Optimization of the cathodic protection system of military ships with respect to the double constraint: cathodic protection and electromagnetic silencing

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Abstract : In ships, materials of different electrochemical potentials - the steel of the hull and the bronze of the propellers - coexist. Once bathed in the sea water and electrically connected by the internal structures, phenomena of corrosion induced by galvanic coupling appear. These phenomena create currents in the water around the ship and induce, in the conducting sea water, a static electric field called "Underwater Electric Potential Field (UEP)" and a static magnetic field associated called "Corrosion Related Magnetic Field (CRM)", harmful to the electromagnetic silencing of the ship. In order to protect the hull and the other sensitive anodic parts of the ship against corrosion, cathodic protection systems are installed on the hull. This paper describes a response surface methodology to optimize the design of cathodic protection systems of military ships with respect to the double constraint: cathodic protection and electromagnetic silencing.

Key words : cathodic protection, electric field, response surface methodology.

I. INTRODUCTION

In ships, materials of different electrochemical potentials - the steel of the hull and the bronze of the propellers - coexist. Once bathed in the sea water and electrically connected by the internal structures, phenomena of corrosion induced by galvanic coupling appear. These phenomena create, in the water around the boat, circulation of currents and induce, in the conducting sea water, a static electric field called "Underwater Electric Potential Field (UEP)" and a static magnetic field associated called "Corrosion Related Magnetic Field (CRM)", harmful to the electromagnetic silencing of the ship.

In order to protect the hull and the other sensitive anodic parts of the ship against corrosion, cathodic protection systems are installed on the hull using either sacrificial anodes or active anodes. Sacrificial anodes are small blocks of more electronegative material than steel, fixed on the hull, which are consumed instead of steel. Active anodes, located on the hull and linked to electric generator, injects current in the sea in order to modify the polarisation state of the ship materials and then to avoid the corrosion phenomena. These both systems modify the current distribution around the ship without reducing the harmful effects in term of silencing. The best way to take into account silencing is to optimise the design of the protection system (number of anodes, anodes' location and anodes' current output)

Several commercial softwares are proposed today to carry out the design of cathodic protection systems of underwater structures, among which the software PROCOR developed by CETIM with DGA and other partners. The PROCOR software, based on the boundary integral method, computes the electric potential distribution on the hull and the electric field in the water. The entrance data of PROCOR are the geometrical description of the hull, the description of the cathodic protection system (the localisation and the characteristics of the anodes) and of the electrochemical data of materials. The PROCOR software does not compute the optimal configuration of the cathodic protection system. In practice, the definition of the cathodic protection system with PROCOR consists in testing various anodes' empirical configurations and selecting the one that achieves the good potential distribution on the hull. During that process, silencing aspects are ignored.

This paper presents, on a realistic case of ship, the results of optimization carried out with PROCOR and the optimization software, named GOT developed by the "Laboratoire d'Electrotechnique de Grenoble", to define a configuration of optimal cathodic protection system in term of cathodic protection and electromagnetic silencing.

II. THE ELECTROCHEMICAL MODEL

Inside the sea water, the current density j and the electric potential u verify the Ohm law:

$$j = -s\nabla u$$

Assuming an homogeneous and isotropic electrical conductivity s , the conservation of the electric charges gives

$$\Delta u = 0$$

Different boundary conditions are considered depending on the nature of surfaces:

- the electrochemical behaviour of the materials (bare steel of the hull paint damage regions and bronze of the propellers) is modelled by polarisation curves which define the current density as a function of the potential. These laws are obtained from experimental measurements carried out on test pieces of material.

$$j_n = -s\ \partial u / \partial n = f(u)$$

- active anodes are modelled by an imposed current density

$$j_n = cte \cdot$$

- sacrificial anodes are modelled by either an imposed potential or a polarisation curve.

III. THE SIMULATION INPUT AND OUTPUT DATA

The entrance data of PROCOR [1] are:

- The geometrical description of the external boundary of the underwater structure of the ship (hull, shafts, propellers,…). The different surfaces are meshed by first or second order surface elements.
- The boundary conditions on the propellers, the hull and the sacrificial or active anodes.
- The conductivity of the sub-regions of the electrolyte.

