Pulsed Eddy Current Measurements of Bulk Steel Pipe Wall Thickness

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Outline

• Experimental Work
  – Motivation
  – Experimental Setup
  – Probe Types
  – Data analysis

• Theoretical Work
  – Theory
  – Wall Thickness Model
  – Validation
  – Future Work
Motivation

• Medium term nuclear waste is stored in an array of steel pipes set in concrete, known as tile holes

• The steel is mainly there to contain the radiation

• Moisture in the earliest tile holes may have caused some corrosion in steel pipe, characterized as bulk wall loss
Test Piece

- 8.25” diameter 7.5 mm thick carbon steel
- 20% thinner and 20% smaller diameter than tile hole liner

1.3 mm deep (17%) full circumference flaw (thin wall)
1 mm deep (13%) localized flaw
Unflawed (thick wall)
Experimental Apparatus

1st stage Amp
Pickup Coil
Handle

Drive Coil
Pickup Coil

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Signal Conditioning

- 10v drive pulse is filtered with a 3kHz low pass filter to eliminate ringing
- Pickup signal goes through two stages of amplification
- Each amplification stage is stitched together
- Further digital filtering

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Measurements

Fitting coefficient $b$ from $v = Ae^{bt}$

Liftoff (mm)

Blue is 7.5mm thick
Red is 6.2 mm thick
Probe Property Summary

Both coils parallel to pipe

Pros
• Liftoff insensitive

Cons
• Lower sensitivity to wall loss
• Missed localized flaw

Drive coil parallel and pickup coil perpendicular to pipe

Pros
• Increased sensitivity to wall loss

Cons
• Increased sensitivity to liftoff
• Missed localized flaw

Both coils perpendicular to pipe

Pros
• Detected localized flaw
• Increased sensitivity to wall loss

Cons
• Lower maximum liftoff threshold
Model Motivation

• Model allows sensitivity analysis of essential parameters
• Facilitates probe optimization
• Can be modified to work for similar projects (ferromagnetic pipe thickness)
• Possibility of using an inverse problem algorithm
General Theory

• For the time scales used in Pulsed Eddy Current (PEC) the diffusion equation is a valid simplification of Maxwell’s equations

\[ \nabla^2 J = \mu \sigma \frac{\partial J}{\partial t} + \mu \epsilon \frac{\partial^2 J}{\partial t^2}, \] where A is magnetic vector potential

• Solution is a summation of exponentials multiplied with Bessel functions

• The first exponential eigenvalue (longest decay time) is \( \tau \sim \mu \sigma L^2 \) used for experimental analysis
Flat Plate Model

• Uses Desjardins et al. model\textsuperscript{[1]}

• Solves the diffusion equation

\[
\frac{d^2 J(r,z,t)}{dr^2} + \frac{d J(r,z,t)}{rdr} - \frac{J(r,z,t)}{r^2} + \frac{d^2 J(r,z,t)}{dz^2} = \mu \sigma \frac{d J}{dt}
\]

• Transformed to spatial and temporal frequency space

\[
\frac{d^2 J(\gamma,z,\omega)}{dz^2} = (\gamma^2 + i\mu \sigma \omega) J(\gamma, z, \omega)
\]

Flat Plate Model

• Solved for impulse response then convoluted with input waveform
• Square wave input allows analytic inverse Fourier Transform
• Truncating infinite integral over spatial frequencies ($\gamma$) introduces high frequency noise at late times
Problem Geometry

Model

Drive Coil

Pickup Coil

Steel

Experiment
Validation
Wall Thickness Sweep

![Graph showing signal vs. time for different wall thicknesses. The x-axis represents time in seconds, ranging from 0.01 to 0.08, and the y-axis represents signal in volts, ranging from $10^{-3}$ to $10^1$. Different lines represent different wall thicknesses: 0.635cm, 0.9525cm, 1.27cm, 1.5875cm, and 1.905cm. Each line shows the signal decay over time for the respective wall thickness.]
Isolated Liftoff Effects

- 0.635 cm wall thickness
- 0.9525 cm wall thickness
... 3.19 cm liftoff
-.- 2.19 cm liftoff
--- 1.19 cm liftoff
— 0.19 cm liftoff
Wall Thickness Sweep

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Principal Components Analysis

• Each eigenvector represents as much variance as possible under the constraint of eigenvector orthogonality
• $Y = \sum S_i V_i$ used to reconstruct original signal
• PCA allows small shape variations to be reflected in only a few scores
• When used directly on the model data, only peak shape ($\sim 1^{st}$ 10 ms) affects the PCA
• Since all wall thickness effects appear after 15 ms PCA allows anything that affects the early signal to be compensated for
Separating Magnetic Permeability from Wall Thickness

Each dot is 5 wall thicknesses that are exactly coincident.
Changes in Wall Thickness sensitivity with Permeability changes

Wall Thickness (mm)

Slope of late time decay

Relative permeability of 300
Relative permeability of 200
Relative permeability of 100
Summary

• Pickup coil axes perpendicular to the pipe axis increase sensitivity but increase liftoff effects.
• Drive coil axes parallel to the pipe axis increase eddy current density at the expense of flaw localisation.
• A flat plate analytical model has been produced.
• It is possible to separate permeability and liftoff from wall thickness effects.
Future Work

• Add more variables to PCA analysis such as conductivity, to see how many parameters can be extracted
• Evaluate how probe parameters affect the sensitivity response
• Measure the permeability of the validation samples experimentally
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Questions?
Measurements

Pickup Coil Response (V)

- ThickClose
- ThickCentered
- ThickFar
- ThinClose
- ThinCentered
- ThinFar

Time (s)

- Far (38 mm liftoff)
- Centered (19 mm liftoff)
- Close (0 mm liftoff)

Tile Hole Liner

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