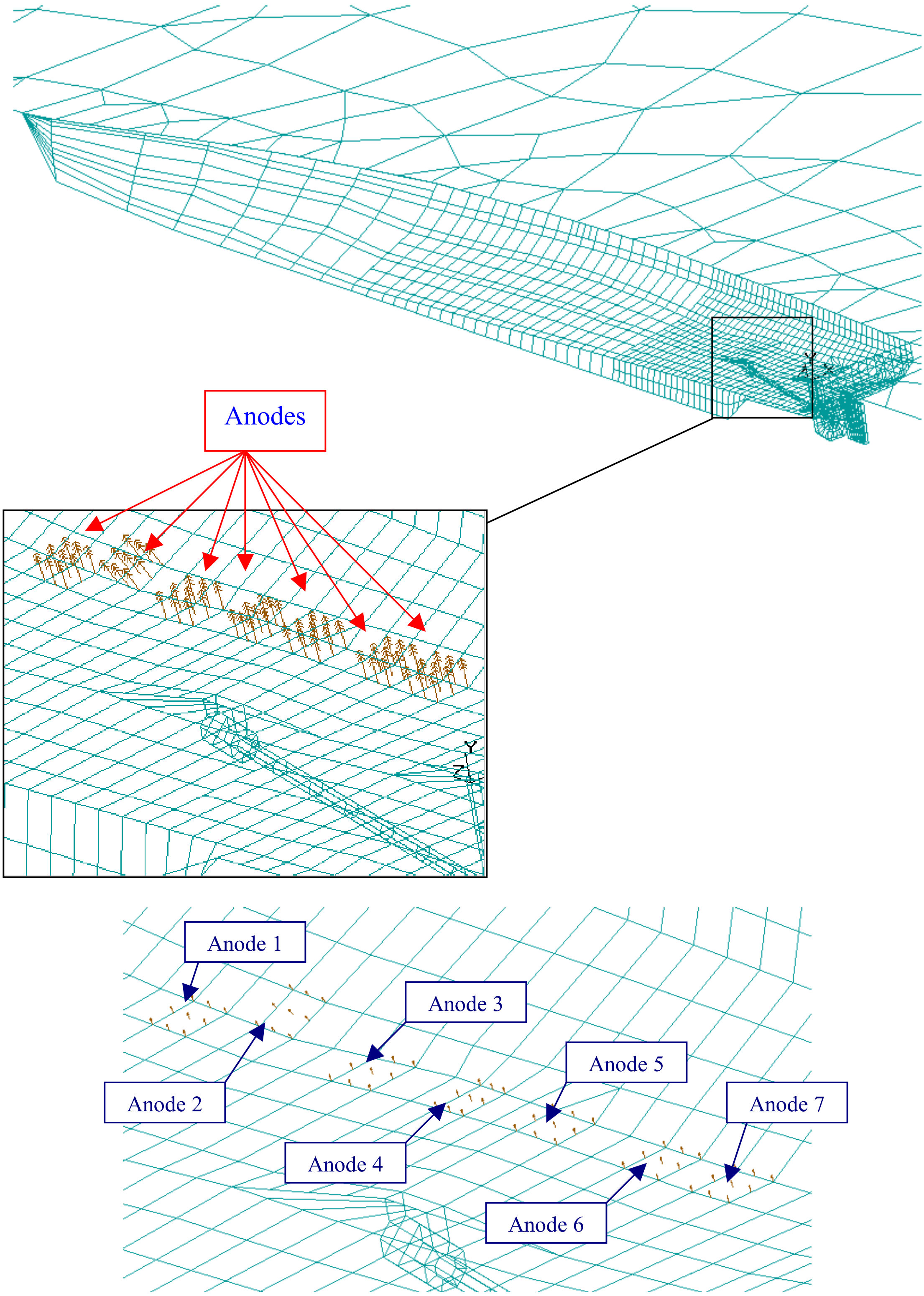

Figure 6: Description of the model

The vessel is completely insulated except the propeller, made of NAB (Nickel Aluminium Bronze), and the propeller shaft, made of steel.

Figure 7 shows the zone of the shaft required to protect with a potential lower than –900mV.

