Validation plan for boundary element method modeling of impressed current cathodic protection system design and control response

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Abstract

In the past 20 years, the US Navy has used the physical scale modeling (PSM) technique to design effective cathodic protection (CP) systems for the ships underwater hull, nickel-aluminum-bronze props and other hull components. In more recent years, a number of computational techniques have been devised in an attempt to fulfill this purpose. Physical models have proven highly adept at ICCP design, since modeled information provides a direct relationship to the actual hull and can be scaled up directly because of confidence in the physically measured data. Boundary element (BE) models have been correspondingly devised that mimic actual hull design and even the PSM layout, but because the BE method is a computational methodology, the calculated data requires systematic validation with a physical analog to insure confidence in the control response. BE literature has discussed design issues regarding mesh layout, intrinsic geometric complexities, accuracy of material response input, the predictive engineering design capability for zonal response, and assessment of electric field response. It does not significantly discuss the accuracy of the BE model calculated work predictive design capability, without the need for "tweaking," and ultimately a rigorous validation of both the mesh and resultant system design technique. This paper presents validation requirements, for any BE model, that is inherently robust enough to be used for CP design and control, and a proposed four-point methodology that will allow for the comprehensive validation of the BE model to predict the ICCP control responses and system performance behavior.
Keywords: boundary element, BEM, cathodic protection, ICCP, validation plan.

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1 Introduction

The factors which affect the corrosion behavior and signature of an underwater ship hull are numerous, often highly complex and variable, and are in many cases directly related to the operational aspects of the ship. The seawater physio-chemical properties, biological growth and engineering aspects of the hull are all important components of the equation. The corrosion of the hull is most basically influenced by the nominal metallic components exposed to the seawater along with the chemical composition and properties of the bulk electrolyte (seawater), such as pH, dissolved oxygen, salinity and surface reactions. Directly controlling the kinetic behavior of these reactions are temperature, velocity and diffusion properties of the surfaces. Biologically, all surfaces foul with marine organisms, which further influence the surface properties of the metals involved.

Presently, the electrolytic PSM technique is required by the US Navy (USN) for the design of impressed current cathodic protection (ICCP) systems as well as for the verification of their operation [2,3]. The Naval Sea Systems Command (NAVSEA) has defined a design protocol [4] that describes the design criteria necessary for electrolytic PSMs. The PSM provides a means of testing the natural response of the system to changes in hull condition and coating damage. The limitations for the PSM technique lie more toward the mechanical and logistical elements, such as: (a) the size of components, and (b) the number of iterations required to test a vast number of hull conditions, control systems and environmental conditions.

The uses of boundary element (BE) computational methods are viewed as a potentially powerful tool for the design and analysis of corrosion prevention systems and resultant electric field generation for seawater structures. It follows, as these are calculated results, that the quality of the output is greatly affected by the detail of the model and the material input information [5]. In contrast with the electrolytic PSM, no equivalent protocol exists for building or validating BE models. In general, BE models are built using the dimensions of the full scale or physical scale items they are to represent. To provide the necessary engineering confidence, the validation process used for the computational model must also include steps to verify geometry, mesh, polarization curves, material response, zonal interactions, and system response. An accurate, validated BE model could greatly assist the ICCP design agent in evaluating and testing the control system architecture, system failure modes and system response under a wide variety of conductivities and temperatures. Without proper BE model validation, a high risk is assumed in control algorithm development, spatial ICCP relationships and assessment of overall life-cycle system operation and performance.

2 Four-step validation plan

A validation plan has been developed that breaks down the underlying components of the BE model and verifies each critical input aspect of the model for a defined ICCP configuration. After each validation step, the BE model is then verified for use to accomplish specific analysis objectives. At the end of the complete validation process, the model will be established as being capable of providing critical data (i.e. current density distribution, potential profiles, etc.) on a given ICCP configuration. The validated model will also be a capable tool for the specified platform for the selection, sizing and locating of ICCP components and to determine the impact of future changes to the ICCP configuration or minor geometric features (major geometric changes would require revalidation of the model mesh). The validation plan consists of four steps as follows:

(1) mesh and geometry validation,
(2) polarization curve and material response validation,
(3) design tool validation (optional), and
(4) control algorithm validation.

