Force
In Permanent Magnet and Iron Core

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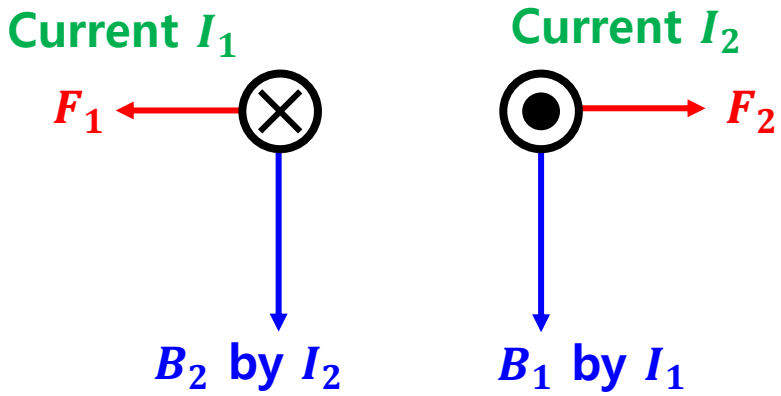
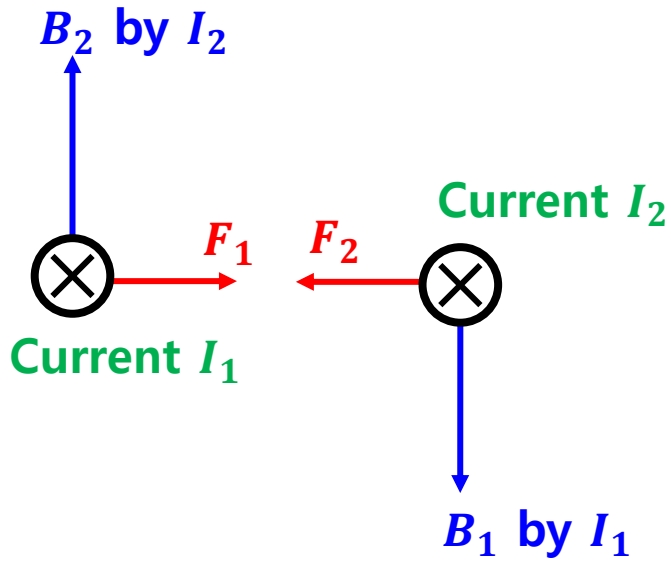
Feb. 04th 2020

Contents

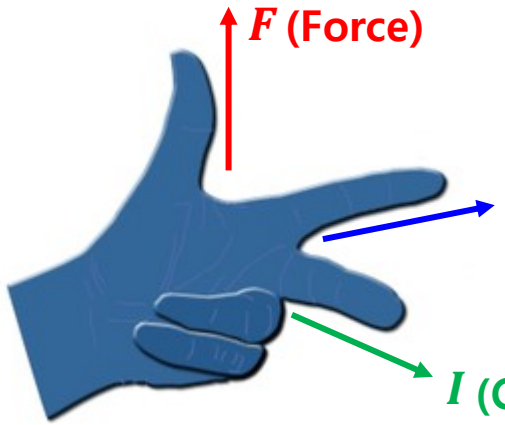
1. Force in Wire



When the direction of currents is different, Repulsive force is generated.



When the direction of currents is same, Attractive force is generated.



