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Influence of a simulated deep sea condition on the cathodic protection and electric field of an underwater vehicle

Y.-S. Kim [a], S.K. Lee [b], H.-J. Chung [b], J.-G. Kim [a,*]

[a] School of Advanced Materials Engineering, Sungkyunkwan University, 2066, Seobu-Ro, Jangan-Gu, Suwon-Si, Gyonggi-Do, 16419, South korea
[b] The 6th Research and Development Institute, Agency for Defense Development, 18th, Jinhae P.O.Box, Jinhae-Gu, Changwon-Si, Gyeongsangnam-Do, 51678, South korea

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ABSTRACT

To investigate the effect of the deep sea condition on the corrosion behavior, cathodic protection and electric field of underwater vehicles, potentiodynamic polarization tests were carried out under a simulated deep sea condition. A 3-D boundary element method (BEM) was used for an underwater vehicle with and without sacrificial anode cathodic protection (SACP). The simulated deep sea condition influenced the cathodic polarization curves due to the difference between the cathodic reactions. Under the deep sea condition, the cathodic protection potential criterion was more easily satisfied as the protection current density of SACP was decreased. The electric field underneath the underwater vehicle showed that the deep sea condition decreased the electric field due to the lower current density and the shape of the electric field distribution changed from one dipole to two dipoles.

1. Introduction

The corrosion of ships, underwater vehicles, and offshore structures in the seawater environment is an important consideration for the corresponding usages and applications, and has led to the development and application of a variety of real-field methods. One of the common prevention methods is *cathodic protection* (Baeckmann et al., 1997). In principle, it can reduce or prevent the corrosion of exposed structures in seawater. The corrosion can be reduced to almost zero, and a properly maintained system will provide protection indefinitely (Jones, 1996). The common cathodic-protection methods for marine structures are as follows: sacrificial-anode cathodic protection (SACP) and impressed current cathodic protection (ICCP). However, an improper cathodic-protection design causes various problems such as an acceleration of the coating breakdown, hydrogen embrittlement, the stray current corrosion, and the formation of an electric field (Hartt, 2012; Wu et al., 2011; Metwally et al., 2008). A proper cathodic protection design is therefore needed to avoid the problems that can arise from the application of an inadequate cathodic protection.

For underwater vehicles and other naval vessels, a minimal underwater signature is important for the provision of a protection against mines, and to avoid the detection of underwater barriers and sensors (Schafer et al., 2011). Especially, the propagated electric field that is caused by the current from corrosion and the cathodic protection covers considerable distances through seawater, and it can be easily detected by a sensitive electric field sensor. Consequently, such detections of the electric-field signal can jeopardize a ship's safety (Donati and Cadre, 2002; Guibert et al., 2009), so it is important to be able to predict the electric-field signal before operation.

The boundary element method (BEM) was applied to the design of cathodic protection systems in the early 1980s (Lan et al., 2012). BEM modelling was applied to various structures and corrosion problems such as the galvanic corrosion region of offshore structures and ships (Danson and Warne, 1983; Aoki and Kishimoto, 1991, Aoki et al., 1988; Zamani, 1988). In BEM-based cathodic protection design, various tasks such as the modelling procedures regarding the structure, environment, cathodic protection criteria and the corrosion property of the materials are carried out. The design aspects of the cathodic protection system such as the number and the location of the anode for protected structures are of absolute importance because of the numerous uncertainties that depend on the corrosion engineer. However, the corrosion property that is the polarization curves in the BEM simulation must be preferentially considered, because the various calculation factors such as the potential and the current of corrosion related electric field are based on the polarization curve. Thus, the achievement of polarization curves that are similar to the real condition is important and consideration of the various environmental factors like the temperature, calcareous, conductivity, flow velocity and pH requires a great amount of effort (DeGiorgi et al.,

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* Corresponding author.
E-mail address: kimjg@skku.edu (J.-G. Kim).

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Table 1
Chemical composition of synthetic seawater.

Component	Concentration (g/L).
NaCl	24.53
$MgCl_2$	5.20
Na_2SO_4	4.09
$CaCl_2$	1.16
KCl	0.695
$NaHCO_3$	0.201
KBr	0.101
H_3BO_3	0.027
$SrCl_2$	0.025
NaF	0.003

1998; Kim et al., 2016).

According to the seawater depth, the corrosion rate is changed due to the influence of various corrosion factors (Venkatesan et al., 2002; Schumacher, 1979; Wan et al., 2016). In fact, the complex conditions of the deep sea include the following examples: local hydrostatic-pressure values, a low temperature of approximately 4 °C, and low-dissolved oxygen. Furthermore, in terms of their influence of the corrosive-behavior result, these conditions are in addition to other factors such as the seawater current, suspended slit, marine biota, decaying organic material, and dissolved sulfides and carbonates (Dexter and Culberson, 1980). It is not possible, however, to duplicate all of the deep-sea variables and changes (Reinhart, 1976); therefore, the dissolved oxygen and the temperature exert major effects on the corrosion rate and the corrosive behavior. However, the consideration of these factors has not been applied due to the difficulty and the complexity of the corrosion tests for the deep-sea condition. Most cathodic-protected structures have been designed by rule of thumb and engineering judgement, and this may lead to the various side effects that are caused by an improper cathodic protection. Thus, for objects that are located or operated under the submerged-seawater condition, the corrosion factors of the deep sea must be considered for the cathodic-protection design.

