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Numerical Analysis of Propeller-induced Low-frequency Modulations in Underwater Electric Potential Signatures of Naval Vessels in The Context of Corrosion Protection Systems

David Schaefer[1,*], Jens Doose[2], Andreas Rennings[1] and Daniel Erni[1]
[1]General and Theoretical Electrical Engineering (ATE), Faculty of Engineering, University of Duisburg-Essen, Germany, [2]Technical Center for Ships and Naval Weapons, Naval Technology and Research (WTD 71), Bundeswehr, Germany
*Corresponding author: Bismarckstraße 81, 47057 Duisburg, Germany; david.schaefer@uni-due.de

Abstract: Since October 2009 the laboratory of ATE has carried out collaborative research with the WTD 71 that aims for prediction, reduction and optimization of so-called underwater electric potential (UEP) signatures. COMSOL Multiphysics is used to numerically simulate potential distributions on the vessels hulls in the context of impressed current cathodic protection (ICCP) systems, and also the corresponding UEP signatures. The electrode kinetics is considered by using boundary conditions based on non-linear polarization curves. We demonstrate how the polarization resistance flattens singular peaks of the electric field at sharp edges, and hence reduces the near-field modulation of the UEP signature. The modulation of the total ICCP current by means of shadowing effects in the propeller-rudder configuration is considered, with the focus on frequency components corresponding to the so-called Vernier-/Nonius effect. In addition an interesting estimation is presented, about what ICCP-settings are recommendable in the context of a silent running (stealth operating mode).

Keywords: Signature, corrosion protection, electrochemistry, polarization diagrams, navy.

1. Introduction

For submarines and other naval vessels (e.g. minesweepers) a minimal underwater signature is vital to prevent the actuation of naval influence mines, and to avoid the detection by underwater barriers. The total signature of a vessel includes (among others) the magnetic signature, the acoustic signature and the underwater electric potential (UEP) signature (cf. figure 1). Today the magnetic and acoustic signatures are most important in the context of naval warfare, because they have been exploited intensively since the Second World War [1]. Most state of the art detection devices are based on very sophisticated magnetic and acoustic sensors, while UEP sensors are not as commonly used in this application area. In the process of the continuously enhancement of naval mine technology it is possible, that future mines will more often exploit the corrosion- and corrosion protection related electric fields of naval vessels. In this case, the development of appropriate countermeasures has to be one step ahead. For this reason the laboratory of ATE has carried out collaborative research with the WTD 71, which focuses primarily on the UEP signatures, and aims for its prediction, reduction and optimization.

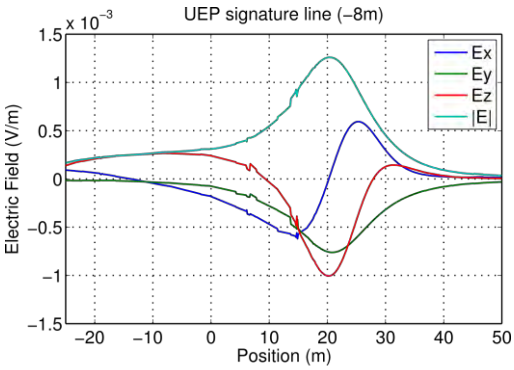

Figure 1. Axial trace of the near-field (8m below the keel) UEP signature of a simplified submarine model, simulated with COMSOL.

2. COMSOL Multiphysics Simulations

The electric potential within the conductive seawater satisfies the Poisson equation for the electric current density distribution. Without considering impressed current density and impressed current source density, this leads to the following partial differential equation:

$$\Delta(\sigma \cdot V) = 0$$

The UEP signature is usually defined by values of the electric field (on a plane surface or along a line), which can be determined by building the gradient of the electric potential:

