

# Predicting the hull state from information of potential measurements of the hull

Ernesto Santana Diaz, Robert Adey

Computational Mechanics BEASY, Ashurst Lodge, Ashurst, Southampton, SO40 7AA,  
UK

Tel +44 (0) 2380293223. Email r.adey@beasy.com

## Abstract

Damages appear on a hull of a vessel during its lifetime. In many cases the correct position of these damages are completely unknown. Its knowledge is important from mainly two points of view.

1. Cathodic protection of the vessel. A corroded hull would be economically inefficient (current and fuel consumption) apart from being potentially dangerous since it is a hot point for crack corrosion.

2. Signature of the vessel. A vessel can be detected from its surrounding electric and magnetic fields.

Modelling techniques normally start from an assumed condition of the vessel. Given some assumed condition the level of protection provided by the cathodic protection system can be predicted as well as the corrosion related electric and magnetic fields. Therefore designers when assessing the signature and the effectiveness of the CP system will perform tests based on a number of possible conditions of the hull expected over the life cycle of the ship.

In typical CP systems the designer knows the source of current (the anodes) but does not have a clear knowledge of where the current goes (the cathode) as this depends upon the condition of the metallic surfaces etc. In this paper a method is presented to determine where the current goes from the anodes and hence predict the general condition of the vessel and possible areas of damage. An additional result of this analysis is the associated electric and magnetic signatures.

The method involves using a mathematical model of the CP system, the ship and its environment and solving an inverse problem to predict the hull condition given information from reference cells and the CP system. Example applications are presented showing how areas of damage can be predicted as well as the associated signatures of the ship.

Data will be presented showing the sensitivity of the predictions to the accuracy of the data and the number of reference cells for example.

## 1. Introduction

On an unprotected steel vessel the two main items that cause corrosion are the steel hull and the bronze propeller. In order to protect the hull of a ship with damaged paintwork from rusting, a cathodic protection system can be used. The corrosion related magnetic and static electric field signatures both arise from the corrosion currents arising from the metals from which the vessel is constructed or from the cathodic protection system used to prevent corrosion which provides an alternative current flow. This current flow creates a characteristic static electric field or Underwater Electric Potential (UEP) and an alternating electric and magnetic fields (ELFE). Sensors placed around the ship could detect these signatures and therefore the ship could be easily identified.

Besides, a vessel can be also detected from its surrounding magnetic fields. There are two main sources of the surrounding magnetic field:

- The magnetic field associated with the permanent/induced magnetism, present because of the material used in the construction of a vessel and the earth's magnetic field.
- The electrical currents driven by the ship into the sea. The principal sources of these currents are related with ship corrosion or the ICCP system. These magnetic fields are named Corrosion Related Magnetic Fields, CRM. The CRM can be a significant proportion of a ship's magnetic signature for vessels constructed using nonmagnetic materials [ 1 ].

Thus, the detection of the areas of the vessel which are acting as sinks of current is of vital importance to know which part of the structure is disclosing the vessel.

Their detection is a difficult matter that generally has to be solved in dry-docks by measuring the thickness of the coating with ultrasonic devices.

On other occasions, when the coating is applied, anti-fouling (AF) paint is applied in two coats of different colours. If this was done properly it could be seen what areas are worn.

To pull the ship out to a dry-dock; to study the coating state is extremely costly. Moreover, in some occasions the area of the vessel which is taking current is concealed and cannot be easily detected even with the method indicated before.

In this work, the coating state of a structure and the position of the damages, is analysed by using the information related with some sensors placed on the hull of the structure.

## 2. State of the art

In 1996, Aoki, Amaya and Gouka [ 2 ] applied the boundary element method to detect a paint defect on the hull of a ship. A ship which has six electrodes and six sensors was considered and assumed that a paint defect was developed in some area. The damaged area could be accurately predicted with this method when the damage is placed on one element of the hull. A larger area could be also predicted; however the effectiveness of the prediction will be reduced with the size of the damage. In case of larger sizes, all the possible combinations of several damages areas, which number is not known, must be carried out to find out where the damages are, which will imply a huge amount of computational time. More difficult cases will be found in the case in which the damages will have different coating thickness, in which cases apart from not knowing the sizes of the damages, the coating thickness relative to each one of the damages is also unknown.

In a real case, the unknown are the following:

- The sizes of the damages.
- The number of damages.
- The coating thickness of the damages.

This method could not cope with this amount of unknown without carrying out with a huge number of combinations.

In the approach followed below, an optimisation method is carried out to match the coating state of the surface.

In this work, the prediction of the coating state is achieved by matching some potential reference data on the hull of the structure. Extra information of the Under Electric Potential (UEP) of the vessel could be included in the search. The sufficient number of information, potential reference data, to obtain a reasonable solution is studied. The prediction of the damaged areas position is achieved by using interpolation functions over the surface, which will try to emulate the coating state.

## 3. Interpolation method

The coating of the prediction surface will be automatically modified by the optimisation method. This will imply that several polarisation curves or at least two polarisation curves should be considered, one with almost fully coated surface and the other with almost fully

uncoated surface, representing the material underlying the coating. When the value of the coating is found amongst the curves, a simple interpolation will give the correct value of the current and potential. A proper polarisation curve of the underlying material is not needed since just a representative curve which emulates the behaviour of the coating will be enough to carry out the optimisation.

The term sensors will be use from now on as point positions on the surface of the hull at which the coating will be modified (Figure 6). The coating of the rest of the surface will be interpolated amongst these sensors. Two methods of interpolation were investigated, the Radial Basis function and the three closest sensors.

### 3.1. Radial Basis function interpolation

Radial basis functions (RBFs) exhibit radial symmetry, they depend only upon the distance  $r = \|x - x_j\|$  between the centre of the function and a generic point  $x$ . These functions can be generically represented in the form  $\phi(r)$ . This means that there exist infinite radial basis functions [ 4 ].

These functions may be classed into: globally supported and compactly supported ones depending on their supports, this is to say, whether they are defined on the whole domain or only on part of it.

The most used ones within the globally supported RBFs are:

$$\text{Multiquadratic(MQ)} \quad \sqrt{(x - x_j)^2 + c_j^2}, c_j > 0 \quad (1)$$

$$\text{Reciprocal Multiquadratic (RMQ)} \quad ((x - x_j)^2 + c_j^2)^{-1/2} c_j > 0 \quad (2)$$

$$\text{Gaussians (G)} \quad \exp(-cr^2) c_j > 0 \quad (3)$$

$$\text{Thin-plate splines (TPS)} \quad r^{2\beta} \ln r, \beta \in \mathbb{N} \quad (4)$$

Within the compactly supported RBFs are:

$$\begin{aligned} & - \text{Wu and Wendland,} \\ & \quad (1-r)^n + p(r) \end{aligned} \quad (5)$$

Where:

$P(r)$  is a polynomial and  $(1-r)^n$  is 0 for  $r$  greater than the support.

$$\begin{aligned} & - \text{Buhmann,} \\ & \quad \frac{1}{3} + r^2 - \frac{4}{3}r^3 + 2r^2 \ln r \end{aligned} \quad (6)$$

The RBFs were tested as too their effectiveness at predicting the coating using the sensors points. The best predictions were achieved by the compactly supported RBFs Wu and Wendland ( 5 ), in the case that  $n=2$  and the polynomial  $p(r)=0$ .

$$(1-r)^2 \quad (7)$$

Briefly an interpolation with RBFs may take the form:

$$s(p) = \sum_{j=1}^N \alpha_j \phi(\|p - p_j\|) \quad (8)$$

In our case:

$$s(p) = \sum_{j=1}^N \alpha_j (1-r)^2 = \sum_{j=1}^N \alpha_j (1 - \|p - p_j\|)^2 \quad (9)$$

Where:

$N$  is the number of generic points.

$p$  is the generic point.

The values of  $s(p)$  are known, coating values, and therefore the set of equations of the form:

$$s(p_1) = \sum_{j=1}^N \alpha_j (1 - \|p_1 - p_j\|)^2 \quad (10)$$

$$s(p_2) = \sum_{j=1}^N \alpha_j (1 - \|p_2 - p_j\|)^2 \quad (11)$$

.....

$$s(p_N) = \sum_{j=1}^N \alpha_j (1 - \|p_N - p_j\|)^2 \quad (12)$$

The  $\alpha_j$  parameters are obtained by solving the above system of equations.

Once the  $\alpha_j$  are found, the equation ( 9 ) can be applied to all the points of the surface.

When the prediction of the coating is executed, the generic points are the sensors points, variables the optimisation will use to modify the coating.

### 3.2. Three closest sensors

The three closest sensors can be used to compute the coating of the current point by using a linear interpolation.

The process is based in the next steps:

1. The three closest sensors to the point considered,  $i$ , are searched; their coating values,  $s(p_1)$ ,  $s(p_2)$ ,  $s(p_3)$ , and their distances to the considered point,  $d_{i1}$ ,  $d_{i2}$ ,  $d_{i3}$ , are taken.
2. The equivalent distance ( $d_{eq}$ ) is computed.

$$\frac{1}{d_{eq}} = \frac{1}{d_{i1}} + \frac{1}{d_{i2}} + \frac{1}{d_{i3}} \quad (13)$$

3. And the value of the coating at the point considered is computed:

$$s(p_i) = \frac{d_{eq}}{d_{i1}} s(p_1) + \frac{d_{eq}}{d_{i2}} s(p_2) + \frac{d_{eq}}{d_{i3}} s(p_3) \quad (14)$$

The equations ( 9 ) and ( 14 ) could be used to predict the coating of the surface, Radial Basis Functions behaved slightly better than the three closest sensors. Thus, RBFs was the method of interpolation selected to implement the experiments below.

## 4. Prediction of the coating from reference cells measurements, Objective Function.

Two, objectives functions could be applied to predict the coating state shown below:

$$Obj_1 = \sum_{i=1}^{i=n} (r_{t_i} - r_{c_i})^2 \cdot \alpha + \left( \frac{V_t - V_1}{V_t} \right)^2 \quad (15)$$

$$Obj_2 = \sum_{i=1}^{i=n} (V_{t_i} - V_i)^2 \quad (16)$$

Where:

$r_t$  is the ratio between each pair of target potential references.

$r_c$  is the ratio between each couple of potential references.

$n$  is the number of possible pairs of references cells.

$V_t$  is the target potential of the first reference cell.

$V_t$  is the target potential of the reference cell i.  
 $V_1$  is the measured potential of the first reference cell.  
 $V$  is the measured potential of the reference cell i.  
 $\alpha$  is a penalty value.

A priori, the equation ( 15 ) is considered more adequate than the equation ( 16 ) since it takes into account the ratio of potentials of the reference cells and also the target potential. It combines both factors, but stresses the ratio of potentials. This has the advantage that if the model cannot represent exactly what occurs in real fact, it will try principally to match the ratio of potentials of the reference cells. Therefore, the equation ( 15 ) will be mainly used to analyse the experiments of this section. The equation ( 16 ) will be also studied and the results compared.