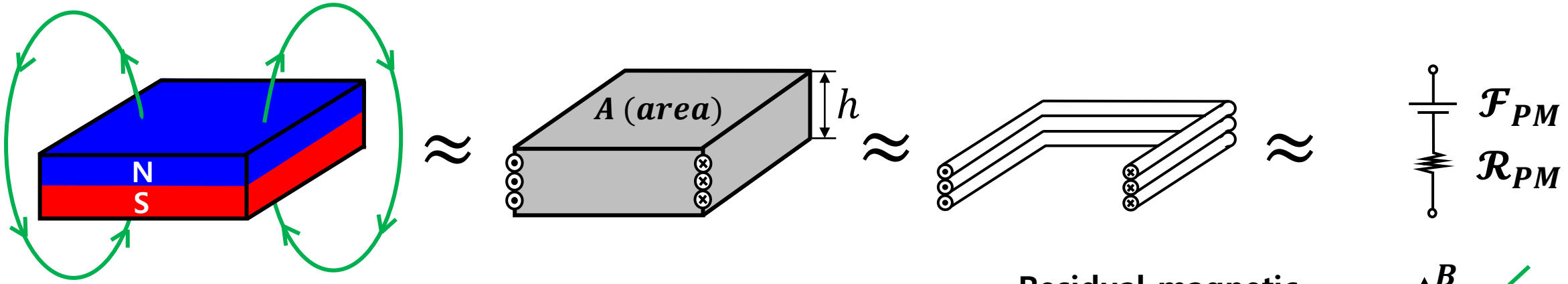
<Flemming's left-hand rule>

https://en.wikipedia.org/wiki/Fleming%27s_left-hand_rule_for_motors

2. Permanent Magnet Modeling

Value Added Mechatronics

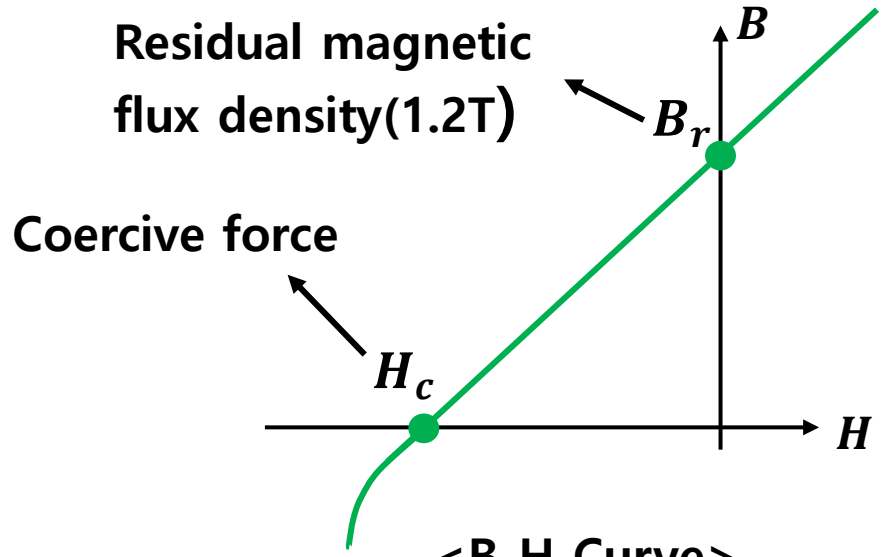
Permanent Magnet ≈ **Current with air core** ≈ **Equivalent Circuit**



Magnetomotive Force of PM $\mathcal{F}_{PM} = \frac{B_r}{\mu_0 \mu_r} h$

Magnetic resistance of PM $\mathcal{R}_{PM} = \frac{h}{\mu_0 \mu_r A}$

Vacuum Permeability	$\mu_0 = 4\pi \times 10^{-7}$ H/m
Relative Permeability of PM	$\mu_r = 1.05$
Relative Permeability of Vacuum	$\mu_r = 1$
Height of magnet	h
Area of magnet	A

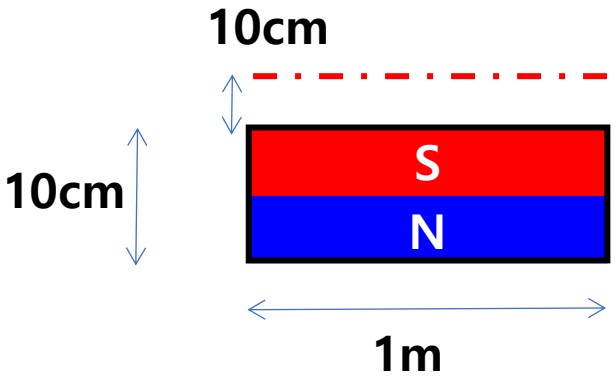


<B-H Curve>

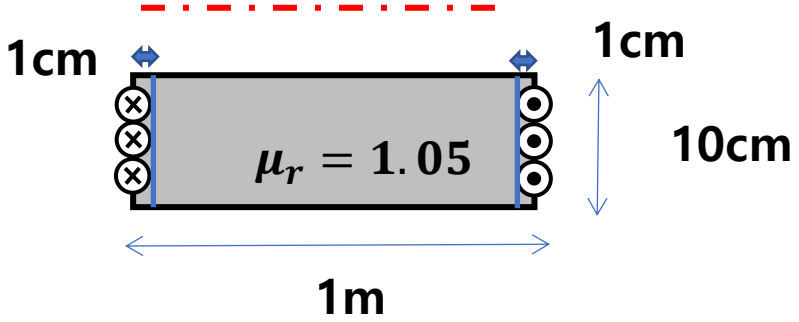
2. Permanent Magnet Modeling

Value Added Mechatronics

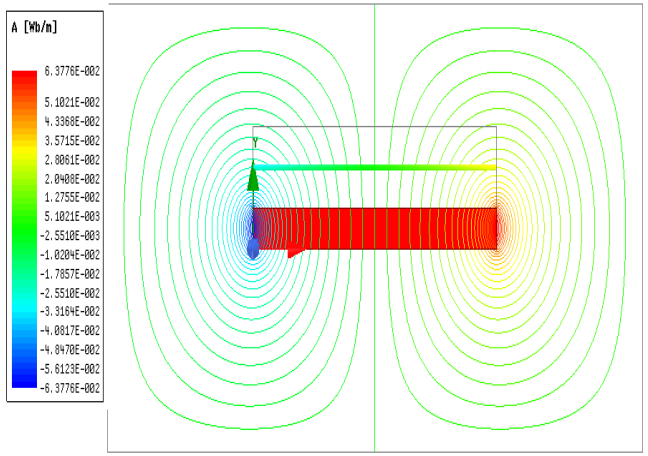
-Flux and flux density calculation by FEM



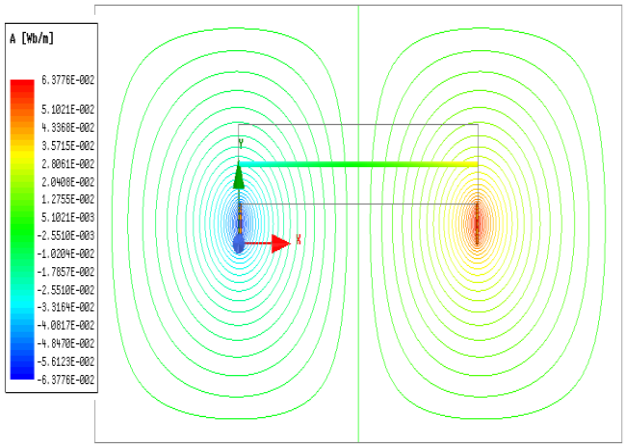
PM model: Br =1.2T



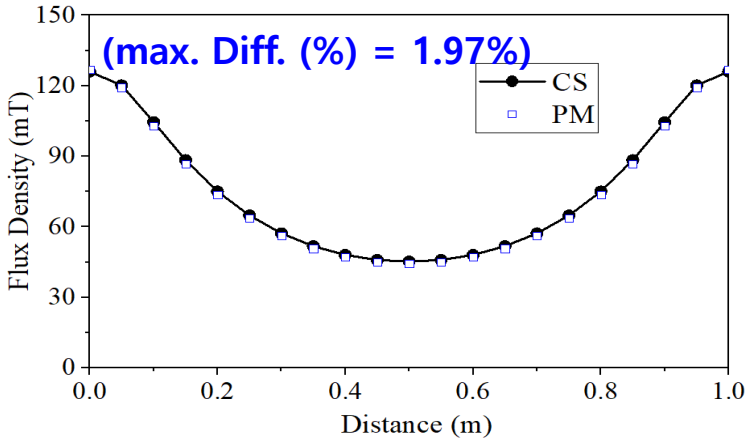
Model by Current Sheet(CS): Current Value($9.1*10^4$ A= $\frac{B_r}{\mu_0 \mu_r} h$)



