

Finite resistivity and shipboard corrosion prevention system performance

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Abstract

In the computational evaluation of electrochemical corrosion systems painted surfaces are often treated as perfectly insulated. While many paint systems have a high resistance; the resistance is finite rather than infinite. In this work a range of finite resistivity values will be assigned to the painted surfaces in a boundary element model of a shipboard ICCP system. The studies performed were developed to provide an increased understanding of the effects of finite resistivity on system performance, provide a quantitative measure of the effects of ranges of finite paint resistivity on system performance and to increase the understanding of modeling methods to issues of damage and material polarization response definitions.

1 Introduction

Corrosion damage is a major factor in ship maintenance and availability. Paints and shipboard impressed current cathodic protection (ICCP) systems are important established tools in the reduction of corrosion damage to ship hulls. In ship hulls, as in many other structures, paints are considered a primary defense against corrosion damage. Paints prevent corrosion damage by isolating the material to be protected from the surrounding environment. ICCP systems are designed as secondary systems to reduce corrosion damage that will occur once the paint is damaged. Paint damage can be either a decrease in isolation capability due to degradation of paint properties or an exposure of metal due to physical damage to the paint.

ICCP systems are designed to take advantage of electrochemical corrosion phenomenon to minimize corrosion of a designated area and material. Protection is provided by maintaining the electric potential on the designated material at or above a critical potential value. An ICCP system uses a power source to provide a source of electrons required for

adjustment of the electrical potential of the material to be protected. The sources of electrodes are defined as anodes. Cathodes are the areas of material to be protected. In ICCP reference cells act as sensors providing information on potential levels along the ship hull. The power sources are controlled through a feedback loop by the measured potential levels. Ship ICCP systems are designed to provide protection for predefined amounts of exposed metal. The proximity of cathodes to anodes has an effect on the required current levels. In reality, paint damage can occur anywhere along the ship hull. Observations of paint damage patterns in dry dock are used to generate typical paint damage patterns for consideration.

2 Scope of Work

In previous computational analyses painted surfaces have been defined with infinite resistivity [1-5]. This corresponds with the test model generated for use in experimental process used to validate the computational results. In the test model painted areas were represented by fiberglass, a non-conducting material. The assumption of perfect paint was therefore appropriate for direct comparison of computational and experimental results. However, when used to predict performance of actual shipboard systems the influence of finite resistivity on computational results should be considered.

In the current work the effects of finite paint resistivity is examined for a specific ship hull and ICCP system. The ship hull considered is a U S Navy CVN air craft carrier. The boundary element model created for this ship hull has been previously validated by extensive comparison with experimental scale modeling results [6]. The ICCP system modeled is an upgrade to the existing CVN-68 system. The system modeled was designed using scale modeling experimental technique. During the validation process four design conditions were evaluated: minimum and maximum damage conditions at static and dynamic flow conditions. In order to determine if finite resistivity effects would be greater than variation due to other material and modeling parameters the conditions which resulted in the maximum variation between experimental and computational analyses are used. Dynamic flow conditions resulted in the greatest difference between experimental and computational results [6] and are therefore used in the current work.

Two studies are completed. In both studies the computational model is modified by inclusion of a finite resistivity for painted surfaces. The finite resistivity of paint is defined as a fraction of bare steel non-linear polarization response. The range of resistivities considered is 0.0001 to 0.1 of the polarization response of bare steel. Voltage conditions corresponding to the validated model are maintained. In the first study system performance at 15% paint damage dynamic flow condition is examined. This is the most severe service condition analyzed. In the second study paint damage is varied from 3 to 15% under dynamic flow conditions. The variation in current distribution and requirements are examined as the paint resistivity on the damaged

regions in excess of 3% damage gradually increases from 0.001 of steel to that of steel. The degradation of system performance is observed. While this is not an extensive study of finite paint resistivity effects, trends in system performance can be observed.

The commercial boundary element program BEASY-CP [7] is used in this work. The information presented should not be unique to the programs used, especially information on establishing the boundary element problem.

3 Theoretical Basis for Modeling

The governing differential equation for electrochemical corrosion for a structure surrounded by a bounded uniform electrolyte is:

$$k\nabla^2\Phi=0$$

Where Φ is the electric potential and k is the conductivity of the electrolyte. For LaPlace's equation to be valid the volume surrounding the structure cannot contain either electrical sources or sinks and the total current in must equal the total current out of the system.

