“A Computational Environment for the Optimisation of CP system Performance and Signatures”

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ABSTRACT

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. 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 has 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 integrated set of computational tools are described which predict the level of protection of a vessel, the associated electric and magnetic signatures and automatically optimisation of the anodes to achieve the desired characteristics of the vessel. The approach adopted was to couple the BEM model of the corrosion electrode kinetics and sea- water electric field with an optimisation algorithm.

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.

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.

Typically computational models like BEASY [1] are used by corrosion engineers and signature specialists to predict how an ICCP system will perform under a given set of conditions describing the environment, the condition of the vessel (coating performance) and the status of the ICCP system. While this type of modelling provides critical information it is not always the best approach to answering design questions. Typical design questions are

How can the ICCP system be modified to achieve protection of the vessel using the minimum current?

How can the ICCP system be modified to reduce the electric field and signature?

How can the ICCP system be modified to achieve a specific signature?

These types of questions can be answered by combining a prediction model with an optimisation algorithm. The problem is defined in terms of

Design Variables

Design variables are the quantities the engineer allows to be changed to achieve the desired results. Typically these are the anode currents and locations

Constraints

Constraints are the limits on the model variables that the engineer imposes. For example a constraint may be the limits on the potential to achieve adequate protection of the vessel. (800mv < vessel potential < 1000mv). Constraints can also be applied to other problem variables and design variables.

Objective

The objective is the goal of the optimisation process. For example this may be to minimise the anode current or to minimise the signature.

Given the design variables, constraints and the objective function the optimisation method will try to find the optimum solution by varying the design variables and searching for a minimum of the objective function that satisfies the constraints.

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.

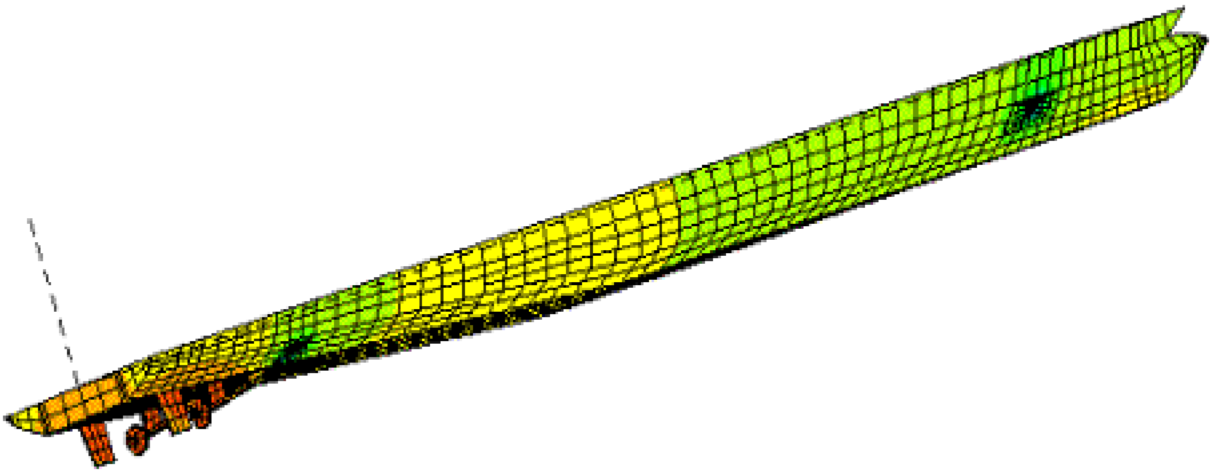


Figure 1 BEM model of a ship (Note: only elements on the wetted surface of the ship)

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).

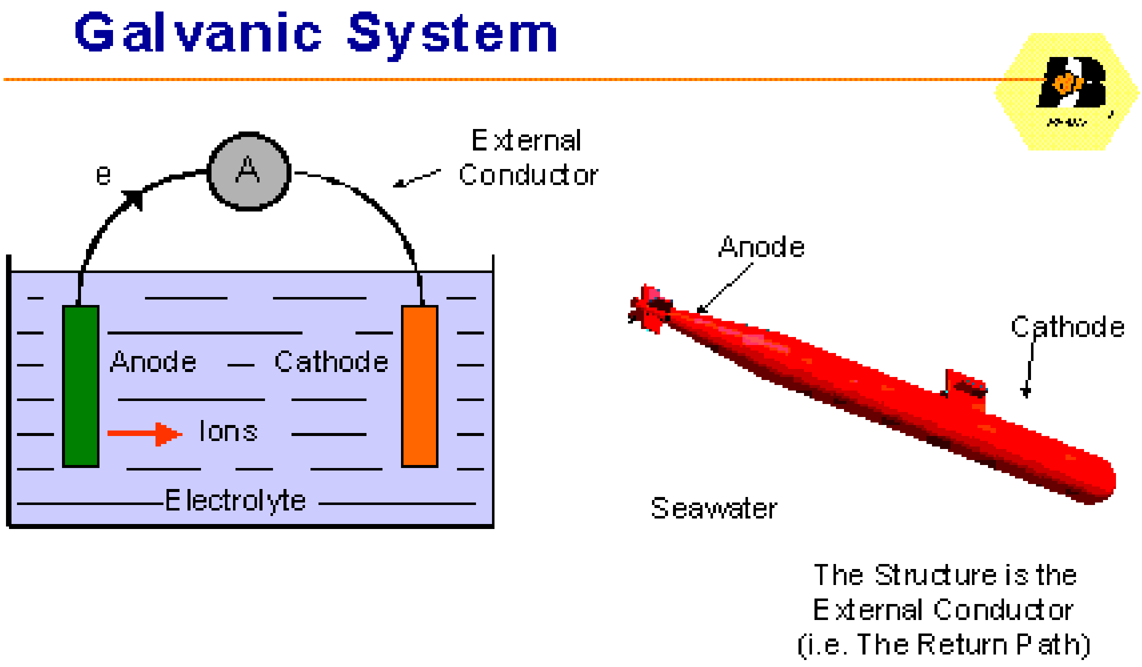


Figure 2 The CP model is a simple galvanic system

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

Software Implementation

In order to simplify the design and 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

1. The components of the optimisation software are the following: -
2. Modelling system (to define the geometry and mesh)
3. Polarization Database
4. Wizard (Java Visual Interface)
5. Interface Boundary Elements Software – Optimisation Software
6. Optimisation Software
7. Boundary Elements Software (BEASY)
8. 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 that 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.