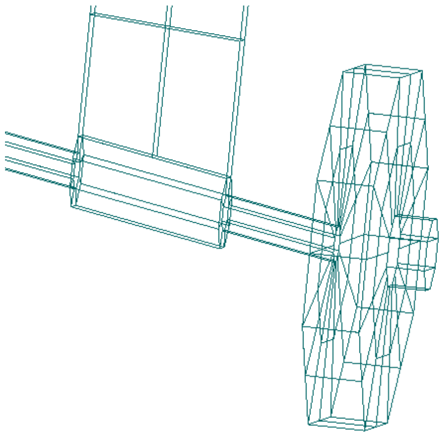

Figure 7: Surface of the shaft required to be protected.

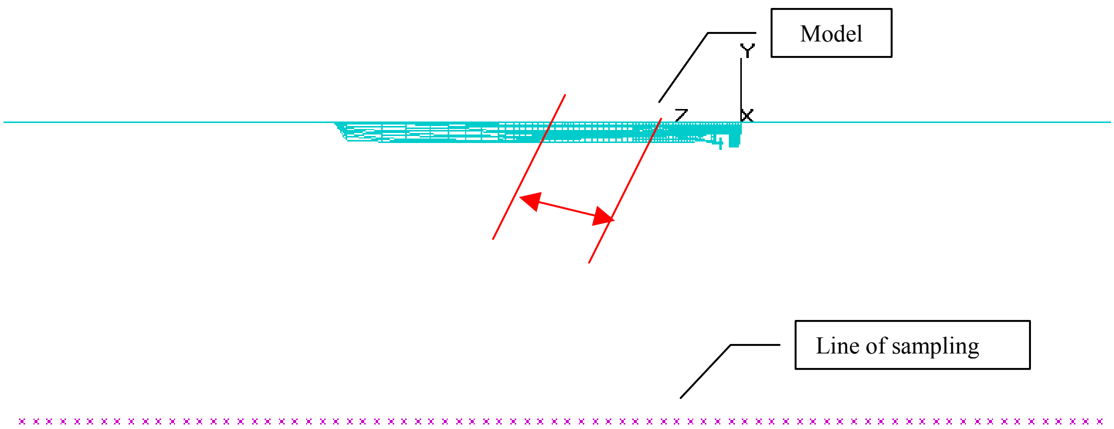

Figure 8: Internal points line underneath the vessel.

Sampling Points.-

A line of sampling points was defined at a depth of 30m beneath the sea level. The solution at the sampling points along this line is used to compute the electric signature and the objective (Figure 8).

Optimisation of the vessel.

The initial design had a single anode pair with a current density of 9240ma/m^2

The optimisation method used was used was Sequential Linear Programming and the optimisation objectives and constraints were:-

- Constraint: Potential on the surface of the propeller shaft should be -900mV or more negative;
- Objective: Minimise the electric signature. Minimise the maximum value of current density at the sampling points underneath the vessel.

Optimisation, using only one anode.

The electric signature of the vessel was minimised using a single anode in the position of the anode 2 in
Figure 6. During the optimisation process, the value of the optimisation function initially increases until the constraints are satisfied on all the elements required to be protected (Figure 9, region A). Once the constraints are satisfied, the optimisation software searches for an optimum solution (Figure 9, region B).

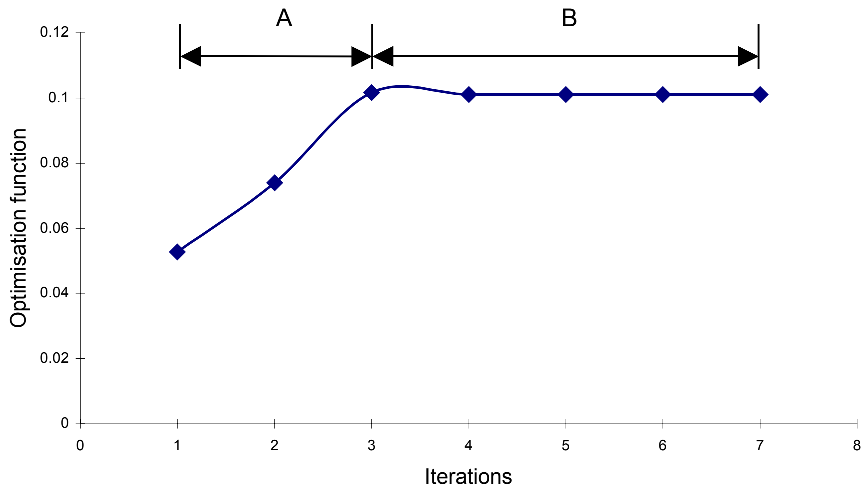

Figure 9: Optimisation function, only one anode.

