Magnetic Sensing in Offshore Operations

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WFS Technologies
WFS Technologies,

- Founded 2003.
- Privately held.
- UK & USA operations.

Solutions for Subsea instrumentation & control based on Magnetic & EM Physics,

- Communications.
- Control.
- Video and Voice streaming.
- Navigation and docking.
- Power transfer.

Field proven products,

- Field experience in N. Sea, GoM & SE Asia
Introduction

• The UK company, WFS Technologies, is based in Livingston, Scotland, and is industrial partner in an STFC funded project at Manchester University.

• This presentation sketches some of the physical principles on which our products are based and shows a range of valuable applications.

• The emphasis here is Engineering and Applied Physics and from a scientific viewpoint it is mature stuff. Scientifically, it is lagging edge, but it is product-innovative and it serves a very real business need.
Technical content – 6 topics

2. Communications using magnetic effect.
3. Inductive Power Transfer.
4. Data transfer through ferrous metal walls.
5. WFS Products in service - examples.
6. Ambition for non-destructive testing underwater.
Terrestrial Magnetic Noise limits communications
20dB below $1 \mu T / \sqrt{Hz}$ from 100Hz to 10kHz

Figure 1 All data and best-fit curves for 7 data sets from 2 locations, 3 seasons, and 4 time-of-day blocks
B-Field, Magnitudes and Frequencies

Adapted from “Magnetic Sensors and Magnetometers”, P. Ripka, Artech, (2001)
What does "1\(pT / \sqrt{Hz}\)" mean in design

- Electronic noise density in 100\(\Omega\) resistance (typical) is about 1.2\(nV / \sqrt{Hz}\).
- Electronic noise in a practical amplifier is about 1\(nV / \sqrt{Hz}\).

\[
V(t) = -\mu_0 \mu_r NA \frac{dB}{dt}
\]
Evaluate at, 3kHz, \(N=1000\), \(A=1cm^2\), Scale factor is, 1885V/T

- So a transduction gain of 1000V/T will raise "\(pT\)" terrestrial noise density to "\(nV\)", the level of electronic noise density and is a practical limit in sensing and receiving.

There are two practical transducers open to a designer, a solenoid and a Hall-Effect device. A solenoid can readily achieve 1000V/T and raise terrestrial noise to observable levels. A H.E. device cannot do this, but it can operate at D.C. whereas a solenoid cannot.
Solenoid sensing

- Solenoid responds to “rate of change of flux”,
  \[ V(t) = \mu_e \cdot Area \cdot \frac{dB}{dt} \]
- Effective area can be increased by adding turns,
  \[ Area = N \cdot A \]
- \( \mu_e \) can be increased by permeable material, but for a solenoid it is geometry dependent and seldom can exceed \( \mu_e = 50 \), even when the core, \( \mu_r = 1000 \).
- So, for sinusoidally varying B-field, response in,
  \[ \frac{Volts}{Tesla} = \frac{2\pi \cdot Hz \cdot Turns \cdot Area (m^2) \cdot Eff. Permeability}{Volts/Turns/Hertz} \]
  while noise generated depends on the sq.-root of the wire resistance.
Core Permeability – may give a design freedom, but much more limited than is frequently understood!

Effective permeability depends on the ratio of length to diameter. This implies that for high effective permeability, coils should be long and of small diameter.

However, cross-section area is important in intercepting flux. There is no escape from “big is beautiful”.

Useful for Rx function.

Core losses may be important.
Hall Effect – the principle

- A charge moving in a magnetic field experiences a force at right angles to the field direction and at right angles to the velocity vector of the charge motion.
- This is called the Lorentz force and is given by the equation,
  \[ F = q.(v \times B), \text{ where ‘}x’ \text{ is the vector cross-product}. \]
- In a combined electric and magnetic field the force on a charge is,
  \[ F = q.(E + v \times B) \]
- \( E \) and \((v \times B)\) are obviously the same substance. That is, a charge moving in a magnetic field effectively sees an influence indistinguishable from the influence of an appropriately directed electric field.
- Interestingly, Edwin Hall, an American doctoral student, discovered the effect in 1879, inspired by what he correctly thought was an erroneous statement in Maxwell’s, “Electricity and Magnetism”, Vol ii, p.157, (Oxford Press edition), where Maxwell insisted that the magnetic force influenced the motion of the conductor and not the “electricity”.