The use of boundary element methods for modeling shipboard corrosion prevention systems is well established [8]. Details of the mathematical formulation can be found in Ref. 1-6 and 8. It can be readily shown that shipboard ICCP systems meet the requirements for application of LaPlace's equation governing corrosion.

4 Material Response

Essential in any computational simulation is the material characterization used. Four distinct material definitions are used in the present work: perfect paint, finite resistance paint, steel, a nickel aluminum bronze alloy (NAB) and seawater. . Perfect paint is defined as an insulated surface. The other three materials are defined with nonlinear polarization response. Finite resistance paint is defined by assigning a fractional value of the polarization response of steel. The responses for steel and NAB were experimentally determined. Seawater is assigned a conductivity of 20 Ohm-cm representing average conditions.

The polarization responses for steel and NAB used are based on series of experiments using scaled conductivity seawater. The water used is that used in physical scale modeling of the CVN system. Physical scale modeling testing is an experimental technique used for examination of shipboard ICCP system performance. In this technique the dimensions of the structure and the electrolyte conductivity are scaled by the same factor [9]. This is the experimental method used to validate the CVN computational model [6].

Paints and passive coatings prevent corrosion damage by isolating the metal from the environment. Passive coatings form naturally and

have been observed to reduce conductivity values by an order of magnitude or more [10]. Paints are engineered materials that are much more effective in reducing environmental contact however paints vary in their effectiveness by several orders of magnitude [11]. One common held rule of thumb is that good paints increase metal resistance by 3 orders of magnitude. The range of ratios of paint to steel polarization response used in this work is based on the effects of natural coatings and this rule of thumb.

5 CVN Geometry and Computational Model

The structure examined is a U S Navy CVN air craft carrier (Figure 1). The section modeled is the wetted portion of the hull. Propellers and rudders are included in the model. Propellers are attached to the hull in the model by a solid section representing the main strut of the support structure. Propellers are modeled as solid disks with the same diameter as the actual propellers. Disk thickness is determined by meshing considerations. The disks are defined with sufficient thickness to avoid numerical difficulties generated by thin sections in the boundary element model.

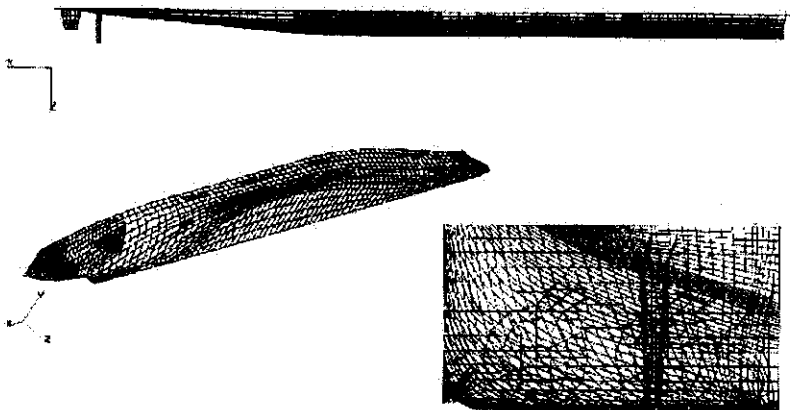


Figure 1. Boundary element model of CVN ship hull.

Symmetry conditions are used to define the ship hull geometry. The boundary element mesh of 1884 elements is shown in Figure 1. Each element is a 9 noded quadrilateral element with 8 side and 1 center node. This is a standard element type in BEASY-CP. The elements have quadratic geometry shape functions and linear representations of potential and flux density. This combination in element definitions and mesh refinement has resulted in accurate predictions of experimental data for other ship hull geometries [2,4,5]. The CVN model was created following guidelines generated from previous analyses.

The ICCP system incorporated in the boundary element model is an existing system. The system consists of 3 independent power supplies and 17 anodes. Anode placement as modeled is symmetric about the hull centerline. The forward power supply is attached to 4 anodes, 2 on either side of the ship. The mid-section power supply supports 8 anodes. The rear power supply support 4 symmetrically placed anodes and 1 centerline anode.

The addition of a large but finite seawater domain surrounding the ship hull completes the boundary element model. The domain is large enough so edge effects are not apparent on the hull model. In this model, the domain extends for 20 ship lengths from the hull model.