$$\vec{E} = -\nabla V$$

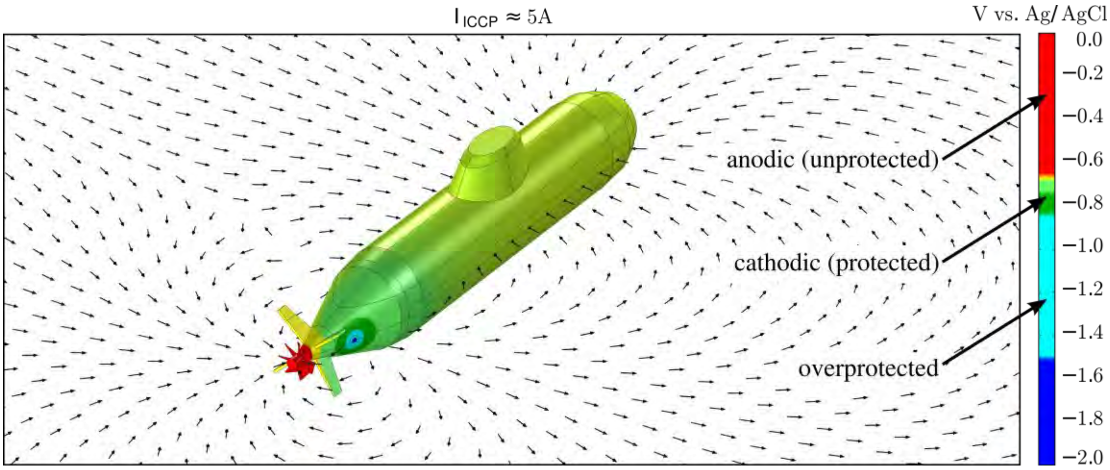

Figure 2. Potential distribution for a simplified submarine model. The colormap is based on the German naval directive "VG 81259" [2]. The arrows are representing the direction of the electric field.

The Poison PDE is solved using COMSOL Multiphysics with the "AC/DC Module" in the "Conductive Media" / "Electric Currents" application mode. COMSOL Version 3.5a, as well as Version 4.2 is used, and most of our simulations are controlled via "LiveLink for MATLAB". Figure 2 shows the simulated potential distribution as "surface plot" on the hull of a submarine model.

2.1 Electrode kinetics considering measured polarization curves

The electrode kinetics at the interface between the hull (electron conductor) and the seawater (electrolytic/ion conductor) were considered by measured polarization diagrams [3], and simulated with Neumann boundary conditions (Named "Inward current density" in COMSOL):

$$\vec{n} \cdot \vec{J} = J_i(V)$$

The relation $J_i\,(V)$ represents a nonlinear polarization curve and was described by a piecewise interpolated function within our COMSOL simulations. In general the polarization curves have to be assumed as "non-bijective" functions. This is important, because our application area includes materials with electrochemical passivity. The most important example is the non-magnetic stainless steel "1.3964", that is used as hull material for German submarines. For this reason the electrode kinetics cannot be satisfactorily described by common approximations such as the Butler-Volmer equation or the well-known Tafel equation.

Instead of the actual hull material "1.3964 steel" and the propeller material "Sonoston", we simulated the hull with "High Yield – 80 steel" (HY-80) together with a "Nickel – Aluminum Bronze" (NAB) propeller.

2.2 Simulation via "LiveLink for Matlab"

LiveLink for Matlab provides us full control of the simulation and makes it possible to implement customized optimization procedures, as well as complex parameter sweeps including e.g. geometry modification. We use an in-house developed toolbox, which allows us to receive entity-ids (like numbers of domains, boundaries, etc) by referring to the nametag of the features.

2.3 Using the "Batteries & Fuel Cells Module"

In the framework of our investigations we carried out simulations with the "Batteries & Fuel Cells Module" in the "Secondary Current Distribution" application mode. In contrast to the "AC/DC Module" the currents that are flowing back through the electron conductor (i.e. the vessel hull) can be easily simulated, e.g. for corrosion protection systems with galvanic anodes. On basis of the complete current density distribution, the Multiphysics capabilities of COMSOL also allow to simulate the corrosion related magnetic field.

3. Propeller-induced modulation of the electric near-field

The rotating propeller blades in the seawater, with currents flowing from the ICCP anode into them, form a "moving boundary value problem". The occurring frequencies are assumed to be low enough to disregard time derivatives and treat it as a quasi stationary problem.

