Magnetic Field Based Wireless for Communications and Sensing Through Barriers

ISA Passive Wireless Sensor Workshop
Washington DC
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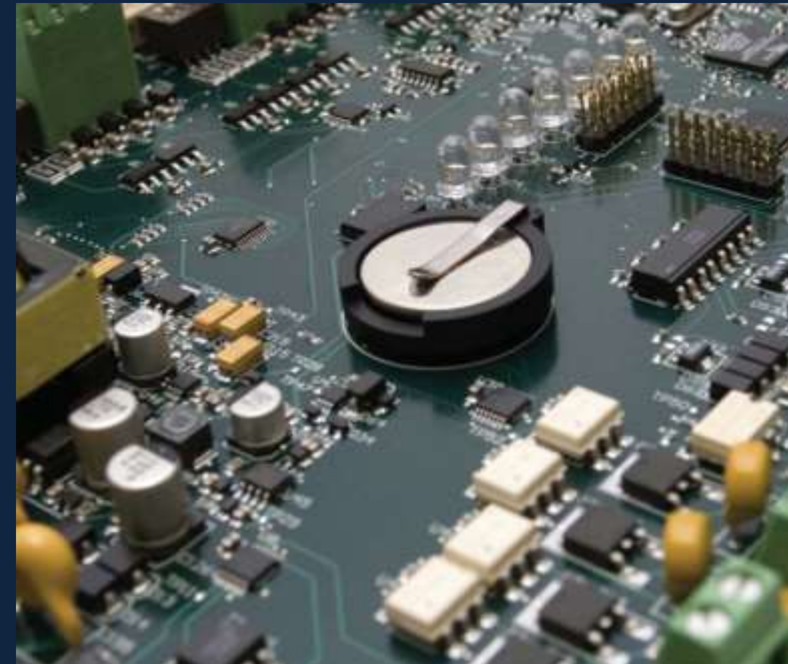
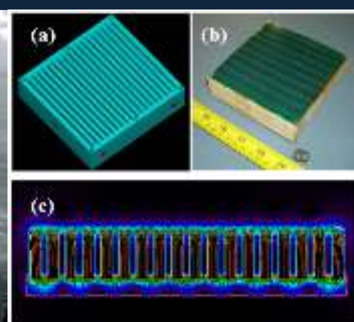
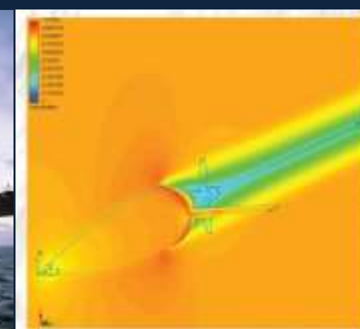
President - Hydro Technologies

HYDRO TECHNOLOGIES







Small company at base of Rocky Mountains (Windsor, Colorado)

Research & Development

- Through barrier sensing, communications, and power

Application Specific Design

- Specializing in defense, oil and gas, and underwater technologies

Custom Electronics

- Pressure tolerant communications, control, and data acquisition platforms

Why Magnetic Based Wireless and Sensing Instead of RF?

- RF is limited by conductivity of a media. As such communications or sensing through most metals is impractical
- Magnetic field penetration is (at low frequencies) dominated by magnetic permeability.
- Comparing attenuation through air versus common structural materials, magnetic fields are much less affected
- Additionally, magnetic fields can wirelessly transfer significant amounts of power

	Air	Carbon Steel (1010)	Ratio
Conductivity	$3.0x10^{-15}$ S/m	$7.0x10^{6}$ S/m	$2x10^{21}$
Relative Magnetic Permeability	1.0	$1.0x10^{3}$	$1.0x10^{3}$

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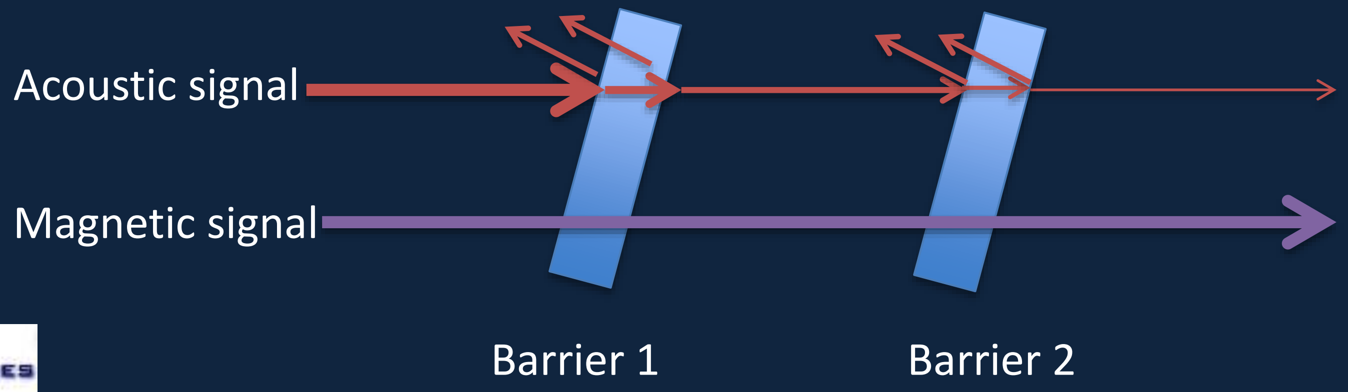
Why Magnetic Based Wireless and Sensing Instead of Acoustic?

- Acoustic communications is strongly limited by the path and variations in acoustic properties of the path. Through thin (<1m) materials, multi-path reflection causes major distortion.
- Multipath reflection in acoustics is an issue due to the relatively slow propagation speed of acoustics. With magnetic fields the propagation is on the order of the speed of light and thus multi-path distortion is avoided at reasonable scales.