The output data are:

- The potential and the current density on the mesh nodes.
- The potential, the current density and the electric field on any points defined inside the computational domain.

IV. THE OPTIMIZATION INPUT AND OUTPUT DATA

The goal of the optimisation software is to define the best configuration of the protection system from corrosion and/or silencing point of view. This solution is the configuration that both checks the catholic protection requirements (potentials lower than the corrosion potential) and minimises the electric field in the sea.

The parameters to be optimised may be:

- The current injected by the active anodes.
- The electric potential of the sacrificial or active anodes.
- The position of the sacrificial or active anodes on the hull.

The objectives and constraints may be:

- The maximum electric field on some test points in the electrolyte must be as low as possible.
- The maximum electric potential on some test points on the hull must be lower than a specified value (the corrosion potential).
- The maximum electric potential on some test points on the hull must be higher than a specified value to avoid paint damage.
- The output currents must be lower than a specified value.
- The sum of the output currents of the active anodes must be lower than a specified value.
- The anode locations must be restricted to certain areas.

V. THE OPTIMIZATION METHODOLOGY

The above optimisation problem has the following characteristics:

- This is a constrained problem.
- The objectives and the constraints are non linear functions of the input parameters.

The use of a numerical tool as PROCOR to evaluate the objective and constraint functions introduces some difficulties in the optimisation process:

- No information on the objective and constraint gradients is available.
- The objective and constraint evaluations are costly.
- The objective and constraint evaluations may be perturbed by some numerical errors.

The classical Response Surface Methodology is a good answer to the above difficulties [2]. This approach consists first to construct surfaces (one surface for each objective and evaluated constraint) giving the responses of the system as functions of the input parameters. Then these surfaces are used in the optimization problem in place of the direct simulation outputs.

For obtaining the response surfaces, several techniques, polynomial, spline, multiquadric, diffuse elements and kriging approximations could be used and compared with a priori or adaptive variants.

For optimizing the problem, several deterministic and stochastic optimization algorithms (genetic algorithm, simulated annealing and particle swarm) are used and compared.

VI. THE MODEL USED FOR TEST

Optimization tests have been carried out with a PROCOR model of a realistic ship (half hull) used for a previous study. The design of the cathodic protection system had been defined after several PROCOR runs with different configurations of anodes (number, position and currents output). The configuration with the "best" potential distribution on the hull (the more "regular" potentials lower than the corrosion potential) in static and dynamic condition for various scenarios of paint defect had been selected as the optimal solution. In this previous study, electromagnetic silencing (minimization of the electric field in water) had not been taken into account for the definition of the cathodic protection system.

The anodes configuration for the static configuration in the 1.5 % of paint defects scenario is as follow:
5 anodes per edge, 6 A injected by these 5 anodes according to the following distribution:

- 1 A for the anodes before and medium 3, 4 and 5,
- 1.5 A for the anodes postpones 1 and 2.

A theoretical estimation (underestimation) of the current consumption of the hull and the propellers can be made from the polarization curves of the model by multiplying the current density corresponding to the corrosion potential (–850 mV) by the cathode's area. On our model, this theoretical value is 5.663 A. In reality, the current value ensuring the protection by active anodes is always higher than this estimation because it is not possible to define a system ensuring on all the hull exactly the maximum of potential (-850 mV).

In the initial model, the active anodes had been modeled by tube elements (2 elements by anodes) detached a few millimeters from the hull. To simplify the displacement of the anodes in the optimization runs, the anodes have been modeled by only one tube.

A view of the model is presented below:

