A combined design methodology for impressed current cathodic protection systems

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Abstract

The corrosion prevention capability of shipboard impressed current cathodic protection systems are effected by the geometry of the ship hull, conductivity of the surrounding water, material polarization response and any material interactions. Changes in system configuration and service environment from those used in design analysis require the capability to analyze system performance under varied circumstances. While individually limited, experimental scale modeling and computational boundary element modeling techniques can be used in concert to design a robust system and to provide a means for quick analysis of system and environmental changes. A methodology for system design based on these two analysis techniques is presented.

1 Introduction

Impressed current cathodic protection (ICCP) systems take advantage of natural electrochemcial reactions of materials to minimize corrosion damage. In an ICCP system, an external source of electrons is provided to the metal/electrolyte combination, for example the hull of a ship in the ocean. In order to achieve protection from corrosion the source of electrons must be sufficient to raise the potential of the structure to a level at which negligible corrosion occurs. Major factors which must be considered in the design of such systems are the geometry, the conductivity of the electrolyte, the polarization behavior of the metal, the location and polarization of any other exposed metal and the magnitude of the power source supplying the electrons. The use of shipboard ICCP systems is well established. In the past decade considerable effort has been spent in the development of design methodologies which have a scientific rather than designer expertise basis. Two such methodologies are physical scale modeling and computational modeling using boundary element techniques. Physical scale modeling has been used to design ICCP systems which have been installed on U S Navy ships. However, it is felt that computational modeling capability is still required. Failure of individual components in an system or unexpected damage require the capability to quickly evaluate the system. Frequently re-evaluation is required in a short period of time and the time required for experimental evaluation is not available.

2 Scope of Work

Th-e purpose of this paper is to review the status, advantages and limitations of physical scale modeling and computational modeling as applied to shipboard ICCP systems. The verification work performed for physical scale modeling and computational modeling is briefly highlighted. A unique combined computational and experimental design methodology is presented. This method which combines the advantages of the individual methods should result in a more robust system design than could be created independently by either method.

3 Physical Scale Modeling

Physical scale modeling is a experimental technique in which the linear dimension of the structure and the conductivity of the electrolyte are scaled by the same factor. Ditchfield et al [1] examined the theoretical considerations of this mechanical scaling factor. Based on modeling of electrochemical cells the physical scale model and full size structure must maintain:

(1) identical current density values at points
(2) identical potential differences at points .
(3) identical polarization potentials at the anode and cathode
(4) identical potential drop across the electrolyte.

Based on theoretical considerations, a correct scaled model results in:

(1) measured potential values identical to those found in the full size structures
(2) values under flow conditions can be obtained from models by applying flow velocities for the full size structure (flow velocities are not scaled).
(3) measured electrical fields in the model are higher than those found in the full size structure but true current densities can be calculated from model results.

Item (1), measured potentials equal to potentials on the full size structure, is one of the most important features with regards to applications of scale modeling techniques.

As an experimental process, physical scale modeling was first introduced in 1985 for shipboard ICCP systems [2]. The scaling factor used is dependent on the model size and magnitude of electrolyte conductivity which can be handled in the experimental facility. Verification of the procedure has included comparison with ship data for a British destroyer [2] and U S Navy CG class system [3,4]. Scaling factors of 1/60, 1/96 and 1/100 have been used for shipboard systems. Work at the Naval Research Laboratory concentrates on 1/96 scaled models and electrolyte.

Physical scale modeling techniques were used to design a two power zone system for the USS Princeton, CG-59 [3]. The ICCP system is a modification of the previously installed system on the CG class. Prior to sea trials, the USS Princeton was modified for data gathering. Additional instrumentation and an incomplete coating system were installed. The incomplete coating system resulted in a hull condition between minimum and maximum damage definitions. The USS Princeton was later evaluated computationally. Physical scale and computational modeling were performed independently. As can be seen in Figure 1, good agreement was achieved between full size ship data, physical scale modeling data and computational results.

