Boundary Element Evaluation of ICCP Systems Under Simulated Service Conditions

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INTRODUCTION

The cost of repairing damage to marine structures and ships attributed to corrosion have lead to the development of technologies which try to limit the corrosion process. Use of cathodic protection systems take advantage of the electrochemical nature of the corrosion processes and attempt to limit the degree of corrosion which occurs. External sources of electrical current are used in impressed current cathodic protection (ICCP) systems. Current is supplied through source anodes and voltage levels are monitored through reference cells. ICCP systems are currently in use on a wide variety of structures.

There are two basic issues involved in the design of an ICCP system; system effectiveness, i.e. the ability to obtain protection potential levels required, and efficiency, i.e. the ability to maintain protection while minimizing or eliminating dangerously high voltage levels on sections or while minimizing current requirements, can be adversely affected by poor placement of source anodes or reference cells.

Many present day ICCP systems are based on designer expertise rather than analytical evaluation of interactions of sources, electrical field distribution and structure geometry. The creation of an ICCP system which performs at a optimum level, providing the maximum possible protection for the minimum possible power input. is a complex task. Skillful arrangement of the individual components can result in an effective ICCP system.

Analytical evaluation of ICCP system performance, either by computational simulations techniques or scale model experimental evaluation, can be powerful tools in the development of ICCP systems which are both effective and efficient.

Mathematical models necessary for computational simulations of electrochemical processes have been developed in the 1950s [1]. Numerical solutions for LaPlace equations have been incorporated into many commercial boundary element and finite element codes. Boundary element and finite element computational simulation techniques have been used successfully to model electrochemical response. Of particular interest to the current work, both boundary element and finite element techniques have been used to model ships and other marine structures [2-8]. While both finite element and boundary element are viable computational simulation techniques it is felt by the authors that the boundary element methodology is better suited to the evaluating of infinite electrolyte domain problems such as the surface ship problem studied in the present work.

In the evaluation of the cathodic protection systems using boundary element methods, the boundary dividing the structure from the electrolyte is modeled. In the case of a structure surrounded by a nearly infinite medium. such as a surface ship surrounded by the open sea, the outer boundary of the computer model is an artificial boundary placed a large distance away from the structure. Since only the interface surface between the structure and electrolyte is modeled, the volume of electrolyte modeled can be very large without effecting the number of elements and nodes required for discretization.

Physical scale model testing involves the scaling of both the geometric dimensions of the structure and electrolyte conductivity [9]. Physical scale modeling experimental results have been successfully compared with data obtained from tests performed on full size ships [10]. The ability to use scale model test results which can be related to full size ship data increases confidence in the reliability of computational simulation results.

The current work consists of evaluations of existing ICCP systems on U. S. Navy CG class surface ships. Current requirements for a six anode single zone and a six anode two zone system are evaluated for ship at rest (static) and ship underway (dynamic) conditions. A zone is defined as a independently controlled power supply which is used to provide current to the impressed current anodes. Anodes within a control zone have identical voltages and current inputs. Computational simulation and physical scale model experimental results are compared in detail for the two systems. The physical scale model experiments were performed using a scaling factor of 1/96 for the models and seawater conductivity.

CRITERIA FOR CATHODIC PROTECTION

The criteria chosen for use with an ICCP, or any cathodic protection system is a means to determine if the structure is fully protected from corrosion.In the present work, a potential of -0.85 Volts with respect to a Silver/Silver Chloride electrode (SCE) was chosen as the target potential. This is considered adequate to maintain full protection for steel [11]. The target potential is bracketed by the range -0.83 to -0.87 Volts SCE for the computational simulation.

ICCP systems are controlled by the potential readings on reference cells strategically positioned on the structure. Generally, one refers to the structure being at the target potential or within the target range. In reality, the potential values which are used to define the behavior of the structure are obtained from a very limited number of locations, i.e. the locations of the reference cells. In the design of an ICCP system it is assumed that reference cell readings within the target range corresponds to adequate corrosion protection for all exposed surfaces. This may or may not be true. Physical scale modeling allows for detailed examination of the potential profile by installation of multiple reference cells.

Computational simulation results can provide detailed information with regards to the potential at all points on the surface of the structure. In the cur-rent analysis, the potential response for the entire surface ship and appendages can be examined. A point by point evaluation of the degree of polarizaton provided by the existing ICCP system can be made based on the computational results. Regions of over-polarization which may result in paint damage or other performance difficulties can be identified from the computational results. Regions of under or over-protection which may occur even though the reference cells indicate full protection can be identified. The ability to map regions of over and under protection can be used as a tool to redefine anode or reference cell locations.

BOUNDARY ELEMENT MODEL

Two ICCP system designs which are currently found on U. S. Navy CG class ships are examined. The two systems are outlined in Figure 1. The first system studied is the six anode single zone ICCP system found on the CG-47 surface ship. The single zone system uses reference cell R1 shown in Figure 1. The second system studied is a six anode two zone ICCP system of the U. S. CG-59 surface ship. The two zone system uses reference cells R2 and R3 as shown on Figure 1. The CG-47 and 59 have identical hull geometries. Symmetry conditions allow for half of the ship to be modeled. Of course, only that portion of the ship below the water line is required in the boundary element model. The boundary element model created for the analysis is shown in Figure 2. The boundary element model of the CG class surface ship consists of 573 quadrilateral constant value elements made up of 700 nodes.

