Experimental vs. computational system analysis

V. G. DeGiorgi & E. A. Hogan
Naval Research Laboratory, Washington, DC, USA

Abstract

Computational and experimental methodologies are often seen as competing resources. This is unfortunate because in the evaluation of complex physical phenomenon often both methodologies are required to develop a complete understanding of the underlying basic science as well as an understanding of the system level behavior. Even though the title implies a contrasting of methods, this work will present how computational methods can be used to supplement experimental techniques and visa versa. Electrochemical corrosion is a complex natural phenomenon that has been studied for many years, however corrosion mechanisms as well as corrosion protection are still not completely defined. The prevention of ship hull corrosion is a major concern for the US Military and the commercial shipping industry due to the large monetary and long-term investment. This paper discusses the physical scale modeling (PSM), shipboard impressed current cathodic protection (ICCP) design technique, how computational methods can be used to augment the design process and presents a number of experimentally determined factors that should be applied to present mathematical code development to improve the computational approach to cathodic protection system design.
Keywords: cathodic protection, boundary element modeling, impressed current cathodic protection, physical scale modeling.

1 Introduction

The need to protect ocean-going vessels from corrosion has existed as long as man has explored the oceans. Today a common approach to corrosion prevention is the use of Impressed Current Cathodic Protection (ICCP) systems. Cathodic protection systems take advantage of the inherent electrochemical characteristics of metals by thermodynamically forcing a reduction (cathodic) reaction on the desired surfaces. The ICCP system thus provides an impressed source of electrons to the metal surfaces, whereby shifting the surface potential from a freely corroding condition to one that favors a cathodic (protected) reaction. Details of the cathodic protection approach can be found in numerous textbooks such as Evans and Morgan [1], [2].

Ships are complex structures that offer challenges to the designers of cathodic protection systems. Not only are material interactions of concern, but operational conditions, surface treatments, biological micro/macro fouling and geometric complexities increase the difficulty of design. Design by rule and design by past experience (empirical designs) have proven not to be sufficient for modern ships. Experimental and computational methods have been proposed independently for ICCP system design. Currently, the accepted design methodology for the U S Navy is physical scale modeling (PSM), which is an experimental approach. However, it is recognized that with proper development and verification, computational analysis can provide significant value.

NRL has been a strong proponent of a combined experimental-computational approach to the design of shipboard ICCP systems. In fact, NRL has applied combined experimental-computational approach to a wide range of research topics. This concept was originally presented for ICCP systems by DeGiorgi et al in 1996 [3]. As advances have been made in both experimental and computational methods, the nature of the interaction between these two approaches has evolved. Originally, as proposed by NRL, experimental and computational studies were independent and sequential. Computational analyses were to be completed first as a preliminary design or screening analysis. Experimental evaluation of a smaller subset of possible ICCP systems would be performed using physical scale modeling techniques. The final design would be selected based on the experimental work.

Today, the combined experimental-computational technique is not proposed as a sequential analysis approach but, rather, as an interactive evaluation approach, that provides direct feedback to both methodologies. This updated approach allows the designer to take full advantage of the strengths of experimental and computational approaches. The present paradigm is a unified experimental-computational approach that requires constant communication between experimentalist and computational analyst. It is a true multidiscipline design approach. Computational methods are no longer seen by the experimentalists as 'just' a design tool but have gained acceptance. This is shown in the recent work where computational methods have been applied to help develop a broader understanding of PSM experimental parameters/allowances such as tank size and geometry, model scale and sensor design [4, 5].

The unified experimental-computational design approach opens up new possibilities in system design. The objective of this work is to briefly introduce the computational community to PSM methods, highlight where the experimental community envisions computational assistance in understanding system performance, and to outline critical areas for combined future work.

2 Physical scale modeling

Physical Scale Modeling (PSM) uses near-exact scale models and scaling factors based on the physics of electrochemical response to provide information on current and potential values on the structure. Kasper [6], Agar and Hoar [7] and Weber [8] define the relationship between scaled geometry, scaled solution conductivity and the resulting interpretation of results. While these early authors addressed theoretical aspects of the problem their work is directed towards electroplating. Theoretical background specifically for ICCP systems and PSM has been presented by Ditchfield et al [9]. Detailed comparisons with real ship data have been used to validate the PSM [10, 11].

