Characterization accuracy in modeling of corrosion systems

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ABSTRACT

Boundary element techniques are well suited for the solution of LaPlace's equation in semi-infinite and infinite volumes. As in any computer modeling, issues must be addressed in the early stages of the analysis for the finished work to be an accurate evaluation of the system. The goal of the analysis must be clearly defined; preliminary and trend analyses often require less mesh refinement than detailed system evaluations. The work presented is a portion of a detailed evaluation of the impressed current cathodic protection system of an U S Navy CG class surface ship. Physical scale model experimental data was available for direct comparison with computational results. The degree of mesh refinement required can be determined through experience or a mesh refinement study. The choice of an appropriate polarization response curve is a more complex issue. Detailed polarization data obtained from conditions similar to in-service conditions is needed for the accurate and effective modeling of complex systems.

INTRODUCTION

Corrosion of structures in marine environments is a major concern. The use of mathematical models to both predict corrosive behavior and to predict the performance of corrosion inhibiting systems is well established [1]. Boundary element and finite element computational simulation techniques have been used successfully to model electrochemical response [2,3].

Electrochemcial corrosion has been shown to be governed by LaPlace's equation:

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

where Φ is the electrical potential. Numerical solutions for LaPlace's equation have been incorporated into many commercial boundary element and finite element codes. Solutions of the governing equation with the appropriate boundary conditions yield the electrical potential and electrical current density at any point in the structure. The polarization response of a material defines the electrical current density present at an electrical potential. The electrical current density is important because it has been shown to be directly proportional to the corrosion rate [4].

In any computational simulation, issues such as mesh refinement, element type and solution tolerances must be addressed. It is possible, in such cases as trend evaluations or preliminary design analyses, that a coarse mesh which may yield less than optimum results is sufficient. In the present financial climate it could be beneficial to determine the gross effects of different parameters, such as water conductivity, on global response using relatively coarse and therefore less expensive computer analyses.

The same approach with regards to mesh refinement and element type may also be taken for design analyses. Relatively coarse, but geometrically detailed meshes may be used to identify regions where impressed current cathodic protection (ICCP) systems as designed do not provide adequate electrical potential for corrosion prevention. It is important, as in the trend studies, to realize that relatively coarse models may not accurately predict all electrochemical values. Steep gradients in either potential or current density are likely to be under-predicted.

Detailed design, as the name implies, should be performed using a highly refined mesh. However, a great deal of preliminary system design may be performed using a less refined mesh. In this manner, the over all cost of computer design may be made competitive with other design methodologies.

Mesh refinement and solution tolerance accuracy must be treated separately and should not be confused. Numerical accuracy is based on solution tolerances and procedures. Solution accuracy is dependent on the numerical accuracy, the mesh refinement and the accuracy of the material characterization used in the solution procedures. It is not the intent of this paper to discuss numerical accuracy criteria. All solutions referred to in this work, from the coarsest mesh to the most refined, are valid numerically accurate solutions. The numerical solution tolerances used were identical for ail mesh refinements.

In the present work, a mesh refinement study is performed as part of a detailed design analysis of an existing shipboard impressed current cathodic protection system. The ICCP system is defined to protect the hull of a U. S. Navy CG class surface ship from corrosion damage. Previous results, when compared to experimental data, indicated the need to examine the basic assumptions, specifically mesh refinement [5].

IMPRESSED CURRENT CATHODIC PROTECTION (ICCP)

The process of corrosion in a submerged structure involves the flow of electricity from an area of metal to another area of metal. The corrosion process is the result of electrochemical reactions governed by LaPlace's equation for steady state conditions.

The areas of metal to which electricity flows are 'cathodes'. The areas of metal from which electricity flows are the 'anodes'. Corrosion damage, or loss of material, occurs at the anodes. The electrolyte surrounds the metal structure and transmits electrical current. The electrical circuit is completed by connecting the anode and cathode. There may be multiple anode and cathode areas on a structure.

Cathodic protection inhibits corrosion by forcing the material to be protected to behave as a cathode. This may be done by attaching sacrificial anodes, pieces of metal which because of their electrochemical nature will act as anodes and preferentially corrode when connected to the metal to be protected. Cathodic protection may also be provided by suppling an external source of electricity which will force the metal to be protected to behave as a cathode. ICCP systems use power supplies to provide the electrical current required to maintain the metal to be protected as a cathode. Electrical potential or voltage levels are monitored through reference cells places at strategic locations on the structure. The use of both sacrificial anodes and ICCP systems is well established for marine structures.