The boundary element model developed has the following features:

(1) detailed modeling of the complex curvature of the hull surface

(2) inclusion of rudder as geometrically distinct but electrically connected component

(3) inclusion of propellor assembly as geometrically distinct but electrically connected component

(4) use of nonlinear polarization response curves to represent material behavior

(5) use of three separate materials (steel, nickel-aluminum-bronze (n-a-b) and paint) to model separate regions of the ship

The boundary element model was created using an interactive graphics program. Constant value quadrilateral elements are used. Nodal point results are used for comparison with physical scale modeling data. Specifically ship centerline and ship surface potential readings at a depth of 3.048 m (10 ft.) below the water line.

The impressed current anodes are explicitly included in the boundary element model. The source anodes have finite areas and fixed locations. Anodes connected to the same zone are prescribed identical voltages as part of the defined boundary conditions. The balance of current input for different zones is calculated as a verification check on the feasibility of the calculated solution.

Three different materials are used to model the hull, propellor and rudder in the model. The hull is assumed to be undamaged paint. The painted surfaces are assigned an infinite resistivity. This is consistent with previous work [6]. In addition, painted surfaces in physical scale model experiments have been modeled using fiberglass [9]. Therefore, the inability to maintain an electrical current is a valid assumption for computational modeling of physical scale model experiments. The propellor and rudder are modelled as bare n-a-b and steel, respectively. The material response used for structural steel in seawater is shown in Figure 3 for static and dynamic conditions. The potentistatic polarization curve used as the mathematical basis for n-a-b behavior is per Reference 12. The polarization response given in Reference 12 is for static conditions. The polarization response for n-a-b at dynamic conditions is obtained by scaling the at rest response based on the ratio between underway and at rest response for structural steel.

The infinite seawater domain is approximated by a box of constant value quadrilateral elements which surrounds the ship model. The edges of the box are at least 20 times the ship’s length away from the ship model. This is so the boundary conditions applied to the box do not affect the potential fields generated around the ship model. The box elements are defined with a current density of zero to approximate the correct boundary conditions at infinity. A resistivity of 20 Ohms-cm is assigned to the seawater.

The painted surface of the ship modeled as free of damage. The n-a-b and structural steel surfaces are assumed to be free of calcareous deposits. There are no time in service effects incorporated in the present analysis.

The total current supplied to each zone is calculated from the boundary element computational results. The magnitude of the current required is limited by the power supply available. For the current analysis, each zone is defined as being powered by a external power supply which is sufficient for the current demands. All power supplies are assumed to have equal amperage.

COMPUTATIONAL SIMULATION

The commercial boundary element program BEASY-CP [13] was used to solve the LaPlace governing equations for the defined ship structure. The boundary element analysis uses input potential values, defined current density boundary conditions on the box defining infinity, and material polarization characterization to determine the potential and current density of all points on the surface ship modeled.

The boundary element code uses an iterative solution procedure to solve the LaPlace equation when nonlinear polarization boundary conditions are used to describe material behavior. A valid solution must satisfy three independent criteria:

(1) the potential satisfies the LaPlace equation throughout the electrolyte domain.

(2) the flux balance is satisfied (the current entering the electrolyte is equal to the current leaving the electrolyte).

(3) the potential and current density results fall on the given polarization curve for each nonlinear material type for each element.

An iterative solution scheme is used by the boundary element program when non-linear constitutive response curves are used to define material behavior. Suggested tolerances are 0.1 to 0.5% for the commercial code used [14]. Particular problems may require an tighter tolerance because of the interaction of complex structure geometry and the nonlinear material polarization curves. In the current work, all cases resulted in a solution in 15 to 21 iterations using a tolerance of 0.05%.

A solution is obtained when the reference cell potential is within the target potential range of -0.83 to -0.87 Volts SCE. (-0.85 310.02 Volts SCE). Reference cells are identified in the schematic of Figure 1. The six anode single zone system uses one reference cell identified as R1 in Figure 1. The six anode two zone system uses two reference cells identified as R2 and R3 in Figure 1. Upper and lower bound solutions are obtained by matching reference cell potential with the minimum and maximum of the target potential range. Upper and lower bounds are defined based on current requirements; more current is required to obtain a reference cell reading of -0.87 Volts SCE so the more negative voltage target is associated with the upper bound limit on current requirements. In the case of the two zone system, the lower bound solution is obtained when the forward reference cell achieves a potential of -0.83 Volts SCE.; the upper bound solution is obtained when the aft reference ceil reaches a potential of -0.87 Volts SCE. This critieria is unique to the computational simulation; in actual operation on a full size ship the forward and aft reference cells would be maintained at the same potential reading. This was difficult to achieve on the computational model so the upper and lower bound scheme described was used to obtain operational limits.

Since the boundary element program uses an iterative solution technique it is possible that the current values associated with impressed current anodes may not be exactly equal for anodes within a zone. The solution tolerance will effect the variation in currents determined as part of the boundary element solution. Because of the iterative nature of the solution procedure a tolerance on current equivalency is required to determine solution acceptance with regards to the criteria imposed on each power supply zone. The impressed current anodes belonging to the same zone must have a total current input within 0.5 Amps of the other anodes attached to the same power supply for the solution to be considered valid.