2.1 Step 1: mesh and geometry validation

The first step requires validation of the model mesh. Geometry is critical to the function and response of ICCP systems. The mesh and geometry validation step ensures that the computational model is arranged properly and has the necessary geometric detail to accurately simulate shipboard conditions. Component sizes, locations, and current values for all anodes and cathodes from the PSM are provided to the computational modeler to be used as input to the BE model. In this step there is no need for characterization of the material responses. The anode and cathode currents are used to exercise the BE model to produce off-board electric signatures at the same distance electrolytic PSM measurements were taken. Comparison of off-board electric signature results that are within 20% root-mean-square (rms) error, result in a model validated for mesh and geometry. The resulting validated model can then be used reliably for simple failure mode studies without system response capability.

The 20% rms error comparison is based on several factors, some of which includes actual full scale measurement error from sensor accuracy and environmental noise. The derivation of this limit is not discussed in this work. This is not an arbitrarily chosen value. The acceptable error value will depend on the structure's end use and sensitivity of the sensors. It is possible that values for one type of vessel may be different than for other types of vessels or structures. The setting of the validation error criteria is part of the overall structure design/validation process.

2.1.1 Mesh details

The BE method is based on solving boundary Laplace integral equations and solves the equations in terms of potential flow. In the corrosion problem, only the vessel-electrolyte boundary needs to be included in the analysis. Electric field potentials and current densities are computed directly on the surface mesh [6]. The mesh can be defined by constant, linear, and quadratic line and surface elements. While quadratic elements provide the most precise results they currently should only be used in areas of high gradients, because the calculations can be time-consuming and memory-intensive. It is important, therefore, that BE models implement the proper combination of constant, linear, and quadratic elements, such that the model results are as accurate as possible within the time and memory constraints. Finding and defining this proper balance is not trivial. The effective BE mesh must be developed that represents all significant surfaces that can influence both cathodic demand and shielding of current. Areas where high surface potential field gradients are expected, need to have a more refined mesh to capture these effects (Figure 1).

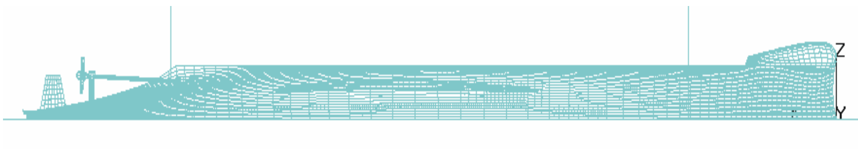

Figure 1: Typical BE mesh for surface ship. Note the concentration of elements in the stern, at bilge keels and near bulbous bow.

2.1.2 Geometry details

In past modeling efforts, it was assumed that approximations of various components, such as a disk representing a propeller, were sufficient to define the geometry of a vessel. Upon further investigation, however, the shape and pitch of the propeller blades make a significant difference to both the on-board potentials, as well as, the off-board electric signature and computationally must be taken into account to yield accurate results. Details of all geometric features have been an issue in modeling on-board potentials. Early work identified the need for considerations of such features such as the bilge keels while more recent work has examined the geometric details and impact of small features, such as the angle and orientation of the bilge keel with respect to the hull [7]. Results showed there was no doubt that small geometric features are also of importance and necessitates the need for even more accurate and complex computational models. Another example related the complex shadowing effects where the computational modeling compares the performance of a static orientation with a stylized geometry representing spinning blades and compares the net on-board potentials [7]. Further, the representation of confined spaces, including ballast tanks and sea chests, and bow thrusters have proved important. Innovative means of defining confined spaces within the limitations of the computational modeling software must be employed. Dual elements were eventually designed by Computational Mechanics to address this issue of thin-walled areas that were exposed to electrolyte on both sides. The size, shape, and presence of grates also impacted the off-board electric signatures produced by the BE model. Figure 2, details some significant surface geometries that must be incorporated in the BE mesh to provide an accurate surface geometric representation of the structure.