The NRL Center for Corrosion Science and Engineering has performed PSM on various ship hulls and hull component geometries since 1987. These models range in scale from full to 1/100th scale and in size from 0.5 to 6 meters in length. A typical representative of ship hull model is shown in Figure 1. The hull is fabricated of fiberglass. Cathodic areas are small-scaled sections of metal attached to the hull as can be seen in the figure. The model is additionally instrumented with scaled ICCP anodes and numerous Silver-Silver Chloride reference cells to provide detail on the hull potential.

Figure 1: Example of a near-exact scale model used in PSM.

PSM modeling is a robust physics based method for the design of ICCP systems. For both PSM and the computational techniques, cathodic protection behaves in accordance with Ohm's Law:

$$E = I\,(R_P + R_{OHMIC}) \qquad (1)$$

where, E = potential (V), I = current (A), R_P = polarization resistance and R_{OHMIC} = electrolyte ohmic resistance. The reader should realize that R_P is highly nonlinear and influenced by environmental conditions. In the scaling required in the PSM technique, $R_{OHMIC} = \rho L/A$, and where, ρ = electrolyte resistivity, L = length of ship or model and A = area. The exact scaling, it is desired for potential relationships to exist, such that $E_{SHIP} = E_{MODEL}$ and for current density (i) behavior, such that $i_{SHIP} = i_{MODEL}$, where $i = A/m^2$ resulting in:

$$E_{SHIP} = I_S(\rho_S L_S/A_S) = i_S(\rho_S L_S) \text{ and } E_{MODEL} = I_M(\rho_M L_M/A_M) = i_M(\rho_M L_M) \qquad (2)$$

where it is necessary that $R_{P\,(SHIP)} = R_{P\,(MODEL)}$ for the model to scale exactly, by definition. For scaled models $L_S / L_M = k$ and $\rho_M = \rho_S\ (k)$, where k = scale factor, the relationship becomes:

$$\begin{gathered} E_{SHIP} = E_{MODEL} = i_S(\rho_S L_M)\ (k) = i_M(\rho_S L_M)\ (k) \\ i_S = i_M \end{gathered} \qquad (3)$$

From (2) and (3) electrical current measured on the model is:

$$I_S = I_M\ (k)^2 \qquad (4)$$

There are three basic assumptions in the derivation of the modeling process and that provide for precision measurement of potential and current on the model with a direct mathematical relationship between the model and full scale system. These assumptions are:

- The wetted surface areas and geometry are exact and scaled such that $A_{SHIP} = A_{MODEL}\ (k)^2$.
- The current density relationship, $i_{SHIP} = i_{MODEL}$ is true, by definition, when the model size, electrolyte dilution and polarization resistance components obey the scaling law.
- $R_P = \Delta E/i_C$ must be same for the model and full scale system, where ΔE represents the polarization from E_{CORR} to the cathodic protection set potential of –0.85 V.

The key to the modeling methodology, in addition to the correct implementation of model size and correct electrolyte ohmic scaling is the polarization resistance behavior. In order to preserve the relationship $R_{P\,(SHIP)} = R_{P\,(MODEL)}$ for direct scaling, NRL has established a pre-conditioning sequence. This process allows for the correct cathodic film to be developed on the surfaces of the cathodes so that the R_p response is the same as the full-scale hull. The U.S. Navy has utilized PSM, as performed by NRL Center for Corrosion Science and Engineering, extensively. There is an established design criteria and PSM is currently the accepted standard technique for design of U. S. Navy ICCP systems. This procedure and other details of PSM approach can be found in References [12, 13].

3 Computational methods

PSM can be used to determine ICCP component placement, life-cycle performance, zone interaction behavior and various failure modes under both static (dockside) and dynamic (underway) operational conditions for a variety of ship and system configurations. PSM is able to directly address difficult geometries, areas of restricted flow, protective coatings degradation, advances in ICCP design technology (i.e. use of digital comptrollers – hardware and software, advanced control algorithms) and complex interaction of multiple power supplies and multiple control point locations (i.e. zone behavior).