The current required to obtain polarization potential considered adequate to maintain protection against corrosion is determined by an iterative solution scheme. Input voltage values are defined for the impressed current source anodes. Anode current levels are determined as part of the boundary element solutions. A valid boundary element solution based on the three criteria listed previously is determined for the prescribed input voltage values. The potential levels at the reference cell locations are queried to determine if adequate protection has been obtained. A potential reading of -0.83 Volts SCE or -0.87 Volts SCE at the reference cell is required for an acceptable solution. If the potential at the reference cell does not meet the criteria for an acceptable solution, the input voltage values are adjusted and the procedure is repeated.

COMPUTATIONAL RESULTS

Six Anode Single Zone (CG-47) System

The current and voltages required for a lower bound solution (reference cell R 1 at -0.83 Volts SCE) for the single zone system at static conditions are:

V_A=-1.3 Volts, I_A=3.4 Amps
V_B=-1.3 Volts, I_B=3.2 Amps
V_C=-1.3 Volts, I_C= 3.2 Amps

where the locations of anodes A, B and C are as defined in Figure 1. The upper bound solution (reference cell R1 at -0.87 Volts SCE) requirements are:

V_A=-1.45 Volts, I_A= 3.8 Amps
V_B=-1.45 Volts, I_B= 4.0 Amps
V_C=- 1.45 Volts, I_C= 3.7 Amps

The total current required is 20.2 Amps for the lower bound solution and 23.8 Amps for the upper bound solution. The propellor and rudder appendages are under protected for the both lower and upper bound solutions. The range in potential for the lower and upper bound solutions at the tip of the propellor on the rudder side is -0.76 to -0.82 Volts SCE.

The current and voltage requirements for a lower bound solution (reference cell R1 at -0.83 Volts SCE) for the single zone system under dynamic conditions are:

V_A=- 1.9 Volts, I_A=7.6 Amps
V_B=-1.9 Volts, I_B=7.8 Amps
V_C=-1.9 Volts, I_C=7.3 Amps

where the locations of anodes A, B and C are as defined in Figure 1.The total the upper bound solution (reference cell R1 at -0.87 Volts SCE) requirements are:

V_A=-2.1 Volts, I_A=8.6 Amps
V_B=-2.1 Volts, I_B=8.9 Amps
V_C=-2.1 Volts, I_C=8.3 Amps

The total current required is 46.3 Amps for the lower bound solution and 52.4 Amps for the upper bound solution. Computational simulation results indicate that the propellor and rudder are under protected for the both lower and upper bound solutions. The range in potential for the lower and upper bound solutions the rudder side propellor tip is -0.62 to -0.66 Volts SCE.

Six Anode Two Zone (CG-59) System

The current and voltage requirements for a lower bound solution of the two zone system (reference cell R2 = -0.83 Volts SCE) for static conditions are:

V_A=-1.3 Volts, I_A= 5.4 Amps
V_B=-1.2 Volts, I_B= 2.5 Amps
V_C=-1.2 Volts, I_C= 2.4 Amps

The current and voltage requirements for an upper bound solutions of the two zone system (reference ceil R3 at -0.87 Volts SCE) for static conditions are:

V_A=-2.0 Volts, I_A= 11.8 Amps
V_B=-1.2 Volts, I_B= 1.6 Amps
V_C=- 1.2 Volts, I_C=1.5 Amps

The total current required is 21.3 Amps for the lower bound solution and 30.6 Amps for the upper bound solution. In the upper bound solution the greater current requirements for the aft region due to the bare metal propellor and rudder are easily seen. It should be noted that reference cell locations for the six anode two zone system are different from the reference cell location used for the six anode one zone system.

The propellor and rudder are still under protected however, the potential readings are significantly closer to the desired protection range. The range in potential for the lower and upper bound solutions at the tip of propellor on the rudder side is -0.78 to -0.90 Volts SCE.

The current and voltage requirements for a lower bound solution of the two zone system (reference cell R2 = -0.83 Volts SCE) for static conditions are:

V_A=-3.0 Volts, I_A= 24.8 Amps
V_B=-1.0 Volts, I_B= 1.1 Amps
V_C=- 1.0 Volts, I_C= 1.1 Amps

The current and voltage requirements for an upper bound solution of the two zone system (reference cell R3 at -0.87 Volts SCE) for static conditions are:

V_A=-5.4 Volts, I_A=48.2 Amps
V_B=-1.5 Volts, I_B= 2.1 Amps
V_C=-1.5 Volts, I_C= 2.0 Amps

The total current required is 54.7 Amps for the lower bound solution and 105.5 Amps for the upper bound solution. The current required by the bare metals of the propellor and rudder under dynamic conditions can be clearly seen in a comparison of anode current requirements. Significantly more current is required by the aft regions.

Once again the propellor and rudder appendages are under protected for both lower and upper bound solutions. As in the static case, the potential readings are closer to the desired target values than in the case of the six anode single zone system. The range in potential for the lower and upper bound solutions at the tip of the propellor on the rudder side is -0.68 to -0.94 Volts SCE.

COMPARISON OF RESULTS

Computational simulation and physical scale model results are compared in detail for each case analyzed. Potential contours along the surface ship centerline and along the surface ship hull at a depth of 3.048 m (10 ft.) are compared. The total current obtained from computational results are compared with physical scale model test data.

Physical scale model solutions have been obtained for each of the ICCP system and operating conditions considered. Physical scale model solution data correspond to reference cell readings of -0.85 Volts SCE.