In summary, important advantages of physical scale modeling include:

(1) ability to duplicate complex geometries

(2) ability to incorporate actual materials and material combinations to capture any galvanic interactions

(3) lack of requirement of polarization response data for the materials and material combinations in use

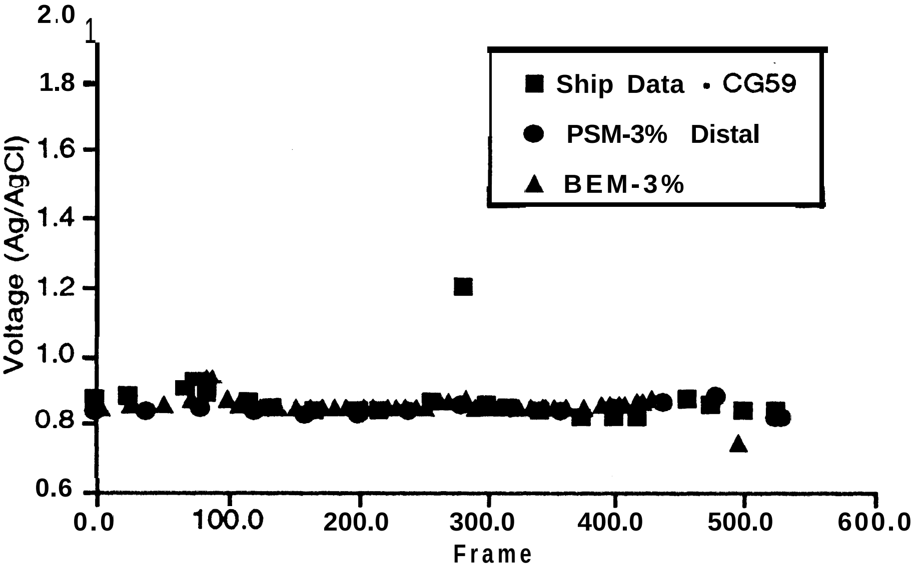

Figure la - Static flow and minimum damage conditions. Measurements taken at a depth of 10 feet.

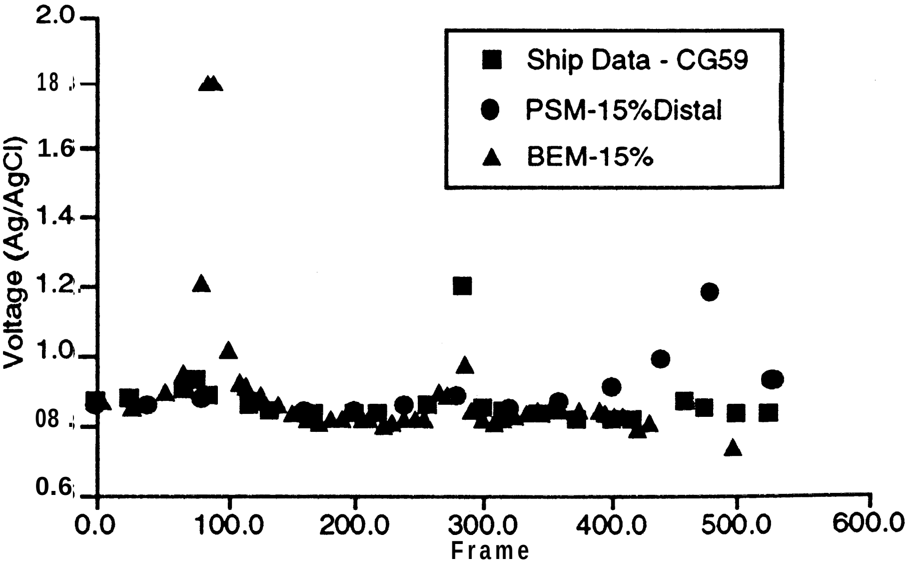

Figure lb - Static flow and maximum damage conditions. Measurements taken at a depth of 10 feet.