Vector directions correct for negative charge carriers
Effect of “B” on a current sheet

Without magnetic field influence

Ohmic contacts in 4 places
Current path electrode
With magnetic field influence
Sensing Electrode
Equipotential lines
Current path electrode
Current drift velocity vector
\( \delta v = 0 \)
\( \delta v > 0 \)

Ohmic contact
Greek cross
Without magnetic field influence
With magnetic field influence

\( W = 70 \mu m \), \( L = 210 \mu m \)

Bonded Hall chip before plastic encapsulation
Geometric correction due to “Short-Circuit” Effects

Top-bottom lines show current density. Left-right shows equi-potentials. Equi-pot lines must be horizontal at contacts. Hence make L large.

Sensor contacts reduce current density in the plate centre, reducing H.E. scale factor. Hence make S small.

Magnetic induction is perpendicular to the plate.

\[ G_{\text{rect}} \simeq \left[ 1 - \exp \left( -\frac{\pi}{2W} \frac{L}{W} \right) \right] \cdot \left[ 1 - \frac{2S}{\pi W} \right] \]

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Hall effect devices in a design context

- The scale-factor transferring B, in Tesla to Volts, is typically 1.0 V/T at a current near 1 mA. Higher currents give proportionally better scale-factor, but thermal effects may be undesirable.
- The internal resistance is typically 700 Ω and the device behaves as Johnson noise source above 1 kHz. At frequencies below this, flicker noise dominates such that the noise density is increased by ~40 dB at 1 Hz.*
- From a design viewpoint, the simple equivalent circuit is, shown here:
  
  ![Equivalent Circuit]

  0.2 V/T/mA

- AC coupling can eliminate offset and drift worries in sensing and communications applications.
- Sensitivity depends on bandwidth. A noise density of 3-4 nV/√Hz is achievable in a practical circuit, which gives a sensitivity better than 1 μT in 1 Hz bandwidth. This is well below what a solenoid could achieve, but it is sufficient in non-communications applications and the device is reliable, geometrically flexible and easy in manufacture.

* Noise spectrum from a delta doped AlGaAs/InGaAs/GaAs pseudomorphic quantum-well Hall device at bias current of 0.48 mA [Lee 1996].
A current loop excited by an alternating current creates 3 magnetic fields, varying with distance as $1/r^3$, $1/r^2$ and $1/r$.

The $1/r$ field is accompanied by a complementary space-orthogonal, time synchronised, electric field and it propagates. The other two fields are reactive and return their energy to the source.

However, any oscillating magnetic field can induce a current in a conductor, so the reactive fields are exploitable for communications.

Conductivity shrinks wavelength, which means high propagation losses, hence low frequencies, hence low bandwidths.

In sea-water, we typically use a frequency of 3kHz and the wavelength is about 30m and 10 – 50% bandwidths are possible to about 60 - 100m.

In any conductive medium, like sea-water, the attenuation constant is 55dB/wavelength.

