Submarines: Corrosion Protection or Enemy Detection?

Numerical analysis of the electrochemical interplay between a coated hull, propeller induced modulations and a submarine's underwater electric potential signature is being used to optimize safety in stealth mode.

BY JENNIFER HAND

The ability to move discreetly below the surface of the sea is a fundamental requirement for a submarine. The alternative is detection or, in a hostile situation, a high risk of actuating seabed mines.

Much research has therefore focused on the signals that vessels inevitably emit when they are navigating underwater. These include acoustic and magnetic 'signatures', and most state-of-the-art detection devices are based on extremely sophisticated magnetic and acoustic sensors. In response, acoustic sources on submarines are avoided or silenced with great effort, and the strategic use of non-magnetic material, such as the nickel alloyed austenitic stainless steel, can reduce their magnetic signatures.

In contrast, the underwater electric potential (UEP) signature created by corrosion and corrosion protection systems has so far received less attention. Yet, mines with UEP sensors are already available and there is growing recognition that mines of the future will increasingly exploit these electric fields. Germany's Technical Center for Ships and Naval Weapons (WTD 71) has therefore commissioned the Laboratory for General and Theoretical Electrical Engineering (ATE) at the University of Duisburg-Essen to undertake research into UEP signatures from submarines.

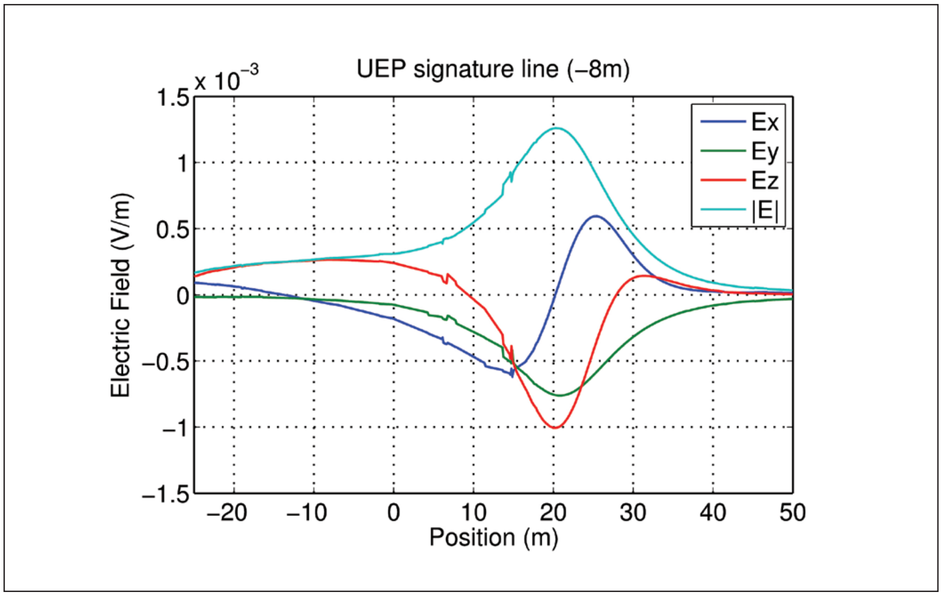


Figure 1: Axial trace of the near-field (8m below the keel) UEP signature of a simplified submarine model, simulated in COMSOL Multiphysics.

Distribution of the Electric Potential and Current Density

As a member of the university team, Dipl.-Ing. David Schaefer explains how the research began: "The UEP signature stems from the fact that the corrosion process and impressed current cathodic protection (ICCP) systems, designed to prevent the corrosion of metal components, create a current density distribution with a related electric field around the vessel. The electric field varies according to environmental conditions, such as the conductivity of the seawater, and the use of different metals throughout the submarine's design." A vessel's UEP signature is usually defined by the value of the electric field on a plane surface or along a line (Figure 1).