The equation ( 15 ) can be divided in two parts, the term ( 17 ) and the term ( 18 ). The term ( 17 ) minimises the ratio of potentials between all the reference cells and the term ( 18 ) minimises the difference between the target potential and the current value measured at the first reference cell. What will be enough to match all the targets of all the reference cells since the equation ( 17 ) will match the ratio amongst the reference cells.

$$\sum_{i=0}^{i=n} (r_{t_i} - r_{c_i})^2 \quad (17)$$

$$\left( \frac{V_t - V_0}{V_t} \right)^2 \quad (18)$$

A penalty value  $\alpha$  is applied to the term ( 17 ).  $\alpha$  is a large value which makes the smoothness of the ratio of the potential have a major influence in the equation ( 15 ).

If the potentials at the reference cells are tightly constrained around the target value, a large value of  $\alpha$  would be sufficient to carried out with the optimisation since the term ( 18 ) will be achieved by the constraints. On the other hand, if the constraints are relaxed, the value of  $\alpha$  begins to have influence in the leading path to the final design. Thus, a large value of  $\alpha$  will lead to a final design in which the ratio of potential of the reference cells are near the target ones but the target potentials may be not achieved. In contrast, a small value of  $\alpha$  will lead to a solution which is close to the target potentials but not the correct ratio of potentials.

## 5. Example Models

Two models of a cylinder and frigate were used to study the performance of the method.

### 5.1. Cylinder model

A model of a cylinder was also used to study the prediction of the coating.

The dimensions of the cylinder are:

- Length: 34.0 m.
- Diameter: 10.0 m.

The model has the characteristics shown in Figure 1. As an initial state of the hull, it was initially considered fully coated. The surface near one of the edges of the cylinder was set of Nickel-Aluminium-Bronze.

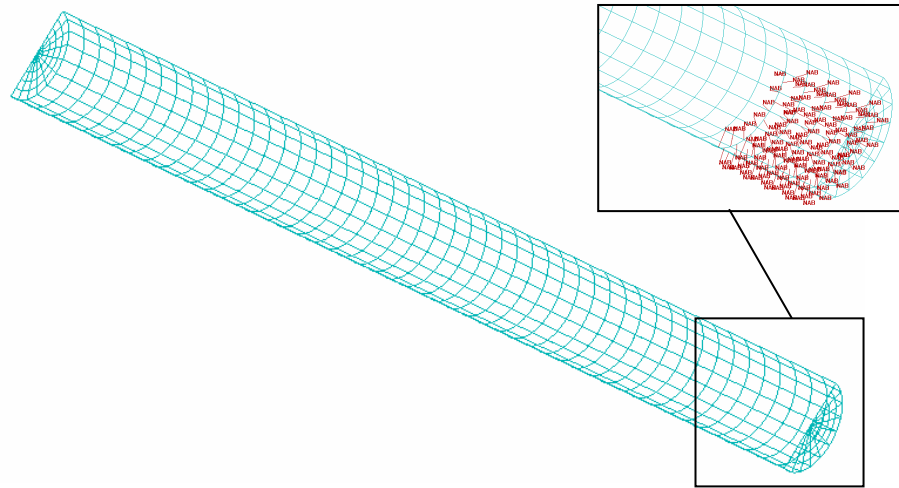


Figure 1 Cylinder model with Nickel-Aluminium-Bronze area.

To speed up the solution and since the model is symmetric only half of it was modelled.

### 5.2. Frigate model

A model of a frigate was developed to investigate several aspects involved in the optimisation process.

The dimensions of the frigate are:

- Waterline length: 34.0m.
- Draft: 2.3m.
- Waterline beam: 6.3m.

The model has the characteristics shown in Figure 2. As an initial state of the hull, it was initially considered fully coated. The propeller was nickel-aluminium-bronze. Several damaged areas were located on the hull surface in areas more likely of having been damaged during the life of the ship. The objective of this task is to create a model representing a typically damaged ship which will be used later used as a test case to identify the position of damage.

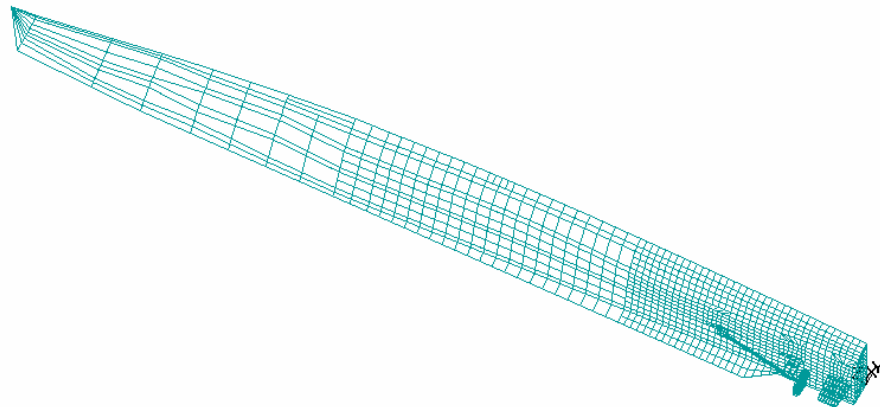


Figure 2 Frigate model.

To speed up the solution and since the model is symmetric only half of it was modelled.

The electrolyte considered was seawater with a resistivity of 20ohm cms, which implies a conductive of about 5S/m.

From the modelling point of view, the model has 1738 elements in the whole. The frigate itself was modelled with 1338 elements in most of the experiments analysed.

## 6. Predicting the condition of the cylinder

To study the effectiveness of the method, several sets of sensors are placed on the surface of the cylinder model. The objective of this example is to identify the location of the three damaged areas and hence the areas of the structure where the anode currents are going. The study is performed in steps whereby the amount of information known from the reference cells is increased until the solution is shown to have converged. The predictions will be carried out assuming no knowledge of the position of the damages.

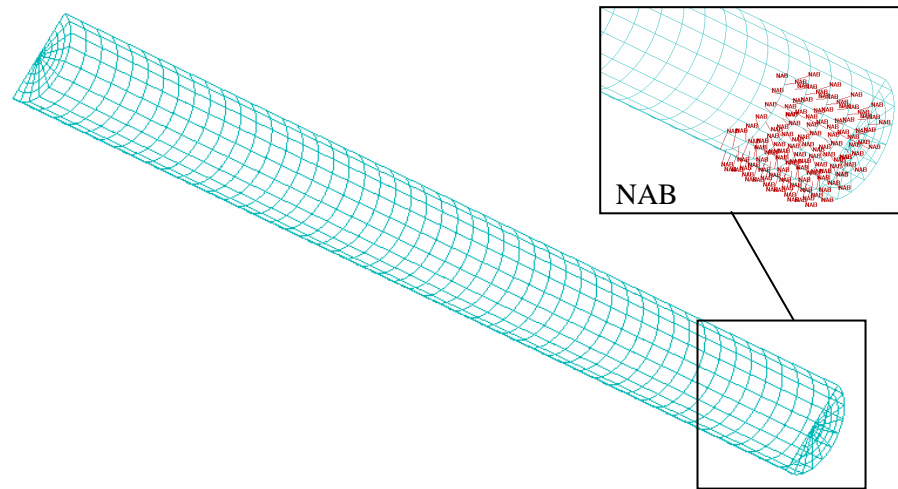


Figure 3 Cylinder model with Nickel-Aluminium-Bronze area in one edge.

### 6.1. Damage areas.

Three damaged areas were placed on the surface of the cylinder. The Figure 4 shows the position and size of the damaged areas. This model will be solved and several cells potentials will be taken and used as targets in the predictions.

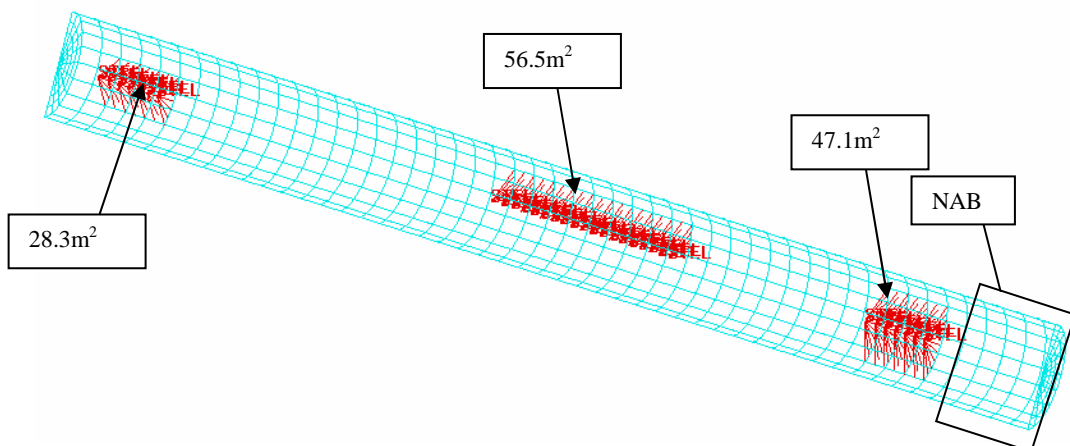


Figure 4 Damaged areas placed on the surface of the cylinder.

### 6.2. Coating searching area.

A searching area is declared. Its coating will be initially set as fully coated and then it will be varied until match the target coating condition. The Figure 5 shows the searching area in which the damages are to be predicted.

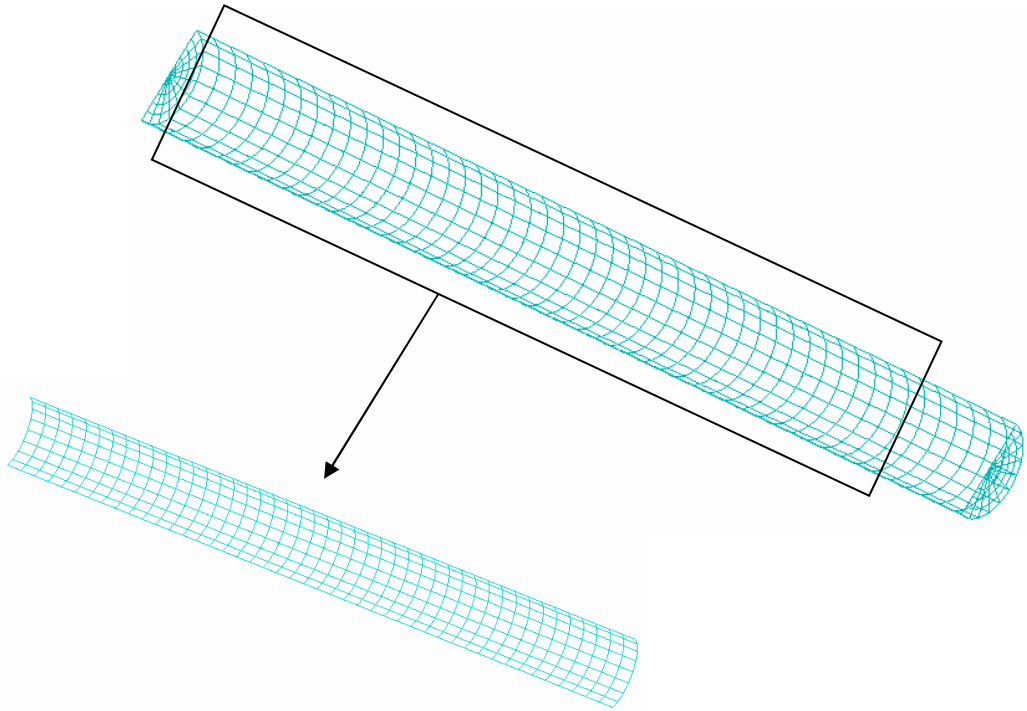


Figure 5 Searching area on the cylinder structure.

