Numerical-analysis-assisted monitoring method for the coating condition on a ballast tank wall

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Abstract

A numerical-analysis-assisted monitoring method was developed for the coating condition on a ballast tank wall. It was proposed that the coating condition is evaluated by the surface resistance. An identification method was developed to obtain the whole surface resistance from the differential potential induced by the impressed current from an optional anode inside a tank. A differential potential measurement and inverse analysis were introduced to obtain the surface resistance representing the coating condition. The potential measurement and quantitative evaluation were conducted in an actual ship. Verification was performed and there was good agreement between the proposed method and the preliminary visual inspection.

Keywords: corrosion analysis, numerical analysis, surface resistance, inverse problem, coating condition, ballast tank.

1 Introduction

In order to prevent corrosion loss, it is very important to inspect the coating condition inside the ballast tank of ships, such as oil tankers, liquefied natural gas (LNG) and cargo ships. The current inspection standard specifies that the ratio of paint defect surface area to the total surface is visually inspected periodically every two or three years. However, the current visual inspection has some problems, such as the dangerous and dark environment for inspectors, inaccurate evaluation results depending on the inspector's skill as well as the time-consuming process and heavy labour required in order to inspect all hundreds of tank compartments. In order to overcome these issues, a quantitative, safe, economic and efficient monitoring method for the coating condition is extremely desirable.

A ballast tank filled with seawater is easily corroded. Corrosion protection by the paint on the metal surface inside the tank, which improves the insulation for the corrosion current, is applied. The paint has problems with age-related degradation and incipient failure. To protect the metal from corrosion caused by these problems, multiple sacrificial anodes are usually installed in the tank. When seawater is loaded in the tank, the inside surface of the tank becomes cathode and the protective potential works, because of the anode effects. The worse the coating condition, the worse the insulation of the paint becomes and the lower the surface resistance. Therefore, there is the possibility that the coating condition can be evaluated by monitoring the surface resistance.

On the other hand, potential measurements are sometimes conducted for the evaluation of the cathodic protection. Since, however, environmental factors, such as temperature, affect the measured potential and the potential is determined by the number of anodes and the coating condition, the coating condition could not be evaluated directly by the potential measurement.

In this paper, a numerical-analysis-assisted monitoring method was developed for the coating condition on ballast tank walls. It was proposed that the coating condition is evaluated by the surface resistance. An identification method was developed to obtain the whole surface resistance from the differential potential induced by the impressed current with an optional anode. Differential potential measurement and inverse analysis were introduced to obtain the surface resistance representing the coating condition. The potential measurement and quantitative evaluation were conducted in an actual ship. A verification of the proposed methodology was thus performed.

2 Proposed method

2.1 Coating condition and surface resistance

The relationship between potential ϕ [V] and current density i [A/m²] in an electrolyte near the metal surface is represented by a function called polarization curve expressed as

$$\phi = -f_m(i) \quad (1)$$

This function is normally non-linear and is determined experimentally. The polarization curve depends on the kind of metal, electrolyte and environmental conditions such as temperature, pH, and concentration of oxygen. In this paper, it is noted that the potential ϕ at a certain location in the electrolyte is defined by referring to the metal and has the inverse sign of the potential E employed in electro-chemistry in which the potential is defined to a reference electrode such as SCE or Ag/AgCl.

Considering a small potential change, eqn (1) gives

$$\delta\phi \cong -\frac{df_m}{di} \delta i = -R\delta i \quad (2)$$

where

$$R \equiv \frac{df_m}{di} \quad (3)$$

The surface resistance R [$\Omega \cdot m^2$] makes the relationship between the potential change and the current density change. When the resistance is big, this indicates high insulation. Therefore, it is here proposed that the coating condition can be indicated by the surface resistance R . In the case when the non-coating surface resistance is R_0 , the ratio of the paint defect area to the total surface area can be evaluated using

$$\alpha = \frac{R_0}{R} \quad (4)$$

2.2 Summary and procedure of proposed monitoring method

The proposed monitoring method is described in this section.

An optional anode and an Ag/AgCl reference electrode for potential measurement are placed in the seawater filled tank to be inspected as shown in Fig. 1. The potential changes at several locations in the tank with respect to the reference electrode are measured in two cases. The first case is that the prescribed current is impressed with an optional zinc anode and the second case is that no current is impressed. In the following, each case is indicated by subscript “ON” and “OFF”, respectively. The potential difference

$$\delta\bar{\phi} = \bar{\phi}_{ON} - \bar{\phi}_{OFF} \quad (5)$$

is calculated from the results.