There are, however, limits to the capabilities of PSM. In terms of shipboard ICCP system design, the limitations are primarily related to the fact that the method uses a scale model representation of the ship hull. It is only possible to fabricate into the model features of a certain dimension. PSM was originally developed for the design of systems that would be operated primarily in open oceans. The scaling of full strength seawater to an appropriate level for testing (as described in the previous section) is possible. However, changes in ship deployment strategy have mandated a closer look at system performance in both brackish and nearly fresh water conditions. It is significantly difficult to scale the conductivity to meet the conditions for testing under these operating scenarios as well as in maintaining an accurate cathodic film due to the extremely low presence or absence of chloride ions in the scaled electrolyte. Finally there is, as always, the cost of testing versus the costs of virtual testing using computational models. Once a hull specific computational model has been created and verified, it is possible to evaluate many scenarios, computationally, without the manpower, time and cost drain of experimental set up and testing. This is true for any experimental methodology.

Computational modeling was seen as a way to supplement the information obtained through experimental techniques. In order to validate computational modeling for ICCP system design and analysis applications, significant work had to be completed to demonstrate capabilities.

4 Priority issues for future development

In reviewing current research the authors have identified areas of concern that should receive priority for future investigation. These are (1) accurate modeling of free flood spaces, including the effects of hybrid systems (combined sacrificial and impressed systems) (2) time-based and spatial variation of polarization design rules, and (3) determining of analysis requirements for on- and off-board electric field calculations. We will briefly discuss each topic.

4.1 Accurate modeling of free flood spaces and hybrid systems

Free flood spaces are confined areas of the underwater hull that have openings to the seawater by means of flood holes, gaps or gratings. Typical of free flood spaces are submarine ballast tanks and surface ship seachests as shown in Figure 2.

As can be seen, the opening and the cavity itself combine to form a complex geometry. These features tend to be small relative to overall underwater hull geometry, however there are variable quantities and sizes on any specific hull, they may or may not have a sacrificial system for local corrosion protection and they incorporated different materials that adds additional galvanic relationships. Experience from ship operations and PSM studies indicate that these features can have an impact on ICCP system performance and the resultant off board electric field signal produced by the electrochemical system [Fig 3].

Figure 2: Picture of a Surface Ship seachest opening (left) with splitter bars removed and close-up (Right) with bars and sacrificial anode installed.

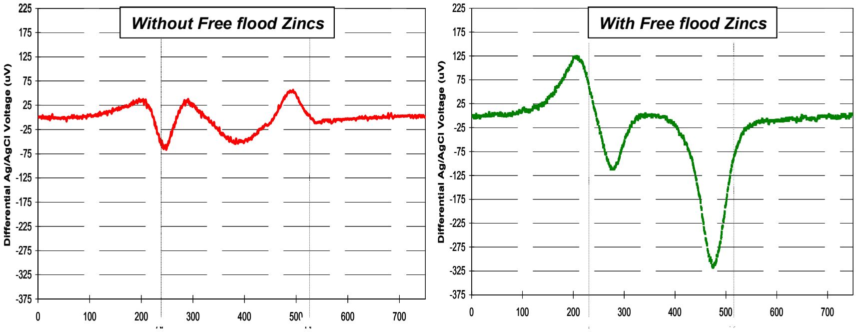

Figure 3: Influence of zinc anodes in free flood spaces on the off-board electric field signal measured during PSM.

There are several technical issues that must be addressed involving these features. It is impractical to incorporate all free flood spaces in PSM test articles. However, it should be possible to incorporate all of these features in computational models. Should these features be included directly in a hull model or evaluated through use of submodeling, must be investigated. Of concern is the applicability of the LaPlace solution approach, used in determining electrochemical corrosion related current and voltage values, in the incorporation of these features in a computational model. The LaPlace solution requires that the electrolyte is of uniform composition. Free flood spaces are small volumes with stagnant regions. Without the free flow of electrolyte along all surfaces, there will be variations in oxygen and other seawater chemical components resulting in different and varying material response characteristics for the subspace environment. It is possible that LaPlace solution is no longer valid. This is a major concern.

4.2 Spatial and time-based variation of polarization design rules

It is known that a key to accurate computational modeling is the use of an appropriate polarization curve to describe the material response. It is also known that polarization response is a sensitive nonlinear material parameter that has been shown to be affected by numerous environmental factors. Recent work has demonstrated that there is a spatial variation of polarization response along the hull of a surface ship as shown in Figure 4. These polarization curves were determined by direct measurement of polarization response at different points along the hull of a PSM test article. A single curve can be generated as shown in by the curve fitted through the squares in Figure 4, but the use of only this curve would greatly limit the accuracy of the final calculated hull potentials and currents.