3.1 Simplified simulations using Dirichlet boundary conditions

As a first approach, simplified simulations are carried out, using Dirichlet boundary conditions (“Electric potential”) instead of the before mentioned boundary conditions based on non-linear polarization curves. The angle of propeller rotation is increased successively, and the maximum values of the electric field in different depths below the submarines keel are extracted and visualized. Figure 3 clearly depicts how the tips of the propeller blades are modulating the electric near-field, when they are “swinging by” the “virtual sensors” during a simulated propeller revolution. The spectrum of the electric field strength shows the expected fundamental frequency (including the corresponding higher harmonics) of:

$$f_m = n_p \cdot f_0$$

In this equation n_p stands for the number of propeller blades, and f_0 is the rotation frequency of the propeller. The modulation decays very rapidly, the further away the “virtual sensors” are located from the propeller.

Another interesting aspect of the simplified simulations can be seen in contour plots (faces with same absolute field strength) of the electric current density (cf. figure 3). As theoretically expected, singular field-peaks occur at all sharp angles and edges of high conducting metallic objects, like e.g. at the tips of the propeller blades. The remote equi-surfaces become deformed, what results in the modulation of the near-field, as they rotate together with the propeller.

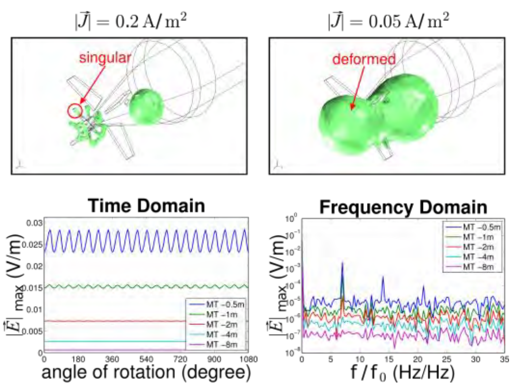

Figure 3. Simulated near-field modulation with Dirichlet boundary conditions [4].

3.2 The “smoothing-effect” of the polarization resistance

In a second approach, the simulations described in the chapter before were repeated, but this time considering the electrode kinetics by applying the non-linear polarization curves. A comparison between figure 3 and figure 4 depicts clearly, that the near-field modulation is now significantly reduced.

The reason for the decrease of the UEP’s modulation amplitude can be illustrated by looking again at the contour plots of the electric current density in figure 4. The contour surfaces seem to be “growing” steadily out of the surfaces of the propeller. Farther away from the propeller they are forming approximately spherical surfaces, so that the electric field around the propeller does not become modulated any more during the revolution.

The reason for the disappearance of the singular field-peaks (at the edges and tips of the propeller blades) is due to the polarization resistance. This quantity is just the “equivalent circuit”-like point of view for the relation between potential and current density existing at the interface between electron- and ion-conductors. It can be understood as a (potential-dependent, and hence non-ohmic) electric resistance per unit area [5]. Just like any electric resistor is somehow counteracting high currents, the polarization resistance is “working against” the singular current density field peaks by producing a local voltage drop over the double layer.

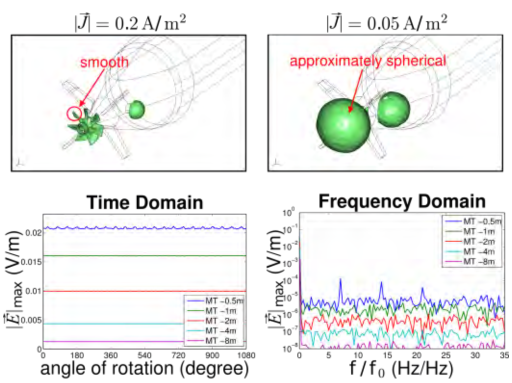

Figure 4. Simulated near-field modulation with boundary conditions based on non-linear polarization curves [4].