### 6.3. First array of sensors, 7 sensors.

An array of 7 sensors was placed on the predicting surface, distributed as it is shown in Figure 6. A radial basis function will be used as interpolation function to simulate the real state of the surface.

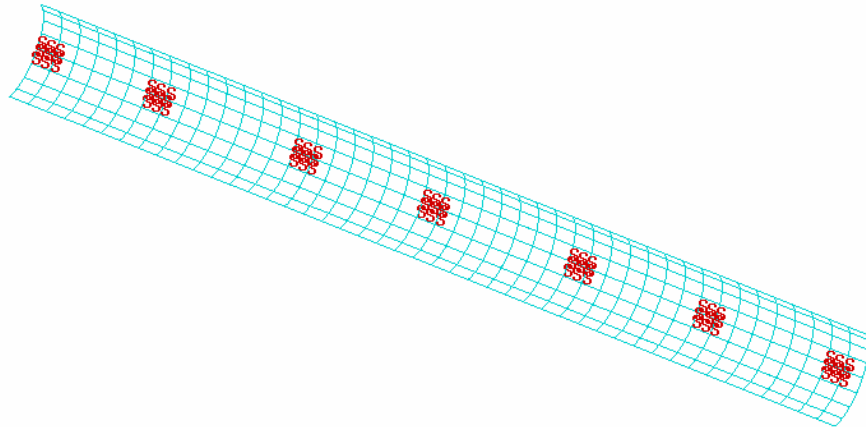


Figure 6 Seven sensors distribution on the prediction surface of the cylinder.

#### 6.3.1. One reference cell.

The first reference cell potential is used as target value in the optimisation process (Figure 7).

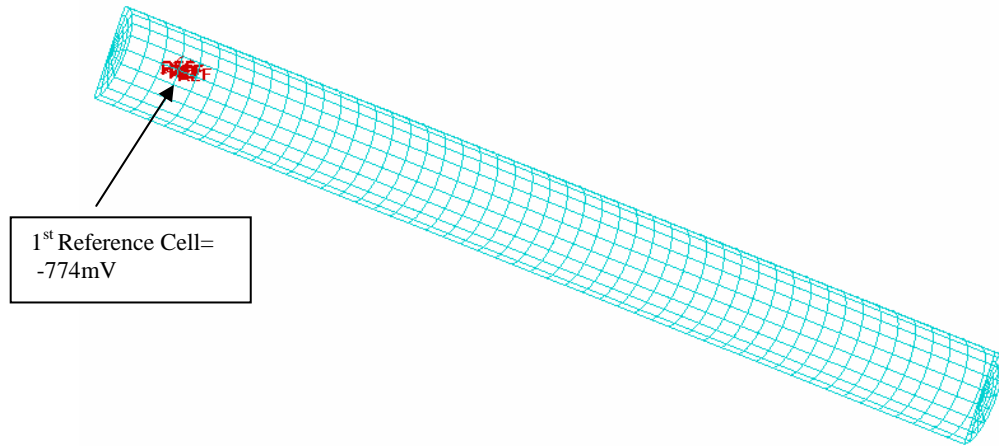


Figure 7 Position of the first reference cell on the surface of the cylinder.

The Figure 8 shows that only the two damaged areas at the edges of the searching surface were found. There is not enough information to represent the real state of the surface since the constraints are satisfied and the objective function presents a small value (Table 1).

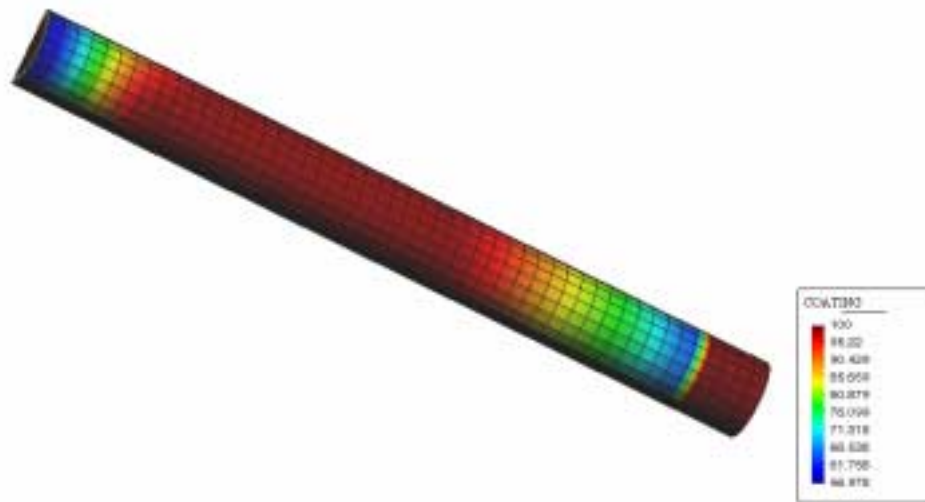


Figure 8 Prediction of the coating using only one reference cell and 7 sensors.

		Target	Constraints	% out target
<b>Iterations</b>	13			
<b>Objective function</b>	0.004			
<b>Number of references in the constraints</b>	1/1			
<b>SURFACE REF1: Potential</b>	-772.5	-774	-770, -777	0.2

Table 1 Summary of results obtained when only one reference cell was used as target value and 7 sensors to simulate the coating.

### 6.3.2. Two reference cells.

The second reference cell potential is added as target value in the optimisation process (Figure 9).

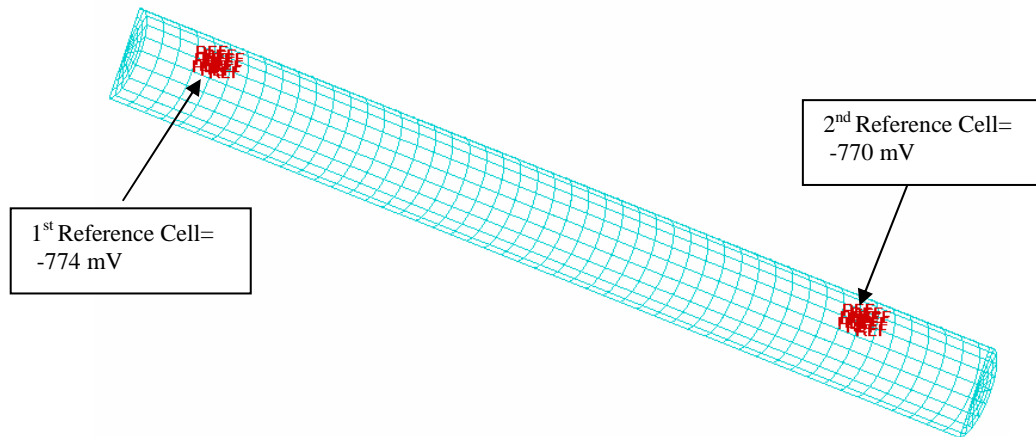


Figure 9 Position of the two reference cells on the surface of the cylinder.

The Figure 10 shows that only the damaged area at the centre of the searching surface was slightly found.

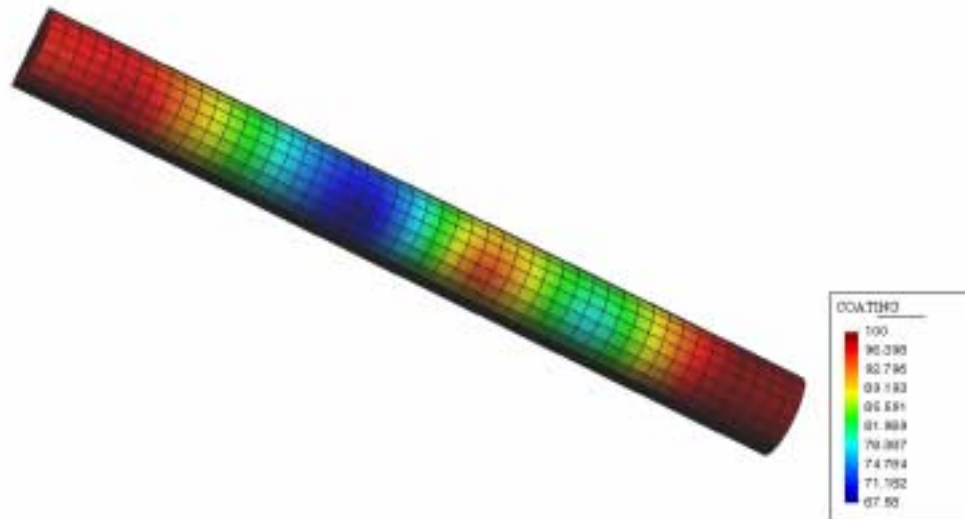


Figure 10 Prediction of the coating using two reference cells and 7 sensors.

		Target	Constraints	% out target
<b>Iterations</b>	21			
<b>Objective function</b>	570.5			
<b>Number of references in the constraints</b>	2/2			
<b>SURFACE REF1: Potential</b>	-771.3	-774	-770, -777	0.3
<b>SURFACE REF2: Potential</b>	-775.0	-770	-765, -775	0.7

Table 2 Summary of results obtained when two reference cell were used as target value and 7 sensors to simulate the coating.

### 6.3.3. Three reference Cells.

The third reference cell potential is added as target value in the optimisation process (Figure 11).