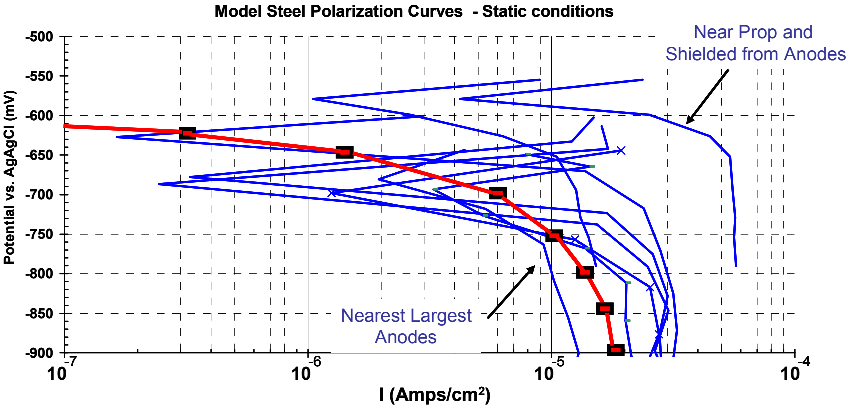

Figure 4: Polarization material response differences as a function of spatial relationship to anodes and noble metals.

The variability in the curves can be related to a time-based phenomenon, whereby hull metal that is near anodes and is not shielded will develop the natural cathodic film faster relative to other more shielded regions on the hull. This calcareous film helps to reduce the cathodic demand of the cathode which results in a shift in the material curves to a lower current density demand. It is possible to assign element regions within a computational model with the appropriate polarization response based on this type of measured data. The mapping of measured values to a computational model implies that there has to be a one to one correspondence between ICCP system on the test article and ICCP system as defined on the computational model. This eliminates a major advantage of using computational methods to evaluate design alternatives.

What is needed is a series of design rules that automatically assigns appropriate polarization response to a region on a computational model based on anode location, cathode location, and material type as well as incorporates a time-based correction to account for calcareous film formation. This would allow the designer to place anodes and cathodes as required with the knowledge that their region of influence will be incorporated into the computational model. The design rules must be based on understanding of the range of influence features such as anodes and noble metals have on the 'basic' polarization response'

4.3 Analysis requirements for on- and off-board electric field calculations

The analysis of real ship behavior is a complex relationship of many of the factors discussed, where these data are taken in real time, using the actual geometry, material relationships and parameters inherent of a natural system. In a simulation of these behaviors, the accuracy of the field relationships measured depend on precision, correlation, magnitude and spatial equivalency of the field behavior and computationally, these intrinsic properties generally come from experimentally determined values feeding the code. The results of previous boundary level models, limited by computer memory and space, produced geometrically simple models where components, such as the propellers, were stylized to provide for the same cross sectional boundaries without the need for the complex detail, illustrated in Figure 5. This subsequent detailed investigation has shown that the geometric detail is necessary and that incomplete geometric description provides significant error in simulation. Error can also be cumulative in nature because near-field effects directly impact the nature of the off-board integration. Errors attributable to localized current density distribution, geometric shielding and variation in materials polarization properties directly impact the primary near-field computational relationships and magnify the error of calculated far-field relationships.

PSM treats the hull as if it were a real ship, except that there are also limitations in what can be modeled and represented. Experience has shown that the computational equivalent has many benefits when expressing and considering numerous variables, but the significance of the data and verification must be fully tested as a design instrument, not just compared against known data.

In addition to the importance and type of the data input into the code, it is the code itself that needs critical review. In most cases, the LaPlace equation that describes the fundamental behavior of the ICCP system, but these relationships are also conditional on certain equilibrium states. The review of data, such as that for tanks, shows a diffusion effect and polarization behavior that falls outside of some computational aspects and may even result in a non-invertible matrix situation. Thus, the code requires the addition of mathematics to define areas with unique boundary properties, diffusion and current crowding. Additionally, structures often have multiple zones in single ICCP systems and have multiple ICCP systems, giving rise to “zone" behavior. Each zone can interact and computationally, it is not known quite how these behaviors relate or how an actual system response compares in performance. This situation can be further complicated by the existence of multiple ICCP systems on a single structure.