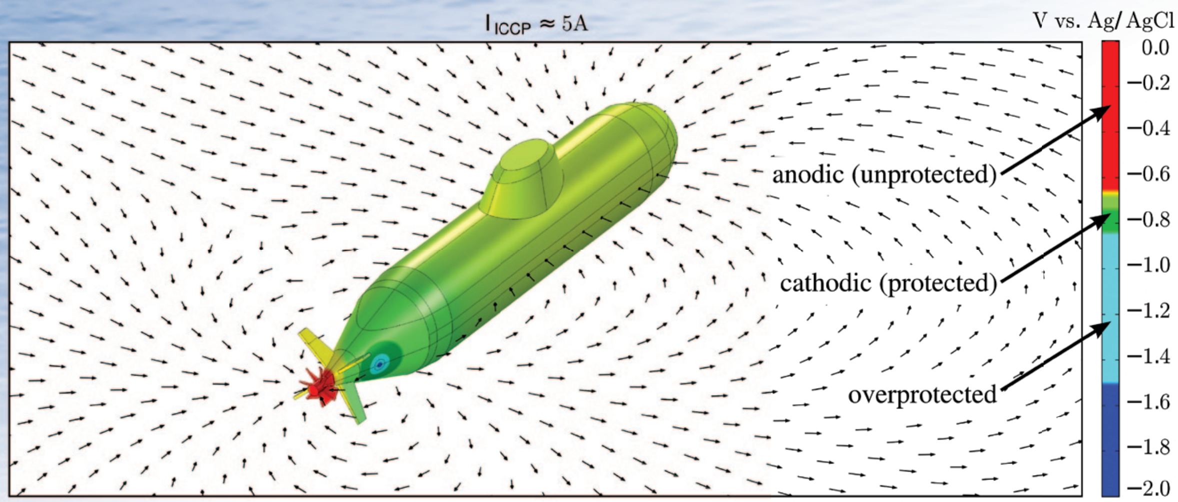
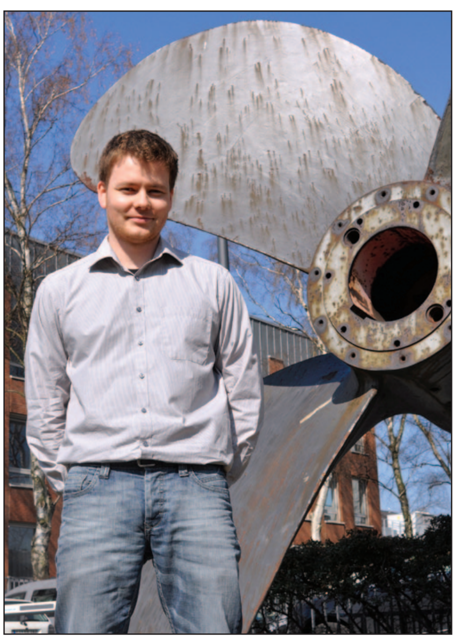


Figure 2: Potential distribution for when cathodic protection is being imposed. The arrows represent the direction of the electric field. Under normal operating conditions the ICCP current would be a little bit higher (about I_{ICCP}=8A) to ensure a cathodic state (green color) all over the hull. The colormap is based on the German naval directive VG 81259.

The team took into account the electrochemical reactions that result from corrosion at the submarine hull. These were simulated using nonlinear polarization curves, which describe the amount of current density that occurs at a certain electric potential in the electrolyte.

The team had to assign the polarization curves as non-bijective functions because this allowed them to consider the electrochemical passivity. Stainless steel, which is used in the hulls of German submarines, normally protects itself against corrosion by building up a dense layer of oxides on its surface. In the polarization curves this so-called "passivity" can be noticed by a decrease of current density for anodic potentials. However, under unfortunate conditions, e.g. high oxygen gradients in gaps, the protective layer cannot develop and the material corrodes rapidly. Thus the word "stainless" is somewhat misleading, because the materials are in fact not completely invulnerable against corrosion, and hence have to be protected. For this reason it was not possible to describe the electrode kinetics by common approximations such as the Butler-Volmer or Tafel equations.