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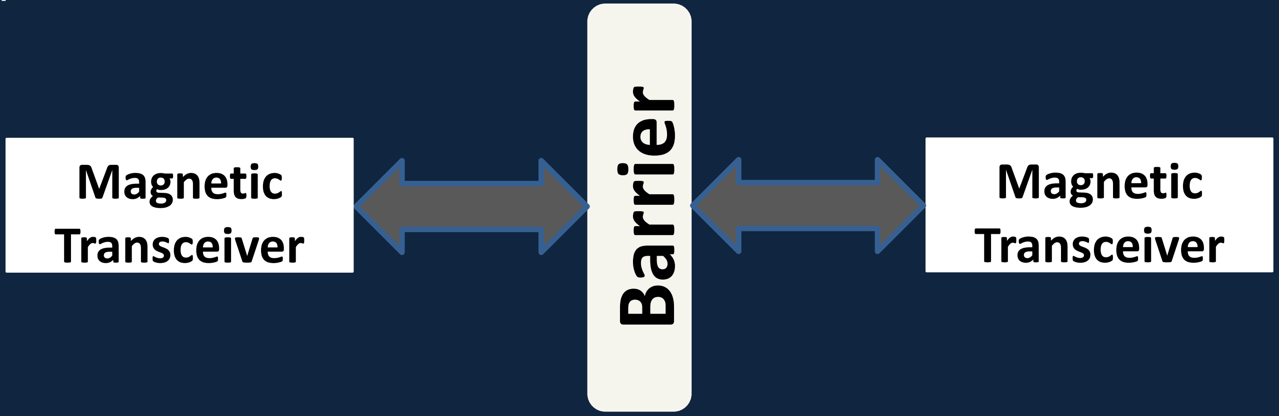
WiΨ - Wireless Power and Signal Interface

- System uses the modulation of magnetic fields to transmit data and power wirelessly
- Works through metals (incl. X65, 1010, Inconel, Super Duplex, aluminum), seawater, concrete, air, and layers of multiple materials
- Deployed on US Navy Los Angeles class submarine as part of a mission and safety critical system
- Recent work focused on application specific oil and gas embodiments as well as major overall technology improvements



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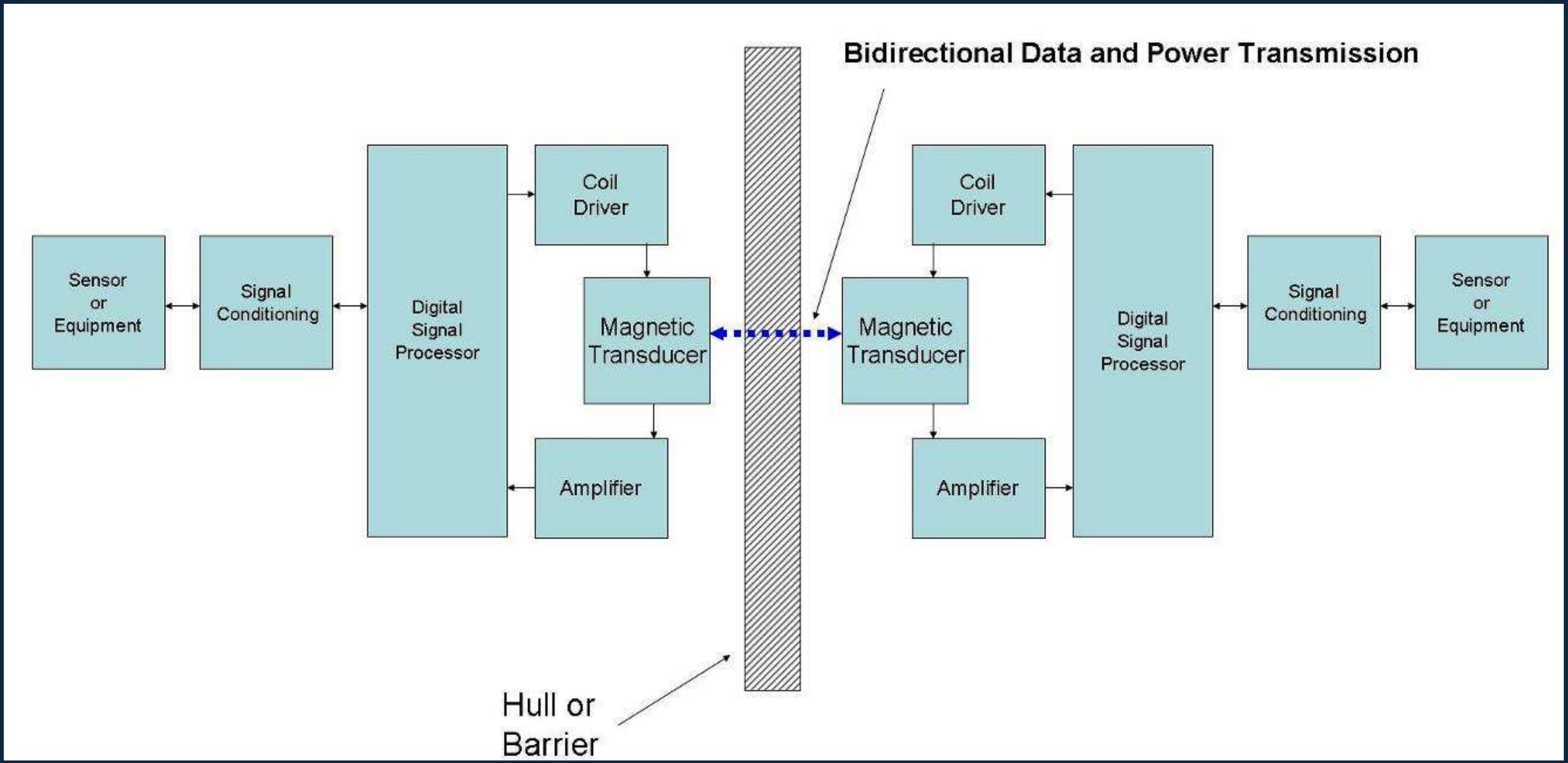
WiΨ — Block Diagram



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WiΨ Data Rate and Power Transfer Through Various Materials

Material	Thickness	Data Rate	Power Transfer
304 Stainless Steel	0.5”	500 kbps	5W
	1”	100 kbps	1W
Titanium	0.5”	500 kbps	5W+
Inconel	0.5”	500 kbps	100W
Aluminum	0.5”	100kbps	<1W
Plastics or other low conductivity media	0.5”	1 Mbps+	5kW+
Steel (1010, X65, 4130, etc)	1”	1 kbps	~1mW *
Steel (1010, X65, 4130, etc)	7”	10 bps	-

*** Recent advances may lead to radical improvement in high μ material power transfer**

Extreme Example of Magnetic Communications

- sensor data through 12” of structural steel

FSK modulated receive data
(yellow is TX signal, blue is RX)