ICCP systems are often powered by more than one source. Power supply zones consist of the electrical power source and the anodes connected to that source. An ICCP system may have multiple power sources. Each power source is linked to at least one reference cell. The power source provides the electrical current necessary to maintain its reference cell at a predefined voltage value.

Typically ICCP systems are designed based on experience. The creation of an ICCP system is a complex task. Skillful arrangement of the individual components is required for the design of an effective ICCP system. Analytical evaluation of ICCP system performance, either by computational simulation techniques or scale model experimental evaluation, can be a powerful tool in the development of ICCP systems.

SHIP GEOMETRY

A schematic of the CG 59 ship hull and ICCP system is shown in -Figure 1. The ICCP system consists of 3 pairs of symmetrically placed anodes, two power supplies and two reference cells. Reference cells are located as shown on Figure 1. The fore and mid-section anodes are connected to a single power supply and use the forward placed reference cell. The aft pair of anodes are connected to a separate power supply. ICCP system symmetry and geometric symmetry of the hull allow for half of the ship to be modeled. The hull of interest is that portion below the design waterline.

BOUNDARY ELEMENT MODEL

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.

The original boundary element model created for the analysis is shown in Figure 2 [5]. All boundary element models developed in this study has the following features:

(1) detailed modeling of the complex curvature of the hull surface
(2) geometrically distinct modeling of the rudder
(3) geometrically distinct modeling of the propellor
(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 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 in the model. The hull is assumed to be undamaged paint. The painted surfaces are assigned an infinite resistivity [6]. 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 polarization curve used for N-A-B behavior is per Reference 7. Only static conditions are considered in the mesh refinement study. Polarization reponse for steel is per Reference 5.

The infinite seawater domain is approximated by a box of constant value quadrilateral elements which surrounds the ship model. The box elements are defined with a current density of zero to approximate the correct boundary conditions at infinity. The surrounding seawater is modeled with a constant resistivity of 20 Ohms-cm.

The total current supplied to each zone is calculated from the boundary element computational results, In this analysis, each power 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 [8] 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 LaPlace's 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.

A solution tolerance of 0.05% was used for all mesh variations in the present study.

MESH REFINEMENT STUDY

In a previous computational evaluation of the CG-59 ICCP system [5] upper and lower bound computational generated potential profiles bracketed experimental results. However there was a lack of agreement in total current required to maintain the reference cell at a set point. Two possible reasons for this variation were noted at the time; mesh refinement and polarization response accuracy.

In order to determine the effect of mesh refinement on the CG hull analysis a systematic mesh refinement study was undertaken.

Mesh refinement can take two forms which are not mutually exclusive. The order of the element and the number of elements may be increased. Use of higher order elements significantly increase the computer and financial resources required for solution. In the present work, the mesh refinement approach taken was to maintain constant value elements but to increase the number of elements in the mesh. Selective refinement was performed. That is, in regions where geometric complexities or material changes occurred, more elements were used to model the hull geometry.

In the CG hull mesh refinement study three criteria were used;

(1) the smoothness of the potential and current density contour plots.

(2) the variation in solutions between two mesh patterns.

(3) the refinement needed to incorrupted small geometric features such as docking blocks and paint

damaged areas.

The first criterion is subjective. The second criterion was assigned an arbitrary difference of 1 Amp on the total current requirements as acceptable. The variation in total current deemed acceptable is based on global system response and the target accuracy designed between computational and physical scale model results. The third criterion is dependent on the geometric dimensions of the features and their relative size with respect to the overall ship dimensions. The third criterion was actually used to add additional elements once the optimum mesh dimensions were determined based on the first two criteria.

In order to evaluate the accuracy which results from a particular level of mesh refinement, computational results for a mesh were compared with the previous slightly coarser mesh. The meshes considered have the same input voltages at the impressed current anodes. The reference cell potential values are not considered in the comparisons. No comparison was made with physical scale model results so there would be no unintentional manipulating to match computational and experimental results.

The material property assignments used in the mesh refinement study were a perfectly painted hull (infinite resistivity), a bare steel rudder and a bare N-A-B propellor. The input voltages . assigned to the ICCP anodes were arbitrarily chosen as - 1.2, - 1.2 and -2.0 Volts for the pairs of fore, mid and aft impressed current anodes, respectively.