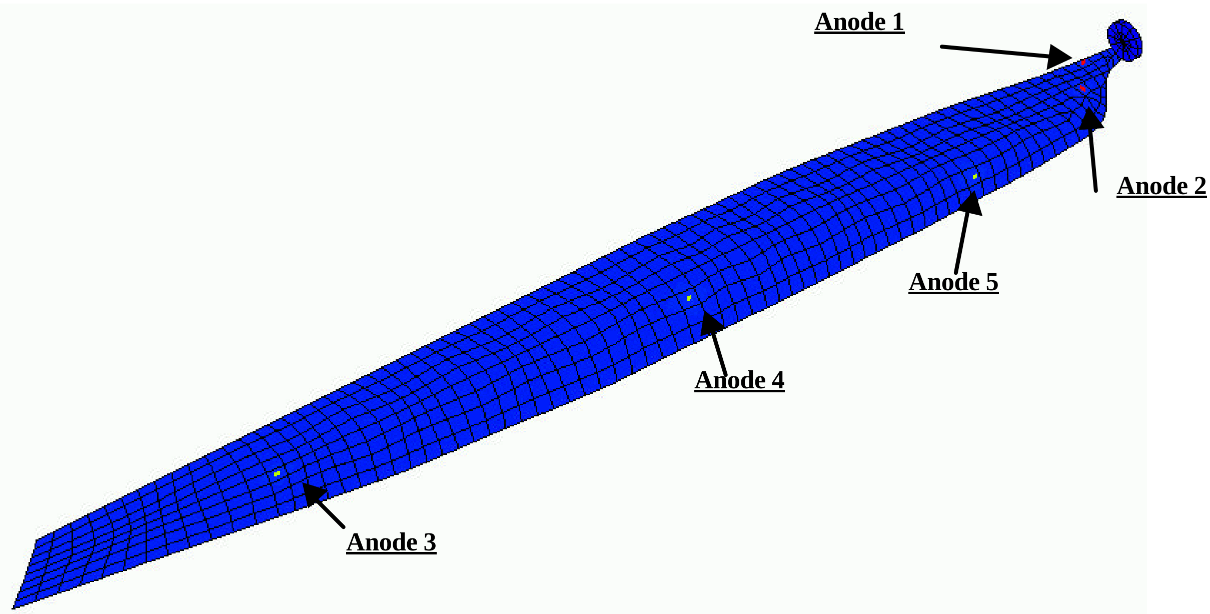

Figure 1 – Model used for tests

In the initial study, the potential computed by PROCOR on the hull was between –831 mV and -944 mV. The potential limit (-850 mV) was not strictly checked.

With this configuration, the electric field computed by PROCOR under the keel, 20 m. below the water line is shown on figure 2.

VII. OPTIMISATION WITH FIXED ANODES

In that case, anodes can not move on the hull. The parameters of the optimisation problem are the five anodes' current output. The objective function is the maximum of the electric field on four points selected 20 m. under the waterline under the keel.

$$f = \max(E1, E2, E3, E4)$$

These four points are points where the electric signature of the initial PROCOR model is maximum (local maximum) under the keel 20 m. under the waterline.

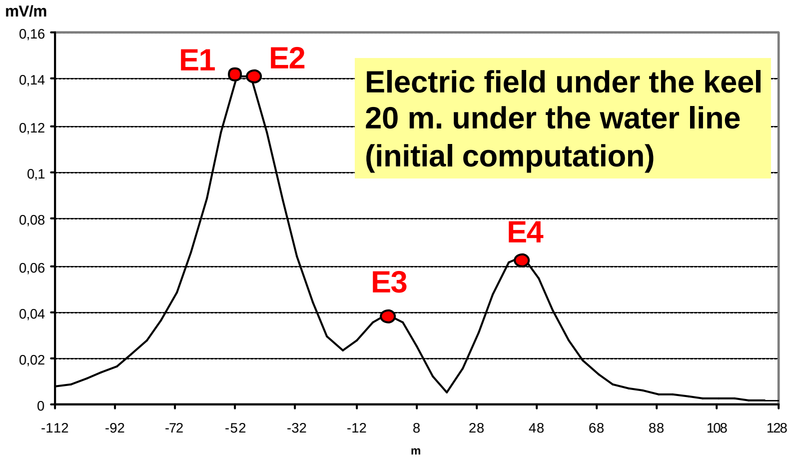

Figure 2 – Electric fields used to define the objective function

Constraints have been defined to control the potential distribution on the hull. To ensure the cathodic protection of the ship, the potential must be lower than –850 mV. To avoid paint damages, the potential must not be too low: -1000 mV is a usual lower limit.
In the case of fixed anodes, the choice of constraints' location is easy as the potential is naturally low under the anodes (anodes are detached from the hull in the PROCOR model) and naturally high far from the anodes. Eleven nodes have been selected to control the potential on the ship:

- 5 nodes under the five anodes,
- 6 nodes far from the five anodes,
- 1 node on the propeller.