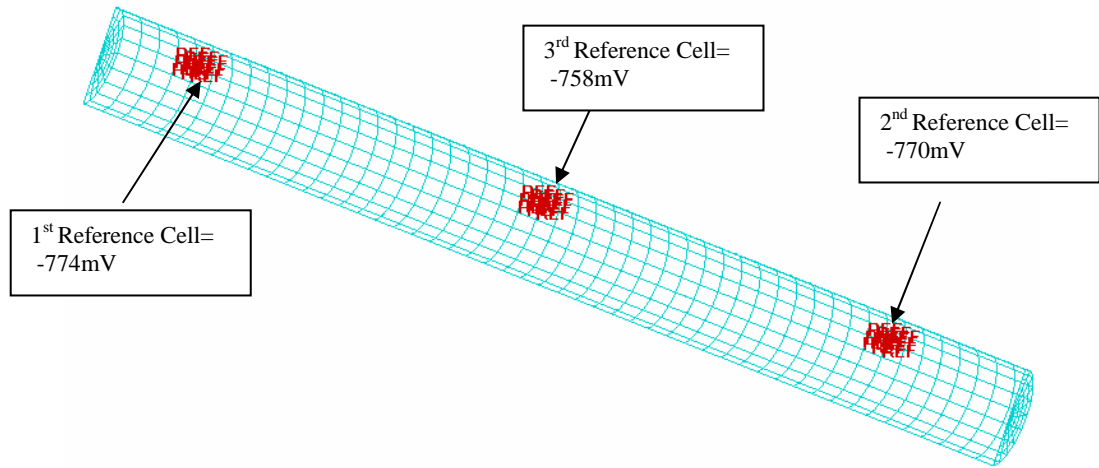


Figure 11 Position of the three reference cells on the surface of the cylinder.

The Figure 12 shows that the three damaged areas begin to be revealed. However, the position of the centre one is not well determined

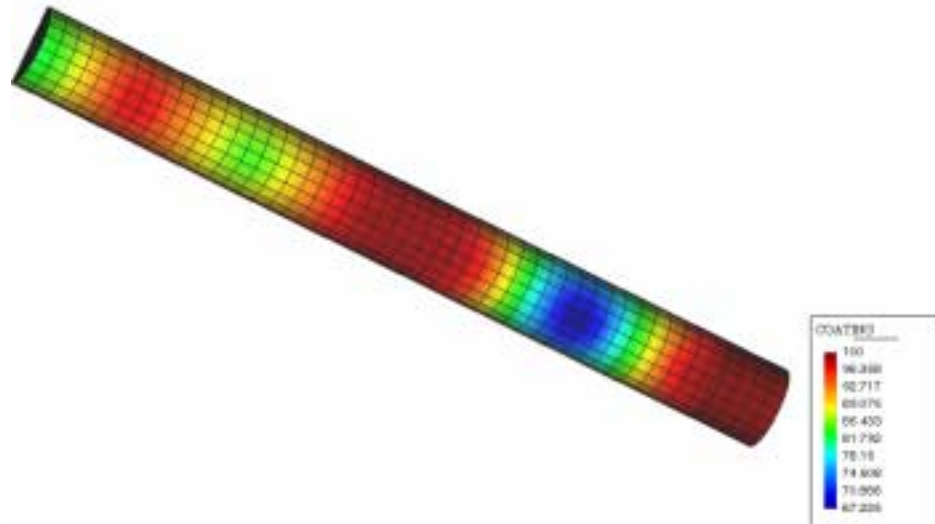


Figure 12 Prediction of the coating using three reference cells and 7 sensors.

#### 6.3.4. Four reference cells.

The fourth reference cell potential is added as target value in the optimisation process (Figure 13).

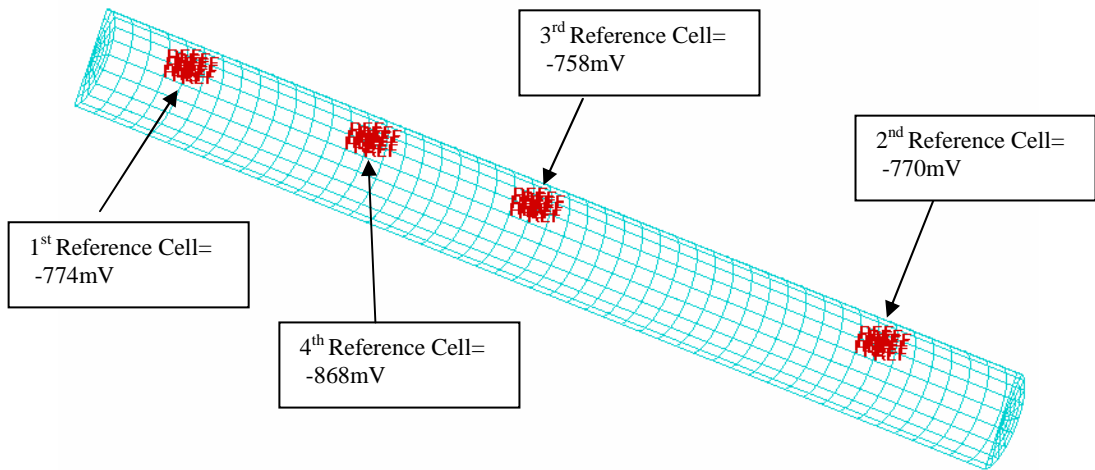


Figure 13 Position of the four reference cells on the surface of the cylinder.

In this case, the Figure 14 shows that the three damages were found in an approximate right position (Figure 4).

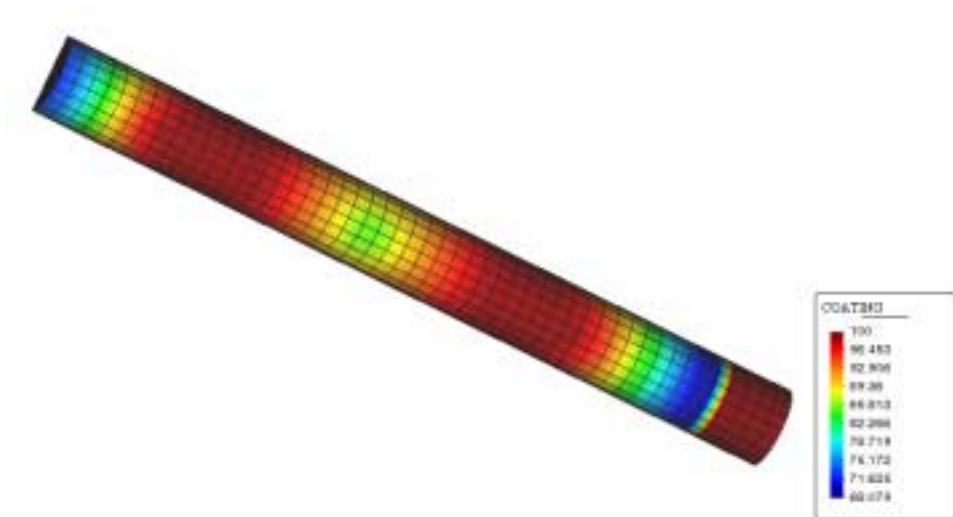


Figure 14 Prediction of the coating using four reference cells and 7 sensors.

**6.3.5. Five reference cells.**

The fifth reference cell potential is added as target value in the optimisation process (Figure 15).

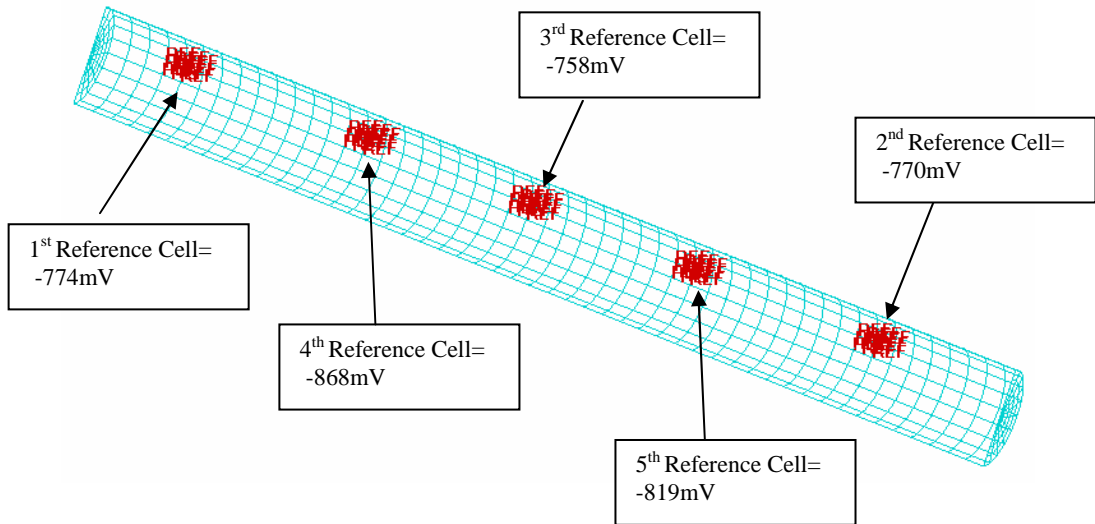


Figure 15 Position of the five reference cells on the surface of the cylinder.

In this case, the Figure 16 shows that the three damages were also found in an approximate right position (Figure 4).

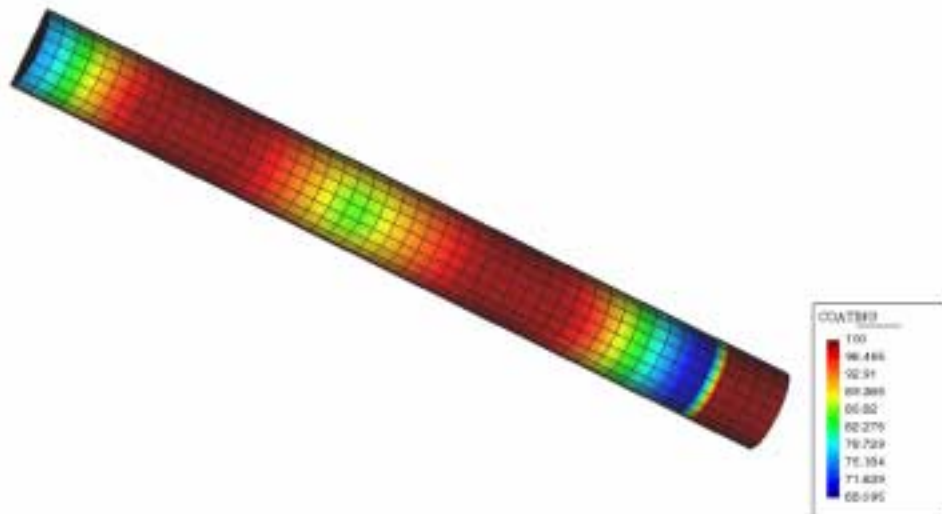


Figure 16 Prediction of the coating using five reference cells and 7 sensors.

#### 6.4. Second array of sensors, 8 Sensors

A second array of 8 sensors was placed on the predicting surface to observe the influence of the number of sensors and position in the performance of the optimisation (Figure 17).