The original mesh consists of 573 elements made of 700 mesh points (Figure 2). Mesh refinement was varied but no area of the model was well refined. The standard input voltages of -1.2,-1.2 and -2.0 Volts resulted in total currents of:

Total Amps for full ship	29.6
Amps to propellor	11.9
Amps to rudder	17.7

The second mesh refinement step resulted in a model of 1166 elements and 1325 mesh points. Solutions results for the standard input of -1.2, -1.2 and -2.0 Volts to fore, mid and aft impressed current anodes, respectively, resulted in:

Total Amps for full ship	30.2
Amps to propeilor	13.1
Amps to rudder	17.1

Modifications were made in the mesh based on 'jagged' transitions between large and small elements. Elements were added which could be used to include masker belts, an artifact of physical scale model test procedures, and docking blocks. The final mesh consisted of 1234 elmeents and 1403 mesh points. Solution results for the standard input of - 1.2, - 1.2 and -2.0 Volts to the fore, mid and aft impressed current anodes, respectively are:

Total Amps for full ship	30.0
Amps to propellor	12.4
Amps to rudder	17.6

The differences in total current meet the requirements set at the beginning of the study. In addition, potential and current density contours meet the more subjective criterion.

Once the optimum mesh was defined, additional mesh refinement in the form of the addition of a three dimensional bilge keel was added. Additional mesh refinement was selectively added to areas where required to model defined regions of paint damage required for future analysis. The location and extent of areas of paint damage are determined from ship design criteria. Regions of paint damage will be modeled as elements assigned steel polarization properties.

The final mesh, including the three dimensional bilge keel and selected mesh enhancement for paint damage, is shown in Figure 3. The final mesh consists of 1583 elements and 1876 mesh points. The mesh consists of constant value quadrilaterial elements. Results based on this final mesh configuration are compared with experimental results.

PHYSICAL SCALE MODELING

Physical scale model testing involves the scaling of both the geometric dimensions of the structure and electrolyte conductivity [9]. The electrical current required to obtain the reference cell reading considered necessary for corrosion protection is determined. Electrical potential readings are obtained from specific locations which have been instrumented prior to testing. Physical scale modeling experimental results have been successfully compared with data obtained from tests performed on full size ships [10].

Physical scale model testing provides the computer analyst with a well defined set of conditions to model. The complex geometry of the actual ship hull is exactly duplicated in the physical scale model. The materials used in the ship hull are duplicated in the physical scale model. Galvanic coupling effects caused by the multiple materials present in the ship hull are duplicated in physical scale modeling.

COMPARISON OF RESULTS

The solution is obtained for a reference cell potential value of -0.85 Volts Ag/AgCl. The reference cells are identified in the schematic of Figure 2. The target value is determined from the electrochemical response of steel; structural steel at -0.85 V Ag/AgCl is considered to be 'protected' from corrosion [11].

The potential profiles along the hull centerline and along the side of the hull at a depth of 3.048 m (10. ft.) are shown in Figure 4. As can be seen, the potential profiles for reference cell readings of -0.85 Volts Ag/AgCl show very good agreement between experimental and computational results.

The total current requirements for static minimum damage conditions are:

	Experimental	Computational
Total Amps for full ship	33.6	35.7
Amps to propellor	26.3	27.7
Amps to docking blocks	7.3	8.0

The difference between experimental and computational results is 6% for total current values, 5% for Amps to the propellor and 10% for Amps to the docking blocks.

Of the two possible reasons for variation, mesh refinement and polarization reponse, the mesh refinement used has been verified to be appropriate through the mesh refinement study. To complete the study of analysis parameters, the issue of polarization response must be addressed. The polarization response used in the anlaysis is based on laboratory testing and may not be representative of the response of the structure under service conditions. In addition, only static conditions were examined in the laboratory test study. For a full anlaysis of service conditions, dynamic conditions which are representative of the ship underway must be evaluated.

POLARIZATION RESPONSE

The material constitutive response of interest in the modeling of ICCP systems is the polarization response. The electrical current demand should be measured for environmental conditions as similar as possible to actual service conditions. The electrolyte conductivity, time exposed to seawater for the formation of films and deposits, the use of natural seawater, and appropriate velocity conditions should be included in the experiments from which polarization response is measured.

In order to meet these criteria a special series of current demand experiments were designed and performed at NRL Key West Corrosion Facility. A series of large test specimens were towed in open seawater. Current demand was measured during low speed, or approximately static conditions, and higher speed, or dynamic conditions. Polarization data from this series of specialized tests represents the material response at the velocities of interest.