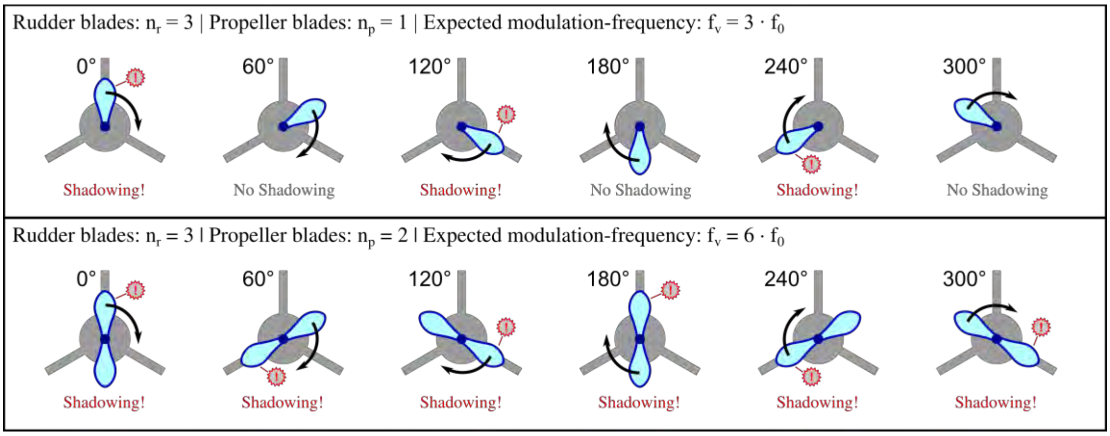

Figure 5. Theoretically example to illustrate the Vernier-/Nonius effect. The figure shows an astern view on a simplified submarine model with three rudder blades.

4. Vernier-/Nonius Effect

Power supply units of ICCP systems usually impress a fixed current, which is controlled by measurements of reference electrodes, which are located at distinct points of the hull. For small time constants, the supply-units behave like constant voltage sources, due to the inertia of the controller. Therefore the total current could be modulated by the propeller rotation.

In general, when two electrodes with different potentials are placed in a conductive media, the current flowing between them will decrease when they are pulled apart, or when an obstacle is inserted between them. In the context of ICCP system this effect is called "shadowing effect", and stands for an imbalanced current distribution on the object, which has to be protected.

A time dependent shadowing effect arises during rotation of the propeller, when the propeller blades get covered behind rudder blades. Due to the different alignment symmetries of the propeller and rudder blades, respectively, the mutual interaction produces a significantly higher frequency component that follows the so-called Vernier-/Nonius effect (cf. figure 5). From the point of view of a single rudder blade, the interference with the propeller can be described as periodic function $s_p(t)$ with the fundamental frequency:

$$f_p = n_p \cdot f_0$$

Analogous, from the point of view of a single propeller blade, the interference with the rudder can be described as periodic function $s_r(t)$ with the fundamental frequency:

$$f_r = n_r \cdot f_0$$

The total interference can be calculated as the cross-correlation between $s_p(t)$ and $s_r(t)$:

$$s_v(t) = \mathrm{CCF}\{s_r(t), s_p(t)\}$$

Simplifying the calculations by assuming, that the periodic functions $s_p(t)$ and s_r(t) consist of Dirac delta functions, the fundamental frequency of $s_v(t)$ can be easily deduced as:

$$f_v = \mathrm{lcm}\{n_r, n_p\} \cdot f_0$$

In this equation "lcm" stands for "least common multiple". In the case of our simulated submarine model the actual Vernier-/Nonius frequency is:

$$f_v = \mathrm{lcm}\{4, 7\} \cdot f_0 = 28 \cdot f_0$$

As depicted in figure 6 a frequency component corresponding to the Vernier-/ Nonius effect is obviously not observable. It's possible, that the amplitude is just too weak and overwhelmed by the numerically noise of the simulation.