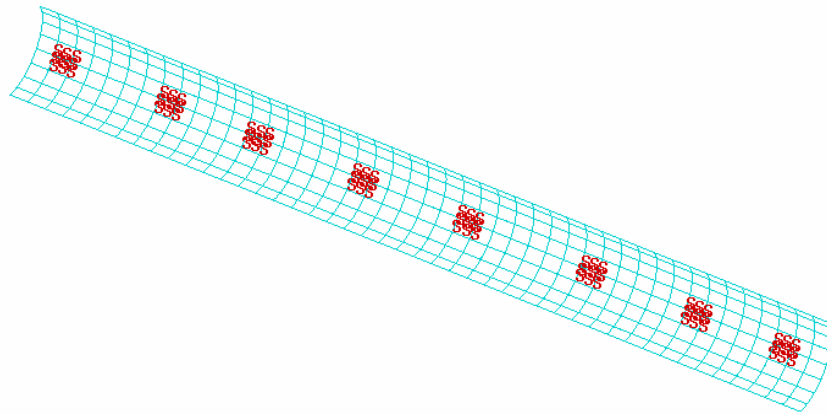


Figure 17 Eight sensors distribution on the prediction surface of the cylinder..

Similar analyses were carried out with several groups of array of sensors to find out the influence of the number of sensors and positions in the performance of the optimisation.

#### 6.4.3. Predicted Condition with Five Reference Cells

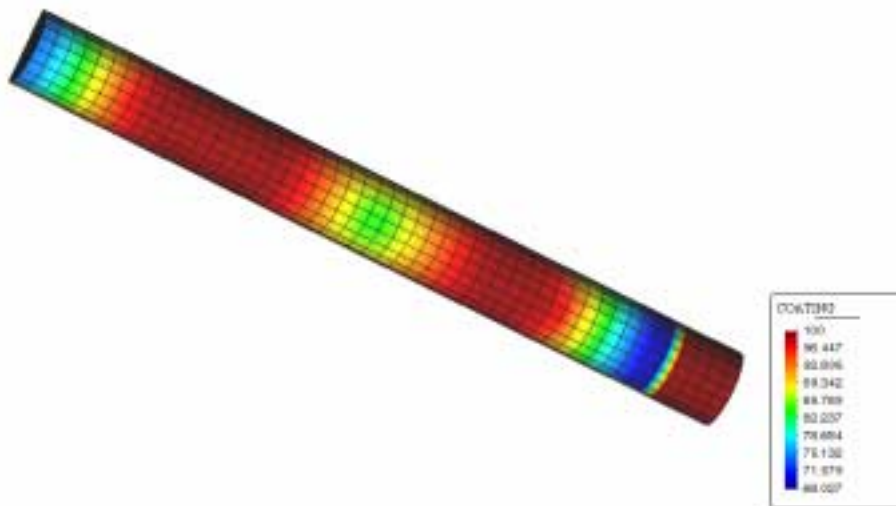


Figure 18 Prediction of the coating using five reference cells and 8 sensors.

#### 6.5. 9 Sensors

A third array of 9 sensors was placed on the predicting surface (Figure 19).

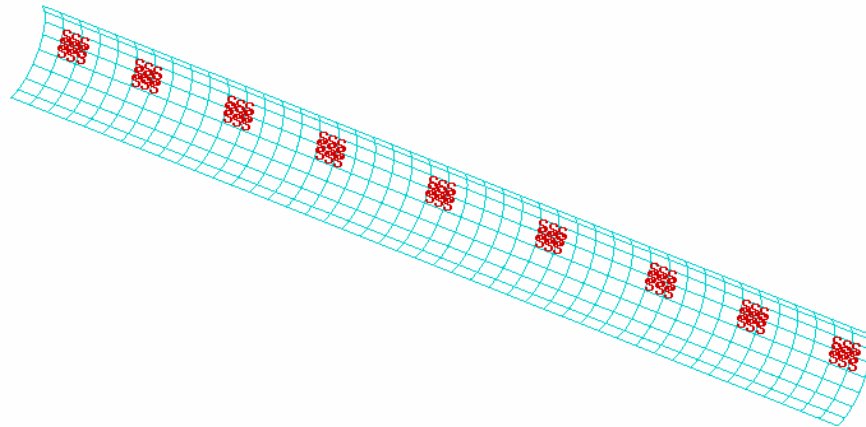


Figure 19 Nine sensors distribution on the prediction surface of the cylinder

### 6.5.2. Predicted condition with Five Reference Cells

The fifth reference cell potential was added as target value (Figure 15).

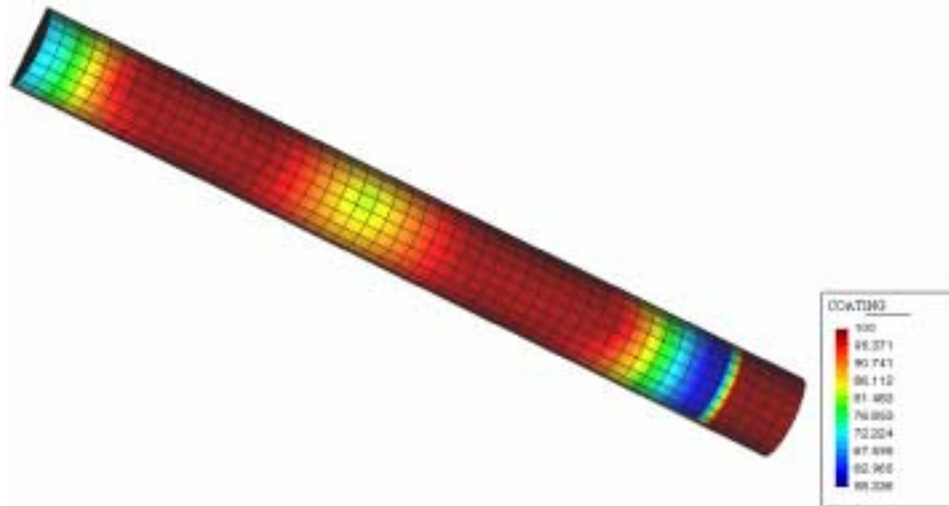


Figure 20 Prediction of the coating using five reference cells and 9 sensors.

### 6.6. Fourth array of sensors, 20 Sensors

A fourth array of 20 sensors was placed on the predicting surface (Figure 21).

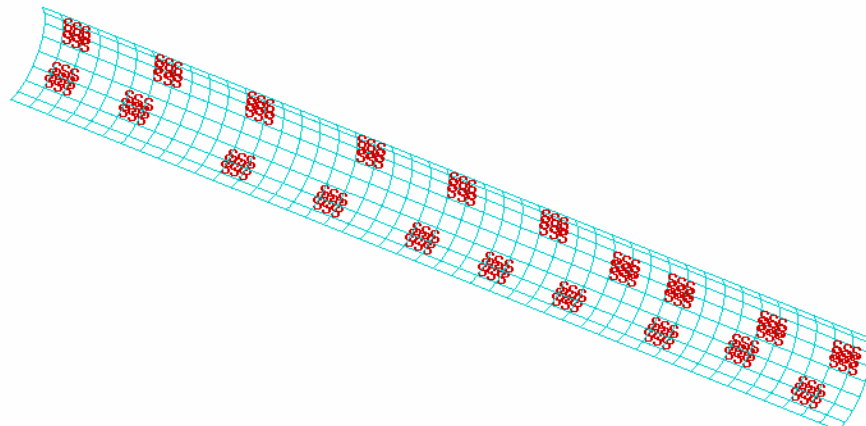


Figure 21 Twenty sensors distribution on the prediction surface of the cylinder.

### 6.6.2. Predicted condition with Five Reference Cells

The fifth reference cell potential was added as target value (Figure 15).

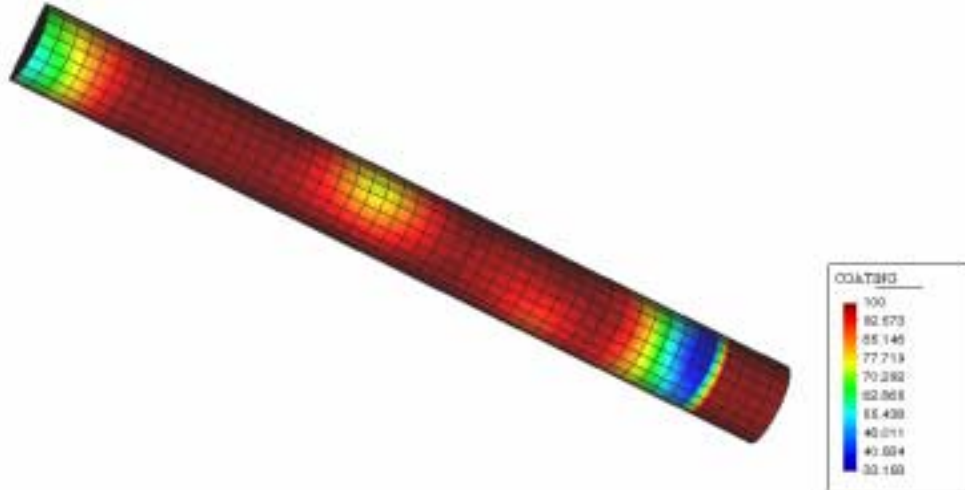


Figure 22 Prediction of the coating using five reference cells and 20 sensors.

### 6.7. Summary, cylinder

The objective function increases its value with the number of the reference cells, since the distribution of the sensors and the RBF<sub>s</sub> do not represent correctly the real situation of the damage areas. The best results, in the experiment analysed, are obtained when the number of reference cells data is at least 4, at that moment, even when the constraints are not satisfied, the results highlight the damaged areas

## 7. Predicting the condition of the frigate

Similar analyses were carried out with the frigate model. As previously, an inverse problem is to be carried out to test the process. The model with three damaged areas is to be initially solved. Once this model is solved, potentials of several reference cells are to be taken and used as targets in the predictions. Several sets of sensors are placed on the surface of the frigate model. Reference cells are to be added one by one to the model to study the effects in the prediction of the coating.