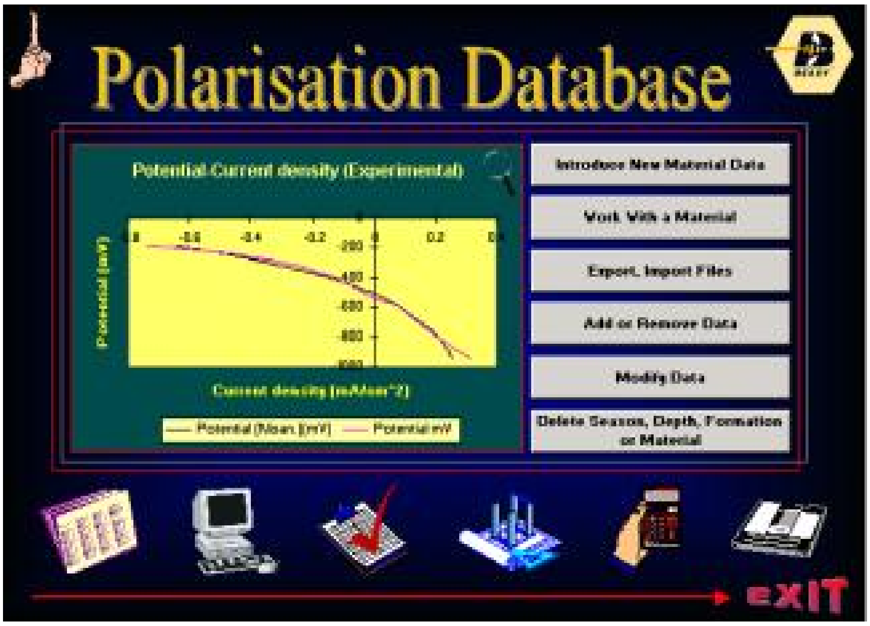
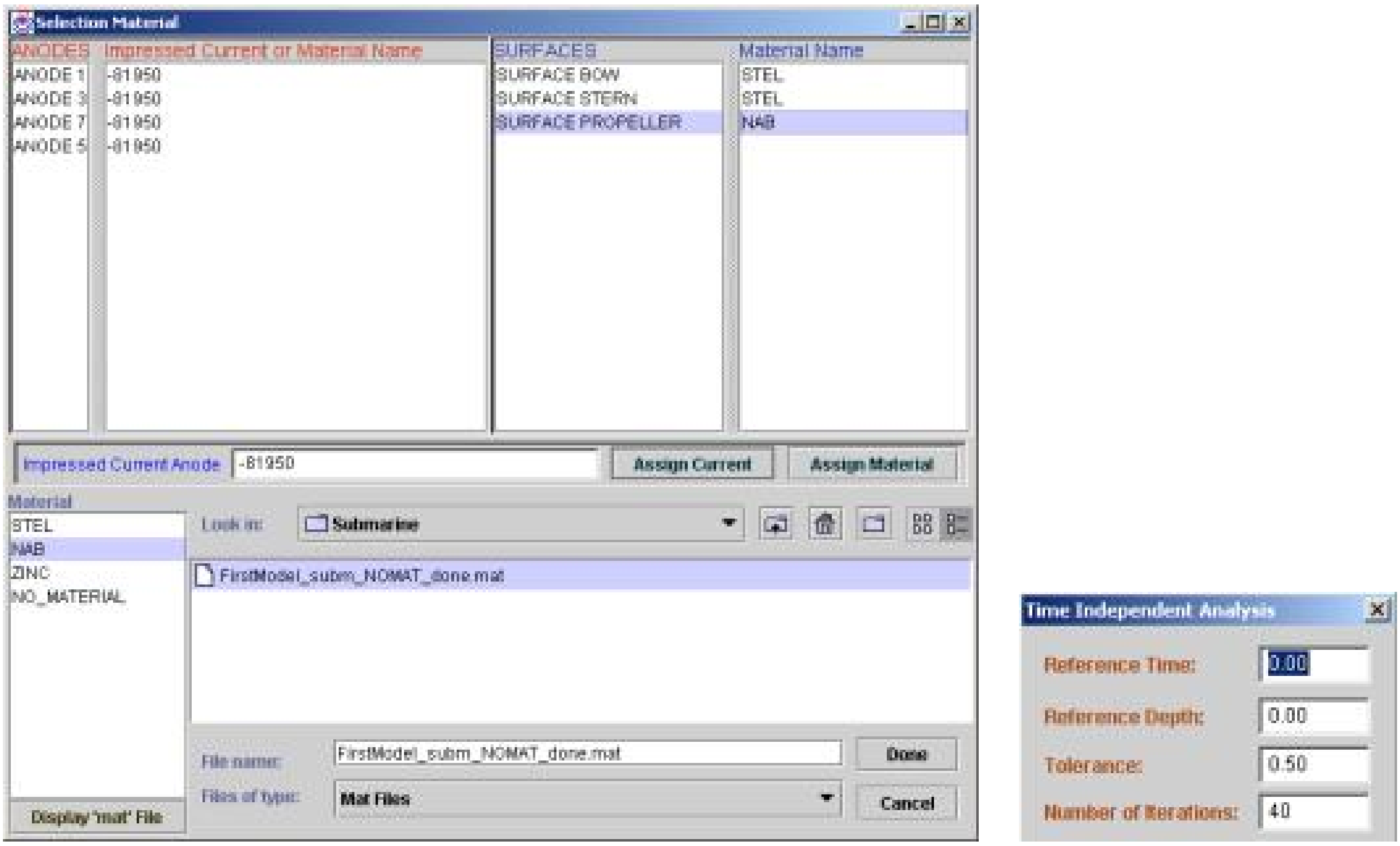


Figure 4 Polarisation Database

Wizard

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. 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.

An example screen is shown in Figure 5 which lists all the main corrosion features of the model. For example the anodes and their properties such as current or material, the metallic surfaces and their material properties and the general details of the model. Additionally a list of mat files included in each one of the folders is displayed together with a list of the materials inside the selected mat file. Every time, it is clicked on any one of the mat files shown, the materials included in this mat file are also displayed, allowing the selection of material from this list.



ANODES	Impressed Current or Material Name
ANODE 1	-81950
ANODE 3	-81950
ANODE 7	-81950
ANODE 5	-81950

SURFACES	Material Name
SURFACE BOW	STEL
SURFACE STERN	STEL
SURFACE PROPELLER	NAB

Impressed Current Anode: -81950

Material:
- STEL
- NAB
- ZINC
- NO_MATERIAL

Look in: Submarine

FirstModel_subm_NOMAT_done.mat

File name: FirstModel_subm_NOMAT_done.mat

Files of type: Mat Files

Reference Time: 0.00

Reference Depth: 0.00

Tolerance: 0.50

Number of Iterations: 40

Figure 5 Main panel, design model . Materials, current densities, anodes and surfaces

Optimisation Design.

The Optimisation Parameters option can be divided in three sub stages.

1. Set Objectives.
2. Set Constraints.
3. Set Optimisation Parameters.

Set Objectives.

Four main objectives can be already carried out and another objectives will be developed in the future. Figure 6 The four objectives are:

1. **Minimise the anode currents.**

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

$$Obj_1 = \sum_{1}^{n} I_1 + I_2 + I_3 + \dots I_n$$

Where:

n= number of anodes

2. Uniform protection of the surfaces

With this objective, the optimisation searches for the anode currents, which satisfy the constraints and attain as smooth a distribution of potential over the surfaces as possible.

$$Obj_2 = \sum_{k=1}^{m} \sum_{j=1}^{n} \left(V_{kj} - V_{target_k}\right)^2$$

Where:

m= number of surfaces

n= number of the elements for each surface

3. **Minimise the electric field.**

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

$$Obj_3 = Max\left(\sqrt{I_{x_i}^2 + I_{y_i}^2 + I_{z_i}^2} \right)$$

Where:

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

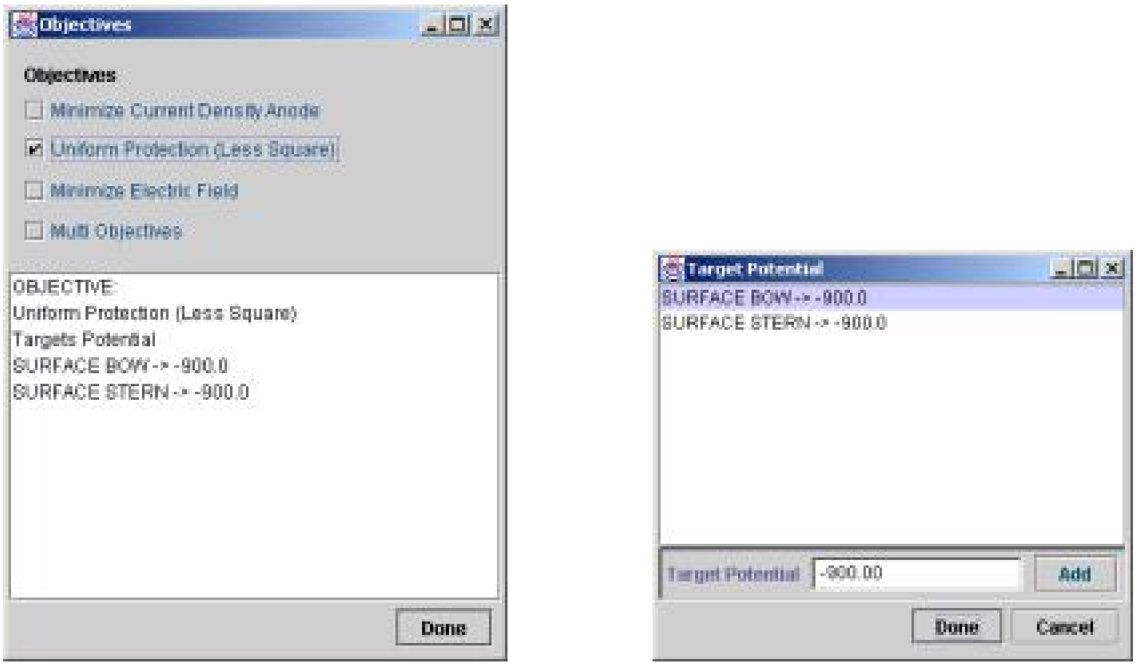
4. **Achieve a specific signature.**

With this objective, the optimisation searches for the anode currents, which satisfy the constraints and produces the closest match to the target current density signature.