PM model : flux line

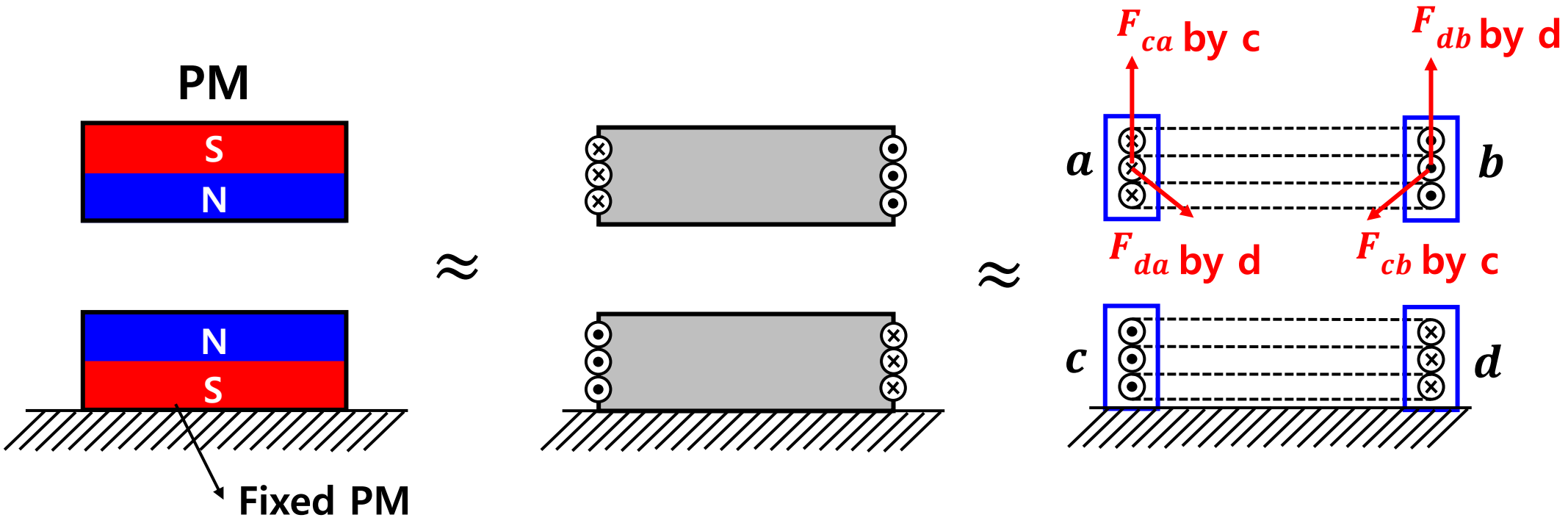


Current Sheet(CS) model : flux line



Flux Density along red line - · -

3. Repulsive Force by Permanent Magnet



∵ Same with air

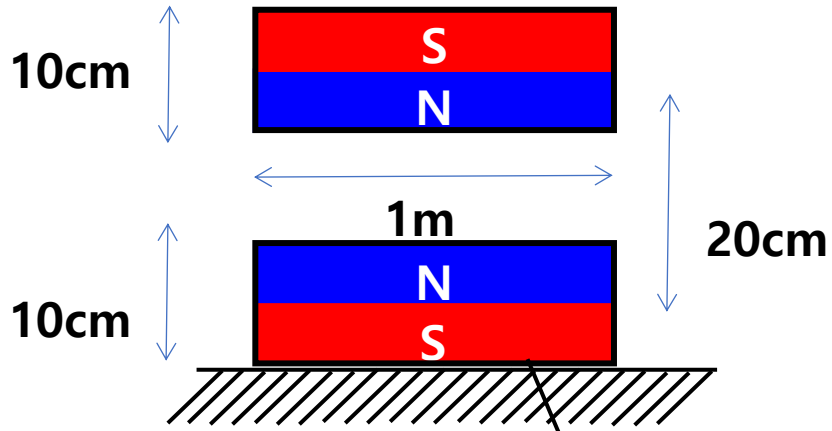
Relative Permeability of PM $\mu_r = 1.05$