The physical scale model test results chosen for comparison contain exposed steel in the form of docking blocks, additional geometric complications in the form of the bilge keel but have painted rudders.The docking blocks represent additional areas of bare steel scatteredalong the hull surface. The bilge keel can be idealized as a narrow ridge which is perpendicular to the hull as shown in Figure 1. The bilge keel effects how current flows over the surface of the hull. Typically the bilge keel acts as a deflector requiring more current to obtain target potential levels at regions shielded by the bilge keel. These features, docking blocks and bilge keel, were not included in the boundary element model because their inclusion would have resulted in a more detailed model than would be reasonable based on time and resource limitations.

In both physical scale model testing and computational data the amount of current which flows to the propellor can be determined. In order to make the best possible comparison of experimental and computational results, the total current which flows to the propellor is used for comparison of physical scale model and computational results. In this way, the effects of bare docking block areas on the physical scale model and bare metal exposed on the rudder on the computational model can be eliminated from the comparisons.

Six Anode Single Zone (CG-47) System

Six anode single zone system boundary element and scale model testing results show similar trends. Under static conditions the propellor and rudder is under protected based on the target potentials while the reference cell is within the target range. The potential of the rudder side of the propellor tip is -0.72 Volts SCE. This is within 5.2% of the range of -0.76 to -0.82 Volts SCE defined by the boundary element solutions. Potential profiles along the ship centerline are shown in Figure 4. The upper and lower bound boundary element solutions shown the same trend as observed in experimental data and are near the same values as the experimental results. Similarly, the upper and lower bound boundary element solutions are shown to be similar to the potential readings along the ship hull at a depth of 3.048 m (10 ft.) (Figure 5).

The total current required for a full size ship calculated from physical scale model test data is 63.9 Amps for a reference cell reading of -0.85 Volts SCE under static conditions. The current to the propellor on the physical model current scales to 43.1 Amps for a full size ship.

Boundary element upper and lower bound solutions yield a total current range of 20.2 to 23.8 Amps. The propellor current range is 10.0 to 10.6 Amps. The remaining current is delivered to the rudder.

There is a difference of 75% between the propellor current determined by physical scale modeling and that determined by the boundary element analysis.Two possible explanations of the difference are the presence of the bilge keel in the physical scale model and the uncertainty in the material polarization response curves used in the computational model. Variation in n-a-b polarization response based on the experimental procedure used to obtain this material behavior characteristic have been observed [12]. Variation in physical scale modeling and computational results could be indicative of the intrinstic variation in the polarizaton response. The bildge keel is a possible source of differences because for this cathodic protection system configuration it is acting as a current deflector and shielding the reference cell. Additional current is required to overcome the geometric effects of the bilge keel. Once sufficient current is supplied to the system to overcome the bilge keel shielding and the reference cell obtains the target value of -0.85 Volts SCE, potential profiles, both centerline and hull surface at 3.048 m (10 ft.) show similar patterns between experimental and computational results.

Six anode single zone physical scale model potential readings for the rudder side of the propellor tip under dynamic conditions is -0.64 Volts SCE. This is within the range -0.62 to -0.66 Volts SCE defined by the boundary element upper and lower limit solutions. Potential profiles along the ship centerline and along the hull surface at a depth of 3.048 m (10 ft.). are shown in Figures 6 and 7. In all cases, physical scale model results shown good agreement when compared with boundary element limit analysis results.

Under dynamic conditions, physical scale modeling estimates a total current for a full size ship of 96.9 Amps for a reference ceil reading of -0.85 Volts SCE. The propellor current scaled to a full size ship is 62.1 Amps.

The boundary element solutions yield a current range of 46.3 to 52.4 Amps. The current delivered to the propellor is bounded by 35.6 to 36.4 Amps. The remaining current is delivered to the rudder.

As in the static case, there is a large variation in the current on the propellor. Physical scale modeling results are 6 1.1 Amps and computational results are 35.6 to 36.4 Amps. The range in difference between the two solution methods is 40 to 42%. As in the static case, two possible explanations of the difference are the presence of the bilge keel in the physical scale model and the uncertainty in the material polarization response curves used in the computational model.

Six Anode Two Zone (CG-59) System

In the six anode two zone system there are three major system design changes from the six anode one zone system. The aft pair of source anodes are powered by an independent power supply. The one reference cell used previously (R1 in Figure 1) is replaced by two reference cells (R2 and R3) which are placed to minimize bilge keel shielding effects.

Six anode two zone systems boundary element and scale model testing results shown similar trends in the potential profiles. Potential profiles for the ship centerline and along the hull at a depth of 3.048 m (10 ft.) are shown in Figures 8 and 9 for static conditions. Boundary element results show qualitatively and quantitative agreement with physical scale model test results. Forward and aft reference cell readings for physical scale model test results are both at -0.85 Volts SCE. The physical scale model potential profiles are closer to the lower bound solution.

The physical scale model determined total current requirement for a full size ship of 33.6 Amps. The propellor current when scaled to a full size ship is 26.3 Amps.

The boundary element solutions yield a current range of 21.3 to 30.6 Amps. Current to the propellor ranges from 10.5 to 12.9 Amps.The remaining current is delivered to the rudder. The upper bound boundary element solution is within 50% of the physical scale model results. It is know from physical scale model results that shielding of the reference cell by the bilge keel has been reduced but not elimnated at the current levels required for static conditions.

In addition, current requirements are determined from the material polarization curves used in the computational simulation. Variation in material polarization curves will have a dramatic effect on the current response. Improvements in material characterizations will result in improvements in the computational simulation results.