$$\text{Obj}_4 = \text{Max}\left[\text{Max}(I_{X_{Target}} - I_{X_{Current}}), \text{Max}(I_{Y_{Target}} - I_{Y_{Current}}), \text{Max}(I_{Z_{Target}} - I_{Z_{Current}})\right]$$

Where:

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



☐ Minimize Current Density Anode
☑ Uniform Protection (Less Square)
☐ Minimize Electric Field
☐ Multi Objectives

OBJECTIVE:
Uniform Protection (Less Square)
Targets Potential
SURFACE BOW -> -900.0
SURFACE STERN -> -900.0

SURFACE BOW -> -900.0
SURFACE STERN -> -900.0

Target Potential: -900.00

Figure 6 Set objective panel

Optimisation Parameters.

The optimisation parameters panel allows additional data on the optimisation process and design variable to be specified. For example the maximum and minimum values of the anode current densities allowed. Figure 7 .

Applications

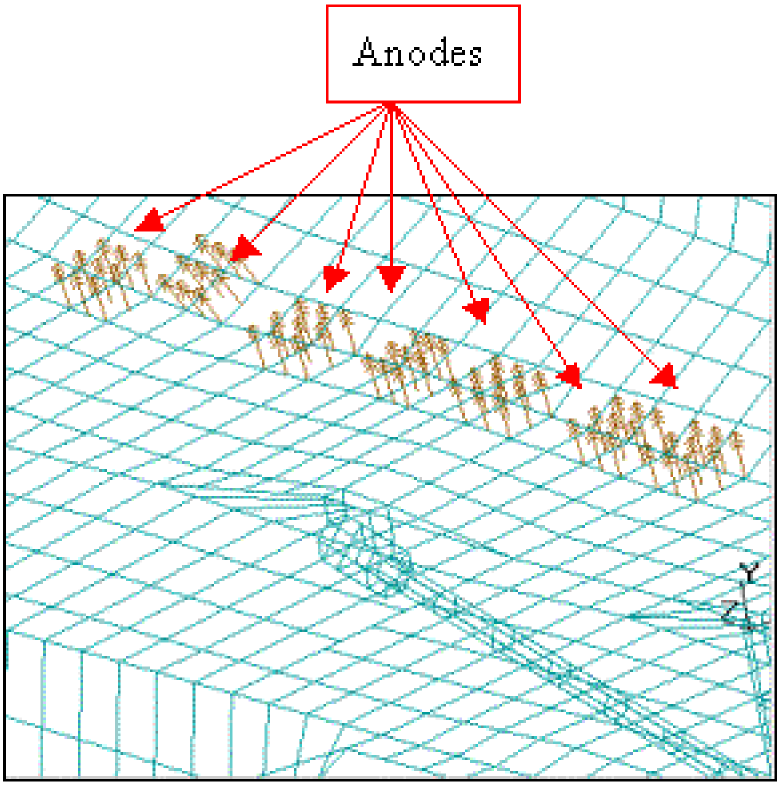
The modelling and optimisation techniques have been applied to the ICCP system design of a ship. The ship model is based on the one originally developed by Pei [7]

The following examples show the application of the optimisation techniques to achieve specific design objectives

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 the vessel was included in the model and symmetry was assumed along the keel line. The model has the following characteristics:

As an experiment to determine the best locations for the anodes, seven anodes were located in a line near the propeller shaft. Figure 8



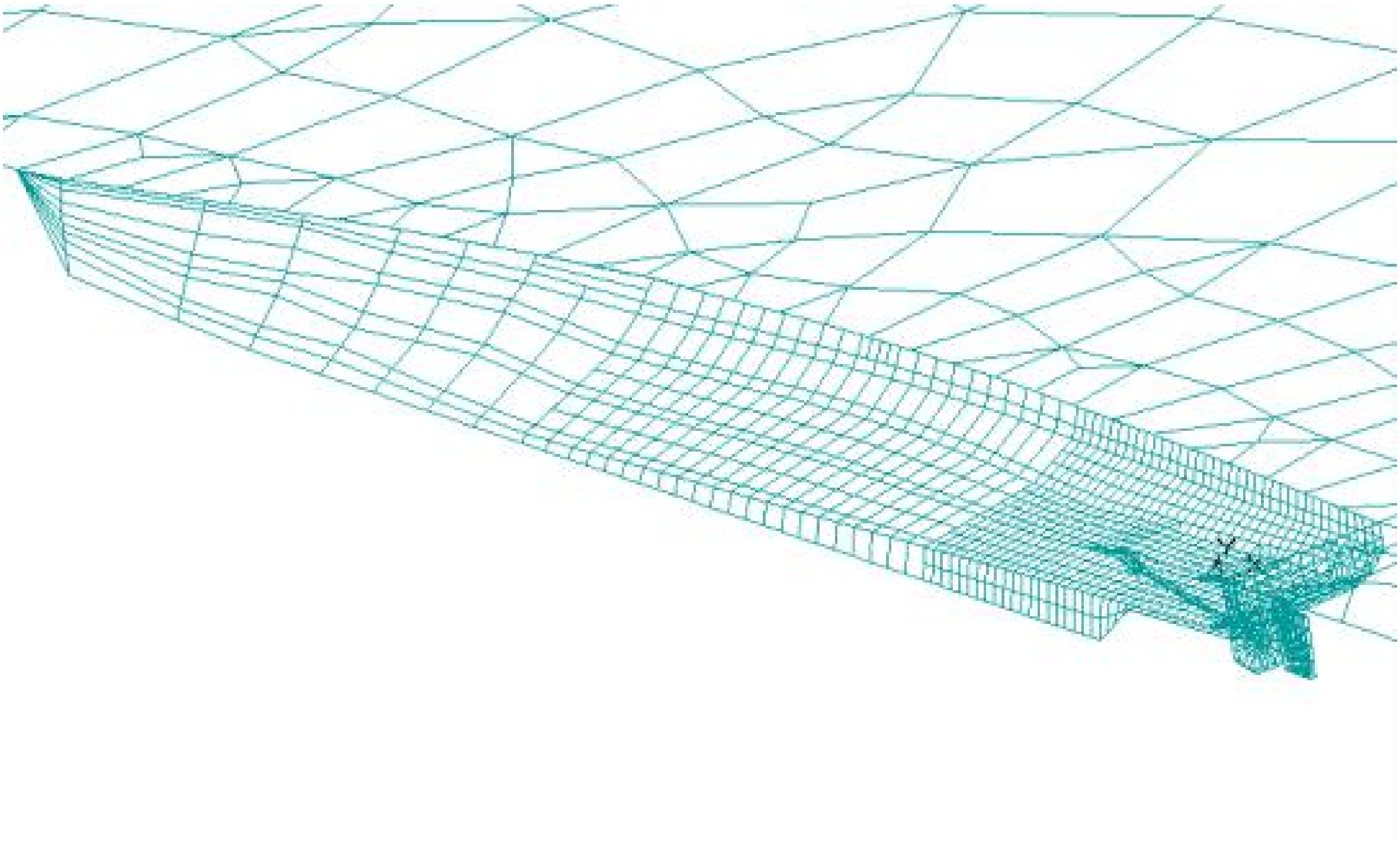


Figure 8: Description of the model

In the first case considered the vessel was assumed to be in a good state of repair with only a few areas unprotected or damaged. Figure 9