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Passive Magnetic Sensors

Early prototype passive temperature sensor puck

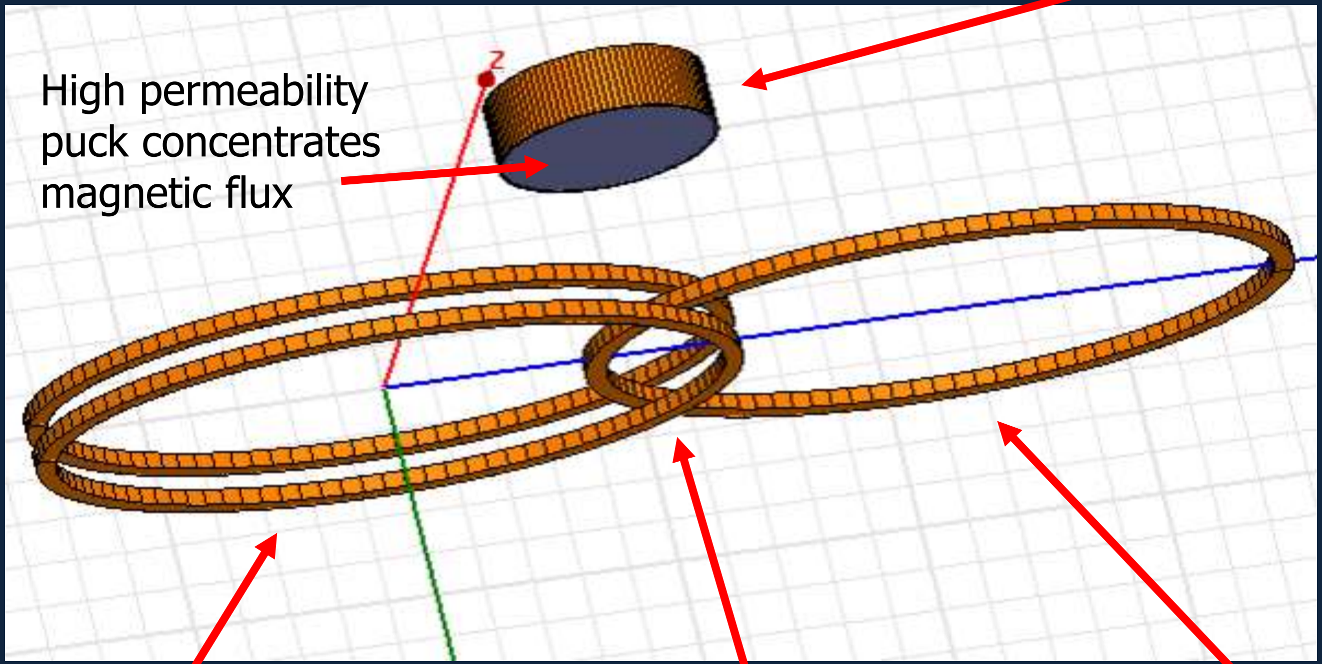
- A completely passive sensor solution is being developed in a collaboration between Hydro Technologies and a major oil and gas company
- The resultant sensor uses magnetic induction and resonant communications to act much like a magnetic RFID tag.
- Some of the benefits include:
  - Is truly passive – it requires no power or wiring to capture and transmit sensor readings even through metal pipes
  - Works in exceedingly harsh environments (completely pressure tolerant, has been tested to 900F)
  - Easy to certify in highly explosive environments (e.g. ATEX) since there are no electronics and it can be completely potted or enclosed
  - Low cost core components
  - Can be integrated with many off the shelf sensors such as thermistors, strain gauges, fluid level detectors, tilt switches, orientation measurement sensors, and flow meters to make them truly passive.

Magnetic Passive Sensor

Simplified Theory of Operation

Windings around puck produce current and hence a magnetic field. Amplitude, phase, and resonant frequency of field varies with circuit properties of anything attached to puck

High permeability puck concentrates magnetic flux



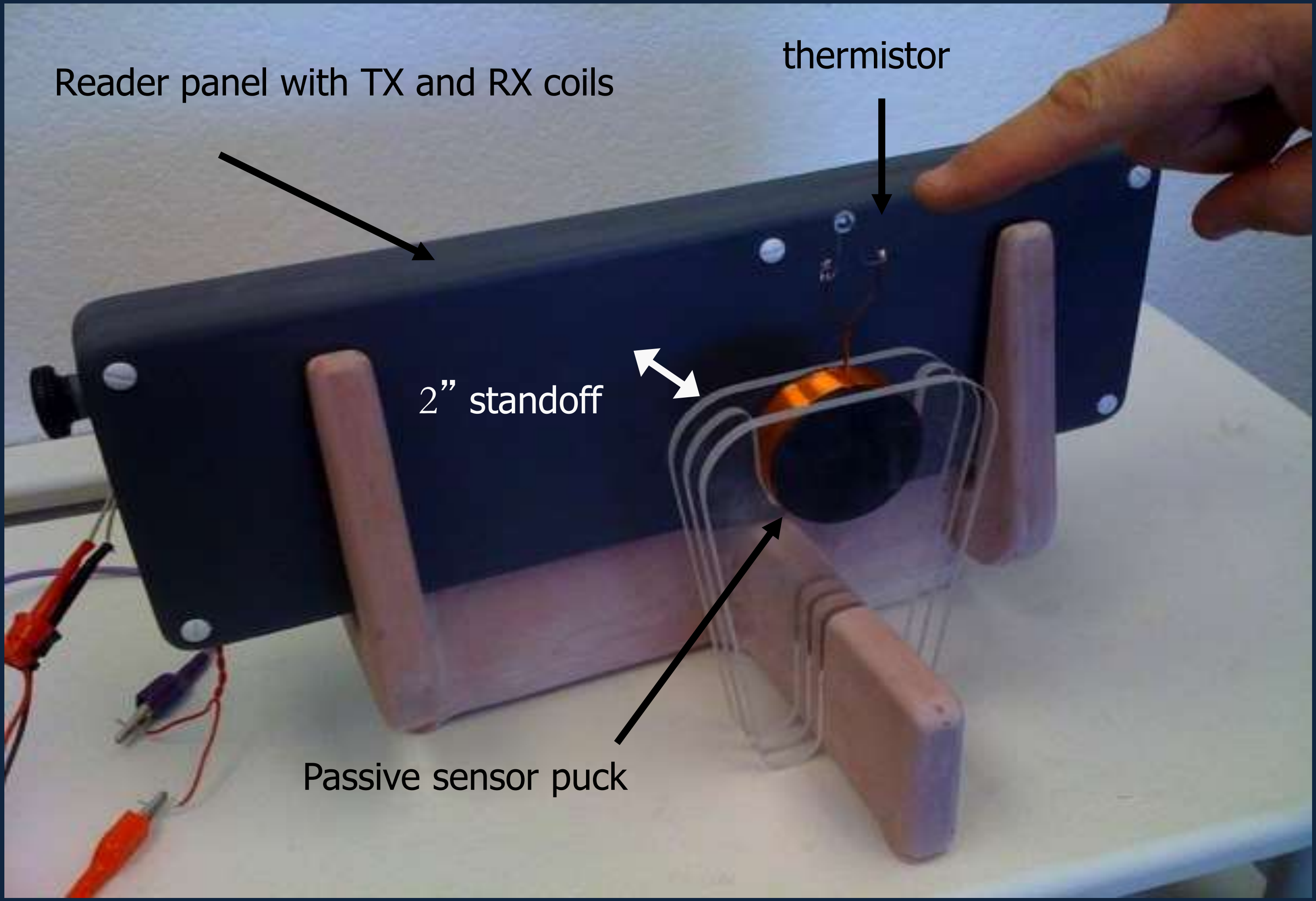
Coils driven with AC current to produce AC magnetic field