Relative Permeability of Vacuum (air) $\mu_r = 1.0$

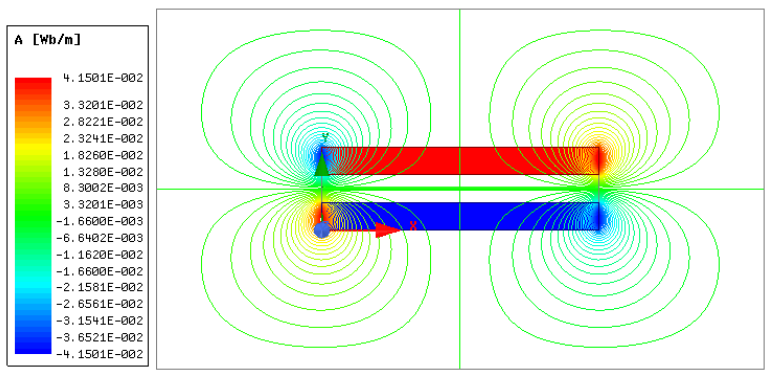
3. Repulsive Force by Permanent Magnet

Value Added Mechatronics

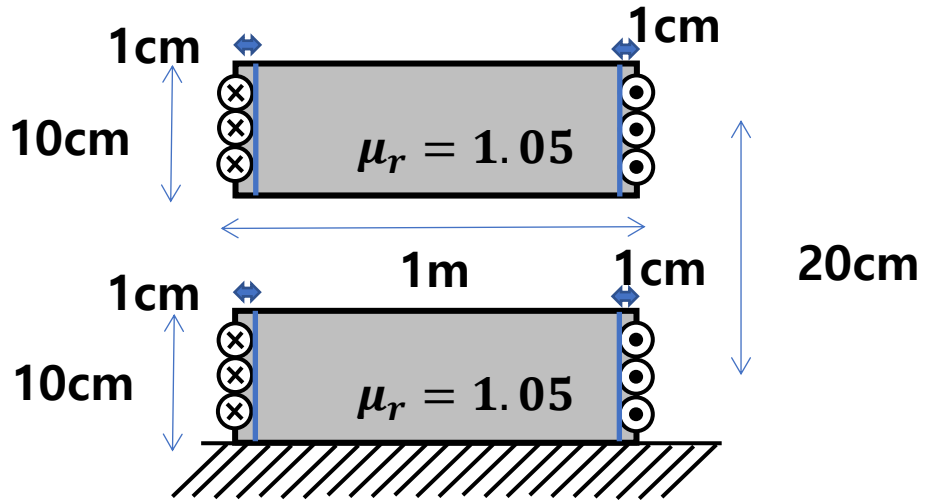
-Magnetic field by FEM



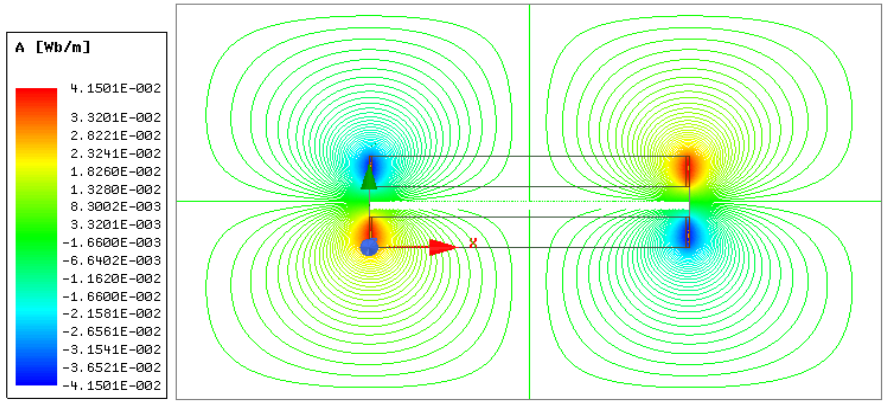
Fixed PM(Br=1.2T)



Magnetic field by PM



Current Value=$9.1*10^4$ A



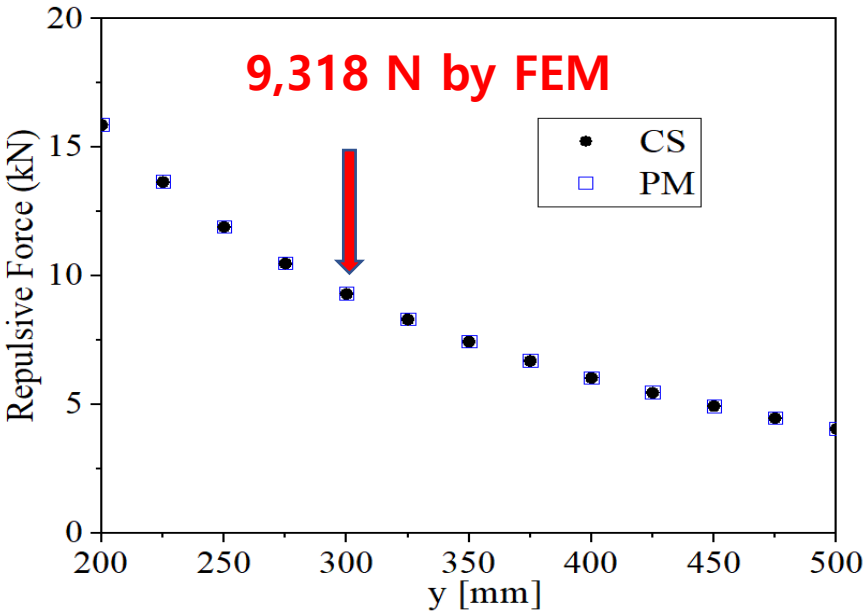
Magnetic field by Current Sheet(CS):