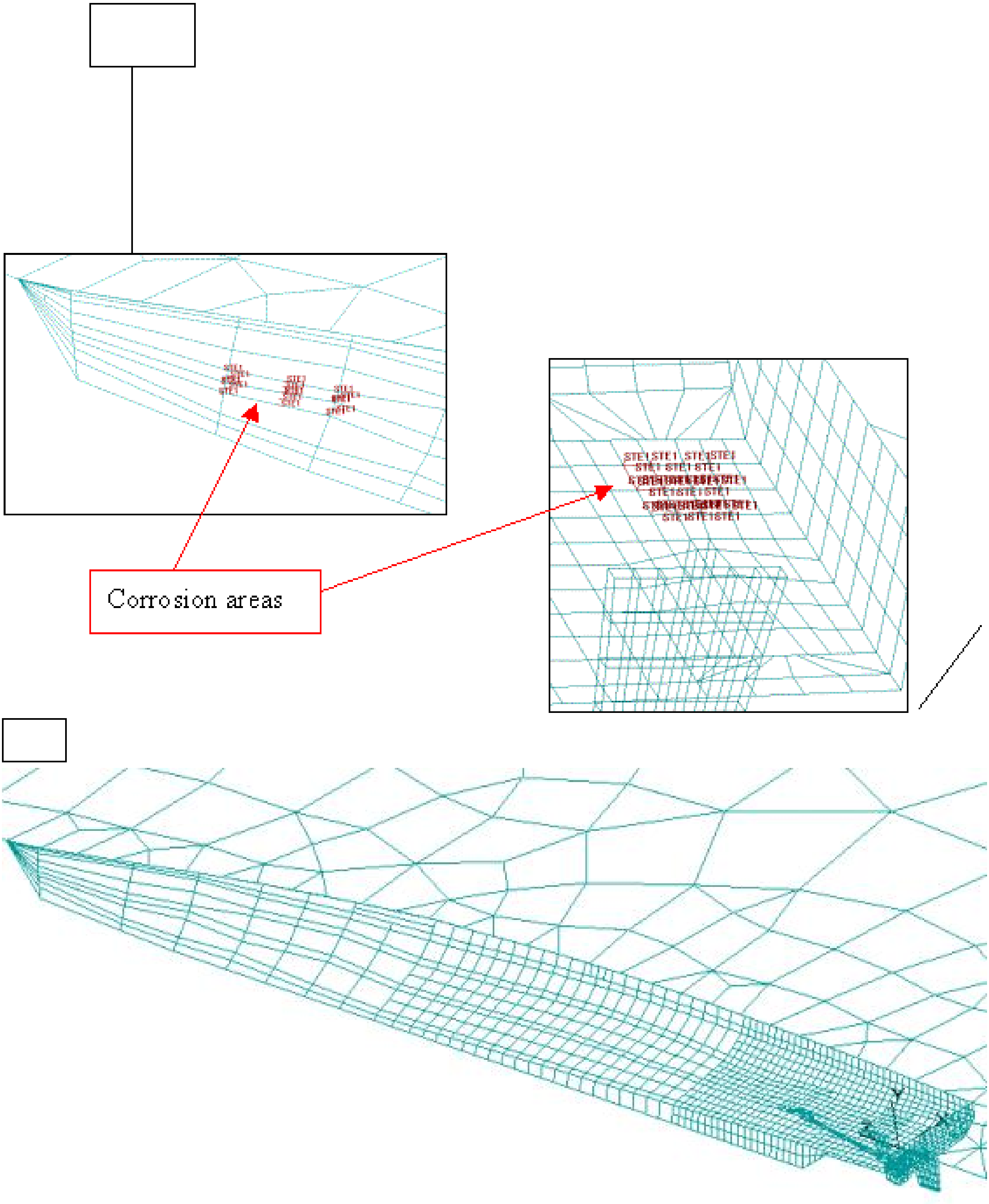


Figure 9 Corroded areas of the vessel

The corrosion areas has the following properties:

Corrosion area at the bow of the ship= 0.77 m^2 (each side of the vessel)

Corrosion area at the stern of the ship= 0.20 m^2 (each side of the vessel)

The corrosion property of the coating was considered to be equivalent to 20% of the properties of the bare steel. The rest of the vessel is completely insulated except the propeller, made of NAB (Nickel Aluminium Bronze), and the propeller's shaft, made of steel. Figure 10 shows the zone of the shaft required to protect with a potential lower than –850mV.

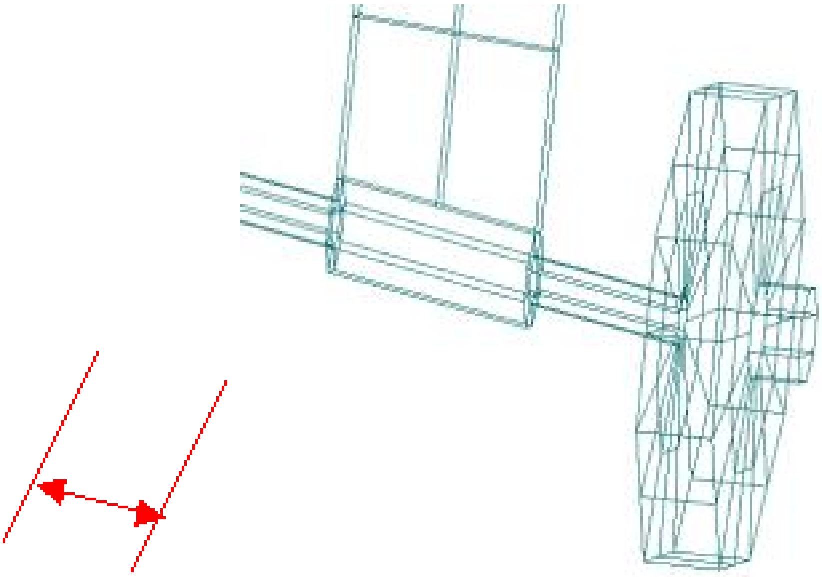


Figure 10: Surface of the shaft required to be protected.

Application 1

The optimisation problem in this first case can be summarised to be

Objectives

Achieve potentials on the vessel as close as possible to the set target potentials:

Target Potential, surface of the shaft: -900mV.

Target Potential, corroded surface at the stern: -900mV.

Target Potential, corroded surface at the bow: -900mV.

Constraints

Maximum Potential, surface of the shaft: -850mV.

Minimum Potential, surface of the shaft: -1100mV.

Maximum Potential, corroded surface at the stern: -850mV.

Minimum Potential, corroded surface at the stern: -1100mV.

Maximum Potential, corroded surface at the bow: -850mV.

Minimum Potential, corroded surface at the bow: -1100mV.

Minimum Potential, corroded surface around the anodes: -2000mV.

Initial Solution.

The initial design has seven anodes placed on the hulk of the vessel as shown in Figure 8 with a current density of 9240mA/m^2 per anode.