Details of the model validation can be found in Ref. 6. Static and dynamic flow conditions are combined with 3% and 15% paint damage conditions for model validation. Locations of bare metal are not randomly defined but are defined by damage protocols based on observations made from similar ships in dry-dock. In the damage protocols no benefit is given for partially damaged paint. Surfaces are defined as either coated or bare metal.

In all cases the potential levels of the impressed anodes are defined as fixed input values. The total system resistance, based on the material response, seawater conductivity and geometry, defines the resulting total current. Potential levels are defined for the baseline conditions for the obtaining of a reference cell potential of 0.85 volts Ag/AgCl.

In this work two parametric studies were completed to examine finite resistivity and system performance parameters. In the first study 15% damage dynamic flow conditions were examined. Voltage input values were maintained at those for the design condition. The painted surface area was assigned finite values of resistivity. Paint resistivity is defined as a fraction of steel polarization response. Paint response is defined as 0.1, 0.01, 0.001 and 0.0001 times the polarization response of steel. Each definition represents an analysis.

In the second study paint damage was allowed to gradually increase from 3% to 15% of the surface area. This was done by defining the polarization response of the damage in excess of 3% surface area as 0.001, 0.01, 0.1, 0.2, 0.5 and 1.0 times that of steel. When all damaged paint elements are assigned the polarization response of steel 15% of the surface area is bare metal. In all cases except the perfect paint condition, non-damaged painted surfaces are assigned a polarization value equal to 0.001 that of steel. Perfect paint condition is that used in the validation of the CVN model [6]. Input voltages values were maintained at levels required for adequate protection at 3% damage dynamic flow conditions.

6 Results

Results highlighted here for each condition are the total current, current associated with specific regions of paint damage and the potential contour along a line at a depth of 10 feet.

Current totals for variations in resistivity for 15% damage dynamic flow conditions are given in Table 1. Current totals for specific areas

are shown in Table 2. Areas of exposed metal of interest are: the propellers, damage areas on the propeller struts, docking blocks, waterline damage areas, bilge keel damage areas and damage areas on the rudder.

Table 1. Current total (Amps) for 15% damage dynamic flow.

Paint Resistivity:					
Exp. Results	Perfect Paint	0.0001 Steel	0.001 Steel	0.01 Steel	0.1 Steel
1837.7	1707.2	1708.2	1710.2	1730.2	1855.3

*Average current in and current out of computational results

Table 2. Current total (Amps) for 15% damage dynamic flow, selected damage areas.

Area:	Paint Resistivity:					
	Exp. Results	Perfect Paint	0.0001 Steel	0.001 Steel	0.01 Steel	0.1 Steel
Propellers	228.2	189.8	190.7	190.2	185.2	153.0
Docking Block:						
Min. Damage	Total:	86.2	98.9	97.9	88.4	28.6
Other	185.2	99.0	86.1	85.4	79.4	39.0
Waterline	229.8	206.8	206.6	205.5	205.5	100.1
Bilge Keel	290.8	174.4	174.4	169.7	167.9	124.4
Struts	104.4	85.8	85.8	85.2	81.2	67.6
Rudder	43.0	85.0	85.5	84.6	82.0	58.1

The variation between physical scale model results and computational results which model perfect paint have been attributed to material interactions and film formation. Major differences are in the region of the propellers. Variations in NAB and interactions between steel and NAB are primary factors in this region and are not addressed by the current analysis. It is interesting to note that there is a slight increase in current to propellers when the rule of thumb resistance (0.001*steel) and higher (0.0001*steel) are used.

Current totals for the transition from 3% to 15% damage due to decreasing paint resistivity are shown in Table 3. Current totals for specific areas previously defined are shown in Table 4. Areas included in 3% exposed surface area are the propellers and docking blocks for minimum paint damage. 15% damage areas include these areas, additional docking block areas and additional area on the hull surface.

Table 3. Current total (Amps)
3% - 15% damage transition, dynamic flow.