Figure 10 shows corresponding changes of current density, which initially increases (region A) until the constraints are satisfied, and then reduces slightly as the optimiser searches for the minimum value of the objective function (region B).

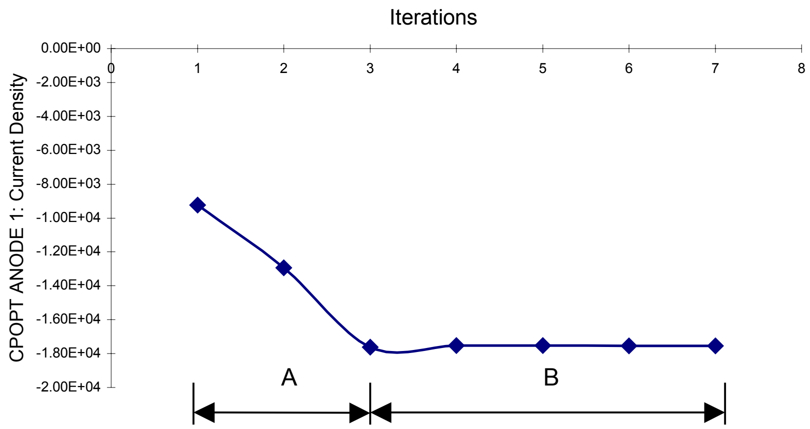

Figure 10: Anode current density for each iteration.

The final value of the objective function was 0.1010, giving an average potential over the shaft surface of –901.4mV. The anode current and current density are shown in Table 1 .

	Current Density (mA/m^2)	Current (mA)
ANODE	-17540	-877

Table 1

The components of current density along the sampling line at 30m depth are shown in Figure 11.

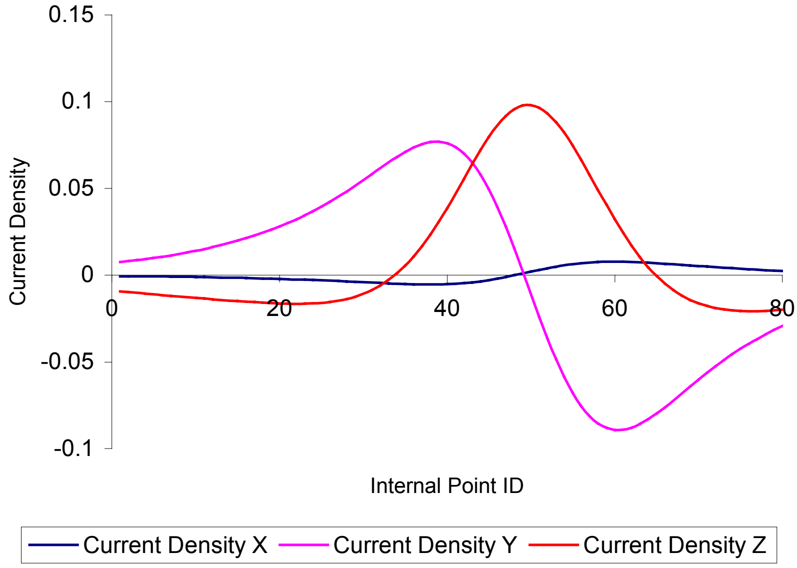

Figure 11: Current Density components along sampling line for optimised solution 1 anode

Optimisation, using seven anodes.

Seven anodes were placed on the vessel as shown in
Figure 6. The minimum allowed current density magnitude for any anode in the optimisation is 0.0001mA/m^2 and the maximum is 1E8m A/m^2. The evolution of the value of the optimisation function is shown in the Figure 12.