Figure 1: Simple measurement model in ballast tank.

The potential in any point is calculated with various R using a numerical analysis. It is assumed that the surface resistance R is constant in this numerical model. The residual of the measured differential potential $\delta\bar{\phi}$ and the numerically calculated $\delta\phi(R)$ is considered next; it is expressed as

$$F(R) = \sum_j^N \{\delta\bar{\phi}_j - \delta\phi_j(R)\}^2 \quad (6)$$

where N is the number of the combinations of the potential measurement points and the anode locations.

Obtaining the surface resistance R is to search for R which minimizes eqn (6). A general optimization method, such as Brent's method [1, 2], can be applied for this search.

2.3 Analysis method for potential difference

In this section, the numerical analysis method to calculate the potential $\phi(R)$ or the potential difference $\delta\phi(R)$ for the assumed surface resistance R is described.

First, the mathematical model of the electrical field in the tank is considered. It is assumed that the surface of electrolyte domain Ω is enclosed by $\Gamma (= \Gamma_d + \Gamma_n + \Gamma_m)$, where Γ_m is the metal surface, while the potential and current density are prescribed on Γ_d and Γ_n , respectively. The potential ϕ in a 3-D homogeneous electrolyte domain Ω satisfies the Laplace's equation:

$$\nabla^2 \phi = 0 \text{ in } \Omega \quad (7)$$

The general boundary conditions are given by

$$\phi = \phi_0 \text{ on } \Gamma_d \quad (8)$$

$$i \left(\equiv \kappa \frac{\partial \phi}{\partial n} \right) = i_0 \text{ on } \Gamma_n \quad (9)$$

$$-\phi = f_m(i) \text{ on } \Gamma_m \quad (10)$$

where ϕ_0 and i_0 are the prescribed values of the potential ϕ and current density i , respectively, $\partial \phi / \partial n$ is the outward normal derivative, and κ is the conductivity of the electrolyte. The actual boundary conditions for the present numerical analysis are described in Table 1 in section 3.3.

Since the two potentials ϕ_{ON} and ϕ_{OFF} both satisfy the Laplace equation, the potential difference $\delta\phi$ also satisfies the equation

$$\nabla^2 \delta\phi = 0 \text{ in } \Omega \quad (11)$$

Eqn (11) implies that in case there are two boundary conditions for one model, the following three conditions are applied instead of eqns (8) to (10):

$$\delta\phi = (\phi_{ON})_0 - (\phi_{OFF})_0 \text{ on } \Gamma_d \quad (12)$$

$$\delta i = (i_{ON})_0 - (i_{OFF})_0 \text{ on } \Gamma_n \quad (13)$$

$$-\delta\phi = f_m(i_{ON}) - f_m(i_{OFF}) \cong \frac{df_m}{di} \delta i \quad \text{on } \Gamma_m \quad (14)$$

In case δi in eqn (14) is small, the approximation becomes better in terms of Taylor expansion. Also, the constant term in the polarization curve, eqn (1), represents the open circuit corrosion potential and can be eliminated; thus, $\delta\phi$ only depends on the surface resistance, defined in eqn (3), according to eqn (2).

The constant term depends on the environmental conditions such as temperature, pH, concentration of oxygen and the reference electrode offset. But the differential method without this term has advantages over the standard method, in case the same reference electrodes are used in the short-time measurement. This formulation easily eliminates the effect of open circuit corrosion potential and reference electrode offset. If the potential or current density is constant in two boundary conditions, the differential boundary conditions are zero according to eqn (12) or eqn (13).

The boundary element method [3] is employed for performing the numerical analysis to solve eqn (11) with eqns (12) to (14). The formulation of the boundary element method is the same as the standard boundary element method applied to eqns (6) to (9) [4–7].

3 Verification of differential method

3.1 Experiment summary

The potential measurement was conducted in a ballast tank of the 23-year-old LNG ship. The LNG ship had ten ballast tanks and each of them was partitioned to approximately ten compartments with bulkheads transversely and vertically. In one of the compartments, the potential was measured by the present method. Five years had passed since the paint-coating of the ballast tank was repaired. The measured compartment was a rectangular parallelepiped (L 3.75 m $\times$ W 4 m $\times$ H 12.8 m) filled with seawater up to 7.6 m in height. There were eight zinc anode electrodes (L 0.1 m $\times$ H 0.1 m $\times$ W 0.5 m) in the seawater within the compartment as shown in Fig. 2.