At present, the data from this test program is being evaluated. Once evaluation is complete, this polarization response will be combined with the detailed mesh pattern which include the three dimensional representation of the bilge keel. It is hoped that this material response-mesh combination will yield computational results which will match observed physical scale model experimental results.

SUMMARY

It is accepted that boundary element methods are a viable technique for determining marine corrosion parameters. However, care must be taken to ensure that the boundary element mesh is appropriate for the purpose of the anlaysis. For anly computational simulation, the anlayst must be aware of the degree of accuracy which can be expected from a particular level of mesh refinement. Detailed refined meshes, verified by a mesh refinement study or experience, are required for detailed design.

Of equal importance as the degree of mesh refinement is whether the polarization reponse is appropriate. It is essential for the anlayst to understand the in-service conditions and the conditions under which polarization responses are determined. Simple laboratory tests often do not accurately reflect actual in-service conditions.

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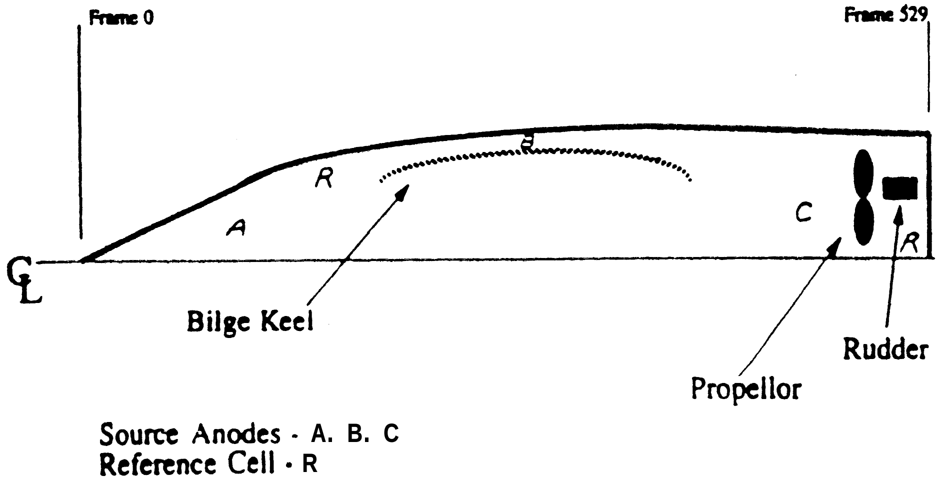

