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

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Outline

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  - Underwater electric potential (UEP) signature
  - Corrosion protection (CP) systems

- **COMSOL Multiphysics simulations**

- **Research results**
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  - Singular field peaks at sharp angles and edges
  - Smoothing effect of the polarization resistance
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  - Optimal ICCP current for “silent running” (stealth mode)

- **Conclusions and Outlook**

- **Literature**
Introduction (I)

Underwater signatures and “Mine warfare” (MIW)

- The term “signature” originally referred to acoustic measurements of a vessel's underwater sound pressure field [1, p.1ff].

- Different types of signatures:
  - Acoustic signature
  - Magnetic signature
  - Electric signature (UEP signature)
  - …

- Vessels (unintentionally) reveal their presence to their environment.

- Signatures exploited in “Mine warfare” (MIW) and “Anti-submarine warfare” (ASW).

- Naval influence mines buried in seabed can monitor signatures and actuate without direct contact.

- Acoustic and magnetic signatures well under control.

- Electric (UEP) signatures not so important until now, but probably in the future → Focus of our research

Diverse influence mines (under CC-license; Author: Darkone@Wikipedia)

Acoustic influence mine found in the Arabian Gulf
**Introduction (II)**

**Underwater electric potential (UEP) signature**

- Reasons for the electric currents in water:
  - Electrochemical reactions (Corrosion)
  - Corrosion protection systems

- Common representation for UEP signature:
  - “Signature line” (Axial trace)
  - “Signature plane” (Slice plot)

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**Sketch of typically electric current paths around a submarine.**

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

**Signature plane of the electric field in a depth of 20m (66ft) below the keel, simulated with COMSOL.**
Introduction (III)

Corrosion protection (CP) for naval vessels

- Active corrosion protection systems:
  - Galvanic/sacrificial anodes
  - Impressed current cathodic protection (ICCP) systems

- Active CP often based on cathodic currents:

<table>
<thead>
<tr>
<th>Equilibrium:</th>
<th>Anodic:</th>
<th>Kathodic:</th>
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<tbody>
<tr>
<td>$\varphi_{\text{vs. Ref.elektrode}} = \varphi_0$</td>
<td>$\varphi &gt; \varphi_0$</td>
<td>$\varphi &lt; \varphi_0$</td>
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<tr>
<td>J = 0</td>
<td>J</td>
<td>J</td>
</tr>
<tr>
<td>Metall</td>
<td>$\text{Me}^{n+}$</td>
<td>$\text{ne}^-$</td>
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<tr>
<td>Elektrolyte</td>
<td></td>
<td></td>
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<tr>
<td>=&gt; Corrosion</td>
<td></td>
<td>=&gt; protected</td>
</tr>
</tbody>
</table>

- Passive corrosion protection:
  - Isolating coatings
  - Protective paintings
  - Proper material combination

- **Question:** What is the ideal corrosion protection setup to minimize the UEP signature?

Galvanic zinc anodes (under CC-license; Author: Hgrobe@Wikipedia)

Galvanic anodes placed on a ships hull
COMSOL Multiphysics simulations

Governing equations

- Poisson equation (AC/DC Module – Electric Currents): \( \Delta (\sigma \cdot V) = 0 \)
- Electric field and current density: \( \vec{E} = -\nabla V \) \( \vec{J} = \sigma \cdot \vec{E} \)

Electrode kinetics considering measured polarization curves

- Neumann boundary condition (“Inward current density”): \( \vec{n} \cdot \vec{J} = J_i(V) \)
  \( J_i(V) \) represents a nonlinear polarization curve.
- Simulated in COMSOL by using a piecewise interpolated function.

Simulating via “LiveLink for Matlab”

- Capability to...
  - ...perform complex parameter sweeps.
  - ...implement customized optimization procedures.
- In-house developed toolbox to receive entity-ids by referring to the name-tag.

Polarization diagram measured my Hack [3].
Research results (I)

Potential distributions on the vessel's hull

Potential distribution on the hull of a simplified submarine model, for different currents impressed by the ICCP system. The colorbar is based on the German naval directive “VG 81259” [2].

- Good protection at $I_{ICCP} \approx 8$-10A for this submarine model.
Research results (II)

Potential distributions on the vessel's hull
Research results (III)

Singular field peaks at sharp angles and edges

- Charges repel each other and move to the surface of the conductor.
- More charge on surface areas with small curvature (e.g. on buckles/angles/edges).
- Relation between $\vec{D}$ and $\sigma$ [4, S.102]:
  \[
  \vec{n}_{12} \cdot (\vec{D}_2 - \vec{D}_1) = \sigma \quad \Rightarrow \quad |\vec{D}_2| = \sigma
  \]

Field- and equipotential lines for an electrically charged “potato” simulated with COMSOL.
Research results (IV)

“Smoothing effect” of the polarization resistance

- Dirichlet: Singular field-peaks occur on sharp edges like the tips of the propeller blades.
- Rotating propeller modulates the electric near-field (rotating deformed equi-surfaces).
- Polarization resistance reduces the modulation (spherical equi-surfaces)

Simulated near-field modulation with Dirichlet boundary conditions.

Boundary conditions based on non-linear polarization curves.
Research results (V)

Vernier-/Nonius effect

<table>
<thead>
<tr>
<th>Rudder blades: ( n_r = 3 )</th>
<th>Propeller blades: ( n_p = 1 )</th>
<th>Expected modulation-frequency: ( f_v = 3 \cdot f_0 )</th>
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<tbody>
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<td>Shadowing!</td>
<td>Shadowing!</td>
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<td>( 240^\circ )</td>
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<tr>
<td>( 300^\circ )</td>
<td>No Shadowing</td>
<td>Shadowing!</td>
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</table>

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<th>Expected modulation-frequency: ( f_v = 6 \cdot f_0 )</th>
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Theoretically example to illustrate the Vernier-/Nonius effect. The figure shows an astern view on a simplified submarine model.

- Propeller blades get covered behind rudder blades during the rotation of the propeller.
- **Question**: Does the total ICCP current become modulated?
- Frequencies corresponding to Vernier-/Nonius **not observable** in simulation.
Research results (VI)

Optimal ICCP current for “silent running” (stealth mode)

- Optimized ICCP currents can in fact reduce the UEP signature (3.5A).
- Switched off ICCP system does not necessarily produce the smallest UEP signature (0A).
- Overprotection can increase the UEP signature critically (16A).

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

Conclusions

- COMSOL simulations provide us with a reliable basis for understanding the principally coherences in the application of UEP signatures.
- Polarization resistance “smoothens” singular field-peaks.
- Frequencies corresponding to Vernier-/Nonius effect not observable.
- Optimized ICCP currents can reduce UEP signature, but overprotection can increase the UEP signature critically.

Outlook

- Simulations of the electric currents flowing back through the electron conductor (Using the COMSOL “Batteries & Fuel Cells Module”).
- Simulations of the corrosion related magnetic field.
- Qualitative changes in the UEP signature of scaled models.
Literature


Thank you for your attention!

Questions?
Meet me at my poster →
When? 17:30 – 19:30
Where? Bürgersaal-Foyer
(also you can find my paper in the conference proceedings)