Dipl.Ing. David Schaefer in front of a corroded ship's propeller.

In the first model (Figure 2) the team simulated the electric potential distribution on the hull of a submarine, which indicates whether or not the material is protected against corrosion. "The ICCP system forces the surface of the hull into a cathodic operating point, which is visualized by the green color in Figure 2," comments Schaefer.

Calculating the Electric Signatures

Having established the potential distribution on the hull for different ICCP setups, the next step was to determine the related UEP signature. "Once we simulated the potential distribution with COMSOL, we were able to directly extract the associated electric field in the water and receive the corresponding UEP signature," said Schaefer.

"Once we simulated the potential distribution with COMSOL, we were able to directly extract the associated electric field in the water and receive the corresponding UEP signature."

One challenge was the moving boundary problem created by the rotating propeller blades. The angle of propeller rotation was increased successively, as a parametric sweep, and the maximum values of the electric field in different depths below the submarine keel were extracted and visualized. Figure 3 clearly depicts how the high fields at the tips of the propeller blades modulate the electric near-field, which decays rapidly the further away from the propeller you measure the field.

DIRICHLET BOUNDARY CONDITIONS: **NON-LINEAR POLARIZATION CURVES:**

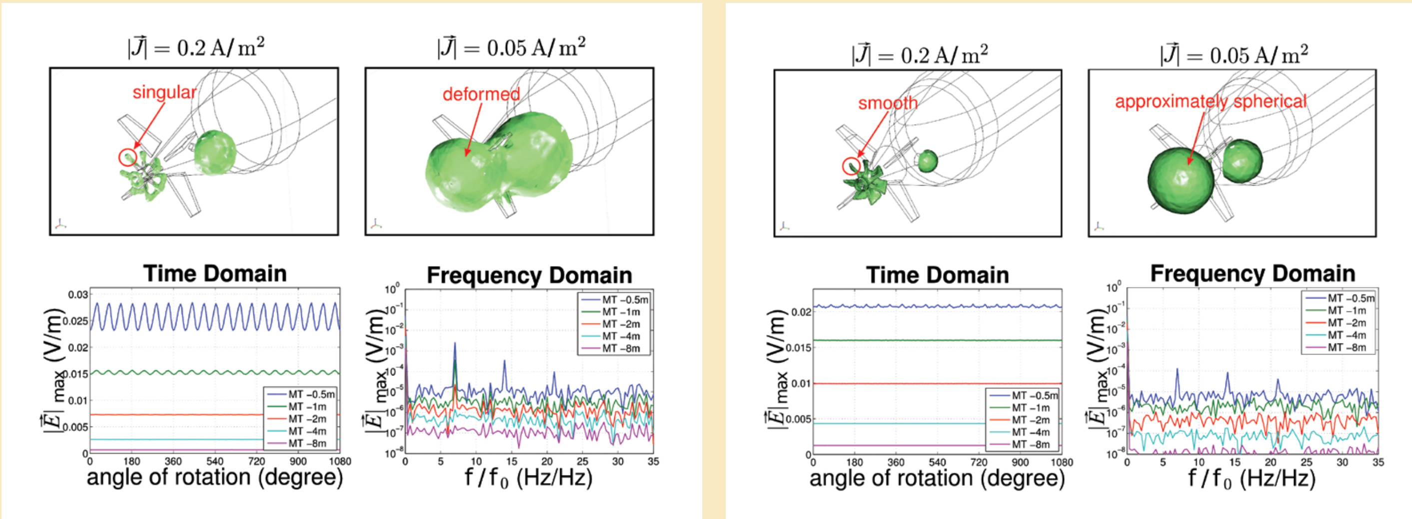


Figure 3: Simulated near-field modulations during propeller revolution. The simplified assumption of Dirichlet boundary conditions (left) leads to significantly more modulation than the consideration of the electrochemical reactions at the boundaries using non-linear polarization curves (right).