Interleave distance between coils set to geometrically null out field from driven coil seen by receiver

Receiver coil. Picks up the field that was induced in puck

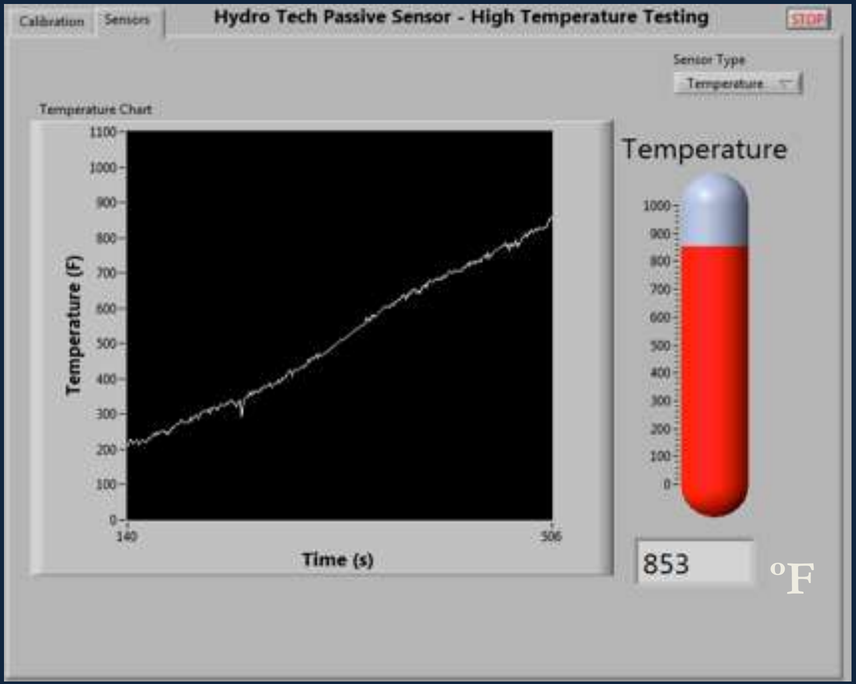
Magnetic Passive Sensor

Initial Proof of Concept



Magnetic Passive Sensor

High Temperature Demonstration



Test setup with passive puck in environmental chamber and TX/RX panel on outside

Screenshot of temperature data received from passive sensor during test to 1000 °F

