Magnetic Sensors: An Overview

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Outline

• Part A: Engineering Theory of Magnetism
  • A short introduction to magnetics
  • The magnetization process
  • Magnetic effects for engineering applications

• Part B: Sensors Based on Magnetic Materials
  • Sensing principles based on magnetic effects
  • Applications of sensors based on magnetic materials
  • Developing a sensor
Part A:

Engineering Theory of Magnetism
A short introduction to magnetics

- Paramagnetism
  - \[ \Delta H \]
  - \[ M \]
  - \[ \chi > 0 \]

- Diamagnetism
  - \[ H = 0 \text{ A/m} \]
  - \[ M \]
  - \[ H >> 0 \text{ A/m} \]
  - \[ M_H = M - \Delta M \]
  - \[ \chi < 0 \]
Ferromagnetism

• **Short range** or **exchange** interaction results in spin-spin alignment of neighboring spins in some TM materials.

• The spin-spin alignment results in the formation of the so called **ferromagnetic domains**.
Magnetic domains cannot be extended to infinity. Domain-domain interaction results in magnetic domains separated by magnetic domain walls.

Orientation of dipoles in domain walls changes gradually.

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The Basic Mechanisms of Magnetization Process

- Domain wall motion:
  - Reversible
  - Irreversible

- Domain rotation:
  - Barkhausen jumps: irreversible effect
  - Small angle rotation: reversible effect
Reversible Magnetic Domain Motion

\[ M = 0 \]
\[ H = 0 \]
\[ M > 0 \]
\[ M_{\text{sat}} \]

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Irreversible Magnetic Domain Motion

- M=0, H=0
- M>0
- Msat

Defect

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Irreversible domain rotation: Barkhausen Jumps
Reversible Rotation of Domains

Reversible magnetic domain rotation after the irreversible magnetisation process
The Magnetization Process

• Virgin curve
  – Intrinsic magnetization changes under external field
  – Main curve: three parts
    • Domain wall motion
    • Barkhausen jumps
    • Rotation of magnetization
  – Minor loops

• Saturation Ms
  – Completely oriented dipoles
The Magnetization Process

• B-H loop
  – Saturation & back
  – Irreversible process – remanence
  – Coercive force (field) & coercive slope
  – Properties & dynamic properties: f, T, σ
  – Single phase systems have symmetric B-H loops
  – Minor loops: Inside the B-H loop
  – Size of B-H loops: hard - soft - semi
  – Non-single-phase materials may result in asymmetric B-H loop
  – Large Barkhausen Effect: an interesting property
B-H loop

Main parameters: Temperature - Stress - Frequency
Magnetic effects

Magnetostriiction:
- Magnetic domain rotation (reversible and irreversible)
- $\pm \lambda(H)$: zero, classic, unhysteretic, giant, colossal
- Dynamic properties, hysteresis
Magnetic effects

Magneostrictive Delay Lines:
an application of the magnetostriction effect

Generated microstrains
Propagating elastic pulse
Detectable change of flux density
Magnetic effects

Z-H loops

Magnetoresistance
(MR, AMR, GMR, CMR)

Magnetoimpedance
(MI, SI, GMI)

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Magnetic effects

Inductive effects

Wiedeman effect

Domain wall nucleation & propagation

Classic set-ups (LVDT, fluxgates)

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Magnetic effects

Magneto-optic effects
Bitter, Kerr, Faraday effects

Use of M-O effects
Case study:
displacement sensor

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Magnetic effects

Spintronics

Spin valves

Spin tunneling

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Magnetic materials

(Fe Co Ni)-(ETM)-(RE)-(NMM)

Bulk
Thin films
RQ (ribbons & wires)
Particulate media
Composites

Stress relief
Inducing anisotropy
Tailoring $B-\lambda-Z(H)$
Nanocrystallization
Micromechanics

Applications of magnetic materials

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Applications of magnetic materials

**Power**
- transformers
- motors
- actuators

**Recording**
- recording media
- recording heads
- technology

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**Sensors**
Magnetic Sensors: An Overview

Part B: Sensors
Sensors

- **Position**
  - Position (tapes, digitizers, 3-d)
  - Dilatometry: LVDT, MDL
  - Speed & vibration: acceleration, …

- **Stress**
  - Load cells & torque meters
  - Pressure gauges and stress sensors
  - Force/pressure digitizers

- **Field**
  - NDT applications
  - Recording
  - Compass

Data from EMSA 2002, Athens, Greece

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Position Sensors

- Position sensor based on the magnetostrictive delay line technique
  - Sensitivity: 5 µm; Uncertainty: ± 10 µm
  - Drawbacks: ambient field sensitive
  - Characteristics are optimised by using amorphous alloys

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Position Sensors
(MDL technique cont.)