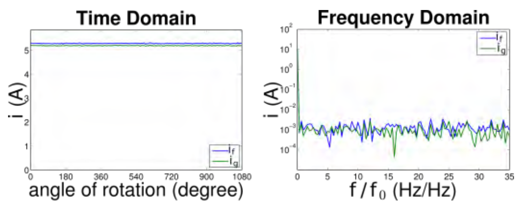

Figure 6. Simulated total ICCP current for rotating propeller. A notable modulation at the frequency $f_v = 28 \cdot f_0$ is not observable [4].

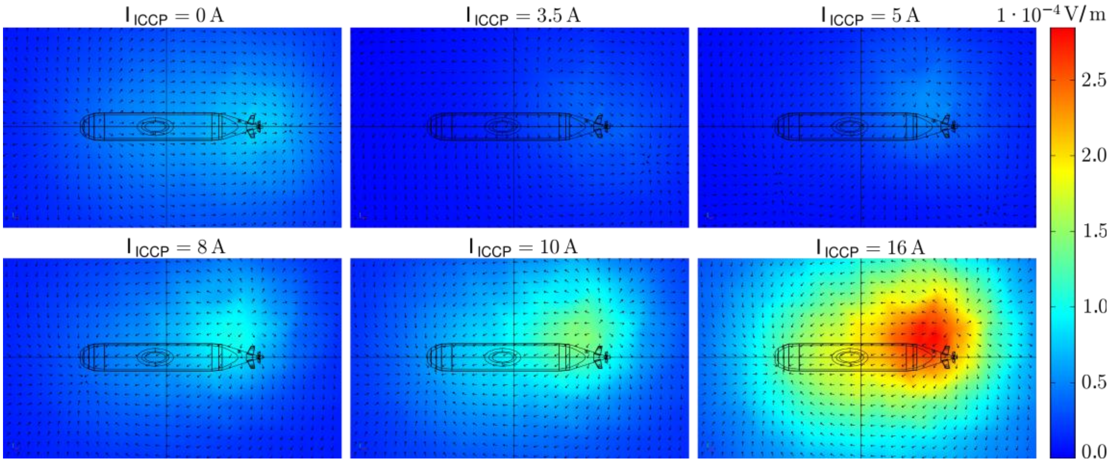

Figure 7. Signature planes of the electric field in a depth of 20m (66ft) below the keel, for different currents impressed by the ICCP system.

5. Optimal ICCP settings for silent running

Figure 7 contrasts several UEP signature planes for different values of the total ICCP current with each other. A value of $I_{ICCP} = 10A$ represents the normal operating status of the system, while $I_{ICCP} = 0A$ refers to a switched-off ICCP system where only the corrosion-related electric field occur.

A comparison between the different graphics in figure 7 indicates that the raw-corrosion-related UEP signature can be less intense, than the signature produced by a normally operating ICCP system. Also it is obvious, that overprotection can lead to critically strong UEP signatures (cf. $I_{ICCP} = 16A$). On the other hand a customized ICCP operating status could reduce the UEP signature, compared to a normally working- and also compared to a switched-off ICCP system (cf. $I_{ICCP} = 3.5A$). It is recommended to determine and use such ICCP settings for silent running (stealth operating mode), as well as for dangerous areas like e.g. mine fields.

6. Conclusions

The simulations we carried out provided us with a reliable basis for understanding the principally coherences in the application of UEP signatures. In this paper we demonstrated, how the polarization resistance at the electron-/ion-conductor interface smoothens singular field-peaks and hence reduces the modulation of the electric near-field.

Propeller-induced modulation by means of shadowing effects was figured out to be negligible. In this context also “unexpected” frequencies corresponding to the Vernier-/Nonius effect could not be observed. On the other hand a propeller-induced modulation of the electric near-field is existent, but it is strongly decaying with larger distances.

Further simulations with gradually altered ICCP currents provided an interesting estimation about what settings are recommendable in the context of silent running (stealth operating mode). It could be shown, that an optimized ICCP current can in fact reduce the UEP signature of a vessel, while unfortunate settings, namely overprotection, can increase the UEP signature critically. The obvious guess, to switch off the ICCP system in hazardous situations, does not necessarily lead to the smallest possible UEP signature.

7. References

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8. Acknowledgements

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