The measurements were conducted with the optional anode ($\phi 15$ mm $\times$ L150 mm) and both (ON) and (OFF) were measured. The potential along the center line was measured with an Ag/AgCl reference electrode every 0.2 m back and forth between top and the bottom of the seawater. The current from the optional zinc anode was measured. HIOKI 8422-50 logger and HIOKI 3257-50 DMM were used for the potential and current measurement, respectively.

3.2 Measurement results

One set of measurements takes about fifteen minutes. The optional anode was located at a depth of 1.6 m from the seawater surface in the first three sets (Fig. 3). The electrode measuring the potential was attached to the cable on edge. The depth in Fig. 3 is actually the cable length from the ballast tank ceiling and a depth of more than 12.8 m shows that the electrode reached the bottom.

Figure 2: Ballast tank compartment with seawater.

Figure 3: Potential distributions (optional anode depth 1.6 m from seawater surface).

3.3 Numerical analysis and surface resistance identification

In order to verify the proposed differential method, the numerical prediction of the differential potential distribution within the tank is compared with the experimental result.

Firstly, the differential potential distribution within the tank shown in Fig. 2 was measured. The experimental conditions were set to be the same as described in the previous section.

Secondly, the tank is modelled as shown in Fig. 4 for the numerical analysis. The boundary element mesh in Fig. 5 was used and the elements are all constant triangle elements. The number of the elements and nodes are 5670 and 3619, respectively. The boundary conditions are applied as shown in Table 1. The surface resistance of the anodes is set to be $0.16 \Omega \cdot \text{m}^2$. The total current amount of the optional anode is set to be 30 mA and the access hole boundary condition is set to be $\delta\phi = 0.005 \text{ V}$ from the experiment. The differential potential distributions are calculated for nine cases whose surface resistances R_{ss} are varied.

Figure 4: Model of the ballast tank compartment.

Figure 5: Mesh for the compartment.

Table 1: Boundary conditions of differential model for the compartment.

No.	Boundary condition	Place
(1)	$\delta I = 30 \text{ mA}$	Optional anode side (ON)
(2)	$\delta i = 0$	Seawater surface
(3)	$\delta \phi = 0.005 \text{ V}$	Access hole to the lower compartment
(4)	$\delta \phi = -R_{SS} \delta i$	SS (walls) $R_{SS} = 1000, 500, 200, 100, 50, 20, 10, 5 \text{ or } 2 [\Omega \cdot \text{m}^2]$
(5)	$\delta \phi = -16 \delta i$	Zn (anodes)

The numerical results for nine cases of surface resistance are shown in Fig. 6, which shows that the whole potential is high when the surface resistance is high. The maximum voltage of the sidelobe of the optional anode is 0.005 V.

Thirdly, the surface resistance was estimated by minimizing the residual function

$$F(R_{SS}) = \sum_j^N \{ \delta \bar{\phi}_j - \delta \phi_j(R_{SS}) \}^2 \quad (16)$$

The residual function consists of three residuals between measurement and calculated differential potential at the depth of seven meters. The minimization was performed with the brute-force search.

Both numerical and experimental potential distributions are shown in Fig. 7 and they show good agreement. It is noted that a good agreement can be achieved even if the open circuit corrosion potential is unknown, polarization curve is non-linear and unknown and there are offsets of reference electrodes.

The paint defect ratio is lower than 0.2% under the assumption of the surface resistance of bare SS $R_0 = 1 \Omega \cdot \text{m}^2$ (see eqn (4)). This result agrees with the outcome of a preliminary visual inspection.

Figure 6: Voltage distributions with various surface resistances.

Figure 7: Voltage distributions (depth 1.6 m from seawater surface, SS surface resistance: $500 \Omega \cdot \text{m}^2$).

4 Conclusion

A quantitative monitoring method was developed for the coating condition inside a ballast tank. It was proposed that the coating condition be evaluated by means of the surface resistance. An identification method was developed to obtain the whole surface resistance from the differential potential induced by the impressed current from an optional anode inside a tank. Differential potential measurement and inverse analysis were introduced to obtain the surface resistance representing the coating condition. The potential measurements and quantitative evaluation were conducted in an actual ship.

Both numerical and experimental potential distributions agree well when the differential method is applied. The good agreement can be achieved even if the open circuit corrosion potential is unknown, polarization curve is non-linear and unknown and there are offsets of reference electrodes. The paint defect ratio calculated from the differential method agrees with that obtained from a preliminary visual inspection.

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