Location	**Initial Results**	**OptimumResults**
ANODE 1: Total Result Current (mA)	-460.06	-133.00
ANODE 2: Total Result Current (mA)	-488.77	-141.46
ANODE 3: Total Result Current (mA)	-338.03	-97.15
ANODE 4: Total Result Current (mA)	-493.26	-142.85
ANODE 5: Total Result Current (mA)	-463.94	-134.27
ANODE 6: Total Result Current (mA)	-488.56	-141.58
ANODE 7: Total Result Current (mA)	-463.39	-133.96
SURFACE shaft: Difference between maximum and minimum Potential (mV)	7.84	2.28
SURFACE corroded at the stern: Difference between maximum and minimum Potential (mV)	14.58	4.51

SURFACE corroded at the bow: Difference between maximum and minimum Potential (mV)	0.3	0.05
SURFACE shaft: Average Potential (mV)	-1927.41	-880.38
SURFACE corroded at the stern: Average Potential (mV)	-2053.09	-915.30
SURFACE corroded at the bow: Average Potential (mV)	-2082.41	-927.90
SURFACE around the anodes: Average Potential (mV)	-2205.56	-957.66

Table 1 Initial solution results

The results show that the potentials are close to the target potential and the surfaces are protected. The evolution of the potentials and the current densities during the optimisation are shown in the Figure 11 and Figure 12 :

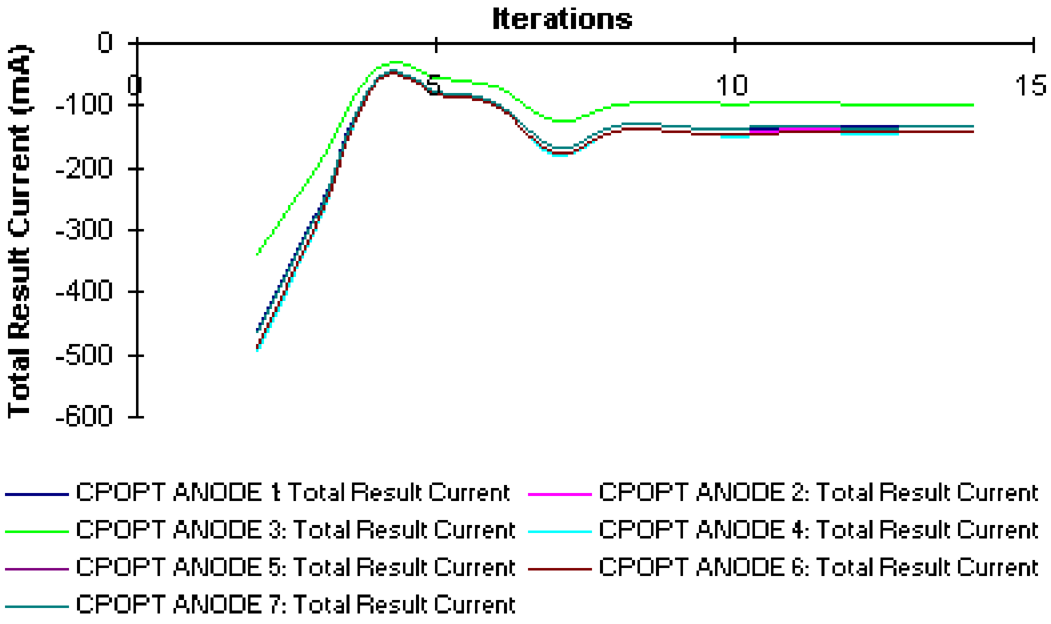


Figure 11 Evolution of the current densities of the anodes during the optimisation