Magnetic Passive Sensor

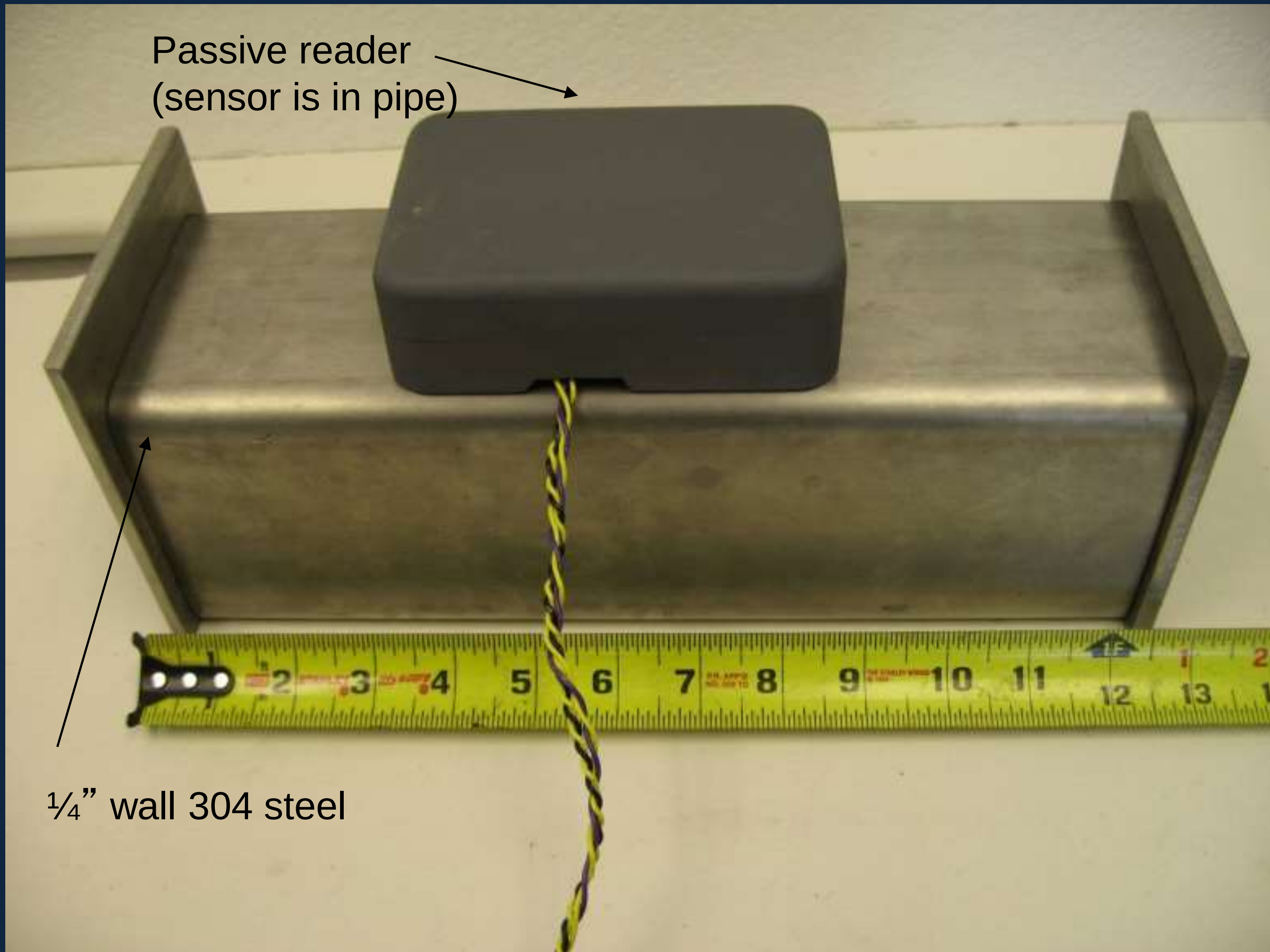
Initial Accuracy Measurements

Resistance (Ω)	**6.89**	**3.3**	**2.73**
Equivalent Temperature (ºF)	69.87	109.48	120.89
N Samples (at 1Hz rate)	1800	1800	1800
Mean (Ω)	6.90	3.31	2.74
Standard Deviation (Ω)	0.0097	0.0074	0.0046
Standard Deviation Translated to Temperature Error (ºF)	+/- 0.07	+/- 0.13	+/- 0.10

Passive sensor measurements of fixed resistances using only phase detection. Single point measurements were taken at 1 Hz for 30 minutes. 2" standoff in air. Temperatures are equivalents for these resistances with a 6.9 Ohm NTC thermistor.