3. Repulsive Force by Permanent Magnet

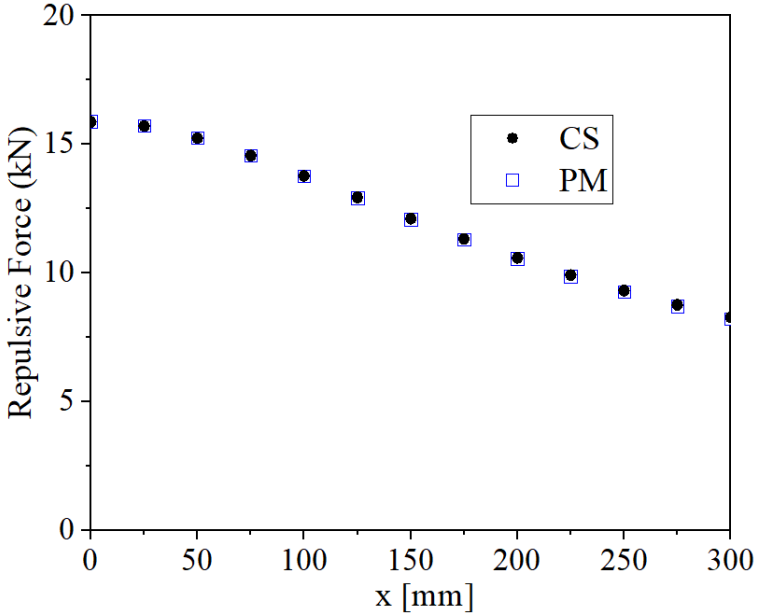
Value Added Mechatronics

-Repulsive force by FEM

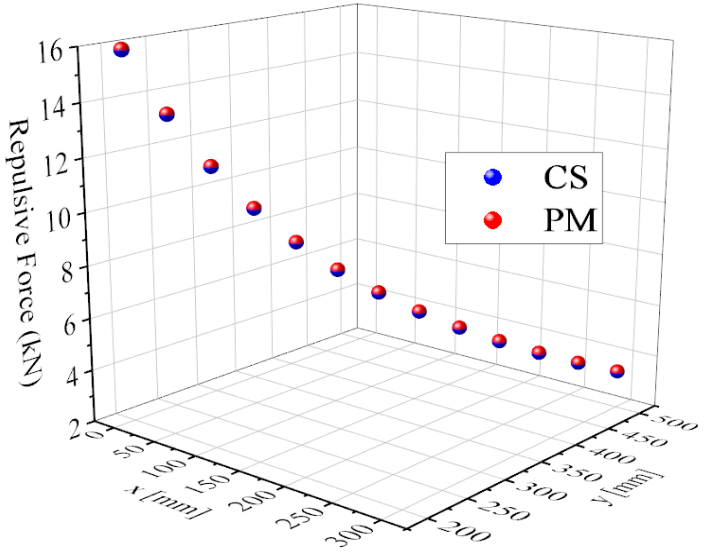
(max. Diff. (%) = 0.4%)



Repulsive force along y



Repulsive force along x



Repulsive force along y & x

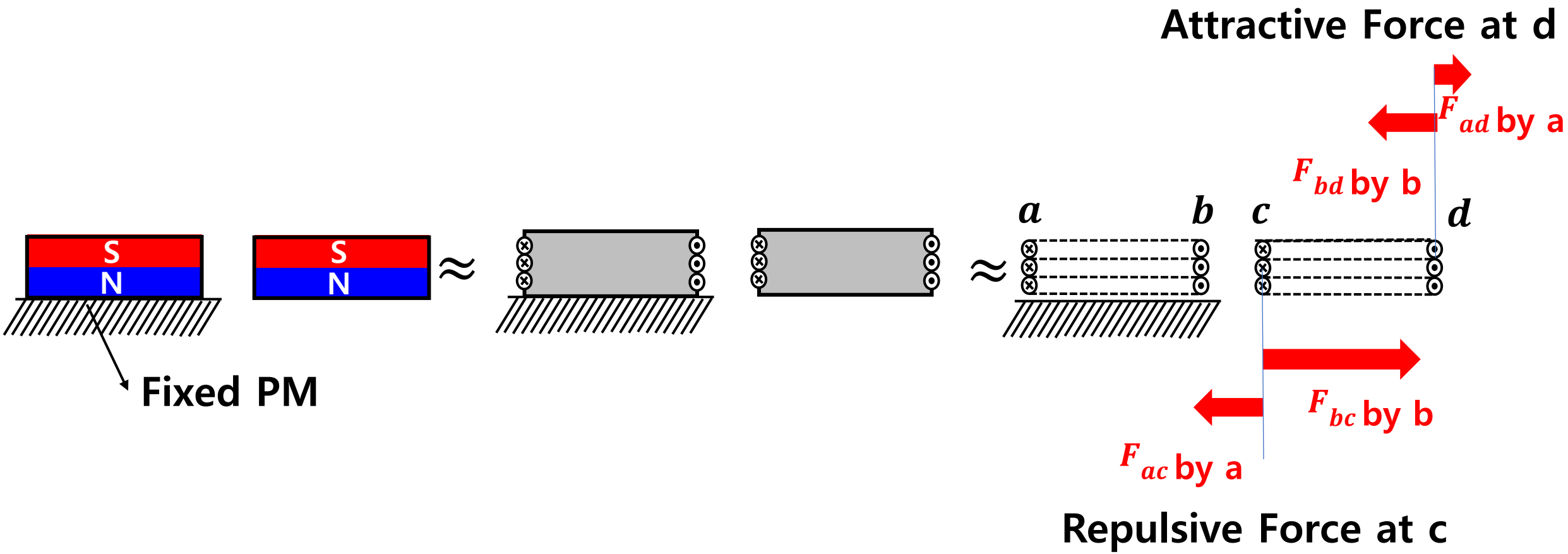
Ref.

-9,318 N by FEM calculation

-11,592 N by hand calculation (see page 12)

The hand calculation is bigger than FEM cal. because Fda and Fcb (in page 4) is not calculated.