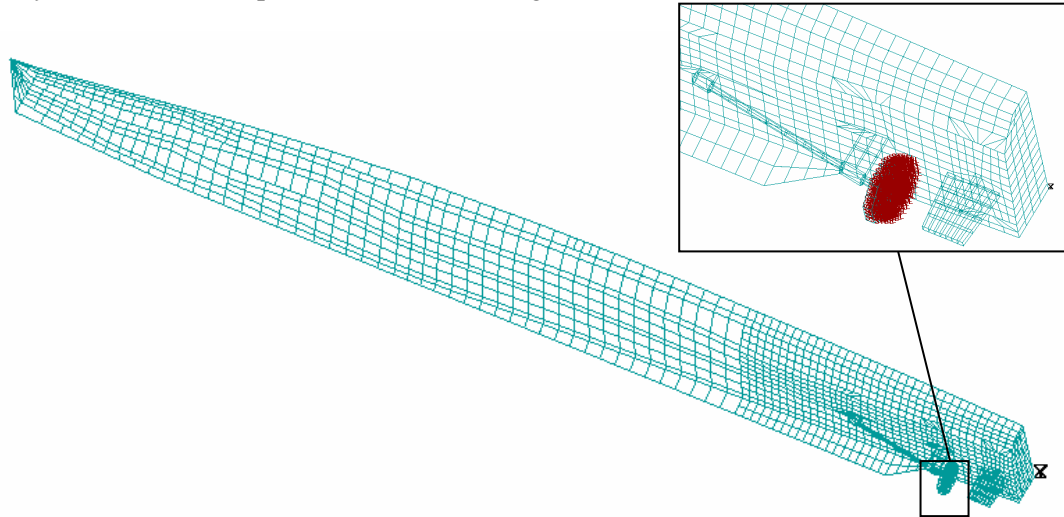


Figure 23 Cylinder model with Nickel-Aluminium-Bronze area.

Three damaged were placed on the surface of the frigate, the model was solved and the results are shown below.

### 7.1. Damage areas

Three damaged areas were placed on the surface of the frigate. The Figure 24 shows the position and size of the damaged areas. This model will be solved and several cells potentials will be taken and used as targets in the predictions.

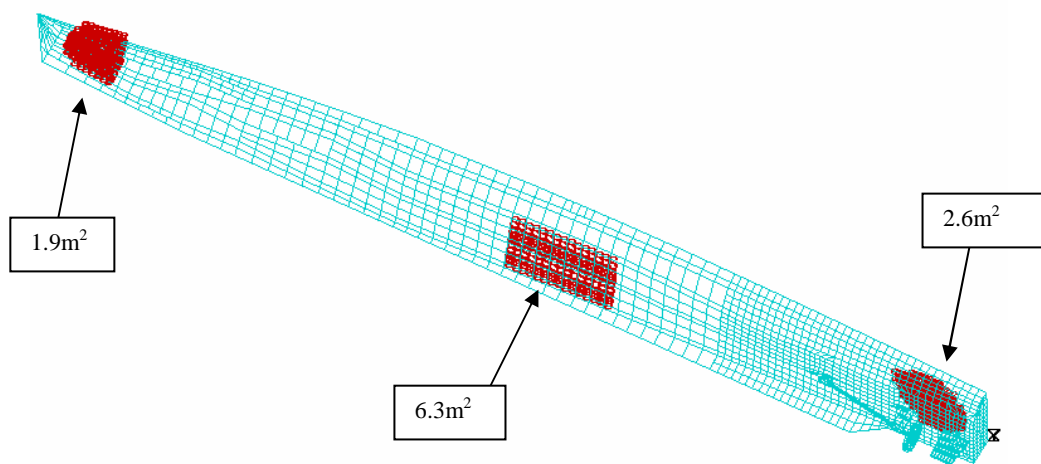


Figure 24 Damaged areas placed on the surface of the frigate.

### 7.2. Coating searching area.

The Figure 25 shows the searching area in which the damages are to be predicted.

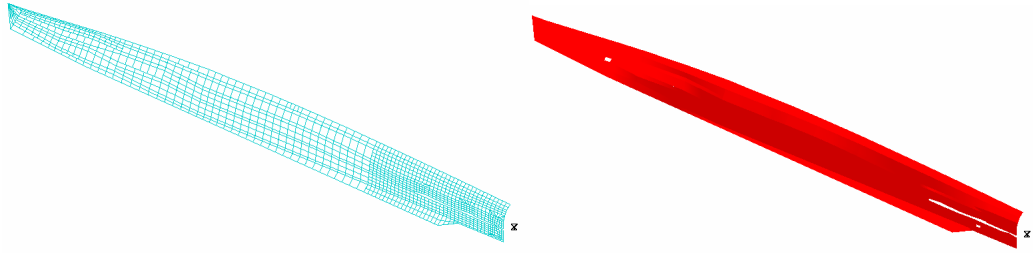


Figure 25 Searching area on the hull of the frigate.

### 7.3. First array of sensors, 7 sensors.

An array of 7 sensors was placed on the predicting surface, distributed as it is shown in Figure 26. A radial basis function will be used as interpolation function to simulate the real state of the surface.

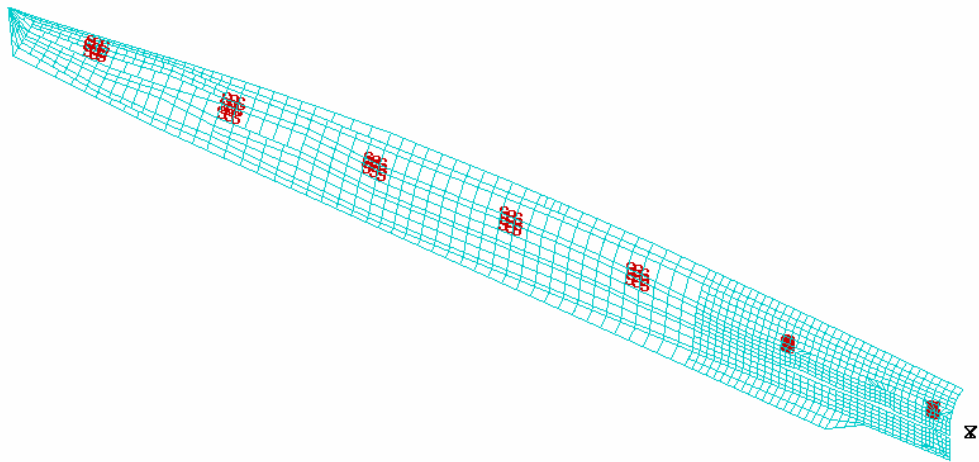


Figure 26 Seven sensors distribution on the prediction surface of the frigate.

#### 7.3.1. One reference cell.

The first reference cell potential was used as target value in the optimisation process (Figure 27).

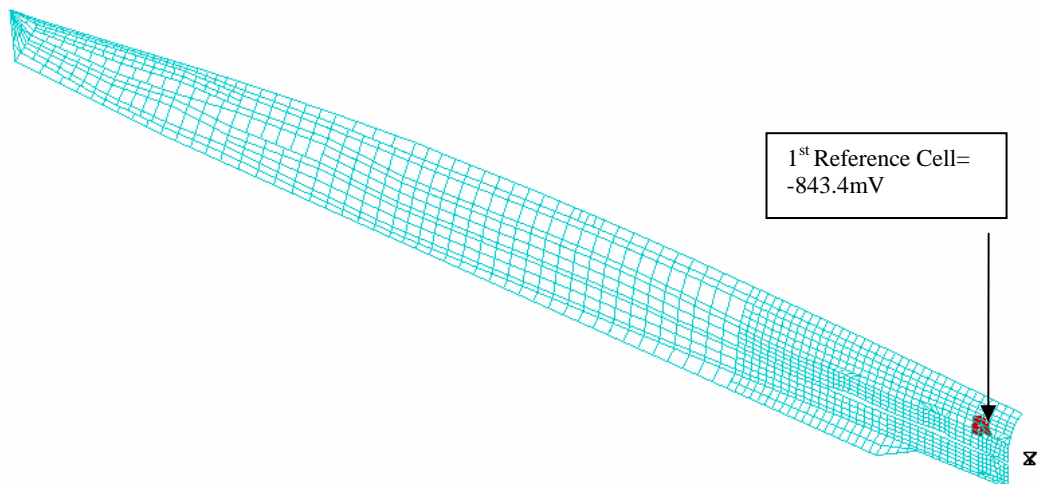


Figure 27 Position of the first reference cell on the hull surface of the frigate.

The Figure 28 shows that only the two damaged areas at the stern and at the bow were found. There is not enough information to represent the real state of the surface as the constraints, even when they are reasonably tight, are satisfied and the objective function presents a small value (Table 3).

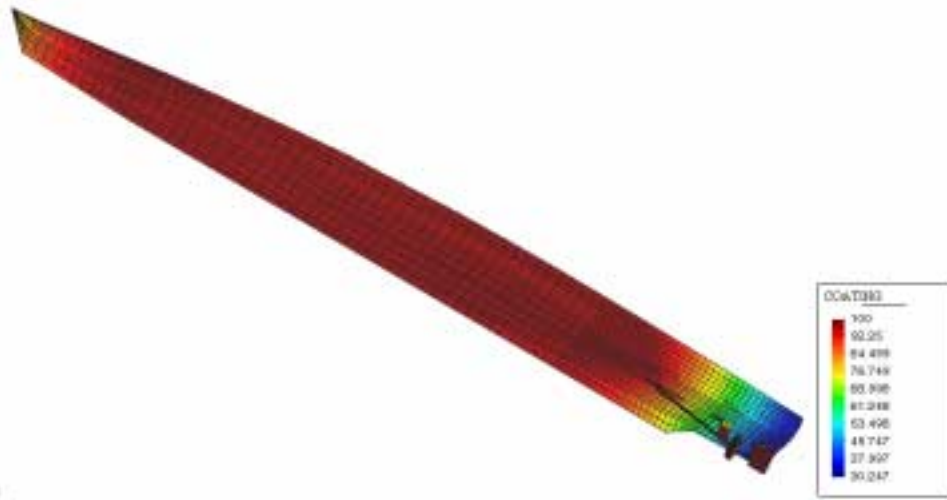


Figure 28 Prediction of the coating of the frigate using only one reference cell and 7 sensors.

		Target	Constraints	% out target
<b>Iterations</b>	9			
<b>Objective function</b>	0.83302129			
<b>Number of references in the constraints</b>	1/1			
<b>SURFACE REF1: Potential</b>	-844.3	-843.4	-840, -850	0.1

Table 3 Frigate, summary of results obtained when only one reference cell was used as target value and 7 sensors to simulate the coating.

### 7.3.2. Two reference cells.

The second reference cell potential was added as target value in the optimisation process (Figure 29).