Physical scale modeling and computational results indicate significantly more current is required by the aft anodes for polarization. The forward to aft current ratios are 0.1 for physical scale modeling and 0.1 to 0.4 for computation31 solutions.

Potential profiles for ship centerline and hull surface at a depth of 3.048 m

(10 ft.) for the six anode two zone system under dynamic conditions are shown in Figures 10 and 11. The boundary element solutions show similar trends as seen in the physical scale model test data.

Physical scale model current requirement for a full size ship under dynamic conditions is 53.2 Amps. The propellor current when scaled to a full size ship is 44.1 Amps.

The boundary element solutions yield a current range of 54.7 to 105.5 Amps. The propellor current range is 37.2 to 55.3 Amps.The remaining current is delivered to the rudder. Physical scale model current supplied to the propellor predictions is in the range defined by the boundary element solutions. The bilge keel effects at the high current levels required for adequate polarization under dynamic conditions are negligible. The current surrounding the surface ship has apparently reached a saturation level with respect to the geometric interference of the bilge keel.

As in the static conditions, physical scale modeling and computational dynamic condition results indicate significantly more current is required by the aft anodes for polarization. The forward to aft current ratios are less than 0.01 for physical scale modeling and 0.04 for computational solutions.

SUMMARY AND CONCLUSIONS

The purpose of this work was to evaluate multiple material surface ship models and compare results, when possible, with scale model experimental results. A commercial boundary element program was used to evaluate the ICCP system designed for the U. S. Navy CG-47 and CG-59 surface ships. The propellor and rudder of the ship were included in the model. Nonlinear cathodic polarization data is used to characterize material behavior. Two ICCP system designs were considered, a six anode single zone system and a six anode two zone system.

Similar trends were found in potential magnitudes and patterns between scale model experimental results and computational simulation results for all conditions considered.

Total current requirements are affected by presence of geometric details, such as the bilge keel, as well as the material polarization response used in the computational model. Material polarization response curves have been observed to vary based on the experimetal technique used and even to vary with the scan rate used [12] so variation between computational and experimental results of the order observed is possible. It is also important to thoroughly understand the effects of even what may at first seem minor geometric details. The extent of the effects of the geometric features such as the bilge keel can be determined by experience or by performing parametric studies. Both physical scale modeling and computational simulations are possible methods to perform parametric studies.

Based on the analysis performed-the boundary element method has been demonstrated to accurately predict global behavior, such as potential profiles and potential readings at particular geometric locations. Differences between experimetnal and computational results can be attributed to variation inherent in the material polarization response and to geometric phenomenon not included in the computational models. The ability to change system design in a computational model will allow for this procedure to be used as a valuable design tool. Additional experimental validation of a final system design would complete the design process prior to installation on an actual ship.

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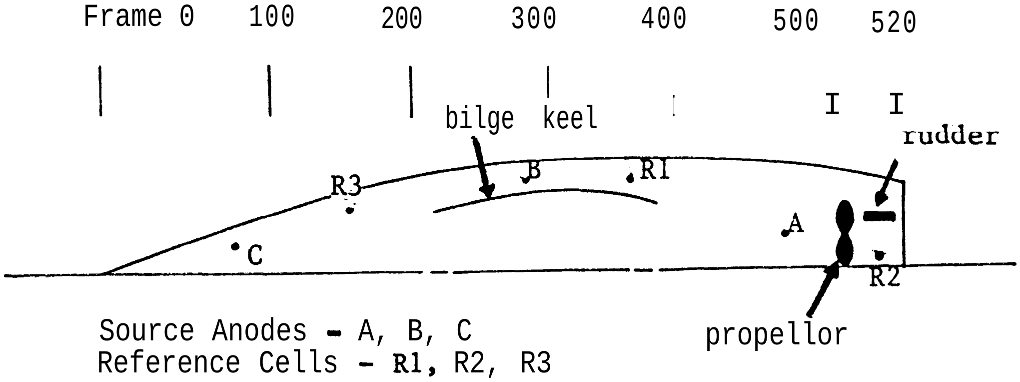

