Three-Dimensional Finite Element Modeling of Magnetic Flux Leakage Technique for Detection of Defects in Carbon Steel Plates


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Outline of Presentation

- Introduction of Nondestructive Testing (NDT)
- Magnetic Flux Leakage (MFL) Technique
- Three-dimensional finite element modeling of MFL system
- Effects of defect location and depth of sub-surface defects
- Results and Discussion
- Summary
Non Destructive Testing (NDT)?

**Definition:** Testing or inspection of materials / components / structures without destroying or impairing their intended use is Non Destructive Testing (NDT)

**Two types of material testing:**

- Destructive (stress-strain, creep, fatigue etc.)

- Non-destructive (ultrasonic, eddy current, X-radiography, magnetic particle etc.)

Component can be used as-it-is, after NDT
Every NDT technique is based on physical principles and nearly all forms of energy is utilized in NDT.
Various NDT Techniques

- Visual
- Ultrasonic
- Magnetic Particle
- Magnetic Flux Leakage
- Eddy Current
- Radiography
- Acoustic Emission
- Infrared Thermography

More than 50 NDT techniques are available today for detection of defects in materials, components and structures.

Selection of technique is very important depending on the material, capability, access and cost.
Magnetic Flux Leakage Technique - Principle

Widely preferred nondestructive detection of defects in ferromagnetic materials.

**Principle:**

When a ferromagnetic material is magnetized, the magnetic flux lines are confined within the material.

When the material has any defect, the magnetic flux lines bend around the defect and, a part of flux lines leak out of the surface. This leakage flux is detected by magnetic sensors and used to estimate the shape and size of the defect.
MFL Technique - Features

Field Detection Sensors:
- Inductive coils (pick-up coils)
- Hall probes (semi conductor)
- Giant Magneto-resistive (GMR) sensors
- Giant Magneto-impedance (GMI) sensors

MFL technique detects and sizes surface and sub-surface defects.

Applications:
- Inspection of oil and gas pipelines using Pipe Inspection Gauges (PIGs)
- Corrosion detection in storage tanks, damages in wire ropes and rail tracks
- Automated testing of axi-symmetric components in production-line.
MFL Inspection of Pipes

Inspection using Pipe Inspection Gauge (PIG)- Automated expert system for data analysis, interpretation and decision making
**Important Aspects:**

- proper magnetization of material
- detection of leakage flux using a suitable sensor
- processing raw data to enhance SNR and
- interpretation of test results
Field Sensor vs. Coil Sensor

- Coils measure the rate of change of a magnetic field
- Hall & GMRs measure the actual magnetic field
- Speed of testing influences the measured output
MFL Modeling

Purpose of modeling:

- Visualization of field/defect interactions
- Optimization of sensor/system design
- Parametric studies
- Generation of defect signatures for training database
- Better understanding and effective utilization of MFL technique
Methods of MFL Modeling

- **Analytical method:**
  - Defects are assumed as magnetic dipoles
  - MFL signals are calculated from the magnetic field of the magnetic dipoles
  - Offer closed form solution
  - Good for simple geometries

- **Numerical method:**
  - Finite difference
  - Finite element (FE)
  - Boundary element
  - Can handle complicated geometries
  - Usually require intensive computer resources

**FE method** is capable of modeling of nonlinear problems and irregular geometries which are difficult to be modeled analytically.
Finite Element (FE) Method

• **Procedure:**
  – Create geometry
  – Generate mesh (discretize solution domain)
  – Select basis function
  – Formulate matrix equation
  – Impose boundary conditions
  – Solve matrix equation
  – Post-processing
3D MFL FE Modeling

**Dimension:**

**Permanent magnet:**
Length 90 mm, cross-sectional area 55 x 50 mm², leg spacing 70 mm

**Carbon steel plate:**
Length 240 mm, breadth 150 mm, thickness 12 mm) with 15 mm long slot
Mesh Structure of 3D MFL Modeling

**COMSOL 3.4 multiphysics software**

Magnet: $M = 100000 \text{ A/m}$

Carbon steel plate: $\mu_r = 100$

Mesh: 214984 tetrahedral elements

Solution time: 2 hours in dual core 64 bit processor workstation

The following equation is solved using FE method:

$$\nabla \times \left( \mu_0^{-1} \mu_r^{-1} \nabla \times A \right) = J$$
Arrow plot for a 4 mm deep sub-surface slot located at 2 mm below plate surface

Sub-surface defects are difficult to simulate experimentally
Effect of Defect Location

Intensity of leakage fields decreases with the increase in defect location below the surface while the lateral spread of fields increases.
Effect of Defect Depth

Intensity as well as lateral spread of leakage fields for the same slot location increase with the increase in slot depth
Effect of Lift-off

MFL signals for a 4 mm deep sub-surface slot for different lift-offs

MFL signal peak amplitudes for a 4 mm deep slot as a function of lift-off

MFL signal amplitude decreases with the increase in lift-off. The decrease of signal amplitude is more prominent for the surface slot as compared to sub-surface slots.
Summary

• Three-dimensional FE modeling has been performed to study the detectability of sub-surface defects in MFL technique.

• The intensity of leakage fields decreases with the increase in defect location while the lateral spread of fields increases.

• The intensity as well as lateral spread of leakage fields increase with the increase in defect depth.

• MFL signal amplitude decreases with the increase in lift-off and it is more prominent for the surface defects as compared to sub-surface defects.

• Features such as peak amplitudes, full width at half maximum (FWHM), slope, etc. extracted from the model predicted signals may be useful for characterisation of defects.
THANK YOU