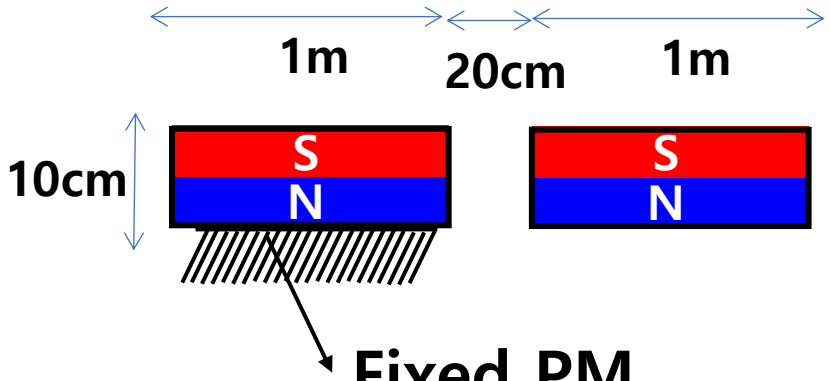
3. Repulsive Force by Permanent Magnet

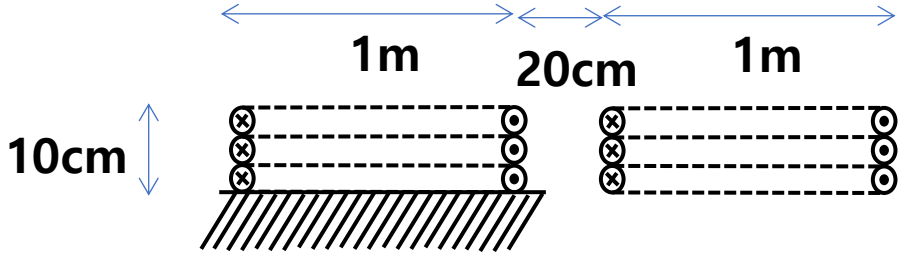


3. Repulsive Force by Permanent Magnet

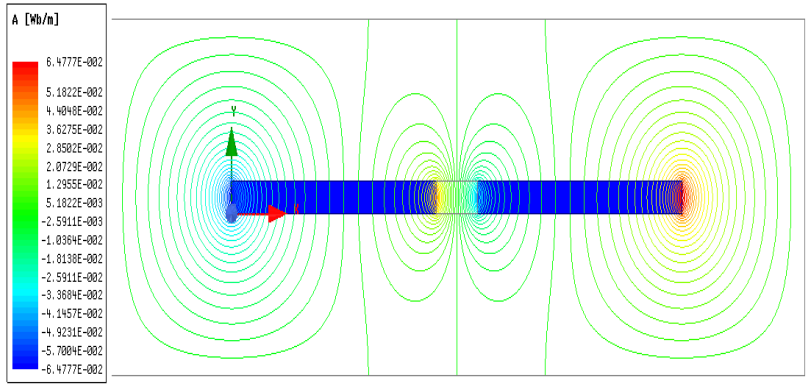
Value Added Mechatronics

-Magnetic field by FEM

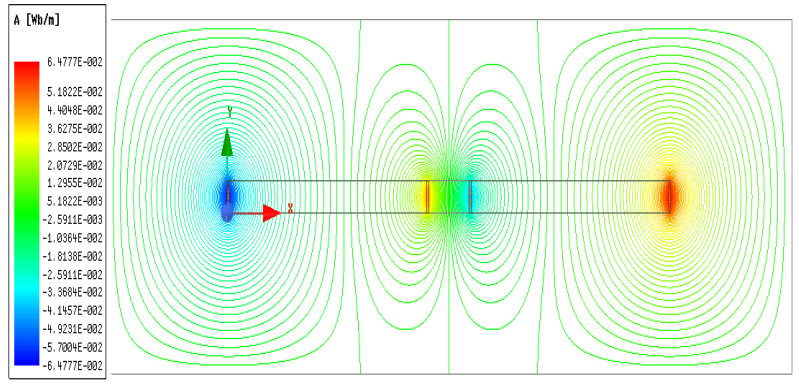




Current Value=$9.1*10^4$ A



Magnetic field by PM



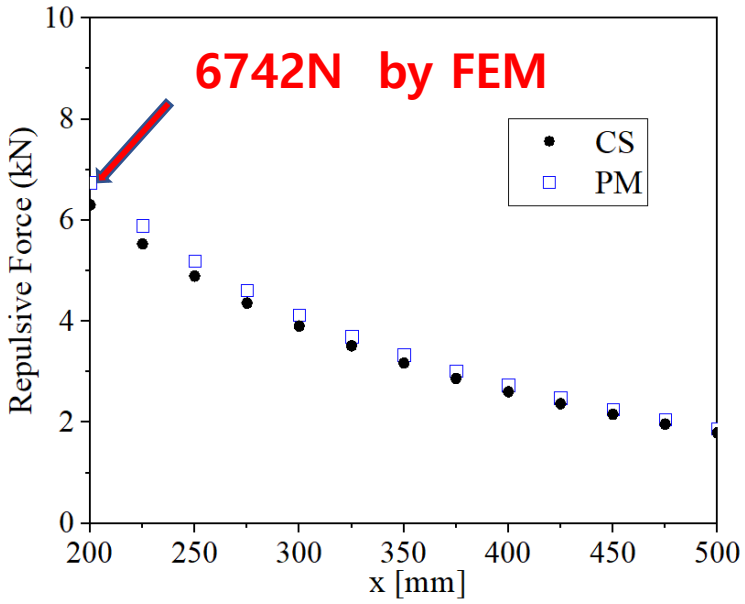
Magnetic field by Current Sheet(CS)