Figure 1 - Schematic of Ship Hull

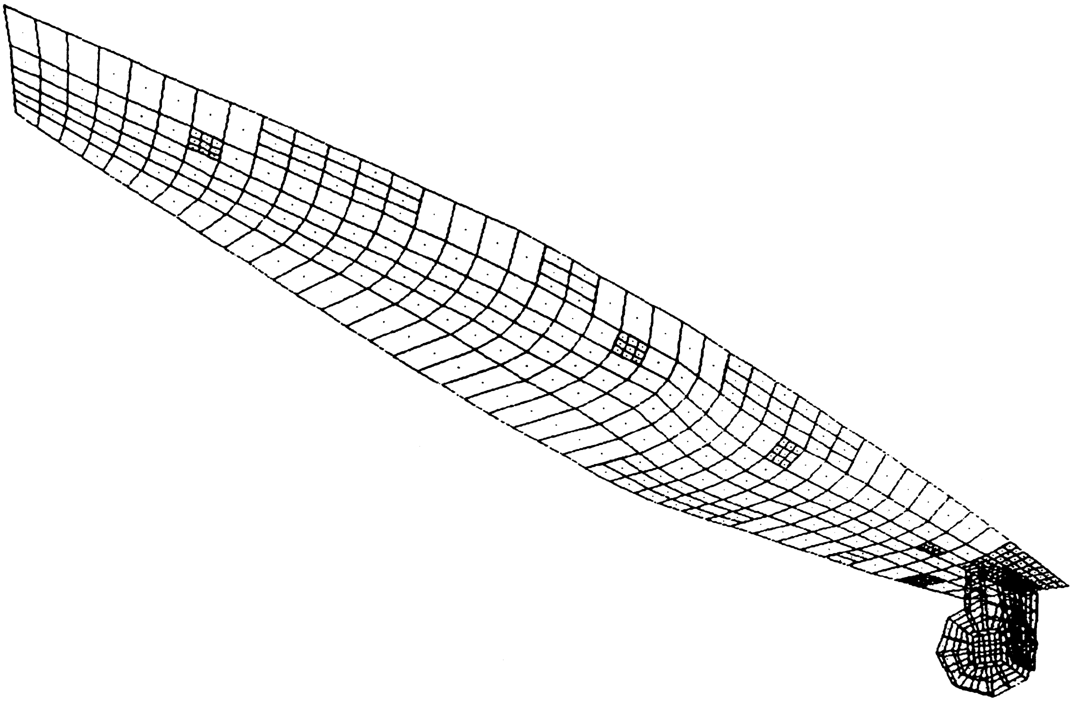

Figure 2 - Boundary Element Mesh

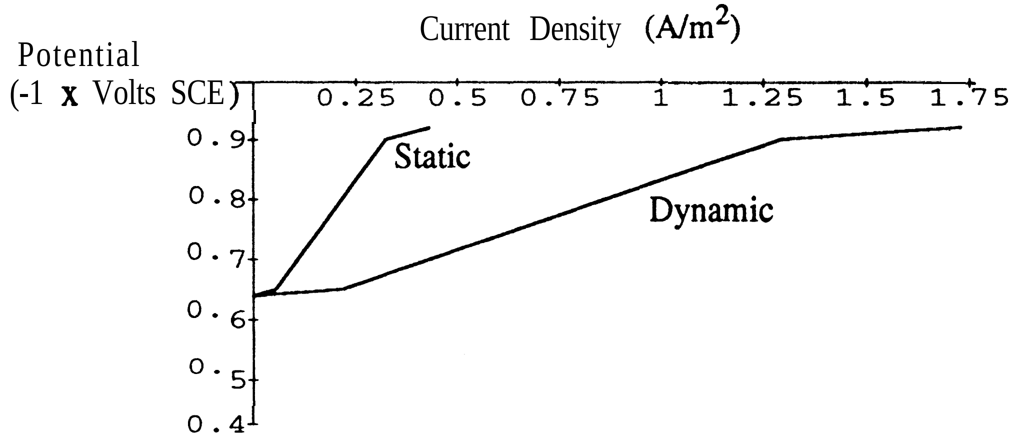

Figure 3 - Potential vs. Current Density for Structural Steel

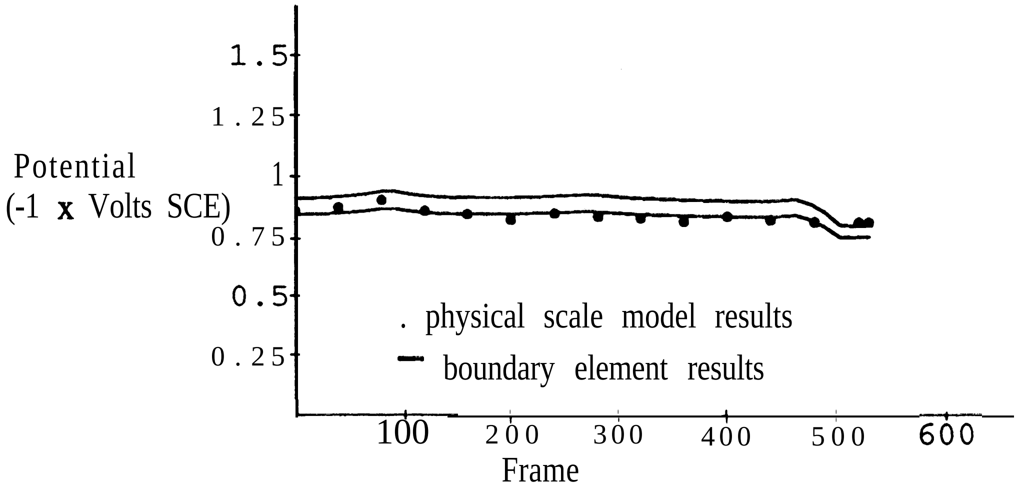

Figure 4 - Potential vs. Frame, Centerline, Static, 6 Anode - 1 Zone System

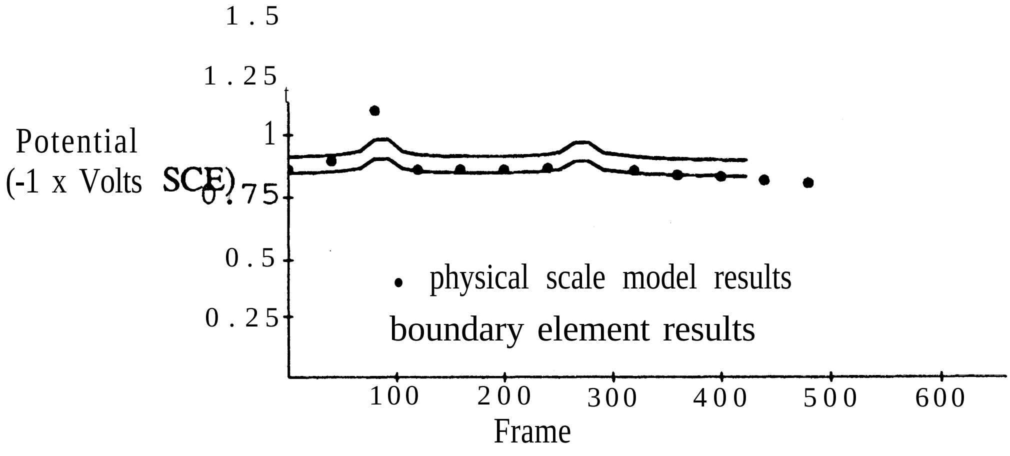

Figure 5 - Potential vs. Frame, Side Readings at 3.048 m (10 ft.), Static