The control of the potential under anodes ensure also that the current outputs will not be too high.

The response surface building required only 27 PROCOR computations (GOT used a Centered Box Wilson design of experiments). The optimal solution, found by a genetic algorithm on the response surface, is presented below: I1 = 2.1 A; I2=2.405 A, I3=0.824 A, I4=0.883, I5=0. The total output current is 6.215 A.
The potential distribution is correct (between –998 mV and –848 mV) as shown in the following figure:

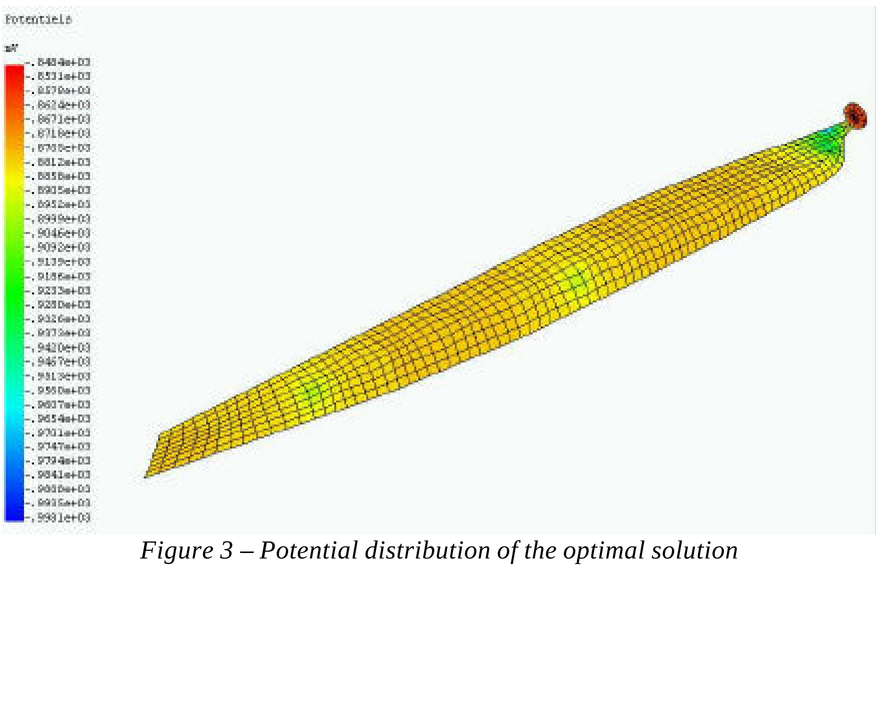

Figure 3 – Potential distribution of the optimal solution

The maximum of electric field under the keel is reduced with a factor of 3.8 as shown in the following figure:

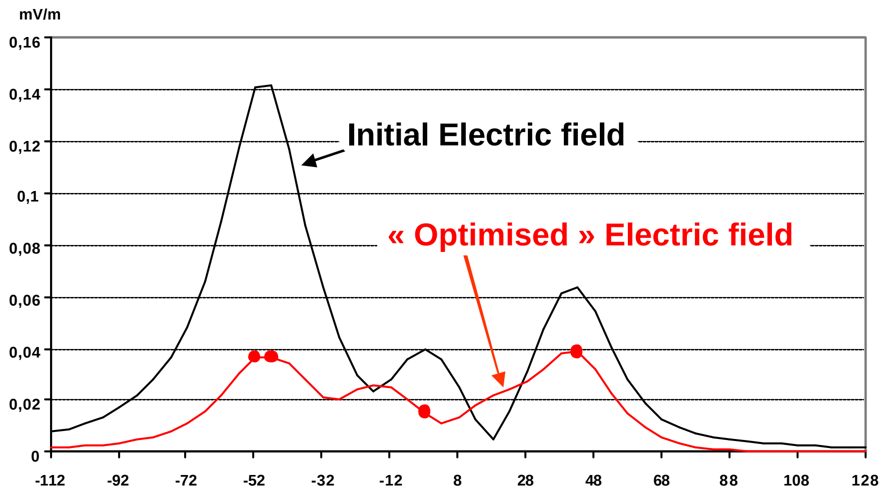

*Figure 4 – **Electric** field under the keel*

VIII. OPTIMISATION WITH MOVING ANODES

In that case, the optimisation parameters are both the location and the current output of the five anodes.
This problem is more complex than the previous one with fixed anodes because the anodes' displacement space is not a continuous space and response surfaces parameters must vary continuously.
The solution to avoid that problem is to describe the anodes displacement as a continuous function by locating each anode on a parameterised (non plane) surface detached a few millimetres from the hull.