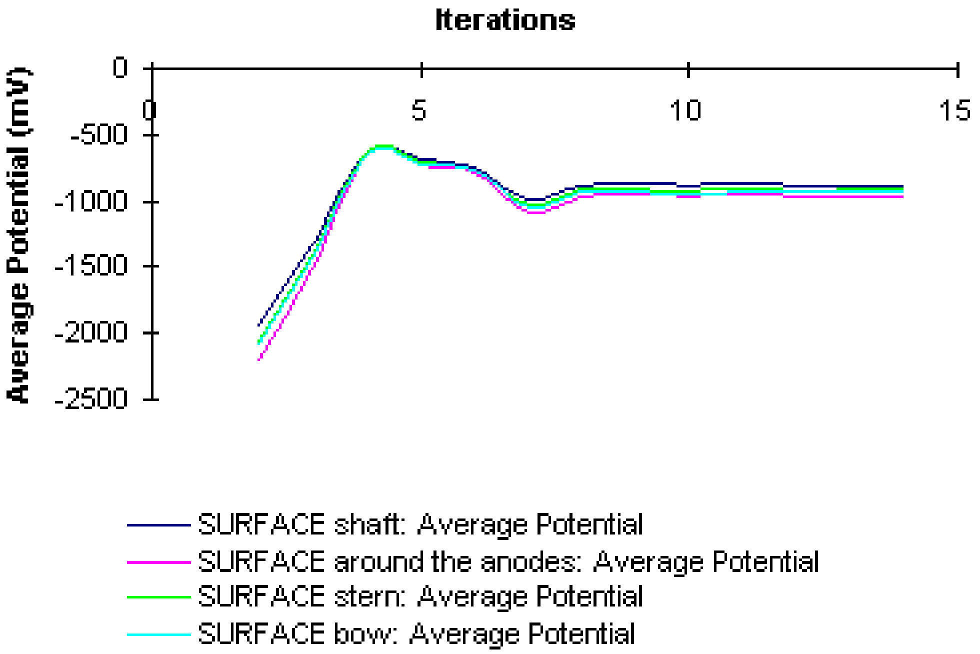


Figure 12 Evolution of the Average Potential during the optimisation

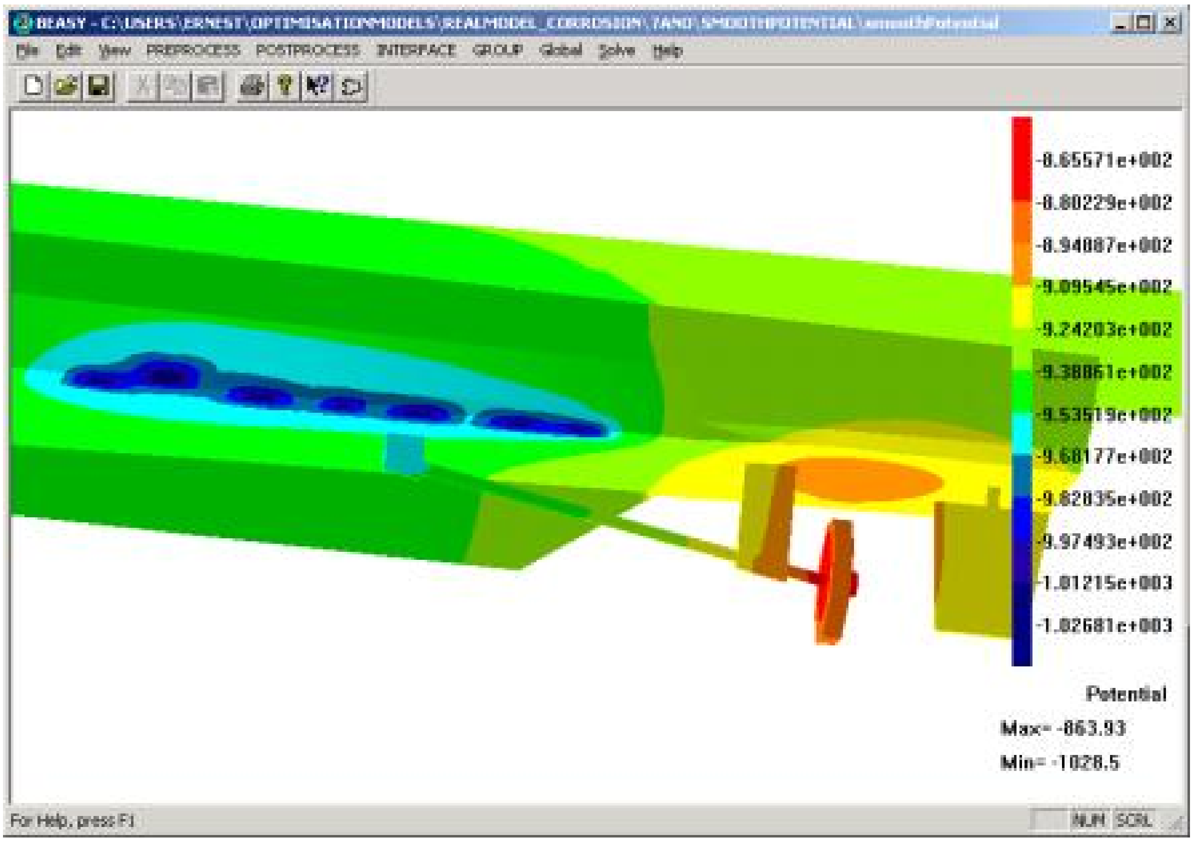


Figure 13 Distribution of potential at the stern of the vessel

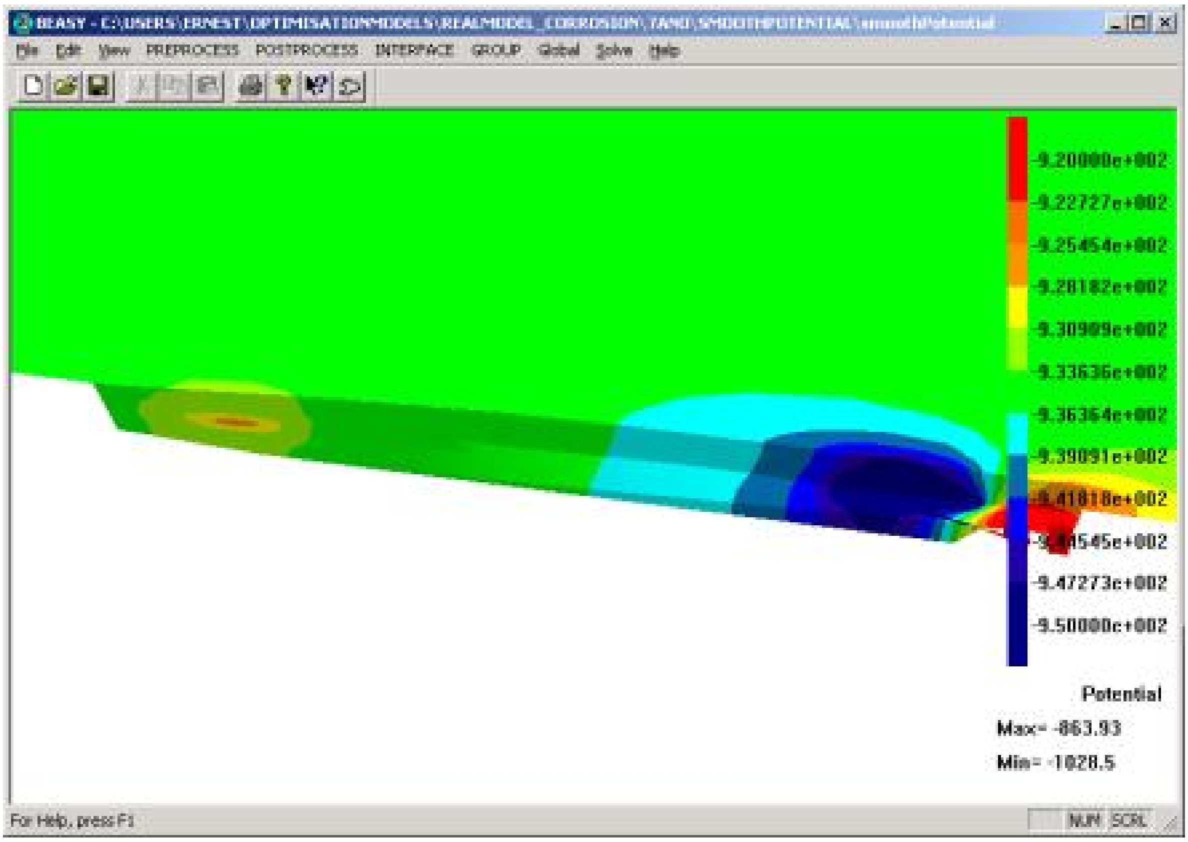
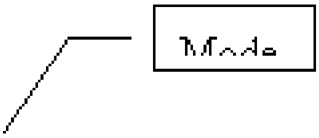


Figure 14 Distribution of potential all along the vessel

The ICCP system has been optimised to achieve satisfaction of the constraints (ie all the surface are protected) and the variation in the values of the potential on the surfaces has been reduced by seventy percent thus ensuring a uniform level of protection.

Application 2 Optimisation of the Electric Field of the vessel.

In this application the objective is to reduce the electric field caused by the ICCP system. A line of points has been defined at the depth of 30m beneath the sea level to simulate the location of a sensor at which the electric field is measured (Note the motion of the ship relative to the sensor is simulated by moving the sensor relative to the stationary ship). The electric field will be minimised at these points (Figure 15).



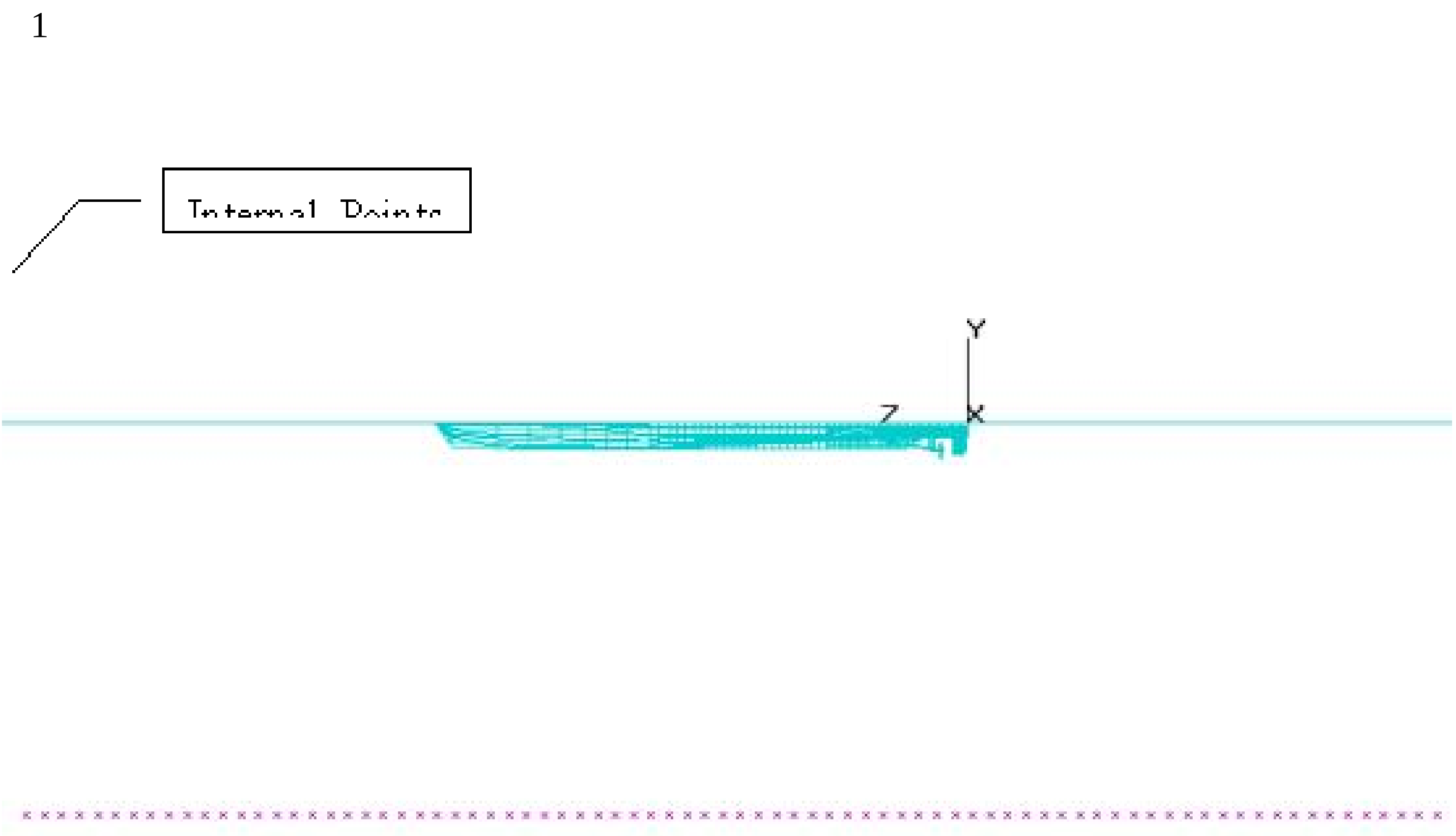


Figure 15: Internal points line underneath the vessel.