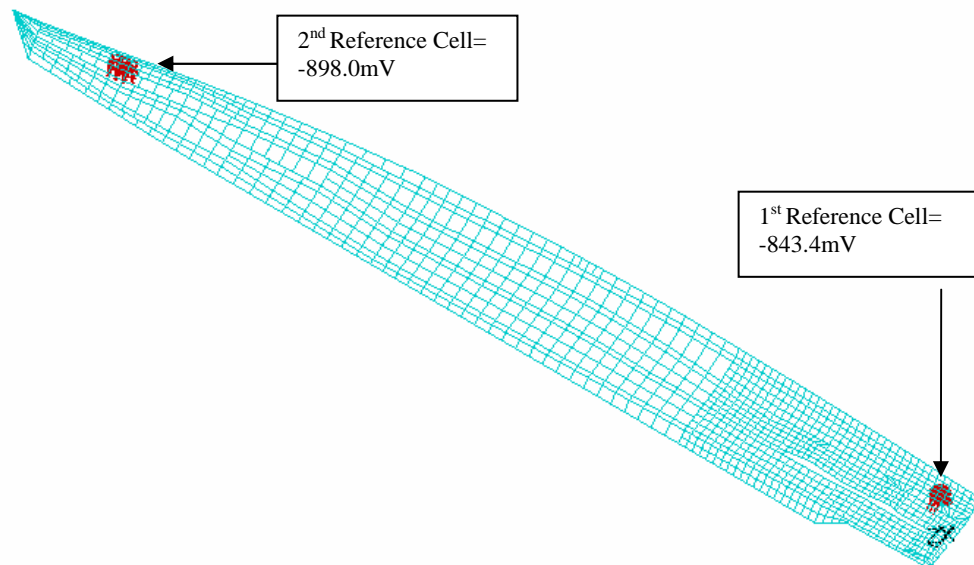


Figure 29 Position of the two reference cells on the hull surface of the frigate.

The Figure 30 shows that only the damaged area at the centre of the searching surface was slightly found and not in the right position.

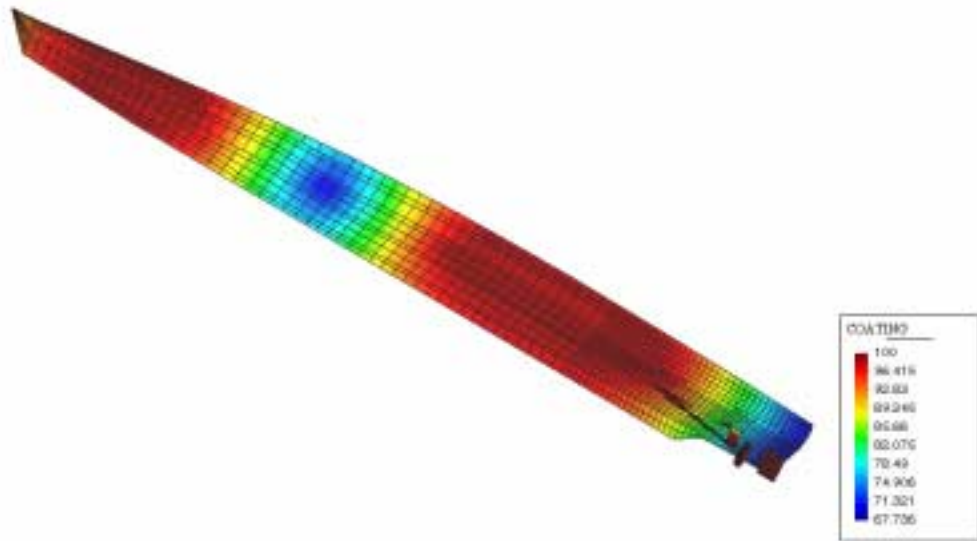


Figure 30 Prediction of the coating of the frigate using two reference cells and 7 sensors.

### 7.3.3. Three reference cells.

The third reference cell potential was added as target value in the optimisation process (Figure 31).

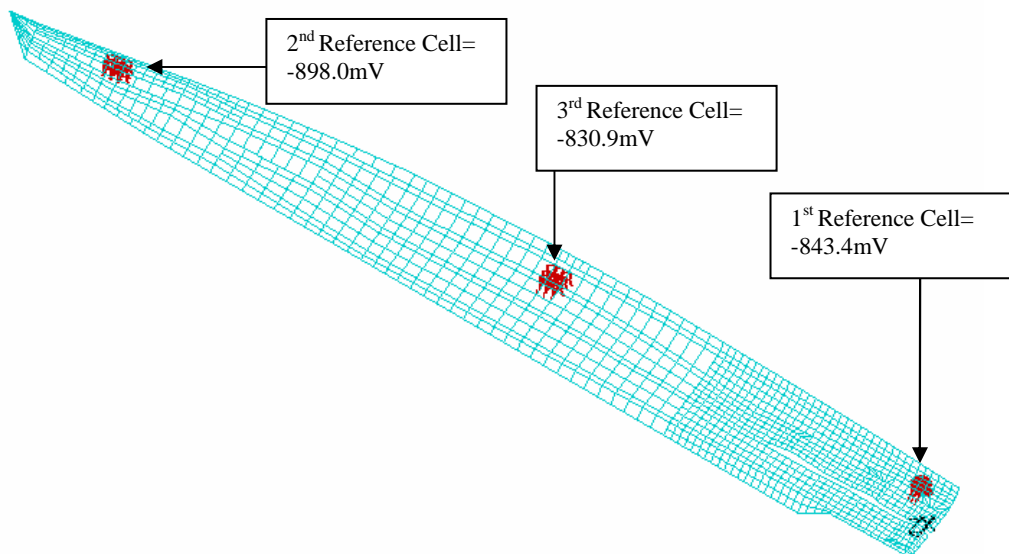


Figure 31 Position of the three reference cells on the hull surface of the frigate.

The Figure 32 shows that the three damaged areas are revealed in approximate correct position (Figure 24), the constraints are satisfied (Table 4) and the target values are matched.

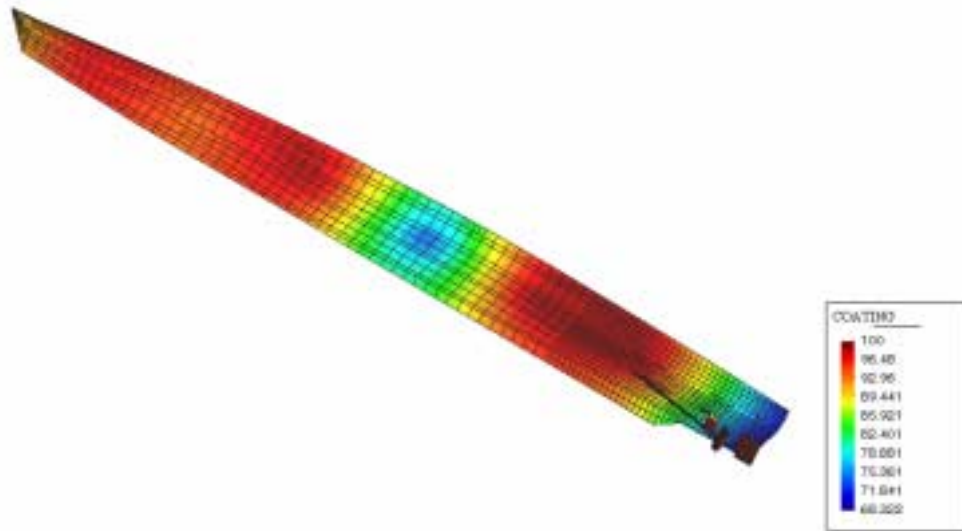


Figure 32 Prediction of the coating of the frigate using three reference cells and 7 sensors.

		Target	Constraints	% out target
<b>Iterations</b>	11.0			
<b>Objective function</b>	44947.3			
<b>Number of references in the constraints</b>	3/3			
<b>SURFACE REF1: Potential</b>	-843.4	-843.4	-840, -850	0.0
<b>SURFACE REF2: Potential</b>	-898	-898	-895, -905	0.0
<b>SURFACE REF3: Potential</b>	-829.7	-830.9	-825, -835	0.1

Table 4 Frigate, summary of results obtained when three reference cells were used as target value and 7 sensors to simulate the coating.

#### 7.3.4. Four reference cells.

The fourth reference cell potential was added as target value in the optimisation process (Figure 33).

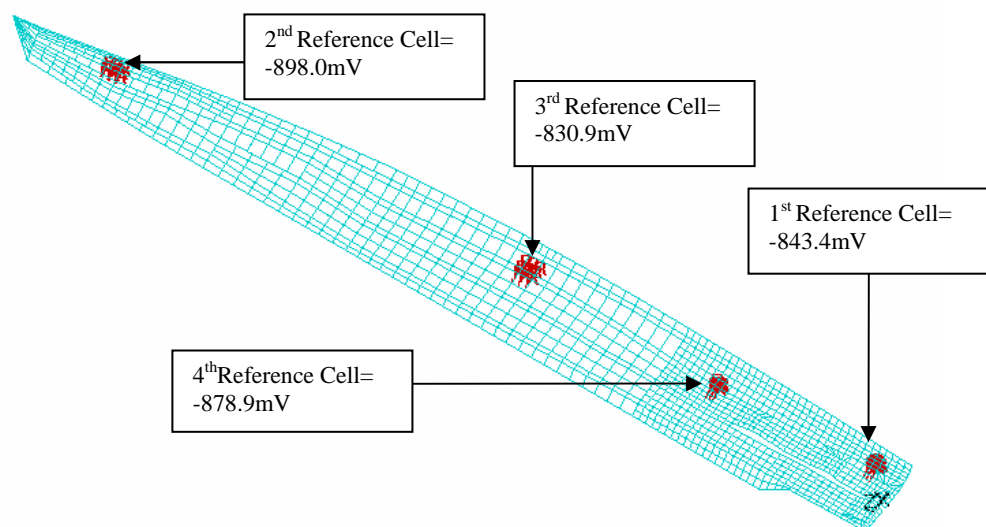


Figure 33 Position of the four reference cells on the hull surface of the frigate.

In this case, the Figure 34 shows that the three damages are found in an approximate right position (Figure 24).

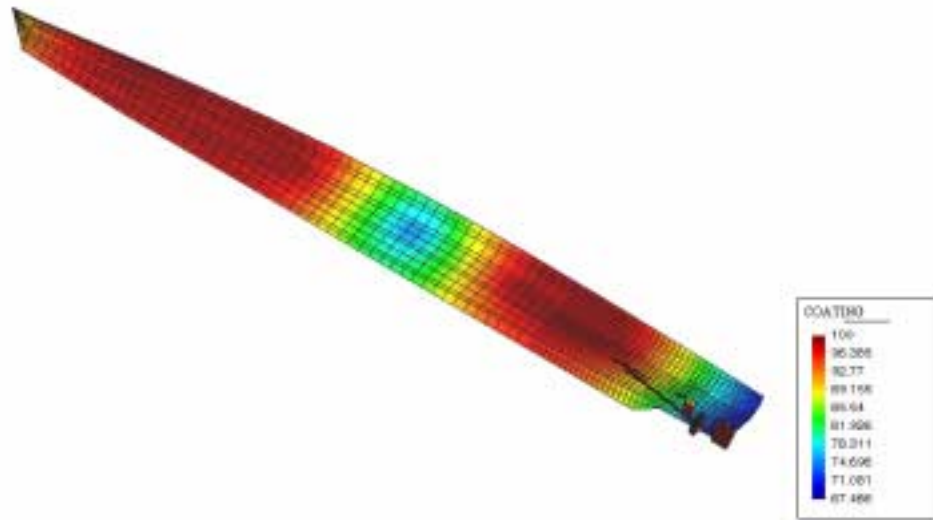


Figure 34 Prediction of the coating of the frigate using four reference cells and 7 sensors.