6 Anode - 1 Zone System

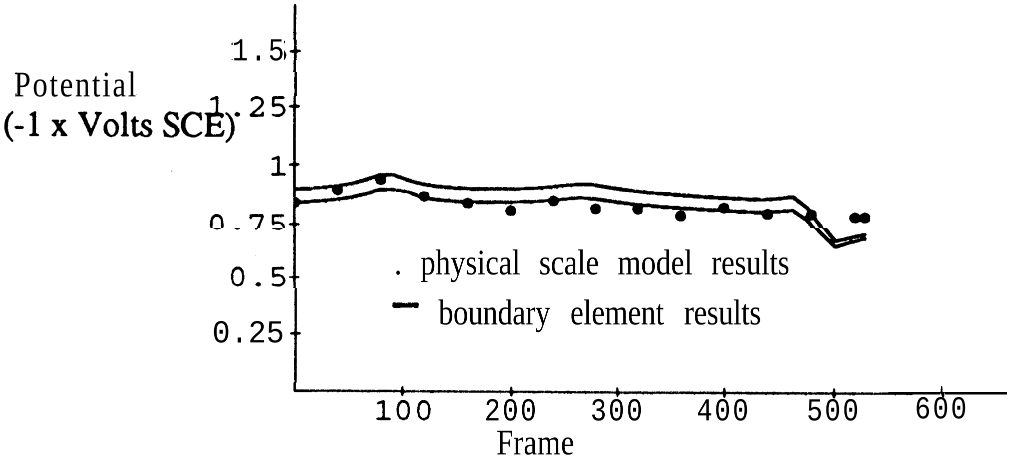

Figure 6 - Potential vs. Frame, Ship Centerline, Static, 6 Anode - 2 Zone System

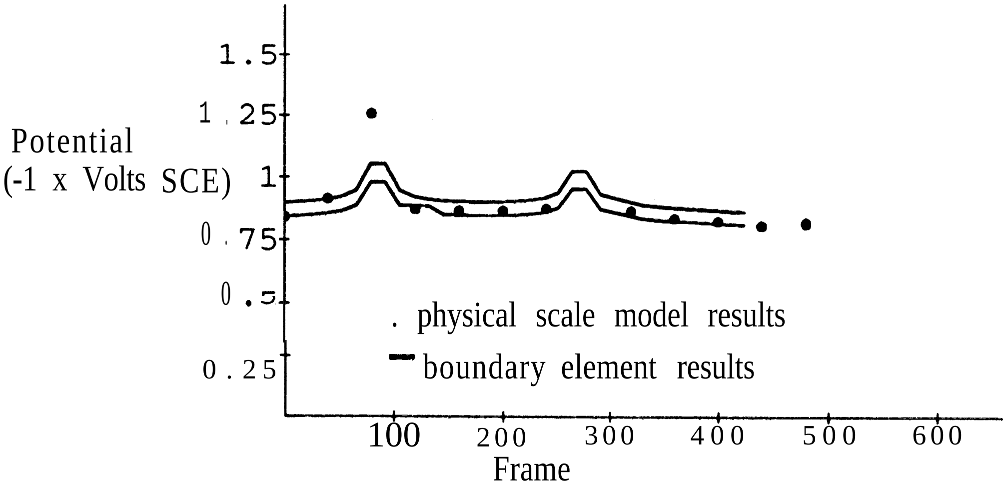

Figure 7 - Potential vs. Frame, Side Readings at 3.048 m (10 ft.), Static
6 Anode - 2 Zone System

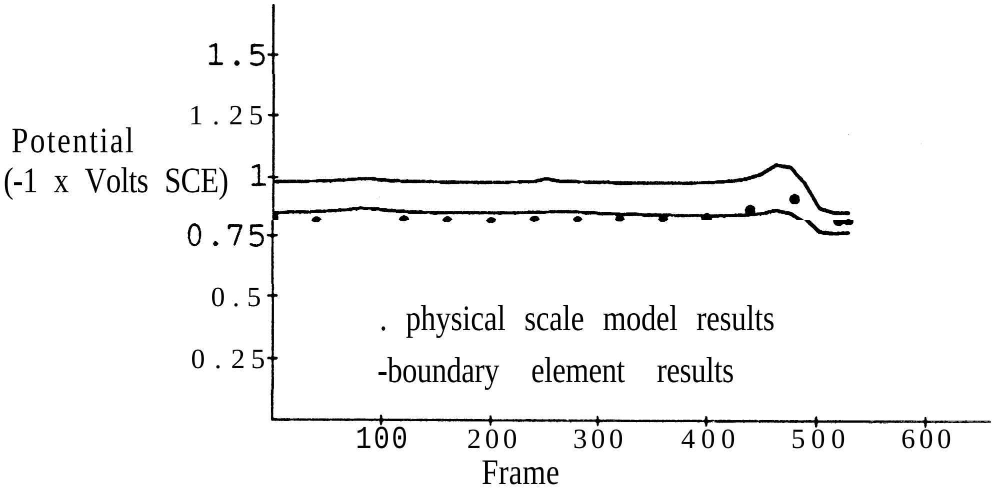

Figure 8 - Potential vs. Frame, Ship Centerline, Dynamic,
6 Anode - 1 Zone System