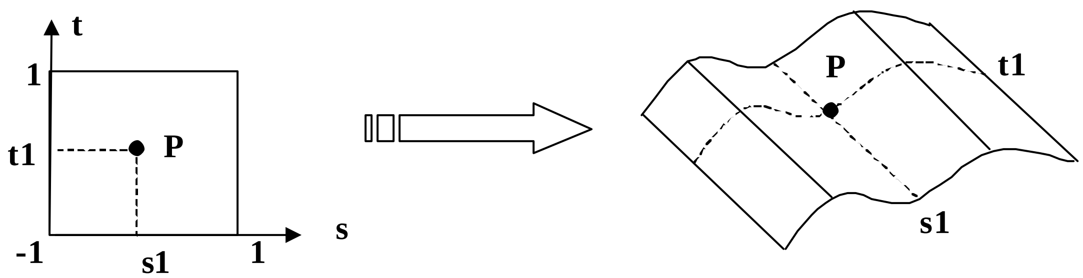

Figure 5 – Anode's location on a parameterised surface

We made a test with only one moving anode (anode number 4). The four others anodes were fixed.

Parameters of the response surface are the five currents intensity plus the two space parameters (s4,t4) of the moving anode on the displacement surface shown in the following figure:

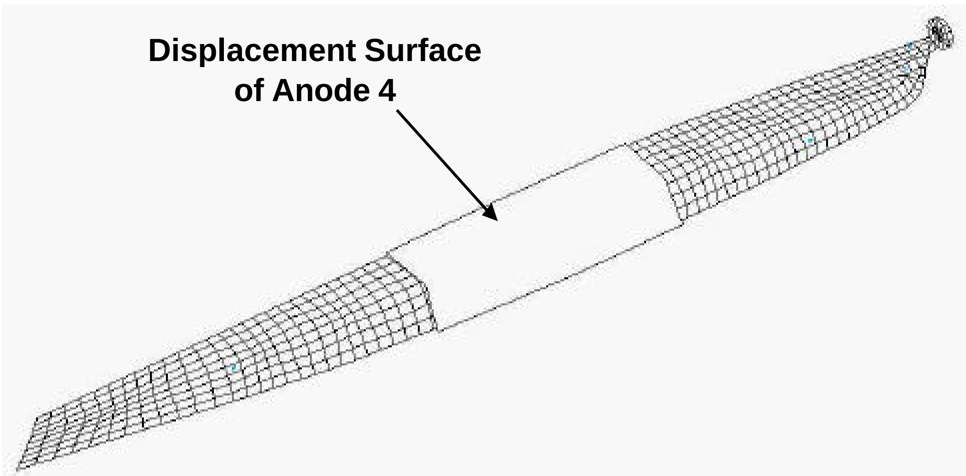

Figure 6 – Displacement surface of anode 4

The displacement surface of anode number 4 is a two degree normalised polynomial surface. The two parameters s4 and t4 are allowed to move between –1 and 1. At each (s,t) couple of parameters, with both s and t between –1 and 1, corresponds a unique anode position on the displacement surface.

The moving anodes create a second problem: the location of the potential control points and the electric fields used in the objective function.
Results shown below have been computed with the same potential control points and the electric fields used in the objective function as those used for the fixed anodes' configuration. This choice is not optimal. A further study would be necessary to develop an "optimal strategy" to define and to locate both the constraints (for potential control) and the electric fields in the objective function. That could explain why the results obtained are not better than those obtained with fixed anodes with more parameters.

The optimal solution computed by GOT with Centred Box Wilson response surface and a genetic algorithm is presented below: I1 = 2.1 A; I2=2. A, I3=0.4 A, I4=1, I5=0.8. The total output current is 6.3 A.