3. Repulsive Force by Permanent Magnet

Value Added Mechatronics

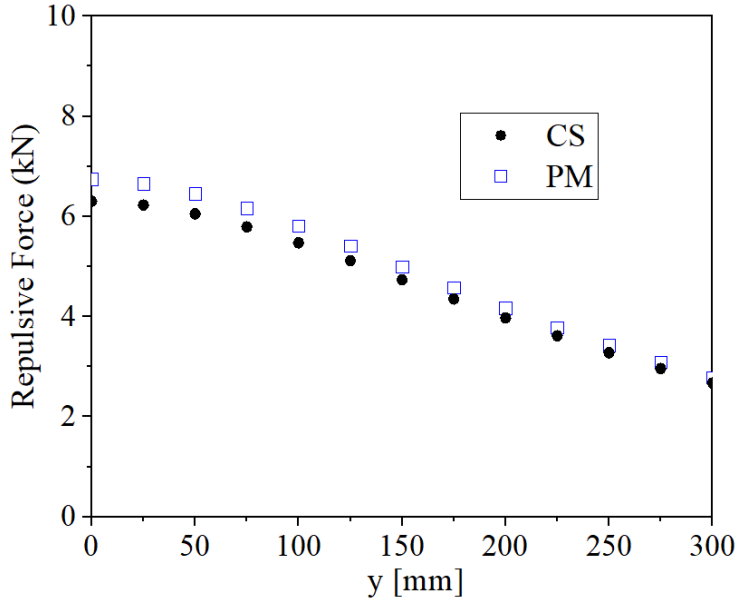
-Repulsive force by FEM

max. Diff. (%) = 6.5%



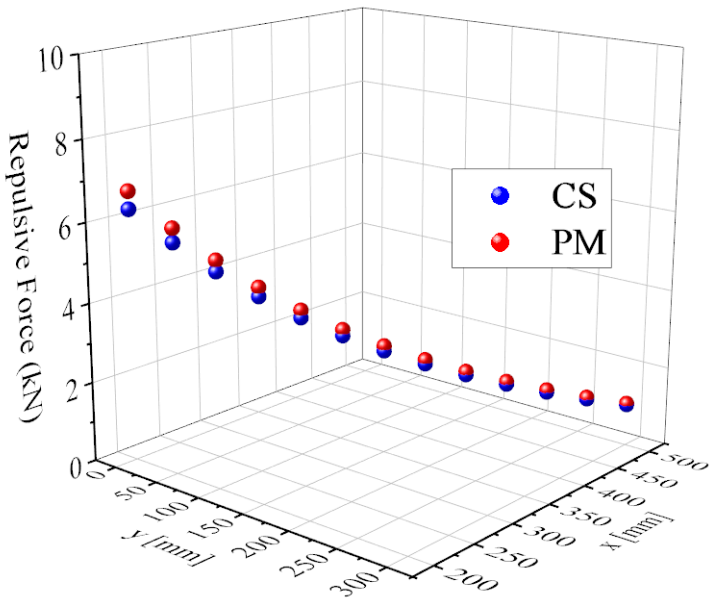
Repulsive force along x

max. Diff. (%) = 6.5%



Repulsive force along y

max. Diff. (%) = 6.5%



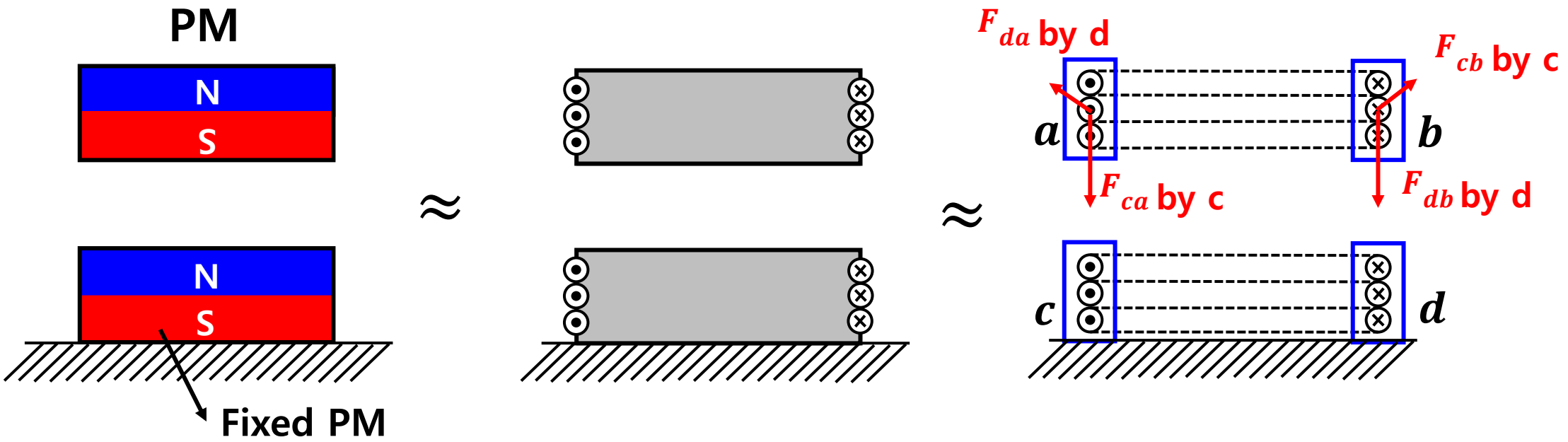
Repulsive force along x & y

Ref.

-6742N by FEM calculation

-6579 N by hand calculation (see page 13)