As shown in Figure 3, the mesh differences between a stylized prop and the complexity of a detailed prop with multiple blades and contours is significant. The multiple blade structure offers more surface area for cathode demand. To provide the necessary surface area on the disk prop and maintain the correct geometric diameter the thickness of the prop had to be increased. The disk prop will not provide the geometric window effect or shadowing between blades nor the overall cathode geometric extent if the surface areas are equal. Off-board electric field data acquired from a PSM experiment is compared in Figure 4 with BE model electric field data using a disk propeller verses a bladed propeller. It is clearly shown in the data that the match to PSM data is much closer with the correct prop model geometry.

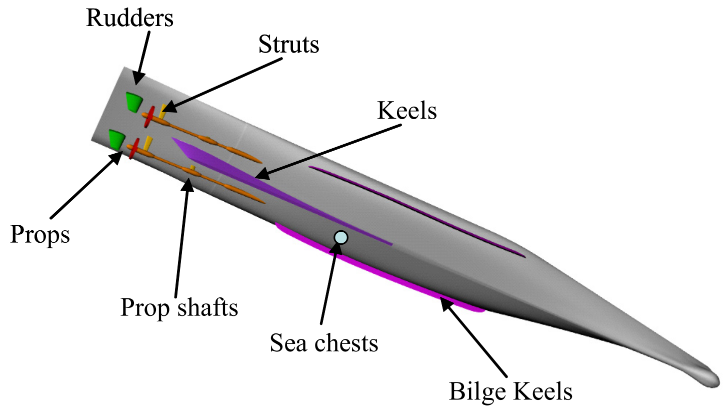

Figure 2: Surface model detail of known significant geometries.

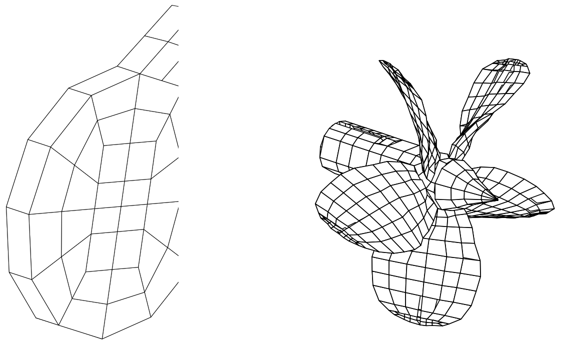

Figure 3: Mesh of stylized disk prop (left) and mesh of actual prop (right) showing accurate number of blades and contours.

2.2 Step 2: polarization curve and material response validation

The polarization curve and material response validation step ensures that the computational model accurately reflects shipboard material characteristics and response, as well as relevant material interactions. During step two of the BE model validation process, the cathode and anode sizes, locations, anode currents, material polarization curves, and a complete hull potential profile from the PSM are provided to the computational modeler to be used as input to the BE model.

This information is used to exercise the BEM model to produce cathode currents, as well as off-board electric signatures at the same distance PSM measurements were taken. Comparison of the BE model and PSM off-board electric signature results within 20% rms error *and* the agreement of cathode currents within 10%, results in a model validated for polarization curve and material response. The resulting validated model can then be used reliably for complex failure mode studies with system response capability.

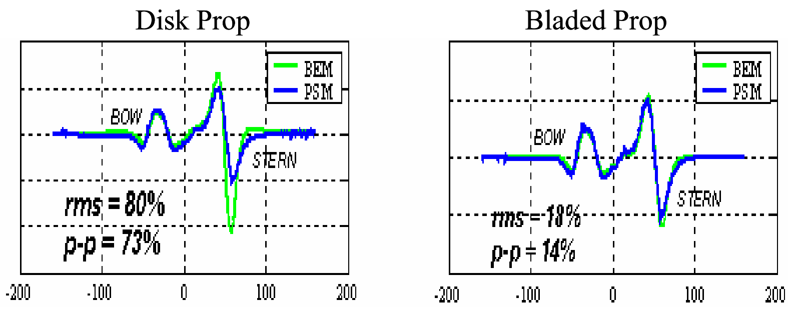

Figure 4: Example of differences in BE model electric field analysis as a function of prop geometric detail and compared to PSM measured data.

Typically, BE computational models utilize polarization curves, which are plots of potential vs. current density, to mathematically describe the dependence of potential on current density. The problem of course, then, is that the quality of the BE model and the validity of its results are directly dependent on the accuracy of the polarization curves utilized. However, the issue is further complicated, since the marine and ship materials not only have individual polarization characteristics, but these are significantly affected by galvanic interactions, surface kinetic effects, biological effects and electrolyte composition. The central electrolyte composition effect for Navy ships are salinity changes, but these effects are well understood and are not discussed in the current document.