- Dilatometer and stress sensor
- Moving magnet sensor
- ECT-MDL digitizer
Position Sensors

- Position sensor based on the linear variable differential transformer (LVDT) set-up. (1) Soft magnetic material, (2) Excitation coil, (3) In series opposition search coils.
  - Sensitivity: 100 $\mu$m
  - Uncertainty: $\pm$ 500 $\mu$m
  - Repeatable response from -70 C to 150 C
  - Drawbacks: ambient field sensitive
  - Improved characteristics by material tailoring
Position Sensors

Position sensor based on an inductive principle

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Position Sensors

- Position sensor based on permanent magnet tape. (1) Permanent magnetic thin films, (2) Searching magnetic head.
  - Sensitivity: 100 \( \mu \text{m} \)
  - Uncertainty: \( \pm 500 \ \mu \text{m} \)
  - Repeatable response from -70 C to 150 C
  - Drawbacks: ambient field sensitive
  - Characteristics can be improved by material tailoring
Position Sensors

- Angular positioning sensor. (1) Radial permanent magnets in tooth arrangement, (2) Searching field sensor.
  - Repeatable response from -70 C to 150 C
  - Great reproducibility allowed use in automobile industry (ABS)
  - Drawbacks: ambient field sensitive
  - Advantages: no dust sensitive
Stress sensors

- Stress sensors based on inductive effects. (1) Soft magnetic element, (2) Inductive excitation coil.
  - More sensitive than strain gauges, if amorphous alloys are used
  - Good noise level after heat annealing
  - Good reproducibility after field annealing
  - Ambient field sensitive
Stress sensors

Pressure, stress & torque sensors based on MDLs

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Stress Sensors

Thickness sensor based on a coilless MDL set-up

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Stress Sensors

- Magneto-inductive (MI) stress & torque sensors. (1) Sinusoidal excitation circuit, (2) MI element.
  - Very sensitive, especially in high frequencies
Stress Sensors: Torque Meters
Air-flux Sensors Based on the Inverse Wiedeman Effect

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Ambient field dependence

• A serious drawback in mechanical sensors based on magnetics

• There are three solutions:
  – Two axes shielding by nanocrystalline thin ribbons
  – Active compensation by induced field in some cases (MDL and MI set-ups)
  – Smart field sensing
Field Sensors

Fluxgates

![Diagram of Fluxgate Sensor]

- **noise PSD (pTrms/√Hz)**
- **frequency (Hz)**
- **time (s)**

- **sensor noise (pT)**
- **1.03760 Hz Y = 2.919 (pTrms/√Hz)**

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Field Sensors

Magnetoresistive heads

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Field Sensors

MDLs

![Diagram showing Field Sensors and MDLs with voltage output and applied field axes.](image-url)
Field Sensors

GMR & Spintronics

![Diagram of field sensors showing layers and current directions.](image-url)
Smart Sensors

Multifunctional system: combination of measurements

- Magnetostrictive delay line
- Magnetoimpedance set-up
- Domain wall nucleation and propagation set-up

Using three different types of response to determine three different inputs
Sensor Applications

- **Industrial**
  - Sensors in production (piston position, stress monitoring, else)
  - Sensing systems for industry
  - NDT&E using field detection techniques

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A Comparison Between Hall and GMR Sensors for NDT&E Inspection

GMR Sensor Response

Shielded GMR Sensor Response

Hall Sensor Response

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A Micro-Fluxgate Arrangement for NDT&E Inspections

The 4 m-Fluxgate Sensors

The Sensor

The Under Inspection Magnetic Anomaly

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Sensor Applications

Biomedical
Field monitoring, diabetes & blood monitoring, stress & strain monitoring, cardiac measurements, artificial sphincters
Electromagnetic Measurements in Bio-Engineering

B (Tesla)

Earth’s Field
Urban Noise
Car @ 50m
Screwdriver @ 5m
Transistor, IC chip @ 2m
Transistor die @ 1m

Biomagnetic Fields

Lung particles
Human Heart
Skeletal muscles
Fetal heart
Human eye
Human Brain
Human Brain (evoked response)
SQUID System
Noise level

GMI Measurements

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Sensor Applications

• Military applications
  – Gyroscopes (field)
  – Magnetic signatures (field)

• Automotive
  – Positioning & tracking (field)
  – Torque sensors (stress)
  – On-off- ABS rotation (positioning)

• Other applications
  – Environmental: E/M low frequency
  – Laboratory: characterization techniques
  – Domestic: current path searcher
Sensor Applications

Electric Current Meter

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Micromagnetic arrangements

AMR Bridge

Micro-coils

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Micromagnetic arrangements
Developing a sensor

• Facing-up the problem
  – measurement – range – sensitivity
  – Field of use (application)
  – Parameters affecting

• Choice of sensing principle (effect)
  – Taking into account: range – sensitivity – parameters
  – Preliminary experiments: indicative results
  – Scheduling the experiment & and the sensor
Sensor Development

- Sensing element: thin film, RQ, powder, else
- Sensing device: the first prototype
- Sensor electronics & calibration set-up
- Measurements
- Parametric effects: field, stress, temperature
- Design of the sensor housing
- Development of the sensor prototype
- Calibration & Corrective actions
- Final prototype & technical envelop
Designing the future

Is miniaturization a future challenge?
- Nanoscale resolution in writing & reading
- Sensors with secondary standard uncertainty (nanotechnology?)
- Smart multipurpose sensors
- Parametric control (field-temperature-stress)
- Silicon-chip magnetic sensors

Is there any key-parameter in designing magnetic sensors?
- Hysteresis: the key point
- Stability of B-λ-Z(H)
- Parametric effects: field-stress-temperature

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