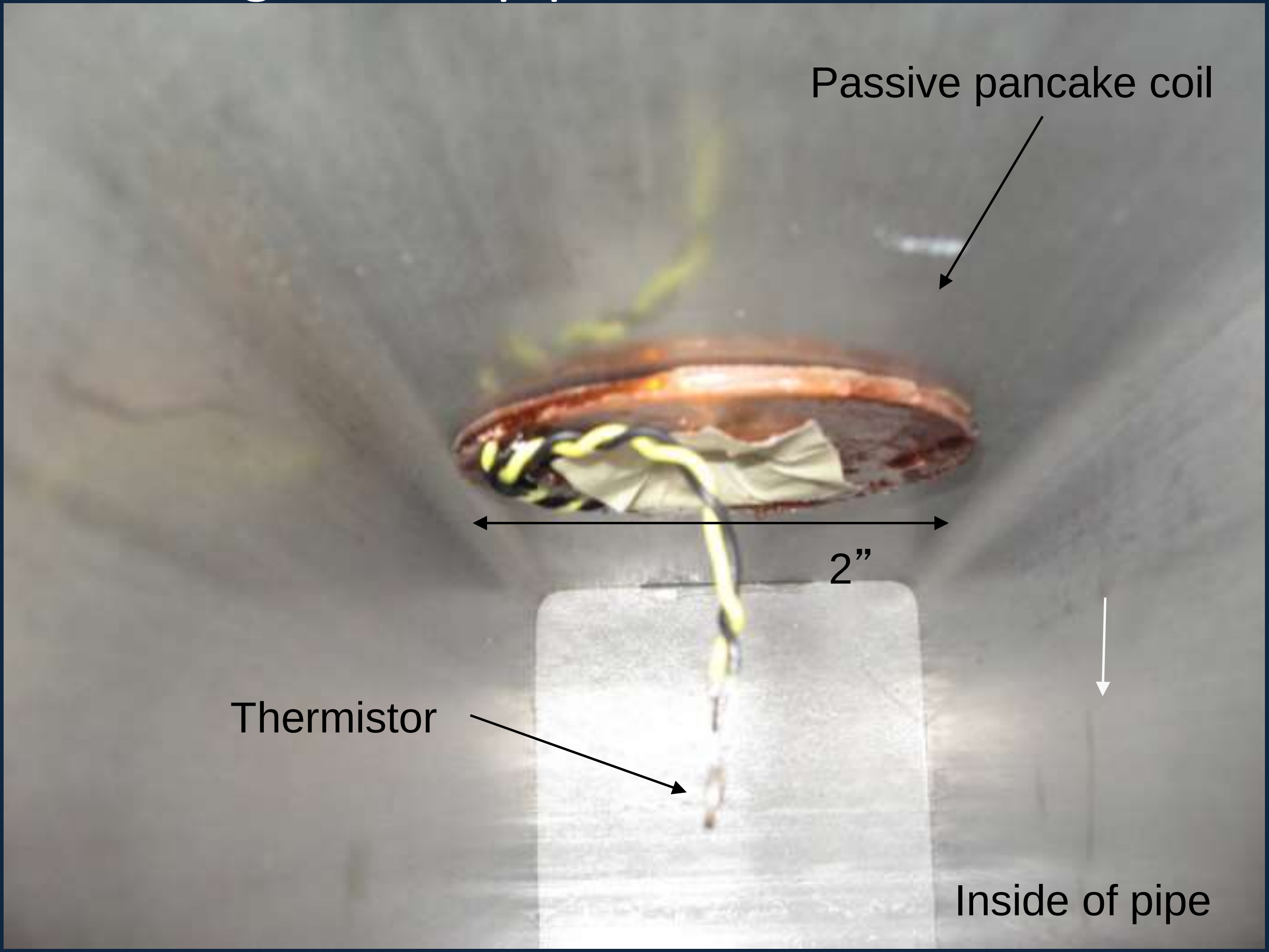
Magnetic Passive Sensor

Early tests through metal pipe walls



Magnetic Passive Sensor

Early tests through metal pipe walls



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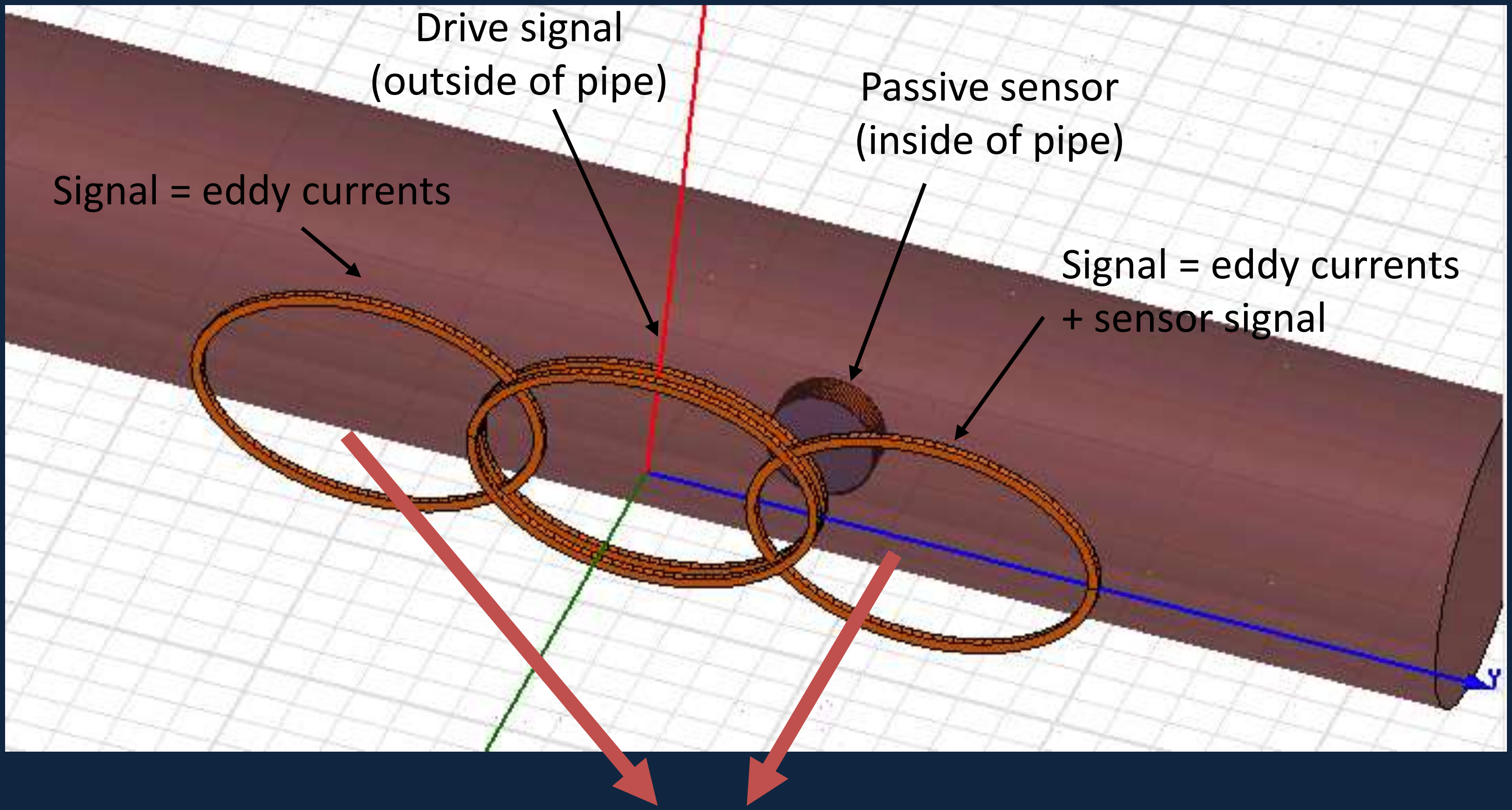
Eddy Current Nulling (Simplified Concept)

- The key to magnetic passive sensing through metal barriers



Subtract these signals and only the sensor signal remains !!!

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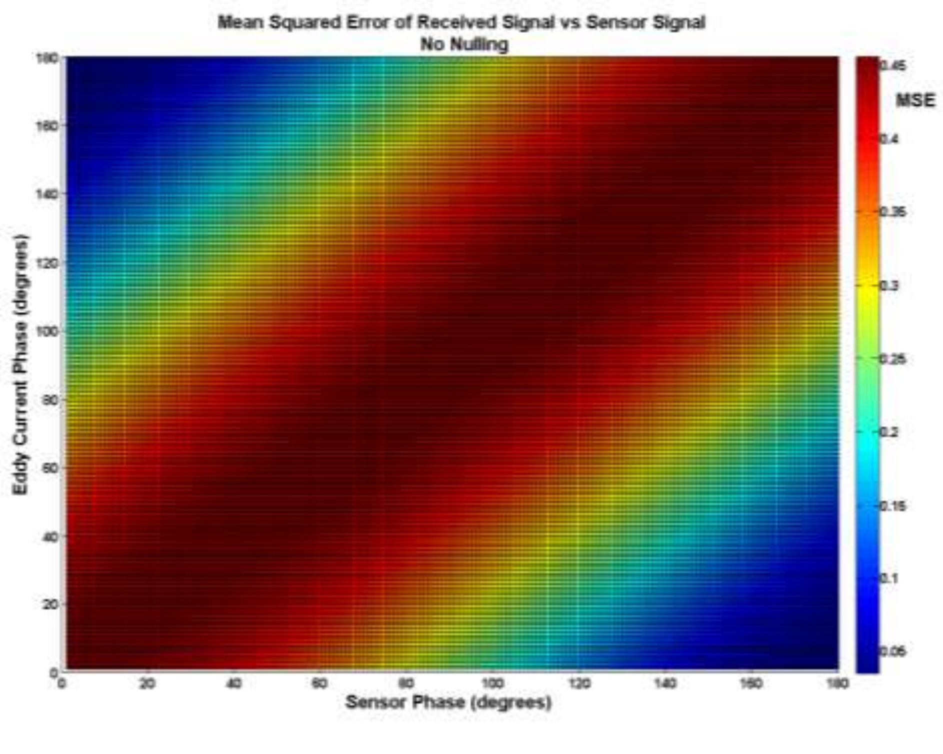
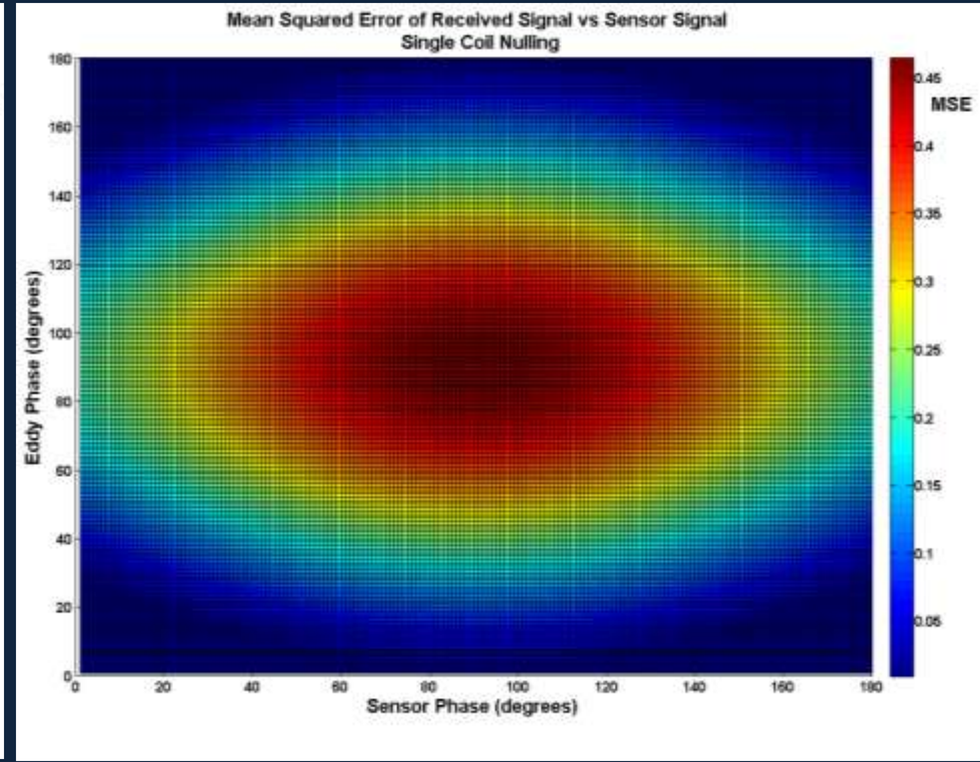
Measurement Error with and without Eddy Nulling