### 7.3.5. Five reference cells.

The fifth reference cell potential was added as target value in the optimisation process (Figure 35).

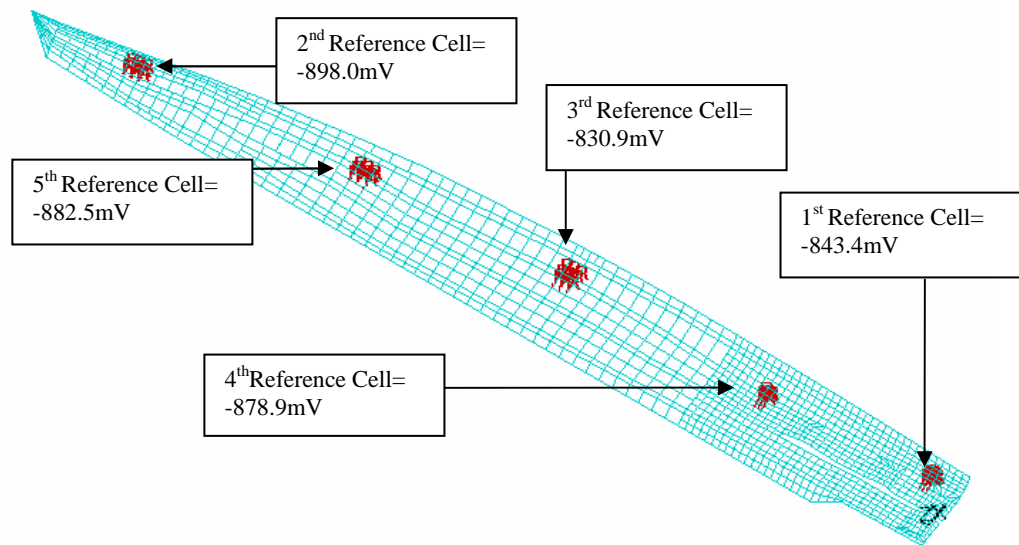


Figure 35 Position of the five reference cells on the hull surface of the frigate.

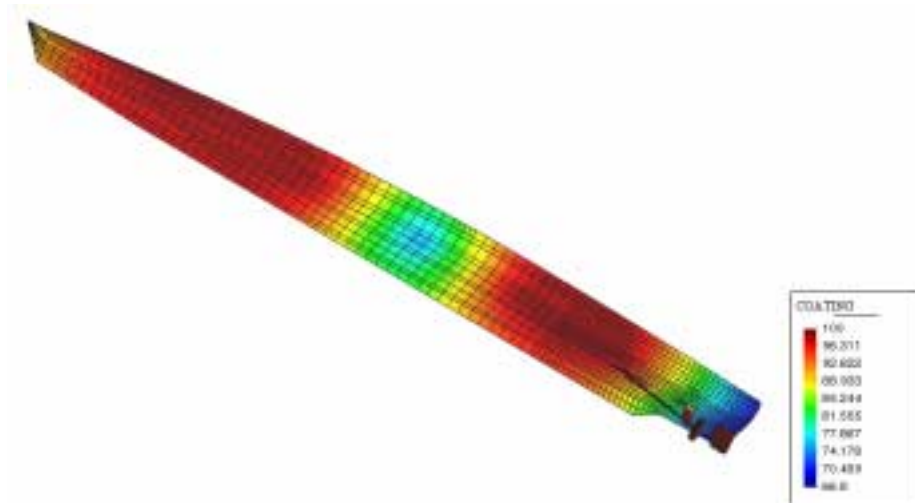


Figure 36 Prediction of the coating of the frigate using five reference cells and 7 sensors.

A second array of 12 sensors was studied and similar results were obtained with a slightly better prediction of the damaged area at the bow of the ship.

#### 7.4. Second array of sensors, 12 sensors

A second array of 12 (Figure 37) sensors was studied and similar results were obtained with a slightly better prediction of the damaged area at the bow of the ship

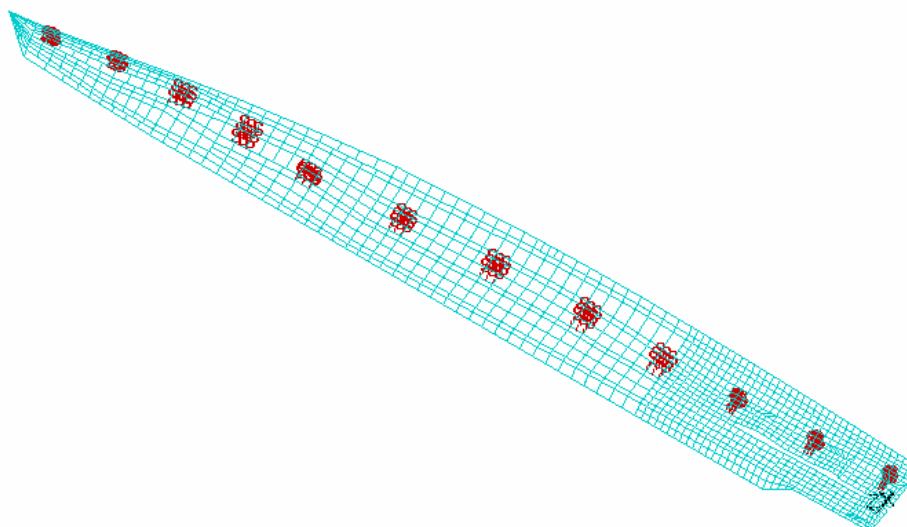


Figure 37 Twelve sensors distribution on the prediction surface of the frigate.

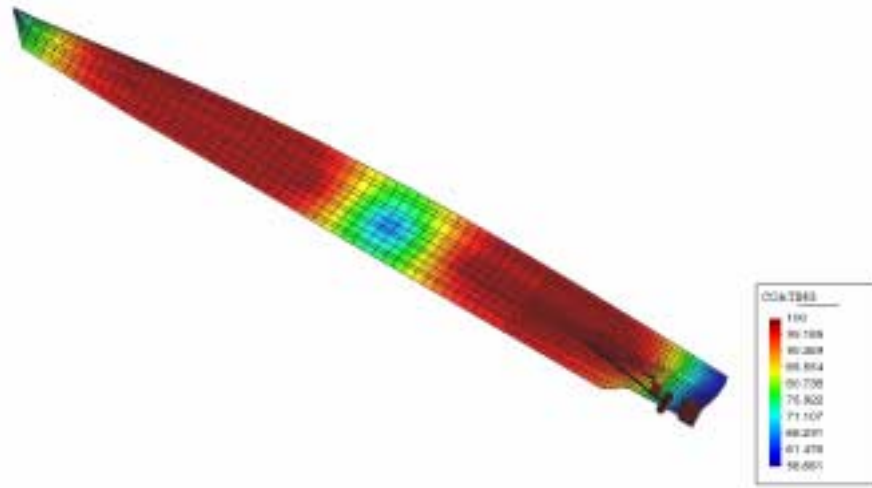


Figure 38 Prediction of the coating of the frigate using four reference cells and 12 sensors.

### 7.5. Summary, frigate

The best results, in the experiment analysed, are obtained when the number of reference cells data is at least 3. When three reference cells were used, the final design showed clearly the damaged areas. The design was still within the range of the constraints, therefore the number and positions of the sensors could satisfy the restriction imposed by the optimisation. When the number of reference cells was increased the final design was still accurate but started to be out of the range of the constraints.

When the number of reference cells is three or above the areas of damage are clearly predicted. As in the cylinder experiment, as of number of sensors was increased the difference between the target and the final design potential became closer.

## 8. Summary

Two models have been analysed, a cylinder model and a frigate model. Both of them had three damaged areas on their surfaces. A compact radial basis function was used since it can represent more local features and it was found to perform well in detecting damaged areas[ 4 ].

The objective function increases its value with the number of the reference cells, since the distribution of the sensors and the interpolations do not exactly represent the real situation of the damage areas. In addition, the constraints are not satisfied when the number of reference cells increases as it becomes more difficult to satisfy the tolerance. However the most important factor is that the solution was found to increase in accuracy as the number reference cells increases even when the constraints could not be satisfied.

The number and position of reference cells to determine where the damage areas are not known a priori. If the reference cell is located near a damaged area, its value will be significant to the optimisation process. However reference cells placed away from the damage will not give significant information about the damage unless they are members of a group of reference cells providing overall data on the hull potentials. Therefore, in some cases the information is sufficient to predict with accuracy what the condition of the hull is but in other occasions more information is needed. To avoid the uncertainty of this lack of information, several positions of the sensors should be studied. If the damage appear consistently in the same area, then the damage areas have been found.

The more the number of sensors, the more the capability of the optimisation to achieve the conditions imposed (constraints). Consequently, increasing the number of sensors makes the difference between the target and the final design potential become closer.

## 9. Concluding remarks

The prediction of the position of the damaged areas on the surface of two models has been achieved by using the potential measurements at reference cells on the structure.

Despite being an approximation to the real state of the coating, the RBFs or the three closest sensors enable the location of the damage to be predicted.

A certain number of potential references are necessary to predict the position of the damages otherwise the prediction will not be accurate enough and only some of the damages will be revealed.

The corrosion related electric and magnetic fields were also predicted for the condition of the vessel identified.

No precise polarisation data is necessary since a curve, which roughly represents the behaviour of the underlying materials, can be used.

The methods presented could form the basis of a condition monitoring system or improved control system for CP systems.

The electric field and the potential measurements on the vessel can provide with reasonable accuracy the position and condition of the damaged areas.

Further testing is required on real shipboard data to validate the techniques further and draw up guidelines for the number of sensors and reference cells required.

## References

[ 1 ] R.G. Rawlins, S.J. Davidson, and P.B. Wilkinson, Aspects of corrosion related magnetic (CRM) signature management, Wembley Conference Centre, London,UK, pp. 237-241. (1998)

[ 2 ] S. Aoki, K. Amaya and K. Gouka, Optimal cathodic protection of ship, In Boundary Element Technology XI, ed. R.C. Ertekin, C.A. Brebbia, M. Tanaka & R. Shaw. pp. 345-356 (1996)

[ 3 ] R.A. Adey, C.A. Brebbia and S.M. Niku, Applications of Boundary Elements in Corrosion Engineering. Topics in Boundary Element Research, ed. C.A. Brebbia, Volume 7 (1990)

[ 4 ] V. M. A. Leitao and C.M. Tiago, The use of radial basis functions for one-dimensional structural analysis problems, Boundary Elements XXIV, ed. C.A. Brebbia, A. Taden & V. Popov. pp. 165-179 (1996)