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# Hybrid snapshots-Steklov BEM basis to identify hull corrosion states from nearby electric field measurements

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**Abstract.** This article presents an innovative approach to diagnose the state of a corroded ship's hull by utilizing measurements of the electric field in its vicinity.

**Keywords:** Inverse problem, corrosion diagnosis, BEM, ships electric signature.

## INTRODUCTION

Ships are prone to corrosion, a phenomenon that deteriorates their hulls and requires proper diagnosis. Natural corrosion occurs when different underwater parts of the hull, each with different materials so different electrochemical potentials, are galvanically connected through conductive seawater. Corrosion generates an electric current in the vicinity of the ship, which can be measured and used to assess hull corrosion state by solving an inverse problem. Previous research has already addressed this topic. Since the phenomena in seawater are governed by the Laplace equation, the forward problem is traditionally solved using a Boundary Element Method (BEM) [1], [2]. In this method, only the hull/seawater interface is discretized, and each mesh element is associated to an impedance boundary condition (Robin condition) that connects the potential to its normal derivative, representing the current on the hull. This boundary condition is known under the name of polarization curve and is an input data of the forward modelling. Once the BEM problem is solved, the potential and current values are obtained for each element of the surface mesh, and an integral post-processing step can be employed to calculate the electric signature. The inverse approach involves inverting the BEM formulation i.e. getting the polarization state for each element of the mesh from electric measurement. The problem consists in minimizing a residual between observed electric field data and the model which is generally parametrized by the normal current density flowing from the hull to the seawater. It can be solved in the least square sense using a linear solver [1] or by using nonlinear optimization techniques that rely on computing parameter sensitivities [2]. However, regardless of the resolution techniques employed, the problem always remains ill-posed, indicating that the solution is not unique. Therefore, it becomes necessary to implement solution regularization techniques. The challenge with these techniques is that the desired physical solution does not always adhere to the regularity criterion. Certain areas of current collection, such as propellers, sacrificial anodes, and bow thrusters, exhibit highly localized behaviour on the hull. Conversely, other areas, such as regions with deteriorated insulating paint, are associated with much more regular current distributions. In this paper, we propose a method to address this issue by projecting the solution of the inverse problem onto bases that better represent the underlying physics of the phenomena.

## INVERSE PROBLEM FORMULATION

### A snapshot basis for localized current collecting area

Some specific areas on the hull that are prone to current collection can be identified in advance. These localized and specific areas, such as the propeller, bow thrusters and sacrificial anode, are generally small compared to the total surface of the hull. Let us notice that if the hull is totally protected by a perfect insulated paint, currents flowing in the seawater are only delivered or collected by these zones. A good strategy is then to project the solution of the inverse problem on a set of snapshots representing these specific current paths, the parametrization of the inverse problem being the weighting total current value. Each snapshot with associated electric signature is computed by the Boundary Element Method (BEM). To ensure impartiality towards any particular solution, each snapshot is computed by imposing a 1-amp current on the collecting area and 0V at infinity. The solution to the inverse problem is then obtained as a linear combination of the fields generated by all these snapshots, with an additional equation that enforces the sum of currents on the hull to be zero.

## Additional Steklov reduced-order basis to identify diffuse current densities

Let's consider a scenario where, in addition to the localized current collecting zones, the current is also able to be collected more uniformly through a larger and diffuse area. This phenomenon may occur, for example, due to a defect in the insulating paint on the hull that we aim to diagnose. The equation derived from the Boundary Element Method (BEM) establishes a connection between the potential and the current flux density. This equation can be reformulated as an impedance matrix using the Steklov-Poincaré operator [3]. A reduced-order model of this impedance matrix can be constructed with a truncated singular value decomposition. Only the vectors associated with the most significant impedance modes are retained (reduced-order Steklov basis). This approach offers several advantages: limiting the degrees of freedom for the inverse problem and obtaining current distribution vectors that are already smooth without requiring additional regularization technique. Each vector of the basis is associated to a measured electric field and completes the previous snapshot basis. The constraint of the null sum of the current is enforced using the first mode of the reduced basis, which is the only one having a non-zero integral value for the current on the hull.

## Global resolution with ECOS optimisation solver

The hybrid current basis used previously successfully solves the inverse problem. However, incorporating additional constraints can further enhance the robustness and physical significance of the solution. One important constraint is to enforce a positive integral of the current associated with Steklov vectors, as paint defects can only deliver current. Another constraint involves minimizing the number of non-zero coefficients in the localized snapshot vectors (parsimonious optimization). To address this constrained inverse problem effectively, a conic solver like ECOS [4] is chosen.

## NUMERICAL EXAMPLE

To validate the methodology, a numerical example is presented using a ship's hull as the object of study. The current is delivered by two sacrificial anodes and two bow thrusters (77% of the total current). The remaining 23% is generated by a diffuse painting defect located on the front of the hull. All the current is collected by the propeller. A numerical computation of electric field measurements is performed on a plane situated 15m below the keel. Additionally, a numerical noise component of 5% is introduced. For the inverse problem, a total of 45 parameters are considered. This includes 5 coefficients for the snapshots and 40 modes for the Steklov basis. The results, as shown in Fig. 1, demonstrate that all coefficients are determined with a satisfactory level of accuracy, with an error rate of approximately 25%. The defect area is obviously found with a less precise but suitably localized definition.

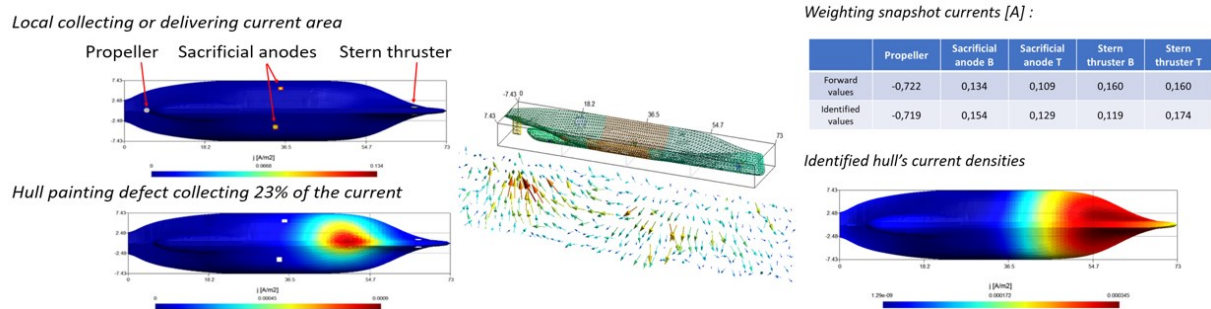


Figure 1: left column: Forward modelling of the hull (top: delivering localized current areas, down: paint defect current density). Middle column: noisy electric field computed signature. Right column: solution of the inverse problem (top: forward and identified snapshot weighting current, down: identified current hull's current density).

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