In this study, to investigate the influences of surface and deep sea conditions on the cathodic protection design (SACP) and the electric field of an underwater vehicle consisting of a carbon steel hull (HY80) and a nickel-aluminium-bronze (NAB) alloy propeller, potentiodynamic tests and BEM simulation were conducted. In the case of a small underwater vehicle, the SACP is applied due to the limitation of the space and the power supply. Then, the potential and electric field distributions of the underwater vehicle operating at 20 m (surface sea condition) and 150 m (deep sea condition) were evaluated using the BEM-based simulation program that is based on the boundary element method.

2. Experimental

2.1. Materials and test condition

HY-80 is one of the common steels that are utilized for the hull and the rudder of underwater vehicles, and the mass% of the chemical composition is as follows: carbon (C) = 0.17; silicon (Si) = 0.21; manganese (Mn) = 0.29; phosphorous (P) = 0.016; sulfur (S) = 0.03; nickel (Ni) = 2.38; chromium (Cr) = 1.34; molybdenum (Mo) = 0.38; copper (Cu) = 0.014; and an iron (Fe) balance. The chemical composition of the NAB that was used for the propeller is as follows (mass%): aluminum (Al) = 10.5; Ni = 4.92; Fe = 2.51; Mn = 1.34; Si = 0.21; and a Cu balance. For the potentiodynamic tests, the specimens were abraded using 220-to-600-grit SiC (silicon carbide) paper, rinsed with acetone and ethanol, and then dried with pure nitrogen gas (N_2). Synthetic seawater of the ASTM D 1141-98 standard (ASTM International, U.S.A.) was used, and the chemical composition of the synthetic seawater is listed in Table 1. To adjust the pH to 8.2, a 0.1 M sodium hydroxide (NaOH) was used. The deep-sea condition (operation at 150 m) was simulated through an elimination of the dissolved oxygen with a 99.99-%-purity nitrogen and the use of an ice chamber to set the temperature as 4 ± 1 °C (Wan et al., 2016). Oxygen was eliminated in this study to observe the significant effect of cathodic reaction difference between oxygen and hydrogen reduction reactions. The tests of the surface-sea condition (operation at 20 m) were carried out at 19 ± 1 °C and without the N_2 purging.

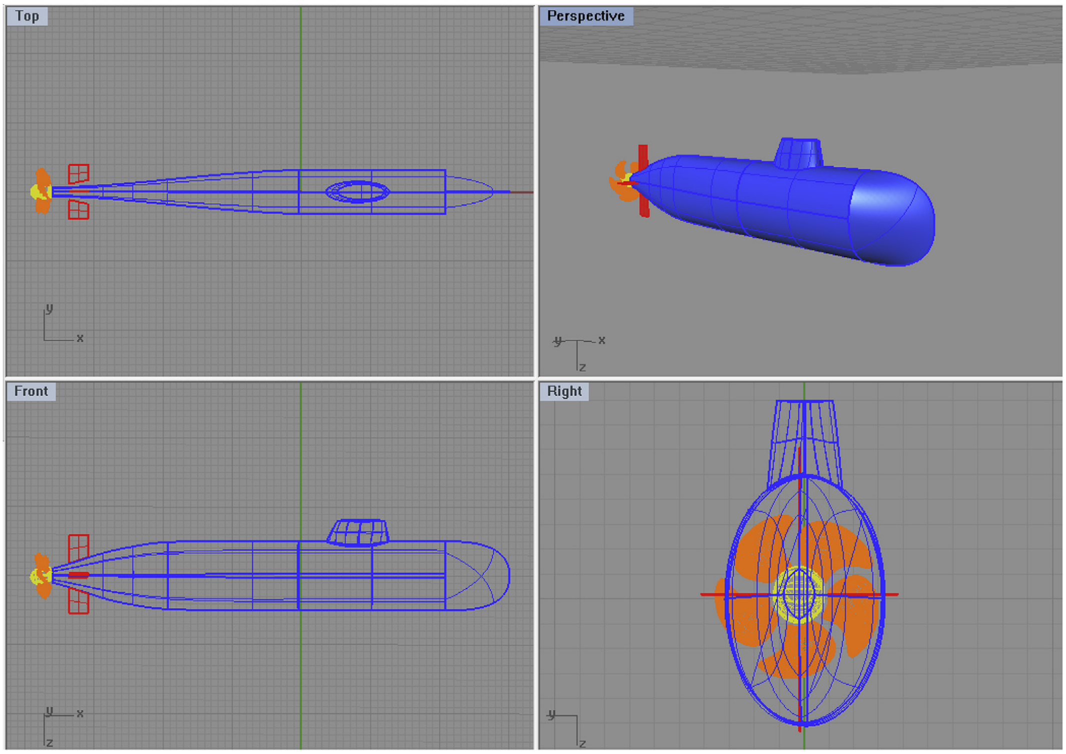

Fig. 1. BEM model of a submarine.