Figure 1 Schematic of Ship and ICCP System Geometry

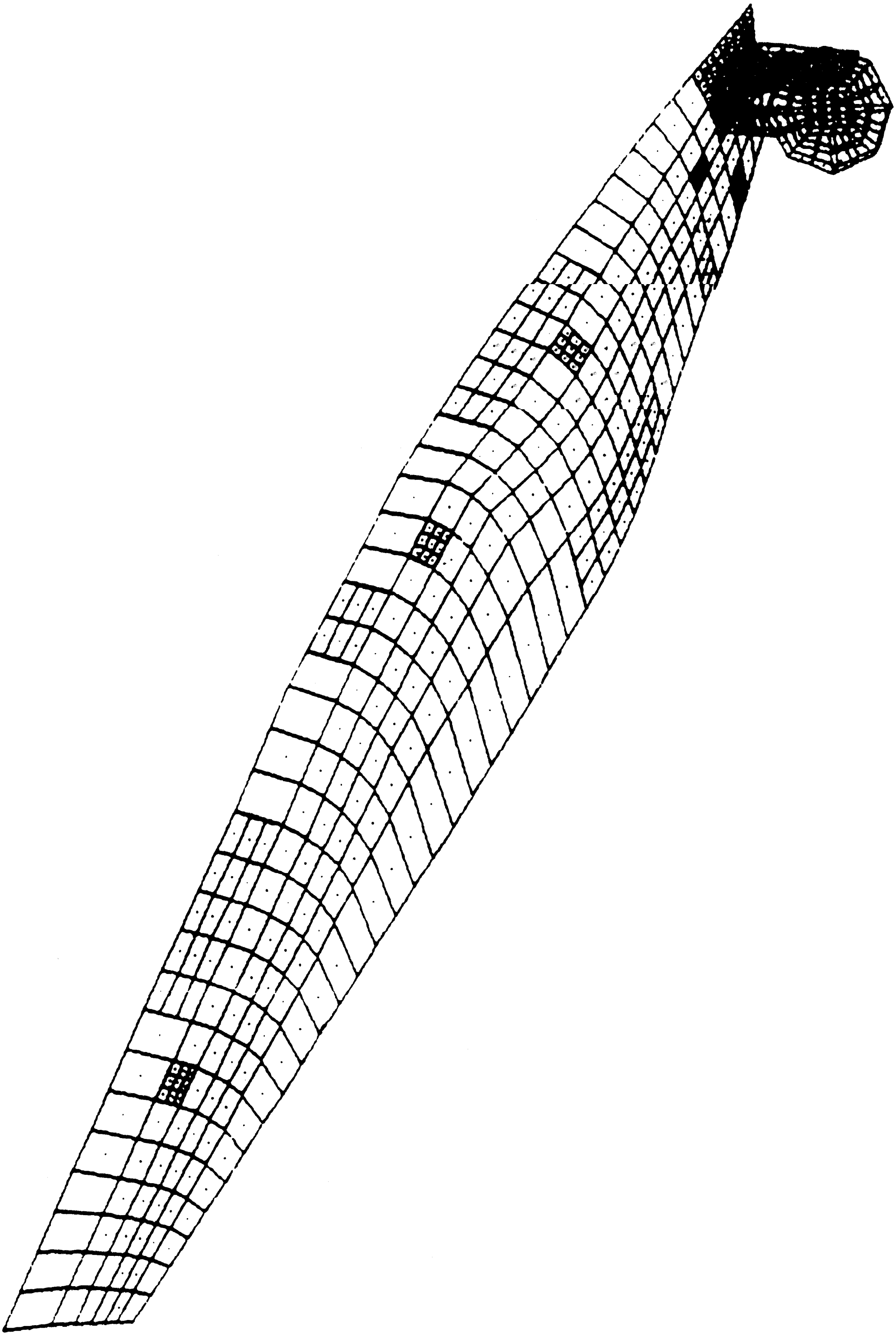

Figure 2 Original Mesh per Reference 5

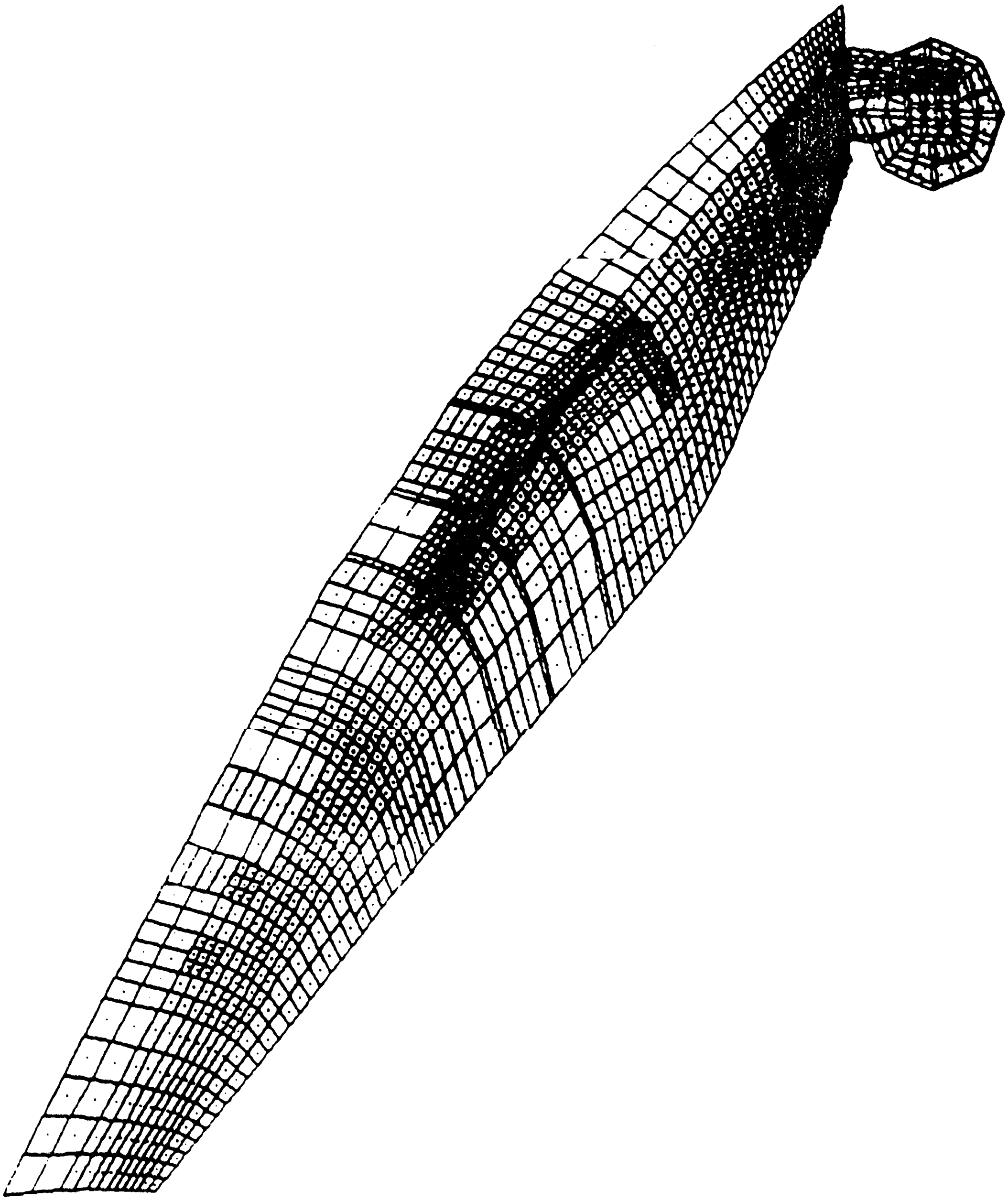

Figure 3 Final Mesh Including Three Dimensionai Bilge Keel