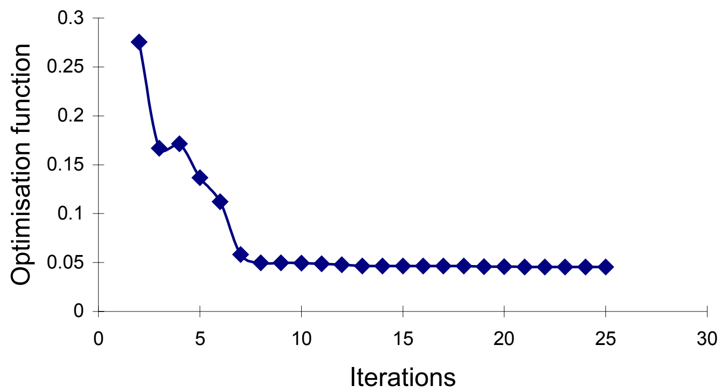

Figure 12: Optimisation function, evolution with seven anodes.

The values of the anode currents as the optimisation progresses is shown in Figure 13.

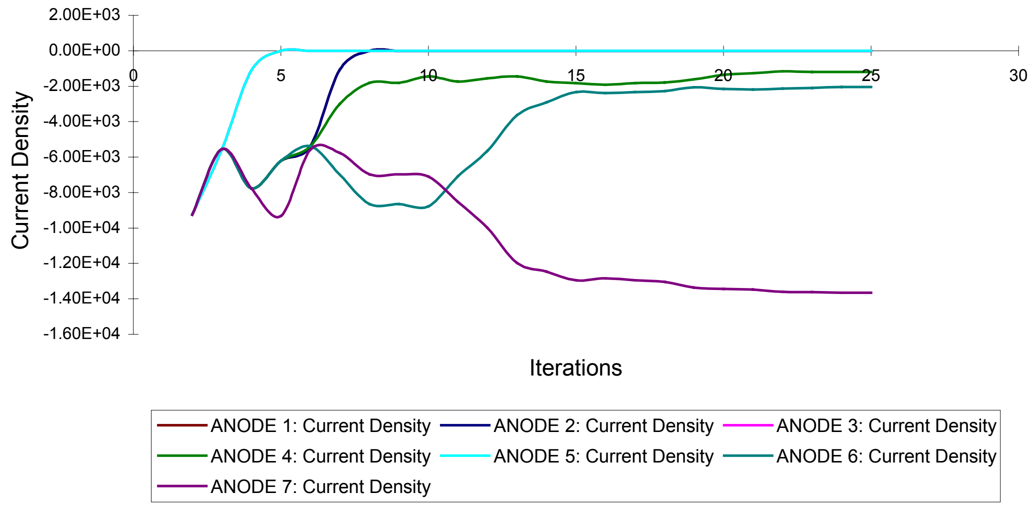

Figure 13: Current Density evolution during the optimisation.

The final value of the objective function was 0.0454, giving an average potential over the shaft surface of –901.21mV. The anode currents and current densities are shown in Table 2.

	Current Density (mA/m^2)	Current (mA)
ANODE 1	-0.83	-0.04
ANODE 2	-0.84	-0.04
ANODE 3	-0.71	-0.04
ANODE 4	-1203.4	-44
ANODE 5	-1.33	-0.07
ANODE 6	-2053	-103
ANODE 7	-13647.3	-722

Table 2

The components of current density along the sampling line at 30m depth for the optimum design are shown in Figure 14.