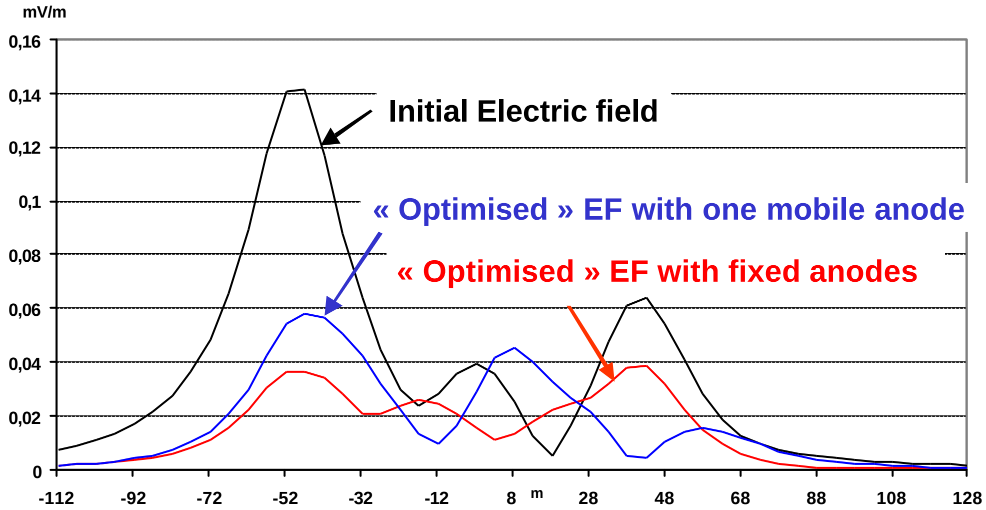

*Figure 7 – **Electric** field under the keel*

The potential distribution is correct (between –1000 mV and –853 mV) as shown in the following figure:

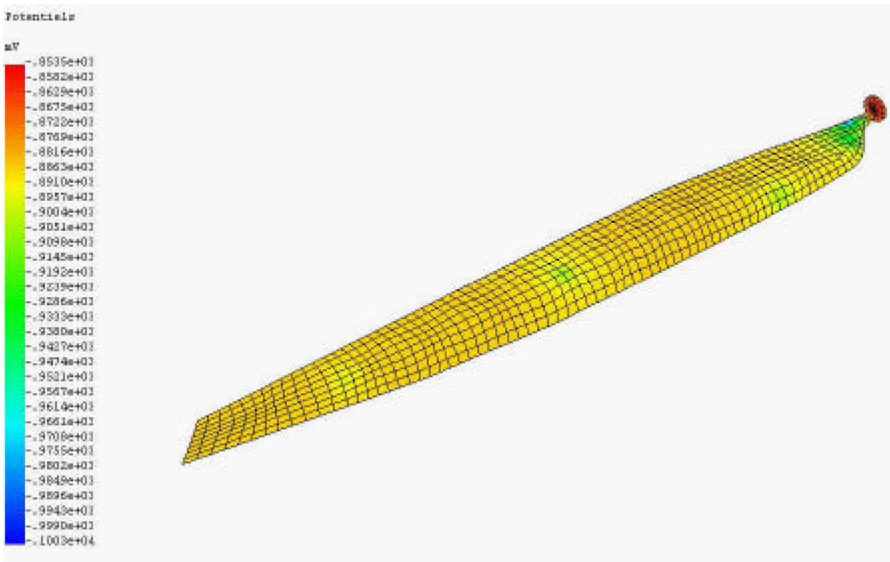

Figure 8 – Potential distribution of the optimal solution

IX. CONCLUSION

This paper presents an efficient method to optimise the design of cathodic protection systems of military ships with respect to the double constraint: cathodic protection and electromagnetic silencing, based on a response surface methodology. This method is very easy to use for non optimisation experts.

With few efforts, an anodes' configuration has been computed for a simple but realistic example with a better electric signature under the keel with an equivalent or better potential distribution on the hull.

A further study would be necessary to develop an "optimal strategy" to define and locate constraints (for potential control) and electric fields used in the objective function. However, the principle used to define the anodes' displacement on a parameterised surface detached a few millimetres from the hull is very interesting as is make possible the use of similar response surfaces as those used for fixed anodes.

X. REFERENCES

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