- With eddy current nulling, there is little of no phase error for highly conductive media (180 degree eddy phase)
- Allows for passive magnetic sensing through all common metals
- These results are for low permeability materials (aluminum, most stainless steels, titanium, etc). High permeability materials present unique challenges (though not insurmountable)

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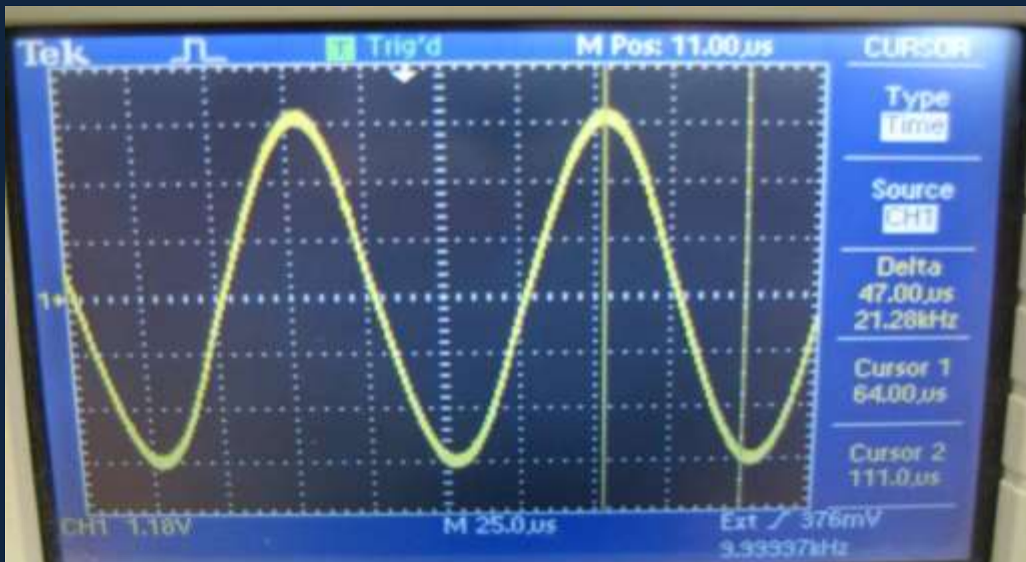
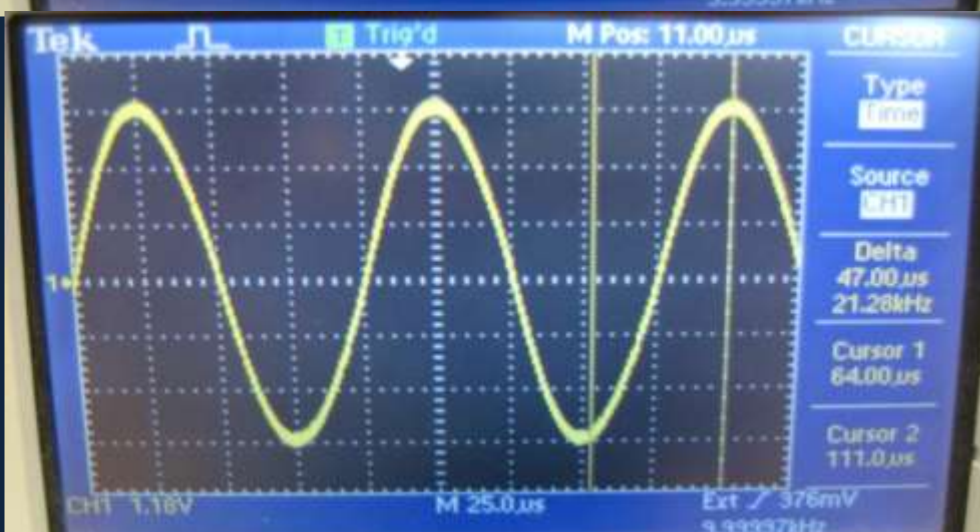
Reflected signals measured through pipe wall with nulling - barrier effect removed, clear sensor phase response!



Passive pancake coil attached to 1 Ohm resistor



Passive pancake coil attached to 1000 Ohm resistor. Nearly 180 degree phase shift! Phase varies smoothly between 1 and 1000 Ohms.