Paint Resistivity:							
Exp. Results	Perfect Paint	0.001 Steel	0.01 Steel	0.1 Steel	0.2 Steel	0.5 Steel	1.0 Steel
314.7	190.6	202.2	209.4	251.0	263.8	279.4	292.1

*Average current in and current out of computational results

Table 4. Current total (Amps)
3% - 15% damage transition, dynamic flow, selected damage areas

Area:	Paint Resistivity:							
	Exp. Res.	Perf. Paint	0.001 Steel	0.01 Steel	0.1 Steel	0.2 Steel	0.5 Steel	1.0 Steel
Propellers	204.1	118.9	123.8	120.0	99.9	95.0	80.1	88.4
Docking Block:								
Min.Damage	110.6	71.7	63.7	58.1	28.4	20.6	13.9	8.6
Other	0	0	0.1	1.2	6.1	6.6	6.6	6.3
Waterline	0	0	0.3	3.8	15.6	17.6	21.9	22.8
Bilge Keel	0	0	0.2	1.6	13.4	20.8	34.1	47.4
Struts	0	0	0.1	1.2	6.8	8.2	9.4	9.8
Rudder	0	0	0.1	0.5	6.6	8.4	9.8	10.4

In this analysis the elements corresponding to 3% paint damage are assigned metal properties. This damaged area consists of the propellers (NAB) and a portion of the docking block area. In addition the elements corresponding to the difference in 15% and 3% damage cases are assigned a material property representing partial paint. The polarization response of this area is a fraction of that of steel. All other areas are assigned paint properties, perfect paint in the one case and 0.0001 of steel in all other. Variations in current totals are due to increased conductivity of additional paint areas. Major changes in current draw do not occur until significant increase in paint resistivity. This indicates that even though paint may continually deteriorate this is not a concern until a relatively low value of resistance is achieved. A more detailed analysis with material information on a specific paint could result in extensions of useful service life basing retirement on cause rather than on simply time in service.

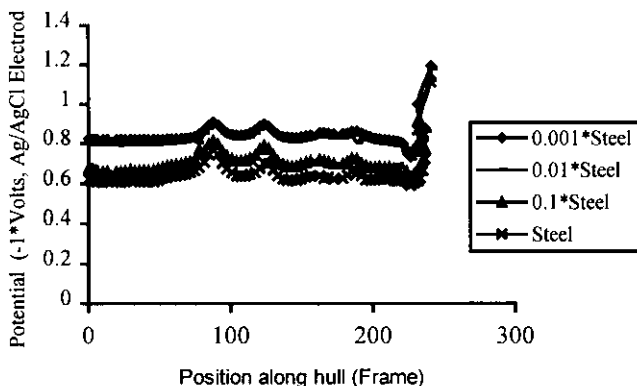


Figure 2. Potential profiles for a depth of 10 feet below waterline transition from 3% to 15% paint damage.

Potential profiles for a depth of 10 feet are shown in Figure 2 for the transition from 3% to 15% paint damage. The reduction in potential levels is due to the increased current draw for identical voltage input. There is negligible change in the potential profile until significant reduction in paint resistivity ($0.01 \times \text{steel}$). This corresponds to observations made based on current totals.

7 Summary

In the current work the effect of incorporating finite paint resistivity in the computational evaluation of shipboard ICCP systems was examined through two studies. In the first study the resistivity of paint was increased from less than rule of thumb values to very near that of steel with a natural passive layer. In the second study regions of defined paint damage were assigned constantly decreasing resistance until a resistance equal to bare steel was achieved. Effects of paint degradation with time, spatial interactions of damaged areas and finite paint resistivities are observed in this study. In summary, the current work has shown that:

- (1) Changes in computational results due to incorporating realistic levels of paint resistance instead of perfect paint assumptions are minimal.
- (2) In worse case conditions, 15% damage dynamic flow, changes are within observed differences between computational and experimental results. These differences have been attributed to material characterization limitations rather than the use of infinite paint resistivity since experimental results are derived from fiberglass models that exhibit perfect paint characteristics.
- (3) Results overall support assumptions that for design modeling paint can be treated as either perfect or non-existence (use of bare metal for damaged areas).
- (4) Results indicate that computational model with specific paint properties could be used to determine useful life of paint based on resistance changes with time. The differences in current patterns resulting from modeling the degradation of paint with time are of interest in paint development and life cycle definitions. Computational analysis would be a significant tool in determining when paint resistivity has degraded to the point where the area covered may be considered damaged.

In summary, the effects of incorporating a finite paint resistivity into computational evaluation of shipboard ICCP systems has been presented. Rather than focus on a particular paint, ranges of resistivity values were evaluated. There are not indications that a more accurate computational based design could be generated by the inclusion of finite paint resistivity. However, detailed study of the interaction between damaged areas with different paint resistivity could increase the

understanding of the spatial and material interactions inherent in electrochemical corrosion systems.

8 References

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