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Corrosion diagnosis of a ship mock-up from near electric field measurements

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Abstract — We present here an original application linking an electrochemical phenomenon and the computational aspect of electromagnetic fields to provide a corrosion diagnosis of a protected underwater steel structure. This is possible with the pairing of a numeric method, the BEM, and the study of inverse problems. After a defined operating time, it is mandatory to check an underwater steel structure. Sadly, current examinations techniques require immobilize the structure for a long time and are less efficient. The purpose of this paper is to replace this checking by a series of close electrical measurements in the electrolyte which provides a corrosion diagnosis of the structure. The new method introduced ensures a great time-saving but also an accuracy never reached before. This paper presents this method and its checking through real measurements on a frigate mock-up.

I. INTRODUCTION

During its operating life, an underwater structure suffers from corrosion. This phenomenon starts when iron paint defects appear on its surface, electrically linked to noble metals (propellers in Bronze and Nickel for example). This reaction, called galvanic coupling, makes the iron an anode and bronze a cathode. To fight against this reaction, two main methods have been developed:

- The Sacrificial Anode Cathodic Protection (SACP): some less noble elements than iron (Zinc, Aluminium, etc...) are placed on the structure to protect it. They are going to be corroded instead of the iron of the structure itself, becoming the new anode of the reaction.
- The Impressed Current Cathodic Protection (ICCP): Platinum anodes are distributed on the structure, injecting currents in the seawater. This places the iron in its passivation zone and protects it.

These two protections lead to a circulation of currents in the seawater, inducing the presence of a varying electromagnetic field. The first step of the study is to predict this electromagnetic field from the electric boundary conditions. Then, the problem will be inverted and a corrosion diagnosis will be deducted, starting from near electric field measurements and leading to the corroded areas localization. This paper, based on electric fields and applied to real measurements on a mock-up, extensively improves a method previously introduced [1].

II. FORWARD MODELING

As said before the forward modeling aims to predict the electric potential and the electromagnetic field from physic

boundary conditions. Trying to achieve to diagnosis tool, the numeric method used must directly link the boundary conditions to the measurement locations, advantage provided by the Boundary Elements Method. Moreover, this method permits a simple modeling of the infinity region [2] [3].

Starting from the Laplace equation, the principle is to use the third Green's identity to write an integral equation on the Γ boundaries of the problem:

$$h(M)\varphi(M) + \oint_{\partial\Gamma} \varphi(P) \cdot \frac{\partial}{\partial n_q} G(M, P) dl - \oint_{\partial\Gamma} G(M, P) \cdot \frac{\partial}{\partial n_q} \varphi(P) dl = 0 \quad (1)$$

where φ is the electric potential and $\partial\varphi/\partial n$ the opposite of the normal current density, within the conductivity σ factor. P is the integration point on the boundary and M the point where the computation is made. $h(M)$ is the solid angle seen by M and G is the Green function $1/r$, where r is the distance |MP|.

After the surfaces have been meshed, a point matching approach of (1) at the barycenter of each element can be provided, leading to a matrix system..

$$[A_{Green}] \left[\frac{\partial \varphi}{\partial n} \right] = 0 \quad (2)$$

Making such an approximation is known as not very precise, but, as the main goal is the development of an inverse method, it is acceptable for us. Of course, this system has more unknowns than equations. To solve it requires the introduction of boundary conditions. At the last step of this forward modeling, we get a non linear system due to the form of the polarization law ($\partial\varphi/\partial n = f(\varphi)$) introduced by the presence of polarizable steel on the boundaries. This system is then usually solved by an iterative Newton-Raphson process.

The electric field anywhere in the domain is then available thanks to the gradient of (1):

$$\mathbf{E}(M) = \frac{1}{4\pi} \oint_{\partial\Gamma} \varphi(P) \left(-3 \cdot \frac{(\mathbf{r} \cdot \mathbf{n}) \mathbf{r}}{r^5} + \frac{\mathbf{n}}{r^3} \right) + \frac{\partial \varphi(P)}{\partial n} \cdot \frac{\mathbf{r}}{r^3} dl \quad (3)$$

If the electric field is expressed in several points, the last equation can be represented by the following system:

$$[A_{Measurement}] \left[\frac{\partial \varphi}{\partial n} \right] = E \quad (4)$$

III. INVERSE METHOD AND IMPROVEMENTS

The main goal is, from real electromagnetic measurements contained in the E vector and the construction of the system (4), to find the X vector. This problem is very ill posed, due to a different number of unknowns and equations, numeric approximations and measurements error. It leads to a very bad

condition number for (4) and a direct inversion provides a good mathematical results but with no physic behavior.