4 Computational Modeling

The use of boundary element methods to model corrosion systems which are governed by LaPlace's equation is well established [5]. The requirements for applicability of LaPlace's equation are an electroneutral electrolyte, an absence of polarization concentration gradients and an absence of electron sources or sinks. Shipboard ICCP systems can be mathematically defined to meet these requirements. Preliminary analysis by DeGiorgi et al [6] and Zamani [7] validated the use of boundary element methods for the design and analysis of shipboard ICCP systems. Zamani analyzed a prototypic Canadian ship modeling the propeller and rudder as equivalent cathodic areas on the ship hull. DeGiorgi et al analyzed U S Navy ships modeling the propeller and rudder as stylized but distinct appendages to the hull. Zamani and Chuang [S] used boundary element methods to determine the optimum control system for a shipboard ICCP system. Trevelyan and Hack [9] have done preliminary work on the incorporation of stray current into a boundary element code.

General information learned about computational modeling based on series of verification analyses performed at the Naval Research Laboratory are summarized here. The commercial boundary element code BEASY-CP [10] was used for all work however the methodology presented should not be limited to this code. Minimum and maximum paint damage conditions were examined for static and dynamic flow conditions. Damage patterns were supplied to the analyst and were developed based on dry-dock information from shipyards. Computational results which were compared in detail with physical scale modeling results included potential profiles, total current and current distribution to selected components. Good agreement was obtained for the CG class hull analysis. Representative comparisons for the CG class between computational and physical scale model data are shown in Figure 1.

As part of the analysis of the CG class hull, a mesh refinement study was completed. It was determined that a relative high level of refinement was required for accurate results. It was found that geometric modeling of the bilge keel was required for the generation of an accurate potential map. A strong correlation between the accuracy of the computational results and the accuracy of the polarization response used in the analysis was observed. The ability to obtain accurate and appropriate data is complicated by the sensitivity of polarization response to environmental factors and testing procedures [11,121.

In a design analysis, less than accurate polarization response may be used to develop potential plots which will identify ‘good’ and ‘bad’ areas of protection. While the absolute magnitude of the results may not be correct, the trends shown are correct. The designer can use these results to determine the number and placement of anodes required to provide protection.

An analysis of U S Navy aircraft carrier CVN hull class was performed to determine the effects of scale on modeling parameters determined by the CG hull class analyses. Scale is addressed directly by the increased size of the CVN, approximately 4 times the surface area as the CG. Scale is addressed by the inclusion of relatively small features such as the bilge keel on the CVN model. Representative comparisons between physical scale and computational results are shown in Figure 2.

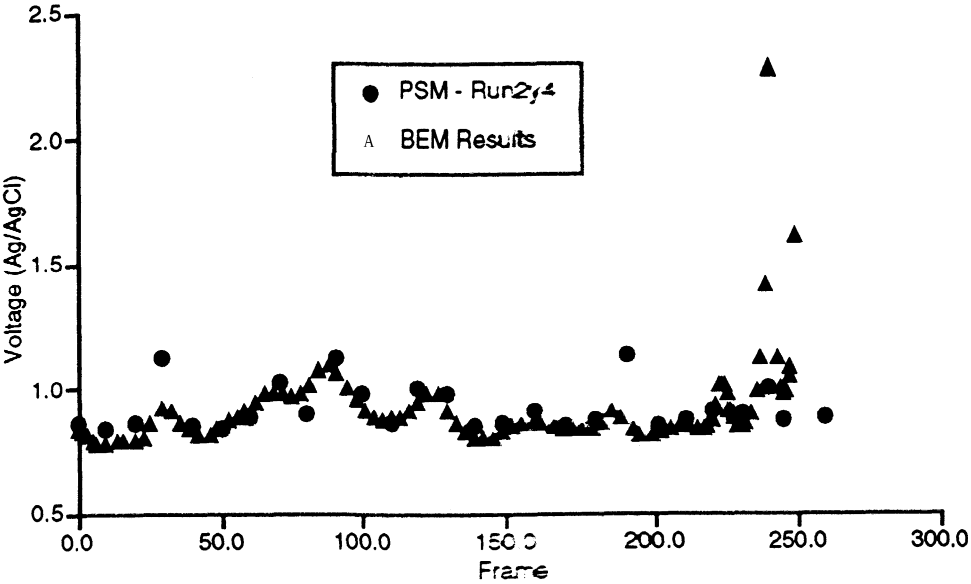

Figure 2a: Dynamic flow and minimum damage conditions. Measurements taken at a depth of 10 feet.