The same vessel was used as in application 1

The optimisation objectives and constraints were:

Constraints

Maximum Potential, surface of the shaft: -850mV.

Maximum Potential, corroded surface at the stern: -850mV.

Maximum Potential, corroded surface at the bow: -850mV.

Objective

Minimise the electric signature. Minimise the maximum value of the current density of the internal points underneath the vessel.

The initial y and z component of the electric field at the beginning of the process and at the end of the process are compared to see the results of the optimisation process (Figure 16 and Figure 17). The results clearly show how the electric field has been reduced by approximately eighty percent while at the same time protecting the vessel against corrosion.

Application 3 Match the electric field to a target electric field curve.

In this case the objective is optimise the ICCP system to create an electric field which is as close as possible to a target curve defined at the sensor (ie line of internal points) In this case the target curve has been defined as one which has been previously predicted for this model so the optimisation process should be able to match the target exactly. However in general any target curve could be specified.

The optimisation objectives and constraints were:

Constraints

Maximum Potential, surface of the shaft: -850mV.

Maximum Potential, corroded surface at the stern: -850mV.

Maximum Potential, corroded surface at the bow: -850mV.

Objective

Minimise the difference between the values of the electric field at the internal point and the specified target values

In Figure 18 and Figure 19 the target signature and the results of the optimisation are compared.

The number of iterations carried out was about thirty iterations. In some cases the match to the target can be quite close but the optimum solution has not yet been achieved. The computer time can be reduced by providing a stopping criterion which enables the optimisation to stop when the electric field is within a certain percentage of the target values. Therefore, a new optimisation was carried out with a tolerance value of 0.003mA/m^2 in order to reduce the number of iterations.

In the Figure 20 and Figure 21 the Current density (initial value), the target (target value) and the final results are shown. These results were obtained with seven iterations compared with thirty for the case with no tolerance.

Sensitivities

The optimisation procedure computes the sensitivity of the key parameters (potential , Current density) to changes in the design variables (anode current). This data can also provide useful information to the engineer by for example quantifying the influence of a particular anode over area of the vessel. Sensitivities are typically computed using a finite difference formula where the anode currents are changed by a small amount.

$$\text{Sensitivity}=\frac{\Delta V}{\Delta I}=\frac{V_f - V_i}{I_f - I_i}$$

Where:

I_f: Increased anode current density.

I_i: Initial anode current density.

V_f: Potential result for the increased of current density

V_i: Initial potential.

Figure 22 shows the sensitivity for anode 1 situated at the bow direction of the vessel (Figure 8), displayed as a contour diagram.

The darker greener areas show the major influence of the anode current on the potential. Therefore, those areas are more suitable to the location of the reference electrode for this anode.

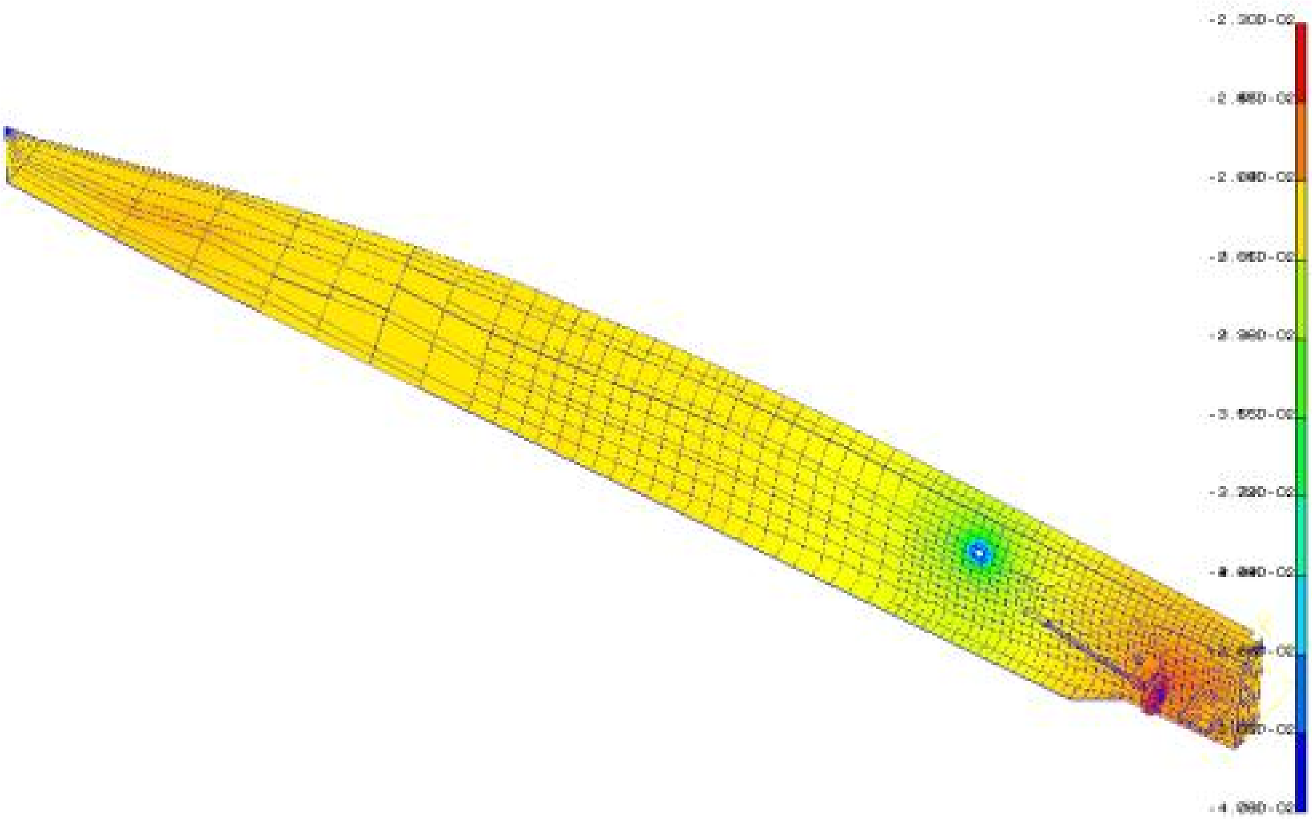


Figure 22 Sensitivity computation of the hulk regarding anode 1

Similar sensitivity data can be displayed for anode 6 situated at the stern direction of the vessel (Figure 8).