An original method to get a better condition number is to add the Green equations from (2) linking all unknowns on the boundaries. This ensures to have a physical result and permits to reduce the number of measurements to make. This first step permits a real facilitation of the inversion [1]:

$$\begin{bmatrix} A_{Measurement} \\ A_{Green} \end{bmatrix} \begin{bmatrix} \varphi \\ \partial\varphi/\partial n \end{bmatrix} = \begin{bmatrix} E \\ 0 \end{bmatrix} \quad (5)$$

In a second time a regularization technique is needed to get the best solution of (5). The one chosen is Tikhonov’s method, its principle being to find a solution minimizing [4]:

$$\min(\|A.X - B\| + \lambda\|L.X\|). \quad (6)$$

The L matrix is called the regularization matrix: a 0-order regularization (L is the identity matrix) privileges solutions with minimum norm; a 1-order one favors continuous solutions and a 2-order one accentuates this continuous behavior. In our study, a 2-order method is chosen. The λ choice, image of the importance given to this regularization (symbolizing the compromise between solution precision and regularization effect) is made thanks to the well-known L-curve technique.

IV. METHOD CHECKING WITH REAL MEASUREMENTS

To check the diagnosis method explained before, real measurements are employed: a composite 1/40th mock-up of a frigate has been equipped with an adapted ICCP, electrically linked to iron plates (simulating the paint defects) disposed on the hull. The mock-up is then placed in a salted water with a controlled conductivity (5,16 S/m).



Fig. 1. 1/40th mock-up set in measurement conditions

When the ICCP is running, some electric field measurements are made on lines at different depths.

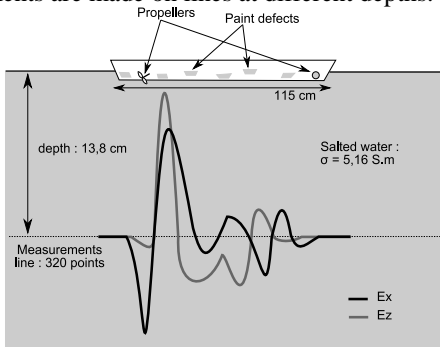


Fig. 2. Real electromagnetic measurements on a 1/40th mock-up

These measurements have been made in the Physical Scale Modeling (PSM) facility of the US Naval Research Laboratory (NRL) located in Key West (Florida). In fact, 640 measurements are made: 320 Ex and 320 Ez, no one made on the y (transverse) axis. The complex meshing of the structure gives 3103 elements, making the system under determined.

By adding the 3103 Green equations through A_{Green} , the new system gets a better condition number. An interpolation is finally made from the electric field measurements, to get a sufficient number of equations and make the problem over determined.

The current density on each anode is known (in the range of the hundred A/m²) as an evaluation of the mean value of the current density on the propellers. The previous improved inverse method gives the following results on the hull:

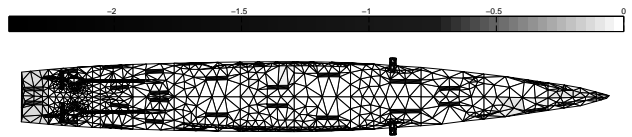


Fig. 3. Current density on the boundaries in A/m²

Current density results are only shown, because of their visibility, but potentials are also obtained. The scale is negative as we want to see the currents going back to the hull, which are the corroded ones. These parts correspond to the less potential areas. The result matches the real location of the iron plates, giving a good diagnosis, with less than 5% of error. The method guarantees good results with a complex geometry and real measurements.

V. CONCLUSION

This diagnosis method succeeds in locating the corroded areas of an immersed part of a hull with real electric field measurements. But some other structures can be studied, as pipelines, offshore platforms, etc... Potential measurements can also be the basis but the use of electric field sensors is more widespread. Moreover, the numerical tools used here can be applied to other scientific domains, such as heat problems for example.

VI. REFERENCES

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