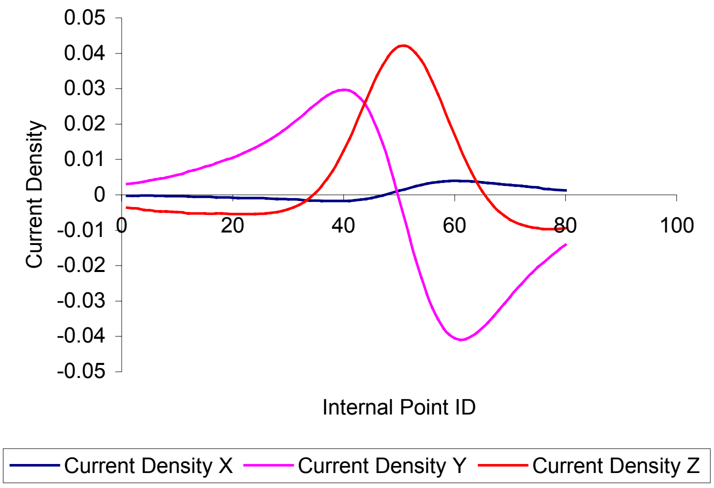

Figure 14: Current Density components along sampling line for optimised solution 7 anodes.

The distribution of potential on the surfaces for the optimised solution is shown in Figure 15.

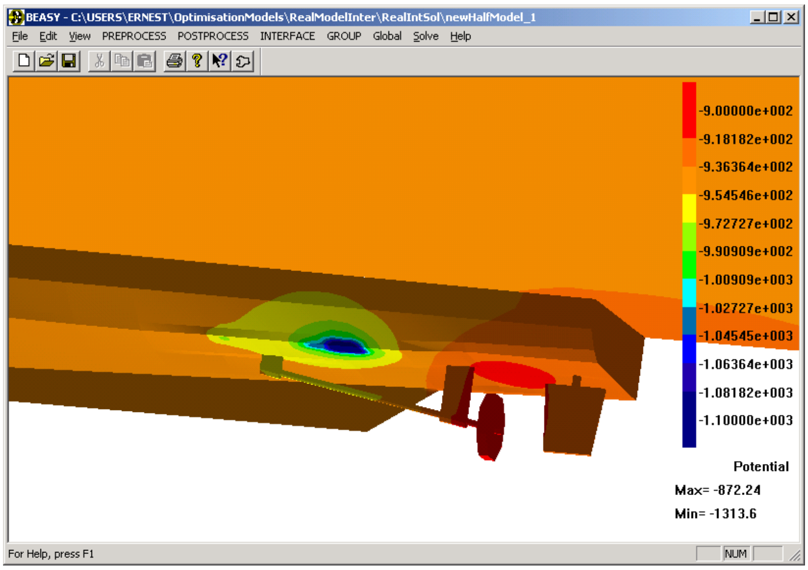

Figure 15: Distribution of potential over the surface.

Comparison of the two solutions

The electric field signatures for the two designs are compared in Figure 16 through Figure 18.