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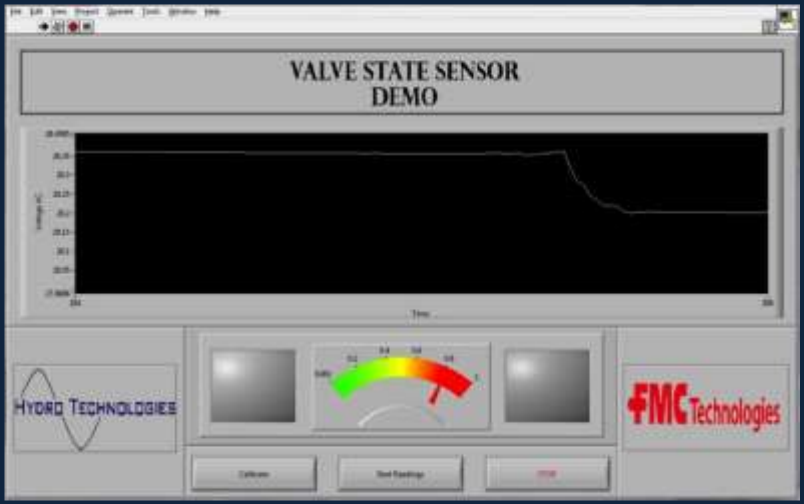
Non-penetrating Valve Sensor

- In this application, the internal passive “puck” is not installed
- Instead we sense the presence of a valve gate as the passive target

Sensor installation



Demo software

Sensor registers 100% opened.

Sensor registers 50% opened.

Magnetic Passive Sensor

Ongoing development

- Refine algorithms to include measurement of resonant frequency, bandwidth FWHM, and peak amplitude instead of just phase. These are orthogonal measurements from a SNR perspective .
- Demonstrate other sensing modalities such as strain, pressure, flow rate, fluid level, fluid/ transition, etc.
- Demonstrate multiple passive sensors on the same reader by using different resonant frequencies
- Develop capability through thick walled high permeability materials, still a challenge
- Find other applications!!!

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Magnetically induced skin effects for nondestructive integrity measurements

Limitations of traditional eddy current based NDE/NDT

- Only conductive materials can be inspected
- Surface must be accessible to the probe
- Skill and training required is more extensive than other techniques
- Surface finish and and roughness may interfere
- Reference standards needed for setup
- Depth of penetration is limited
- Flaws that lie parallel to the probe coil winding and probe scan direction are undetectable
- Eddy Currents normally cannot penetrate ferromagnetic materials. Consequently, testing on ferromagnetic materials is limited to inspection of surface defects only.

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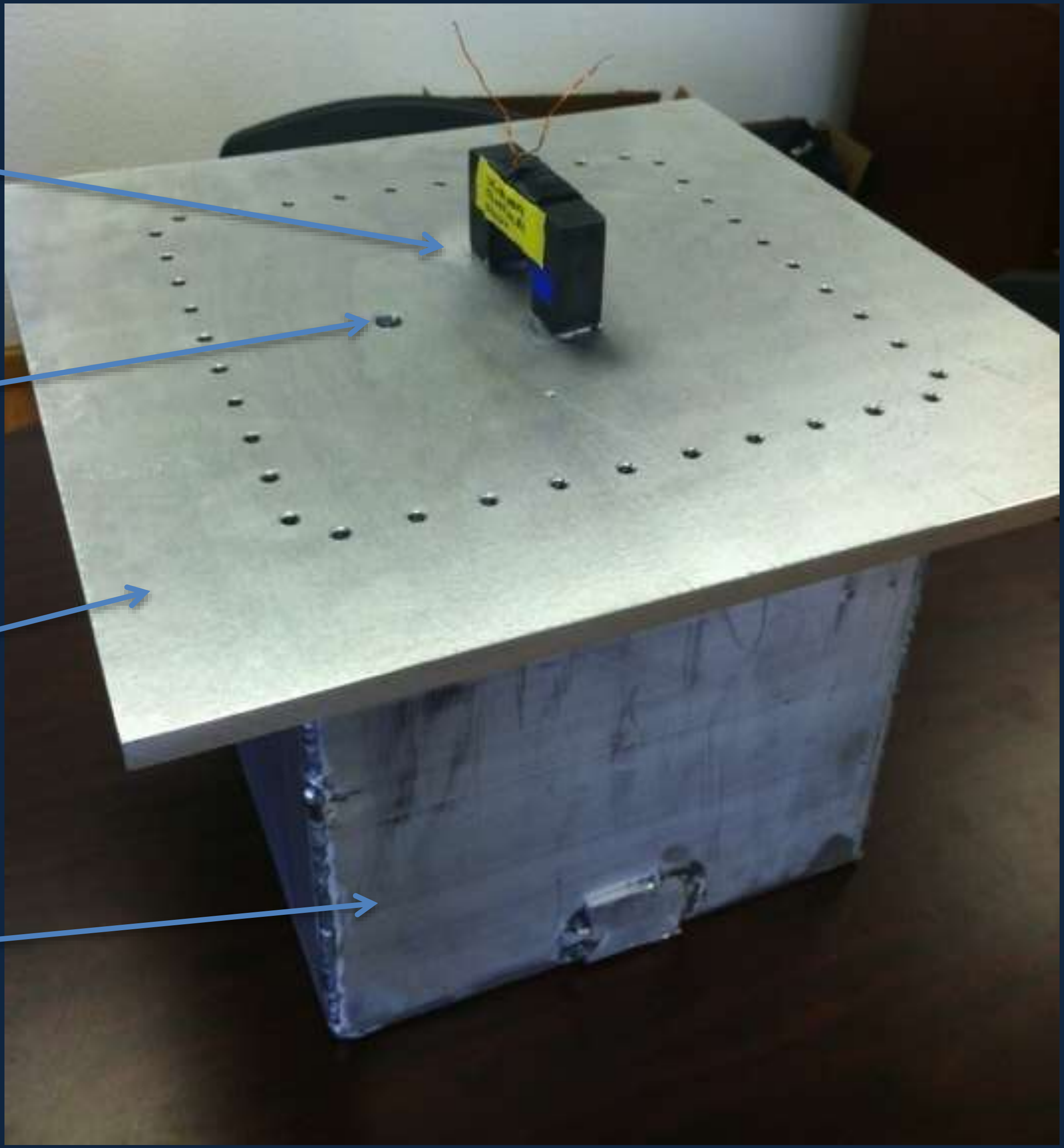
Magnetically induced skin effects NDE proof-of-concept testing

Receiver (magnetic "transmitter" enclosed in box)

Hole, varied in test from 0.06" to 0.5"

Lid (1/2" aluminum), not bolted down in this image

Sealed (welded) ¼" thick 12"x12" aluminum box



Magnetically induced skin effects NDE proof-of-concept testing – results