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A Simple Calculation Method for Center Magnetic Flux Density of a Magnetic Core Electromagnet with a Wide Air Gap

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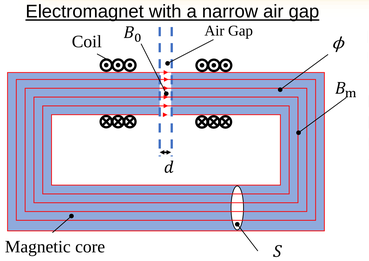
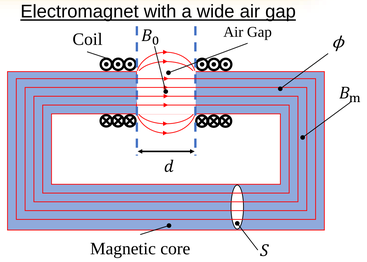
Introduction

Electromagnet with a narrow air gap



Electromagnet with a wide air gap



$$\phi = \frac{LI}{N} = \frac{NI}{\mathcal{R}_{\text{core}} + \mathcal{R}_{\text{air}}} \quad (1)$$

$$B_m = B_0 = \frac{\phi}{S} = \frac{LI}{NS} \quad (2)$$

$$\mathcal{R}_{\text{core}} = \frac{l_{\text{mag}}}{\mu_0 \mu_r S} \quad (3)$$

$$\mathcal{R}_{\text{air}} = \frac{d}{\mu_0 S} \quad (4)$$

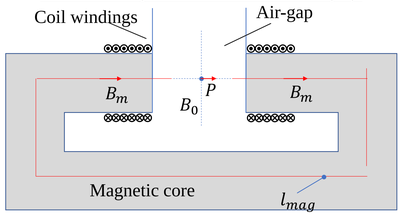
- $\mathcal{R}_{\text{air}}$ can not be estimated by the air gap space volume because of the magnetic flux spread.
- $B_0 \neq B_m$ because of the magnetic flux spread.

Research objective of this work:

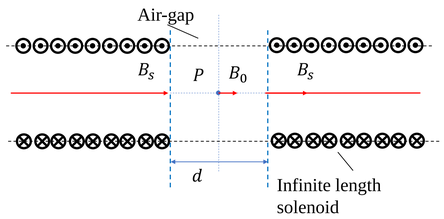
Carry out a simple analyze Model for Electromagnet with a wide air gap include:
- Formulation for reluctance of the wide air gap.
- Calculation for the self-Inductance of the electromagnet with the wide air gap.
- Estimation method for center magnetic flux density of air gap.

A simple equivalent model of the electromagnet with a wide air gap

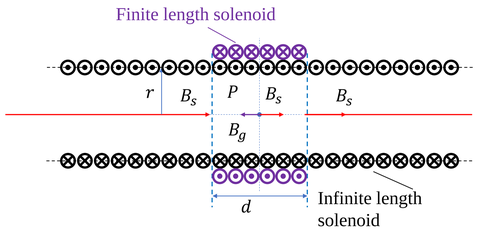
Electromagnet with a wide air gap



A infinite length solenoid with a wide air gap

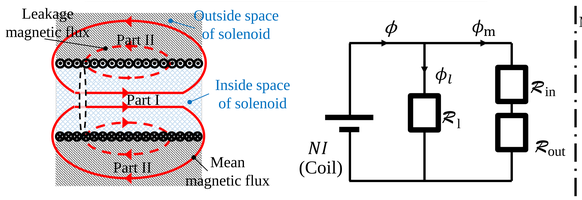


A infinite length solenoid with a reverse direction finite length solenoid

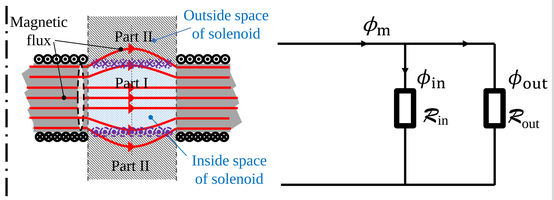


Formulation for reluctance of the wide air gap and the self-inductance of electromagnet

Magnetic flux distribution of the finite solenoid coil



Magnetic flux distribution in the wide air gap



Self-inductance of the finite solenoid can be calculated using the Nagaoka coefficient K_n

Assuming the leakage flux can be neglected $\Rightarrow L = \frac{N^2}{\mathcal{R}_{in}+\mathcal{R}_{out}}$

$$\frac{1}{\mathcal{R}_{air}} = \frac{1}{\mathcal{R}_{in}} + \frac{1}{\mathcal{R}_{out}}$$

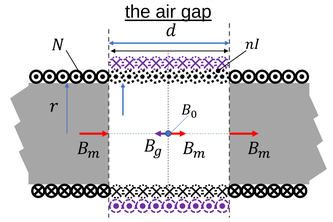
$$L = K_n \frac{\mu_0 S}{d} N^2 = K_n \frac{1}{\mathcal{R}_{in}} N^2 = \frac{N^2}{\mathcal{R}_{in} + \mathcal{R}_{out}} \Rightarrow \mathcal{R}_{out} = \frac{1 - K_n}{K_n} \mathcal{R}_{in} \quad (5)$$