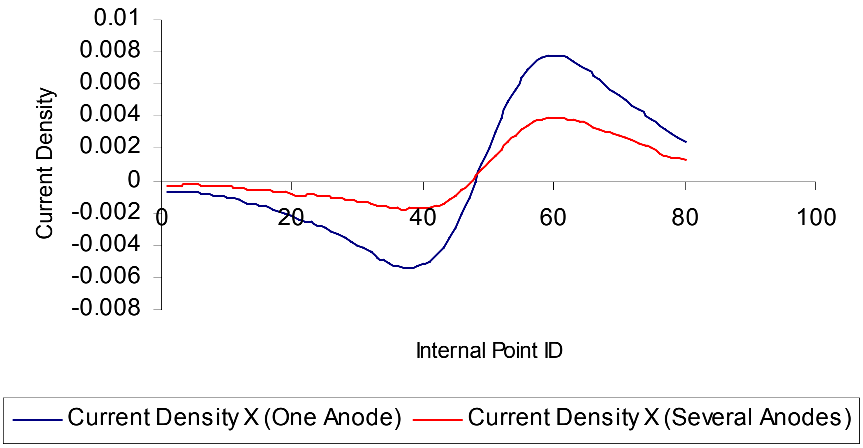

Figure 16: x(horizontal transverse)-current density along sampling line

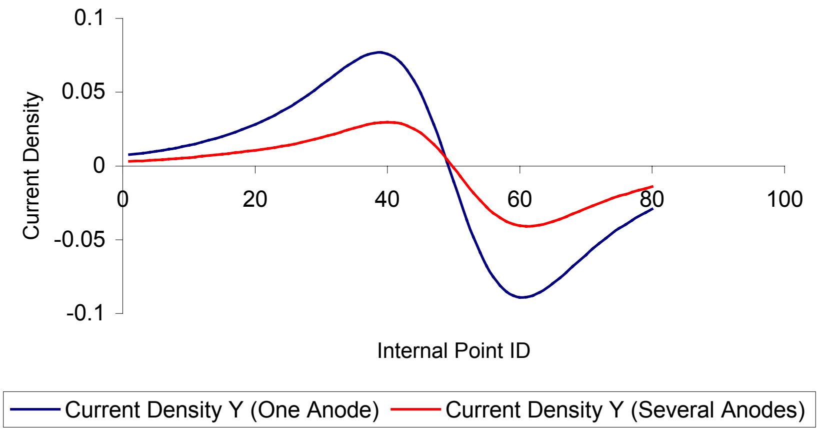

Figure 17: y(vertical)-current density along sampling line

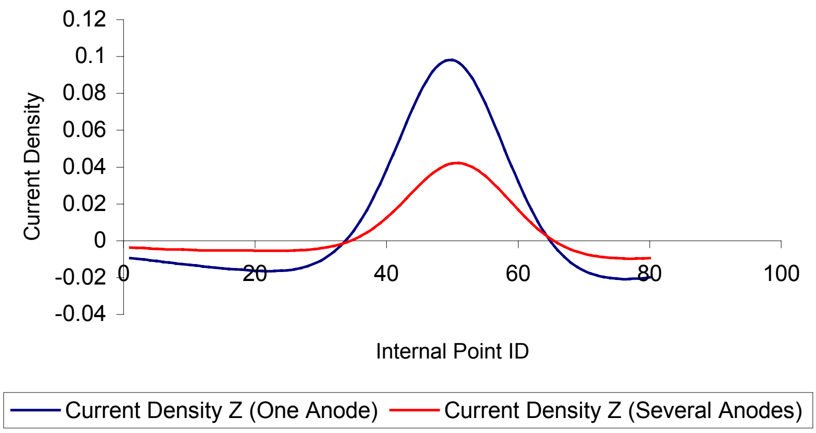

Figure 18: z(horizontal forward)-current density along sampling line

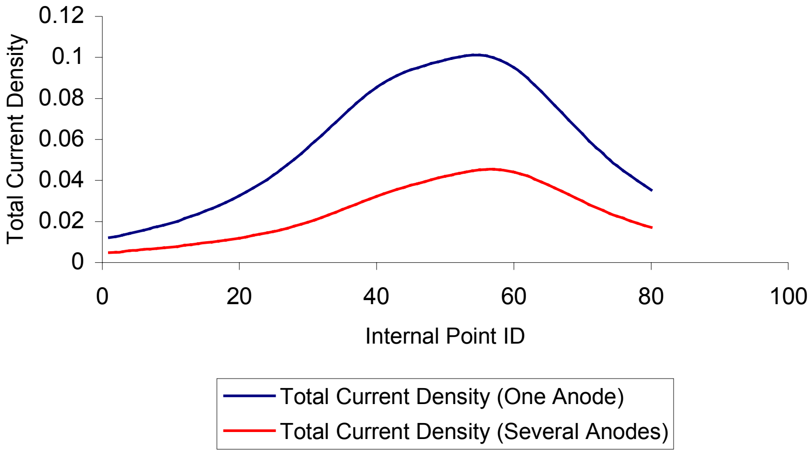

Figure 19: Resultant-current density along sampling line

The total anode current was 877 mA for the 1 anode design, and 826 mA for the 7 anode design.

Conclusions

An integrated approach to the prediction of corrosion related electric and magnetic fields as well as the effectiveness of ICCP systems has been presented.

The software tool provides a mechanism for optimisation of the design and operation of ICCP systems. In the application presented the electric signature was reduced sixty percent by selecting an alternative anode position

The 3D model enables the impact of small changes to the geometric design, coating condition, location of anodes etc to be assessed.

The approach adopted provides a flexible way of optimising electric and magnetic signatures as the definition of objectives and constraints is very general.

Work is continuing on investigating additional objectives and selecting the optimum anode locations.

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