Moreover the power expended to make such a link is a limiting factor for battery-driven equipment.
The three H-fields plotted in sea water

- The cross-over point is always near $\lambda/(2\pi)$. This is the point at which a plane-wave is established and the propagation may be described as “far-field”.
- As a simple rule, data communications at bandwidth 10% of carrier is usually achieved to twice the wavelength, i.e. for 3kHz, 300 bits/sec. to 60m is possible.
Wavelength in conductive media

- Sea-water, 4 S/m
- Fresh water, 0.001 S/m
- Free space

Radio 2, Long Wave, Wavelength contraction $\frac{1500}{3.5} = 429:1$
Attenuation, variation with Frequency

Frequency in Hz

Attenuation in dB/metre

- 10.0 S/m
- 4.0 S/m, Sea Water
- 1.0 S/m
- 0.1 S/m
- 0.01 S/m
- 0.001 S/m
- 0.0001 S/m
- Fresh Water

Attenuation in dB/metre

- 1.0 S/m
- 0.1 S/m
- 0.01 S/m
- 0.001 S/m
- 0.0001 S/m
- Fresh Water

Frequency in Hz

Attenuation in dB/metre
Wireless Power Transfer - Nothing New

- In 1901 when Marconi was happy to transmit a tiny wireless signal across the Atlantic, Tesla had bigger plans.
- Financed by the J.P. Morgan, he experimented with Inductive Power Transfer on a large scale.
- This could not work (and was never finished). WPT works efficiently over distances of the order of the radius of the coils used, not over long distances.

Tesla’s Wireless Power Transfer Experiment
Wireless Power Transfer (WPT) - Physical Principles

- WPT exploits the transformer principle in which power is transferred between coils through an oscillating magnetic field.
- Conventional transformers are designed to ensure that all the flux produced by the primary winding links the turns of the secondary winding. This is achieved by placing both windings on a common ferrous core.
Wireless Power Transfer – loose air-coupling

- An WPT device is a space-transformer, with separated windings so that the flux coupling is necessarily partial.
- Flux that is not coupled, does not transfer power, neither does it consume power – it returns its energy to the source.
- WPT devices may be air-cored, or ferrite cored, so core losses are low and the dominant loss mechanism is the resistive heating of the copper windings. This can be controlled in design.
- Power conditioning at input and output will add losses depending on application.

Commercial-in-Confidence
Wireless Power Transfer - System Diagram

- Coil design and matching networks depend critically on specific load.
Wireless Power Transfer
- Power control by PWM – \( P = i^2 \times R_{\text{load}} \)

Power = 50kW  
Peak o/p current 30A

Power = 20kW  
Peak o/p current 20A

Commercial-in-Confidence
2kW WPT Prototype on test in water bath

- Planar spiral coils.
- 7 cm separation.
- 82% transfer efficiency.
- 20kHz frequency.

LITZ wire spiral coils
Data transfer through steel walls

- Treat this as a transmission line problem.
- Establish the wave impedances at both sides of material discontinuity and account for reflections.
- Account for loss in the conductive material as 8.7 dB/skin depth.
- Practical at low frequencies with attenuation ~200dB.
## Subsea Wireless Instrumentation & Control Products

<table>
<thead>
<tr>
<th>Model</th>
<th>Function</th>
<th>Bandwidth</th>
<th>Seawater Range</th>
<th>Antenna</th>
<th>Power Consumption</th>
<th>Inductive Recharge</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>S100</td>
<td>Controller Datalogger Modem</td>
<td>2.4kbps</td>
<td>2.5-5m</td>
<td>Internal External option</td>
<td>Lo Power Rx: 0.05W Rx: 0.18W Tx: 0.6W</td>
<td>10W – 2kW</td>
<td>Compact, low power Networking Connectors &amp; jumpers</td>
</tr>
<tr>
<td>S200</td>
<td>Modem Location</td>
<td>10bps – 8kbps</td>
<td>10–40m (up to 500m through air)</td>
<td>External 0.5–2m</td>
<td>Rx: 4W Tx: 16W</td>
<td>10 W–2kW</td>
<td>Medium range, Instrumentation</td>
</tr>
<tr>
<td>S300</td>
<td>Controller Datalogger Modem Video streaming</td>
<td>25 kbps–156kbps</td>
<td>4 – 8m</td>
<td>External 0.5–1m Internal option</td>
<td>Lo PowerRx: 0.05W Rx: 5W Tx: 16W</td>
<td>10W – 2kW</td>
<td>Broadband, short range</td>
</tr>
<tr>
<td>Viewtooth</td>
<td>Video Streaming</td>
<td>75kbps &amp; 156 kbps</td>
<td>4 – 7m</td>
<td>External 0.5–2m Internal option</td>
<td>Lo Power Rx: 0.05W Rx: 11W Tx: 19W</td>
<td>10W – 2kW</td>
<td>Streaming video</td>
</tr>
</tbody>
</table>