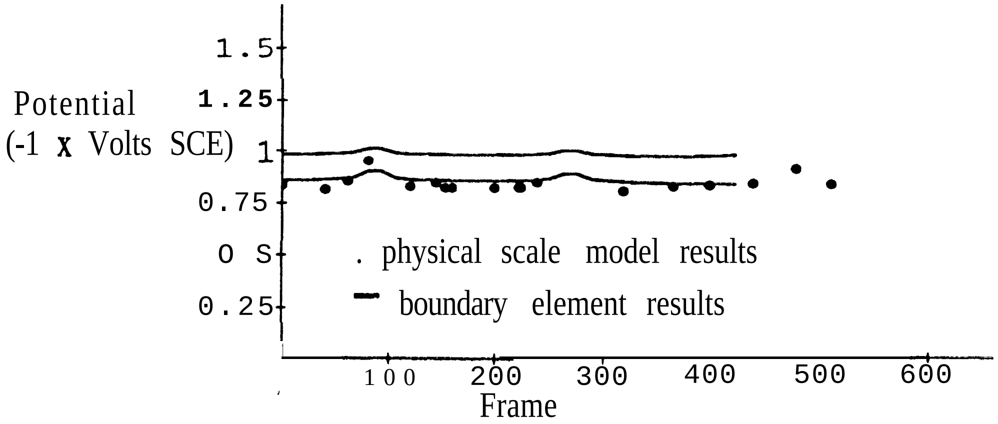

Figure 9 - Potential vs. Frame, Side Readings at 3.048 m (10 ft.), Dynamic, 6 Anode - 1 Zone System

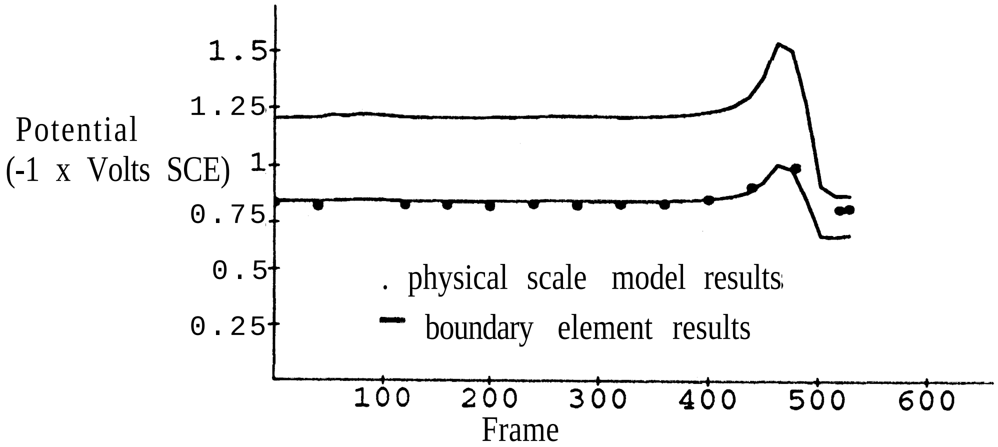

Figure 10 - Potential vs. Frame, Ship Centerline, Dynamic, 6 Anode - 2 Zone System

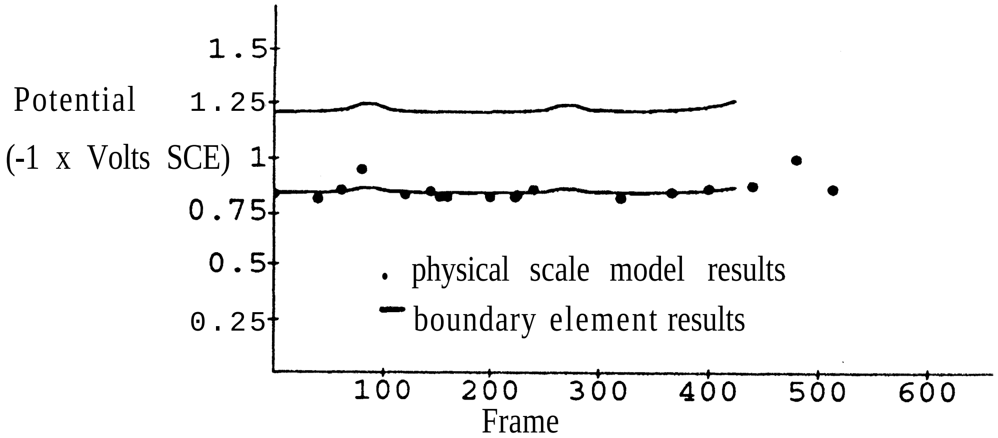

Figure 11 - Potential vs. Frame, Side Readings at 3.048 m (10 ft.), Dynamic 6 Anode - 2 Zone System