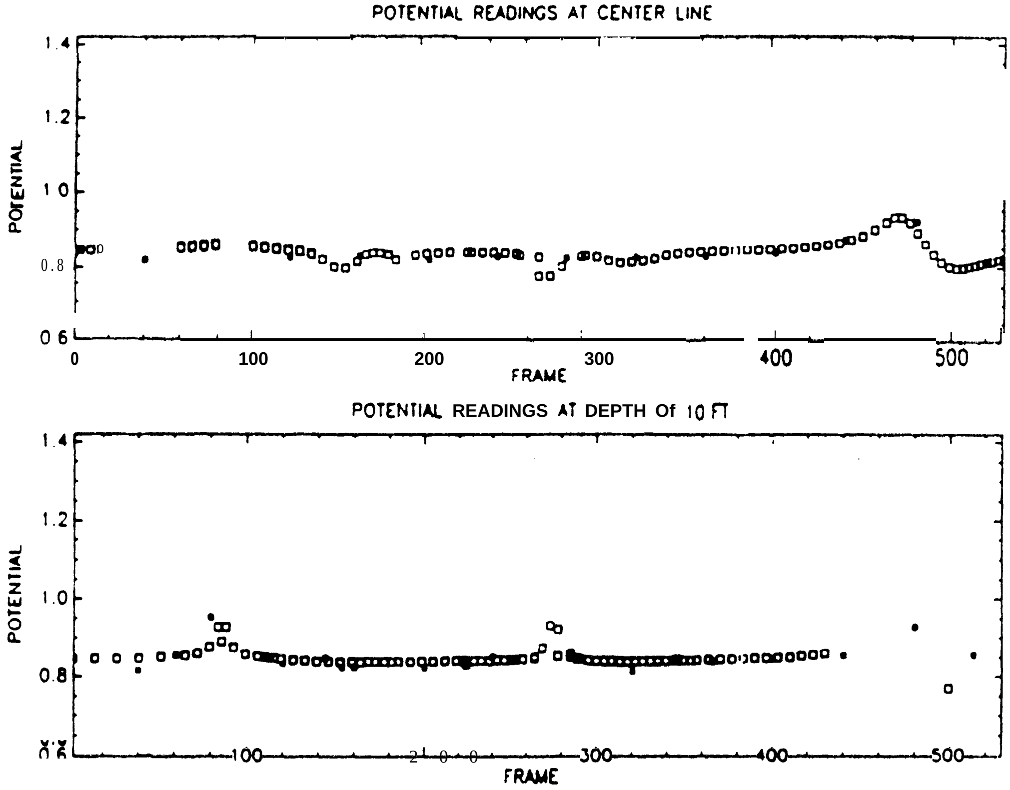

Figure 4 Potential Profiles Along CG-59 Hull, Minimum Damage, Static Conditions

Solid Squares = Physical Scale Model Data

Open Squares = Computational Results