**OEM version of S100**

- S200 with 0.5m antenna
- S300 with 0.5m antenna
- Viewtooth with 0.75m antenna
- Seatooth + Power
Wireless Integrity Management and Flow Assurance

- **Wireless Integrity Management**
  - Upheaval buckling
  - Riser over-temperature
  - UT monitoring
  - Pig location
  - Smart CP monitoring
  - Mooring monitoring
  - Pipeline pre-commissioning

- **Wireless Flow Assurance**
  - Retrofit temperature control
  - Cooling spool performance monitor
  - Wax build-up
Upheaval Buckling

- Objective:
  - Prevent temperature induced upheaval buckling of subsea pipelines.
Ultra-sonic Thickness Monitoring

- Objective:
  - Identify excessive internal corrosion.

- Seatooth PipeLogger:
  - Transmit wall thickness data through 20mm pipe coating.
  - Wireless comms through seabed and concrete blanket.
  - Harvest data by ROV, Diver or AUV.
  - Battery life typically 10 years
Smart Corrosion Protection Monitoring

• Objective,
  – Extend asset life through improved monitoring and maintenance.

• Solution,
  – Seatooth CP:
    • Integrated Voltage and Current sensor.
    • Electronic ‘CP Stab’ at pre-determined time intervals.
    • Battery: up to 10 years.

• Diagnostics tool: Identify and measure imbalanced CP.
• Monitor inaccessible locations.
Retrofit Temperature Monitoring

- Hard-wired sensors are vulnerable to damage.
- A battery powered data logger and magnetic transmitter can be sealed for 10 years and protected under concrete.
- Low bandwidth link using magnetic transmitter sends data when stimulated by a transceiver on an ROV.
**Problem**
- Monitoring complex subsea activities avoiding safety hazard of snagging umbilicals from multiple ROVs.

**Solution**
- **Viewtooth® Subsea Wireless Camera.**
- **IRM (Inspection, Repair, Maintenance)**
  - ROV stands off at safe distance,  
    - e.g. strong currents.
  - Record of activities around an asset.

*Viewtooth® Trials on Schilling UDH ROV*
B-CAM Project – where does it apply?

- DC field monitoring for traces of vertical field.
  - Any material defect causes emergence of vertical components in the magnetic field.
  - Line array reduces need to mechanically scan the sensor.

- Could replace ultrasonic measurement subsea.
- Fits perfectly with data logging and magnetic data transfer.
B-CAM project – AC field monitoring

- Current distribution in the component produces a characteristic magnetic signature.
- Component is held in a non-conducting jig.
- Replicate components have signatures compared with reference from gold-standard component.
- B-CAM can be constructed to be conformal, e.g. on a cylinder.
Summary, Thank-you and Questions

• Faraday’s Law and Lorentz Force, 19\textsuperscript{th} century science, coupled with 21\textsuperscript{st} century technology, still making business.
• Partnership between Manchester and WFS Technologies will exploit B-CAM in O&G and industrial non-destructive testing.
• Project has delivered demonstration prototypes at 1-D and 2-D levels and is exceeding expectations.
• Entering AC sensing phase of this work with new applications to examine in the 150\textsuperscript{th} year following Maxwell’s famous work:

\textit{PHILOSOPHICAL TRANSACTIONS:}

\textbf{A Dynamical Theory of the Electromagnetic Field}

J. Clerk Maxwell

\textit{Phil. Trans. R. Soc. Lond.} 1865 \textbf{155}, 459-512, published 1 January 1865