2.2.1 Galvanic effects

Since ship hulls are comprised of a variety of materials, galvanic interactions are anticipated. The most common combinations include steel (hull plate and structure), nickel-aluminum-bronze (propellers), copper-nickel (sea chests) and zinc or aluminum (sacrificial anodes). Note, with respect to the latter, it is not uncommon to have sacrificial anodes in free flood spaces adjacent to the ICCP protected hull which can interact with the control response of the system. The net effect of these material combinations is to shift the polarization curves of the attached materials. These shifts can occur in either or both the current density and potential direction and is a strong function of the polarization resistance of the material, the relative surface area ratios and the proximity of the materials.

2.2.2 Surface kinetic effects

Surface kinetics, at least within the context of this document, is primarily a function of dissolved oxygen diffusion to the cathodic surfaces. Increased availability of dissolved oxygen to the cathode site results in higher cathodic reaction rates and increased current demand to support the oxygen reduction reaction, eqn. (1):

$$\frac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^- \cdot \qquad (1)$$

The effect on the polarization behavior is that the cathodic polarization curve becomes independent of current density at the limiting current density (i_L) and the point of oxygen depletion. The ships speed directly affects oxygen availability to the steel and results in a concentration polarization effect whereby i_L is shifted to right with increasing ships speed until oxygen diffusion and availability at the cathodic site is no longer the corrosion rate limitation. However, throughout the concentration polarization region increased i_L results in increased CP requirements. Note that this effect is mimicked in the PSM through bubbling of air beneath the model to simulate ship motion and increased oxygen availability.

Surface kinetics is also affected by CP deposits; cathodic polarization in seawater promotes the formation of calcareous deposits. Oxygen reduction and subsequent hydroxide formation at the cathode surface result in an increased pH at the cathode/seawater interface, such that calcium carbonate precipitates according to equations 2:

$$HCO_3^- + OH^- \rightarrow H_2O + CO_3^{-2} \quad \text{and} \quad Ca^{+2} + CO_3^{-2} \rightarrow CaCO_3 \qquad (2)$$

At higher current densities, magnesium hydroxide can also form. Calcium carbonate and magnesium hydroxide are important, because they serve to limit diffusion of oxygen to the cathode. This results in enhanced oxygen concentration polarization and a lower net current density to maintain the same polarization level of CP [8–10]. The formation of these protective films significantly affects the material response and overall ICCP performance and control. This effect is included in the PSM through an initial ageing period in which calcareous films are deposited on the cathode surfaces until a specified maintenance current density is achieved. Any useful BE model must be able to accommodate into the polarization curves both the formation of calcareous films and the effects of ship speed on surface kinetics to make accurate predictions of ICCP performance and response.

2.2.3 Biological effects

Materials can change their polarization behavior just with exposure to seawater for extended periods of time, as shown in Figure 5. Super duplex stainless steel samples (AL6XN) were exposed to natural seawater and electrochemical tafel curves were conducted on the samples after 24 hours and 1 month exposure periods. The figure shows the significant change in the cathodic polarization behavior and electropositive shift in the corrosion potential. Notably, this effect is exhibited by a large range of alloys, predominantly passive alloys, and is termed "ennoblement". While the exact mechanism of ennoblement has not been identified, biological film growth is considered to be directly involved. This polarization curve is an example of how important it is to verify the material property curves being used in the BE model to account for the conditions of interest.