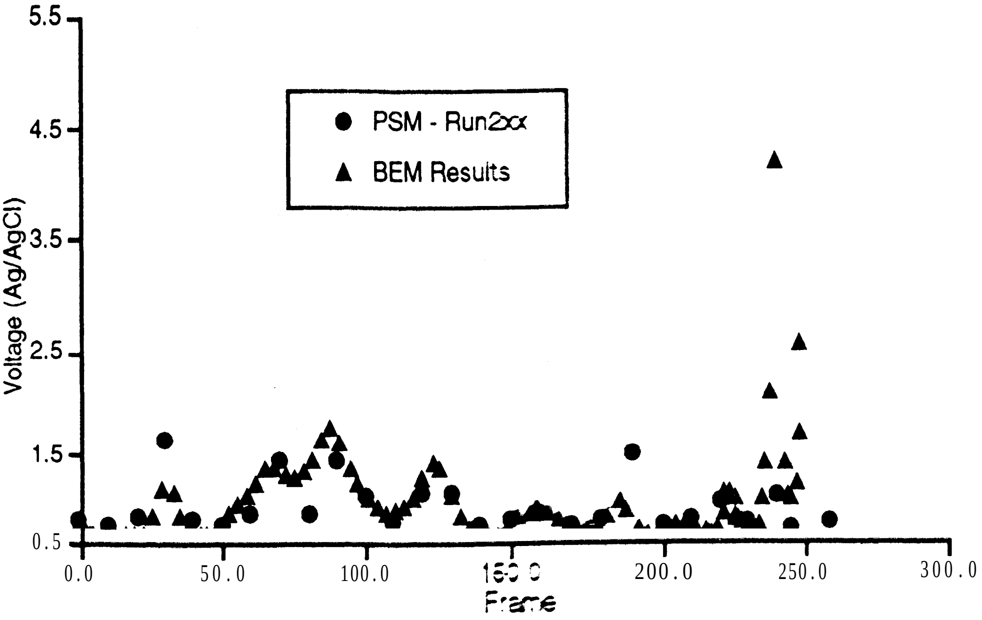

Figure 2b: Dynamic flow and maximum damage conditions. Measurements taken at a depth of 10 feet.

Good agreement was observed in most instances. Differences between computational and experimental results were determined to be the results of model simplification or material characterization. Potential contours along regions of small geometric detail indicated that more refinement could improve results. The polarization response does not incorporate material interaction. The formation of a protective film, which has been observed in testing, is not addressed in the polarization response. Effects of initial current level on subsequent polarization response, an observed phenomenon was not incorporated into the response used. The polarization response at high current levels, such as observed near anodes in the computer model, was not incorporated into the response used. These issues are not generally addressed in any laboratory testing program for polarization response and may be difficult to quantify.

In summary, the advantages of computational modeling include:

(1) ease of model manipulation for addition or movement of anodes
(2) ability to examine potential maps of the entire structure to determine under and over protection regions based on a generic polarization response
(3) the ability to quickly evaluate changes in anode, reference cell or damage configurations.

5 Combined Design Methodology

The proposed combined computer-physical scale modeling procedure is shown in Figure 3. A two phase methodology is proposed in which computational modeling is used for preliminary system design and evaluation while physical scale modeling is used for final verification. Computational modeling is used to evaluate multiple candidate ICCP system designs. Changes in anode number and placement, reference cell number and placement and power zone definitions can be readily evaluated. The final design as determined by computational analysis is then evaluated by physical scale modeling. This eliminates uncertainty due to polarization response definitions used in the computational analysis. The uncertainty in polarization response is one of most severe limitations of accurate computational evaluations. In addition, a final check of the proposed ICCP system design by physical scale modeling will identify any inaccuracies which may have been inadvertently introduced in the computer model by model simplification or material characterization. Final anode placement, reference cell placement and power supply magnitudes will be validated by examination of physical scale modeling results. The combined procedure results in significant cost and time savings with an increase in design confidence.