Reluctance of the wide air gap $\Rightarrow \mathcal{R}_{air} = (1 - K_n)\mathcal{R}_{in} = (1 - K_n)\frac{d}{\mu_0 S}$ (6)

$$L = \frac{N^2}{\mathcal{R}_{\text{core}} + \mathcal{R}_{\text{air}}} = \frac{N^2}{\mathcal{R}_{\text{core}} + (1 - K_n)\frac{d}{\mu_0 S}} \quad (7)$$

Center magnetic flux density estimation

Calculation model for center magnetic flux density of the air gap



$$B_0 = B_m - B_g \quad (4)$$

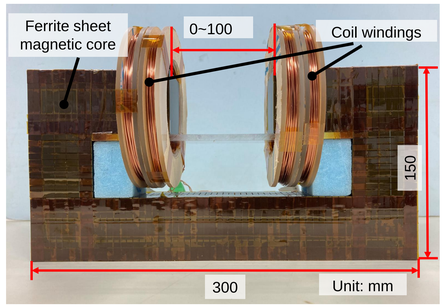
$$B_m = \frac{LI}{NS} = \mu_0 nI \quad (5)$$

$$B_g = \frac{\mu_0 nId}{\sqrt{4r^2 + d^2}} \quad (6)$$

nI is the magnetomotive per unit length of the equivalent infinite length solenoid.

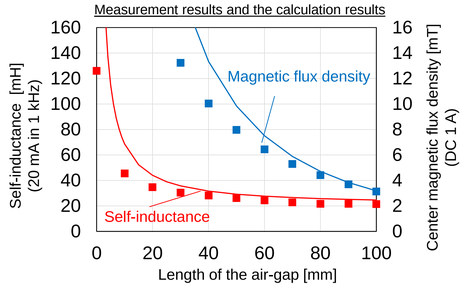
Verification experiment using two test electromagnet

Test electromagnet with a constant total magnetic path length

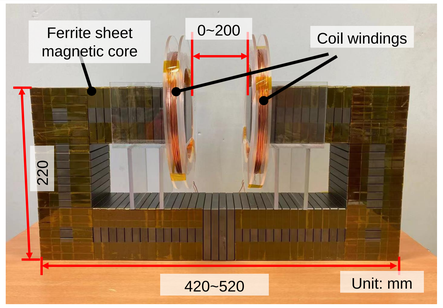


Cross-section are of magnetic core	50 mm × 50 mm
Total number of turns	4 sets × 100 turns
Relative permeability of magnetic core	2300
length of magnetic core	0.6 m~0.7 m
Length of air gap	0~0.1 m

Measurement results and the calculation results

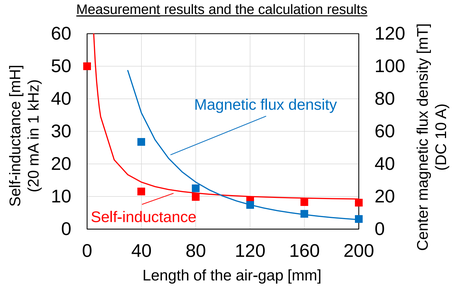


Test electromagnet with a constant magnetic core length



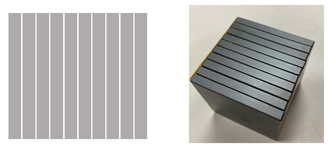
Cross-section are of magnetic core	79 mm × 70 mm
Total number of turns	2 sets × 100 turns
Relative permeability of magnetic core	2300
length of magnetic core	1 m
Length of air gap	0~0.2 m

Measurement results and the calculation results

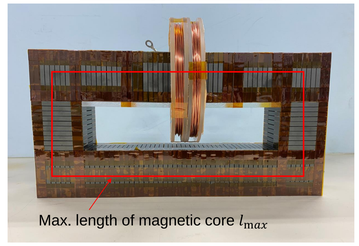


Correction of the reluctance of Magnetic core

Slight gaps in the ferrite sheet magnetic core



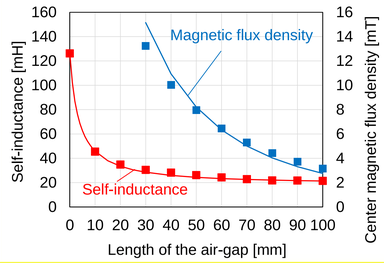
Electromagnet without air gap



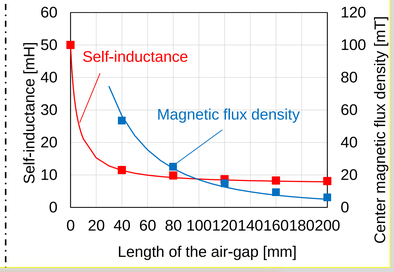
Before the correction : $\mathcal{R}_{\text{core}} = \frac{l_{\text{mag}}}{\mu_0 \mu_r S}$

After the correction : $L_0 = \frac{N^2}{\mathcal{R}_{\max}}$ $\quad \mathcal{R}_{\text{core}} = l_{\text{mag}} \cdot \frac{\mathcal{R}_{\max}}{l_{\max}}$

Measurement results and the calculation results after the correction



Measurement results and the calculation results after the correction



Conclusion

- Calculation results are agreeing well with the measurement results when the air gap is wide enough.
- Calculation accuracy can be further improved after the correction of the reluctance of the magnetic cores.