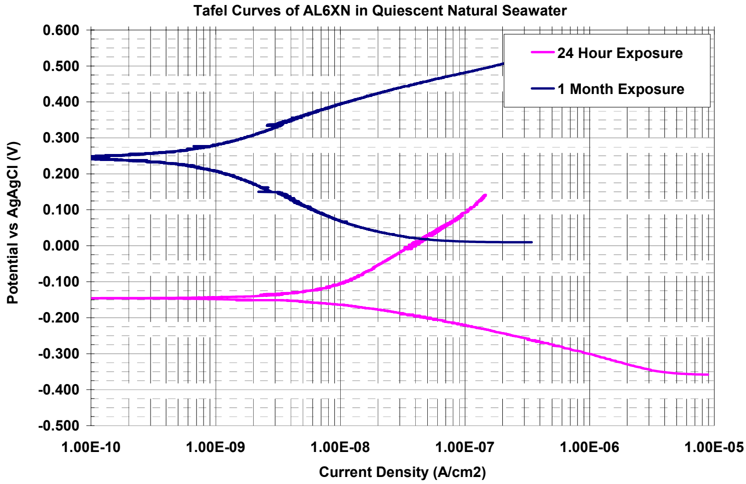

Figure 5: Electrochemical tafel curves on alloy AL6XN after exposure to seawater.

2.3 Step 3: design tool validation

The design tool validation step is considered optional as it allows for assessment of CP and signature requirements under various conditions outside of the initial ICCP system design. Cathode locations and overall percent damage; anode sizes, locations, and current values; and only the ICCP system controlling and sense reference cell potentials from the PSM are provided to the computational modeler to be used as input to the BE model. This information is used to exercise the BEM model, under different hull coating damage conditions, to produce an on-board hull potential profile, cathode currents, and off-board electric signatures at the same distance the PSM measurements were taken. Comparison of off-board electric signature results within 20% rms error, agreement of cathode currents within 10%, *and* agreement of hull potentials within ±10 mV results in a model validated as a design tool. Completion of this validation step allows the user to make changes to the BEM model ICCP design, such as, anode or reference cell location changes, painted versus unpainted surface changes and paint damage condition changes. Additionally, the validated BE model can be used to evaluate minor changes in geometry and effects of adjacent sacrificial systems.

2.4 Step 4: control algorithm validation

A properly designed computational model should respond to system input appropriately based on the applied control algorithm, whether it is lead-lag compensation, proportional-integral-derivative (PID) compensation, etc. A basic control system is designed to provide an output that closely follows a desired value (see Figure 6). The system output should be stable, as well as, reach and maintain steady-state within the desired timeframe and fashion. Determining controller parameters is not always straightforward, as system transfer functions may not be available. In such cases, final parameter selection may be completed during initial system operation.

Accordingly, the final step to BE model validation requires the control system response to be evaluated. The control algorithm validation step ensures that the computational model can sufficiently predict system response with the desired control algorithm in place. As with step 3, anode sizes, locations, and current values in addition to controlling and sense reference cell potentials from the PSM are provided to the computational modeler to be used as input to the BE model. This information is used to exercise the BEM model under varying control parameters to produce a hull potential profile and off-board electric signatures at the same distance the PSM measurements were taken. Comparison of off-board electric signature results within 20% rms error and agreement of hull potentials within $\pm$10 mV result in a model validated for control. Completion of the control algorithm validation step allows for the BE model to be exercised under a wide range of scenarios and results in a platform specific computational model that allows for calibration with only ICCP system component inputs.

While correct control algorithm operation under ideal conditions is important to verify, it is equally important to determine how the controller and system respond under varying conditions, such as conductivity changes or component failures. Verifying correct control system response under such conditions is imperative to validating a BE model.

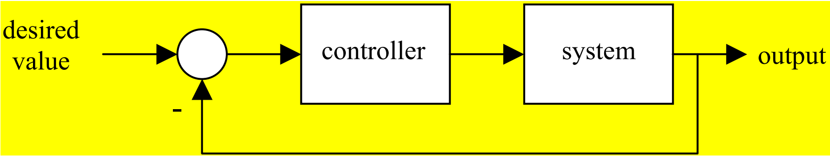

Figure 6: Basic controller scheme.

3 Summary

To develop confidence in a comprehensive computational model that addresses all aspects of the complex nature of the corrosion response for design, life-cycle analysis, and control system development, a rigorous validation process is necessary. The BE model must be shown to have the correct geometric detail, cathodic and anodic polarization inputs, correct response to changes in configuration and have the correct system response to test control algorithms. An error in any of these stages can lead to progressive error in the completed model. The validation process is progressive, such that the model can be validated at each step and success will provide a model that can be useful for specified tasks. A four step process has been provided that identifies each significant aspect of the computational model that needs to be validated.

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