To demonstrate how electrochemical reactions affect the near-field modulation in principle, the team also performed simulations using Dirichlet boundary conditions (Figure 3, left) where electrochemistry is completely disregarded. A comparison of the resulting isosurface plots in Figure 3 illustrates how the electrochemical reactions reduce the modulation by smoothing the field peaks at sharp angles and edges. According to Schaefer, "The smoothing effect is a result of the 'polarization resistance' at the interface between the electron conductor (metal) and ion conductor (sea water). The polarization resistance counteracts the high currents at sharp edges, and thereby reduces the field strength in the surrounding water."

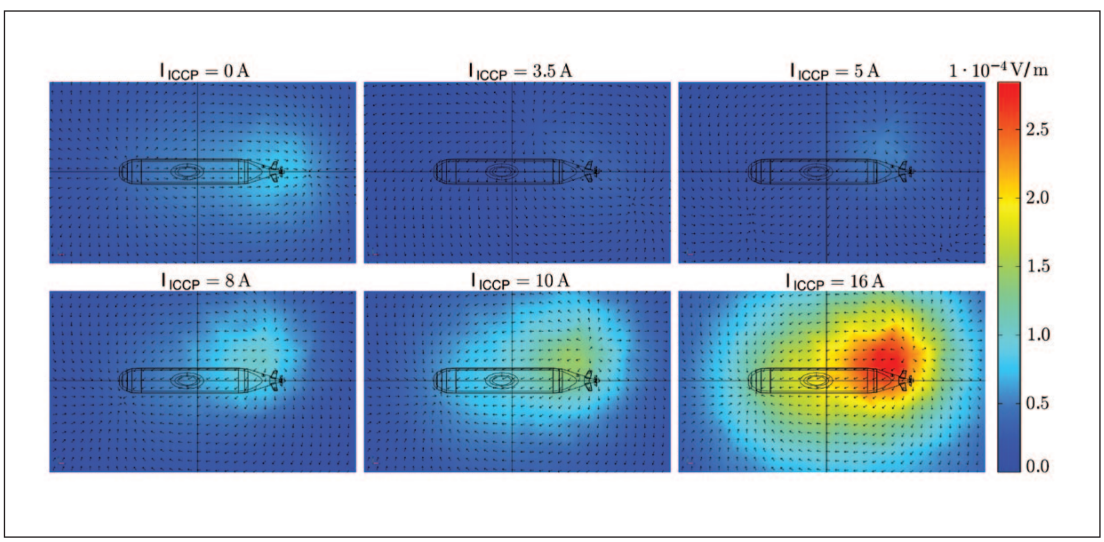


Figure 4: Signature planes of the electric field in a depth of 20m (66ft) below the keel, for different currents impressed by the ICCP system. A signature is evident when ICCP is switched off (top left), which can be optimized at 3.5 A (top middle). Overprotection, on the other hand, leads to a large UEP signature (I_{ICCP}=16A, bottom right).

Optimal Settings for the ICCP

Practical experience indicates that the signature becomes more pronounced for great ICCP currents, especially when the hull is forced into overprotection, which means that it is more cathodic than necessary. It is therefore an obvious guess that the UEP signature could be less intense for a switched-off ICCP system.

Figure 4 shows that surprisingly neither the switched off mode (I_{ICCP}=0A) nor the normal operating conditions (I_{ICCP}=8A) produce an optimal UEP signature. Instead, the smallest field strength appears to be in between these two ICCP setups (I_{ICCP}=3.5A). The figure also affirms the assumption that overprotection leads to a critically high signature (I_{ICCP}=16A).

"There is clearly a balance to be achieved between corrosion protection and UEP signature. It is vital that we understand the consequences of changing ICCP settings, particularly in stealth situations," concludes Schaefer. "Yet, we have also shown that it is possible to optimize ICCP to reduce the UEP signature." ■