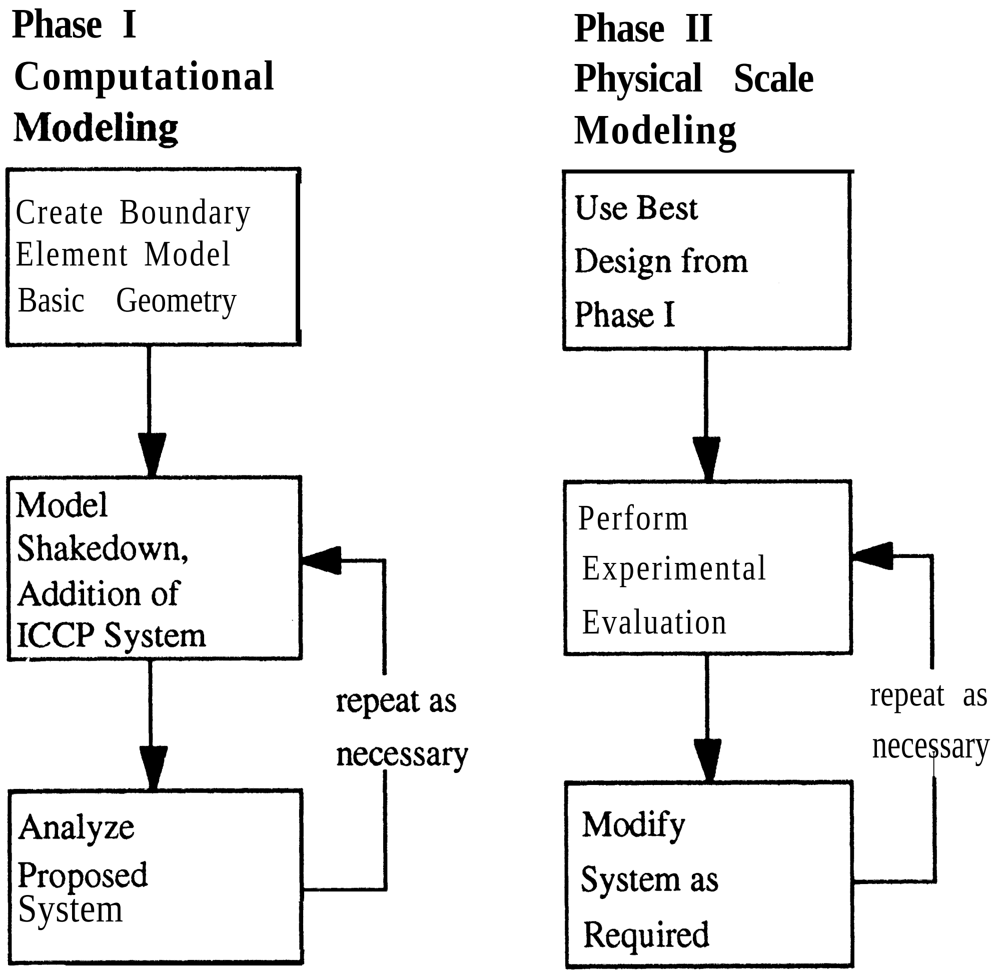

Figure 3: Combined experimental and computational design methodology

6 Summary

Physical scale modeling can be an expensive and extremely time consuming method to evaluate multiple ICCP system designs. Computational modeling on the other hand is well suited for the quick evaluation of multiple ICCP system designs once the hull geometry has been defined. Conversely the accuracy of computational modeling is critically dependent on accurate characterizations of polarization response while physical scale modeling does not depend on the mathematical representation of polarization response. Therefore while a comparison of system attributes may be quickly obtained using computational modeling, the absolute accuracy of results may be limited. The accuracy of physical scale modeling results is not affected by the ability to correctly define the polarization response and in this respect the method is more suited to determining absolute current requirements than the computational modeling method. Combining the two methods results in a more robust methodology with fewer intrinsic limitations than either methodology when considered separately.

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