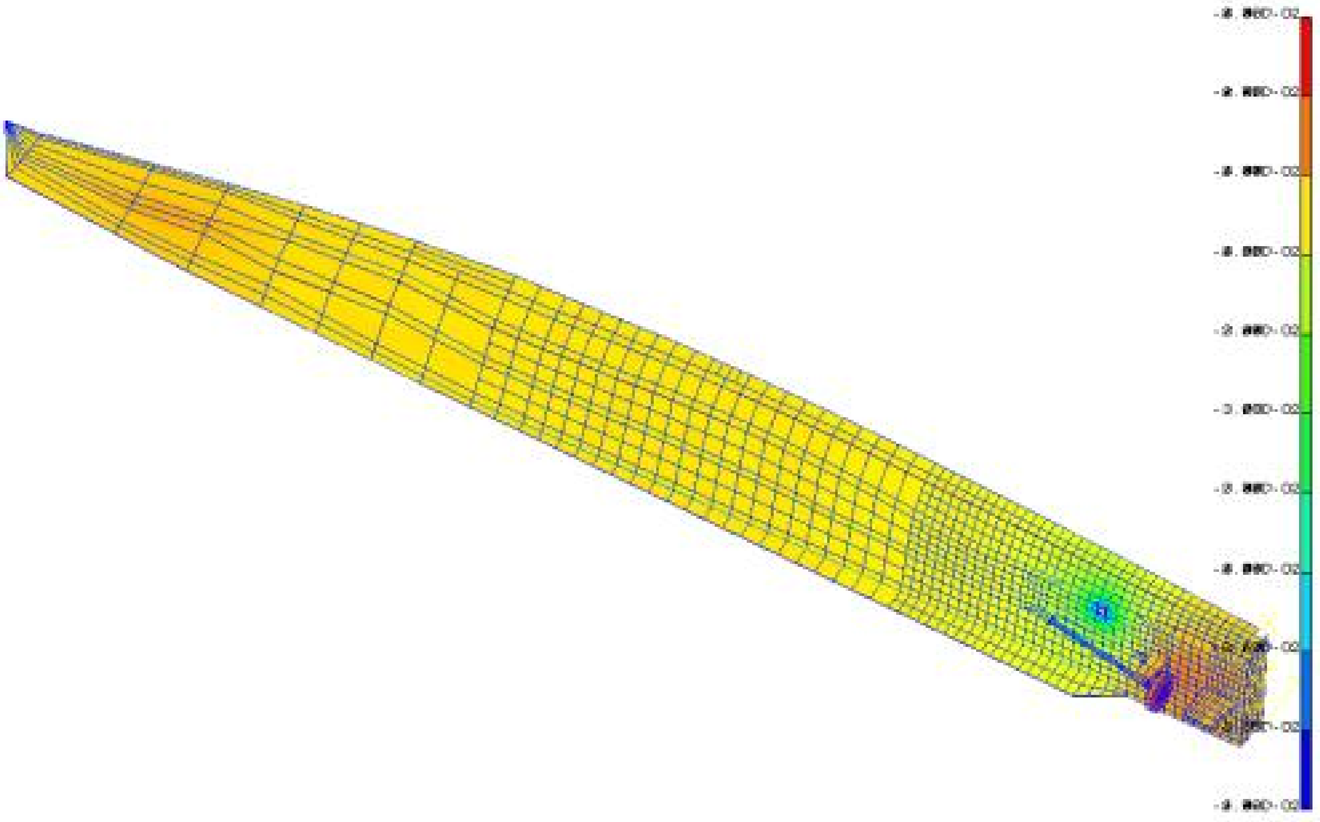


Figure 23 Sensitivity computation of the hull regarding anode 6

Similar calculations can be made for the electric field at the internal points beneath of the vessel with respect to the variation of the anodes current density. In this case the current density sensitivity is displayed which gives an indication of the influence of each one of the anodes has on the surrounded electric field.

The signature sensitivity for the anode 1 is shown in Figure 24 and Figure 25

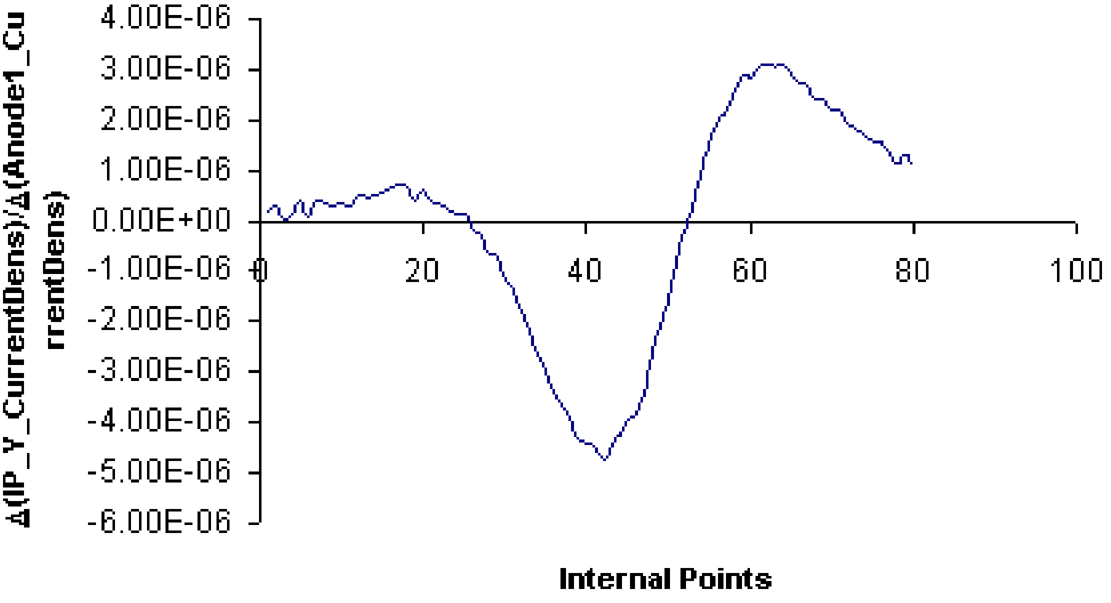


Figure 24 Sensitivity computation of the Y component of the electric field regarding anode 1

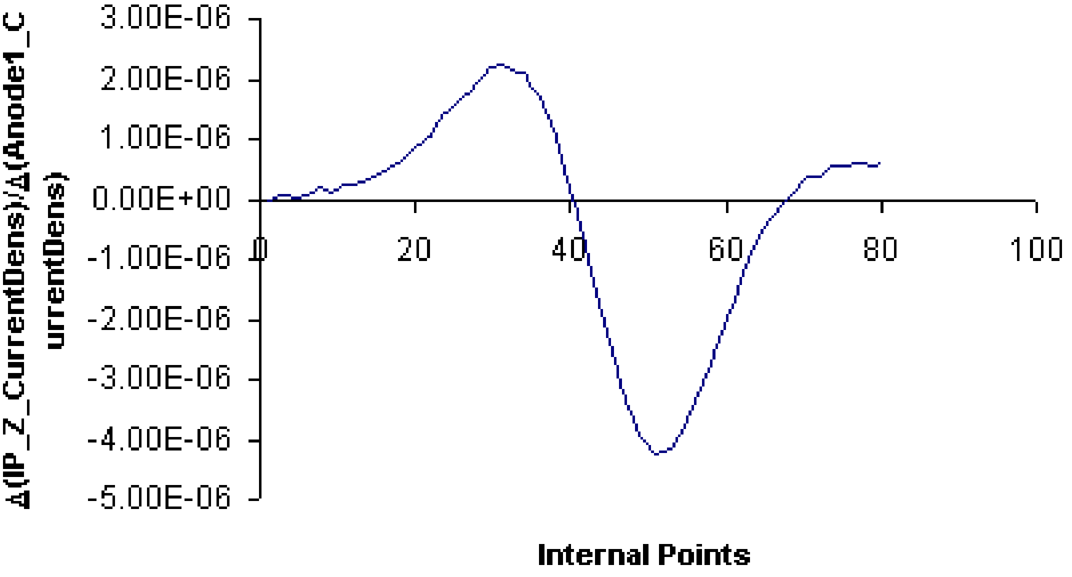


Figure 25 Sensitivity computation of the Z component of the electric field regarding anode 1

The alteration of the current density of the anode 1 has a major influence in the Y component of the electric field of the internal points placed underneath of the stern of the vessel and in the Z component of the electric field of the internal points placed underneath of the bow of the vessel.

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.

An automated procedure has been described which is capable of optimising the design of ICCP system to improve the protection of vessels and reduce the associated signatures.

In the application presented the electric signature was reduced seventy percent by changing the current density of the anodes in order to calculate the minimum possible value of the electric field.

A procedure has been presented to enable the ICCP system parameter to be modified to achieve a target signature.

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

Acknowledgements

The ship model was provided by Y H Pei of DSO National Laboratories, 20 Science Park, Singapore 118230.

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