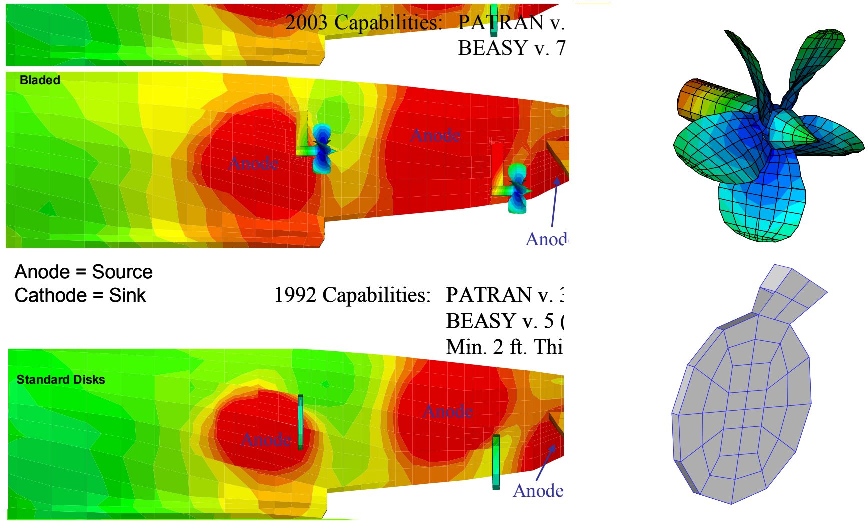

Figure 5: Effect of Geometric mesh detail on computationally derived surface potentials.

5 Summary

Design of an effective ICCP system is critical to maintain the Navy’s long-term investment and fleet readiness. Presently, a combined experimental and computational approach to design has proven to be the most comprehensive. Further understanding of the electrochemical response of an ICCP over the ships lifecycle and environments is needed to shift the combined approach to be more dependent on the computational results. Ideally this will lead to the situation where design will be totally based on computational analysis. This paper has discussed three major areas where further understanding is required and needs to be addressed in future computational programs.

Acknowledgements

The support of Dr. A. I. Kaznoff and Mr. E. D. Thomas, Naval Sea Systems Command, is gratefully acknowledged. The authors also wish to thank Mr. K. E. Lucas, NRL Code 6130, and Dr. S. A. Wimmer, NRL Code 6350, for their assistance.

References

[1] Evans U. R., Metallic Corrosion Passivity and Protection, Edward Arnold and Co, 1948.

[2] Morgan J., Cathodic Protection, NACE, 1987.

[3] DeGiorgi, V. G., Thomas, E. D., Lucas, K. E. & Kee, A., Boundary Element Technology XI, 335-345, 1996.

[4] Wimmer, S. A., DeGiorgi, V. G. and Hogan, E., Boundary Element Technology XV, 213-222, 2003.

[5] DeGiorgi, V. G., Wimmer, S. A., Hogan, E. & Lucas, K. E., Boundary Element Method Vol. XXII, 439-447, 2002.

[6] Kasper, C., Trans. of Electrochemical Society, Vol. 77 and 78, Papers I-IV, 1940.

[7] Agar, J. N. & Hoar, T. P., Discussions of Faraday Society, No. 1, 162-168, 1947.

[8] Weber, J. T. & Fagen, B., J. of Electrochemical Soc., Vol. 103, No. 1, 64-72, 1956.

[9] Ditchfield, R. W., McGrath, J. N. & Tighe-Ford, D. J., J. of Applied Electrochemistry, 25, 54-60, 1995.

[10] McGrath, J. N., Tighe-Ford, D. J. & Hodgkiss, L., Corrosion Prevention and Control, April, 33-36, 1985.

[11] Thomas, E. D. & Parks, A. R., Proceedings Corrosion 89, Paper No. 274, NACE, 1989.

[12] Lucas, K.E., Thomas, E. D., Kaznoff, A. I. & Hogan, E. A., Designing CP Systems for Marine Structures and Vehicles, STP-1370, ASTM, 17-33, 1999.

[13] DeGiorgi, V. G., Hogan, E., Lucas, K. E. & Wimmer, S. A., chapter in BEM and Corrosion, WIT Press, In Press.