4. Attractive Force by Permanent Magnet

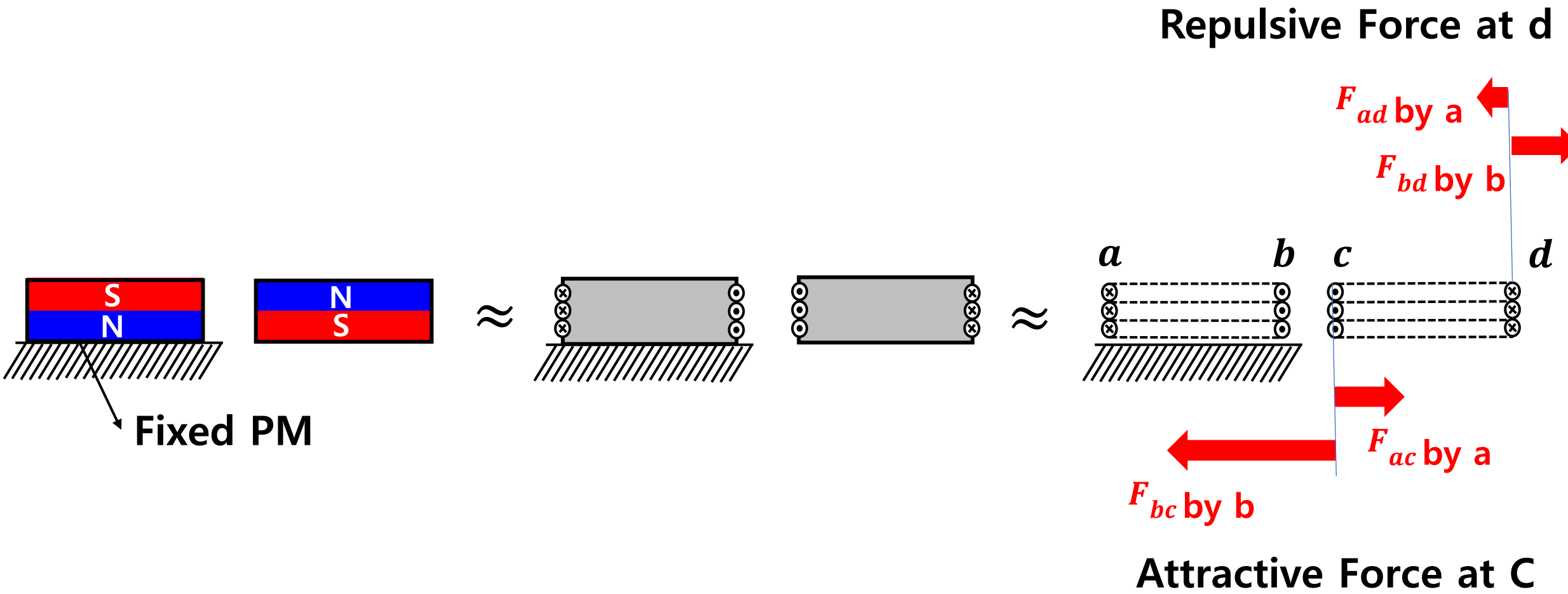


∵ Same with air

Relative Permeability of PM $\mu_r = 1.05$

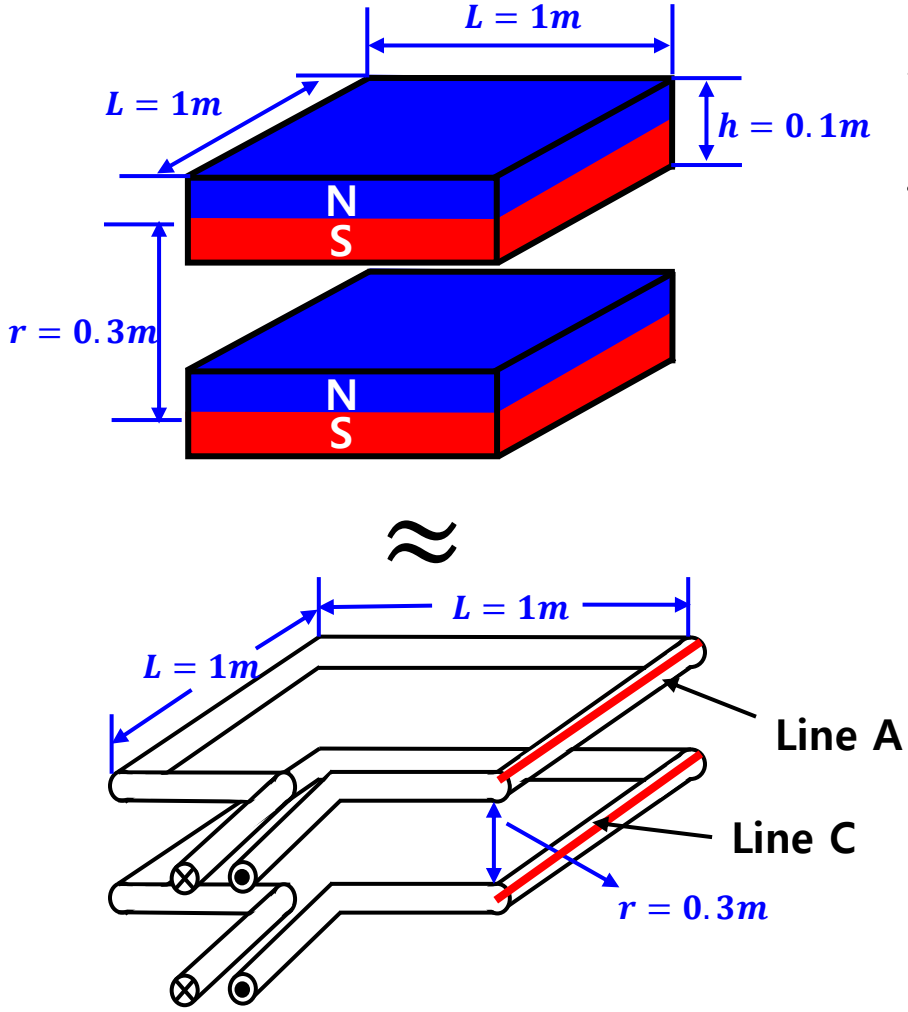
Relative Permeability of Vacuum (air) $\mu_r = 1.0$

4. Attractive Force by Permanent Magnet



5. Simple Calculation Example

When under two PMs with distance 0.3m, what is the total force F_{tot} which reacts to below PM?



- **Magnetomotive Force of PM $\mathcal{F}_{PM}$ in line A** $= \dfrac{B_r}{\mu_0\mu_r}h$
- **Magnetic Flux Density B *in line C by line A***

$$B = \mu_0\mu_r H = \mu_0\mu_r\frac{\mathcal{F}_{PM}}{2\pi r} = \mu_0\mu_r\frac{1}{2\pi r}\frac{B_r}{\mu_0\mu_r}h = \frac{B_r}{2\pi r}h$$

- ***Force in line C by B and $\mathcal{F}_{PM}$ in line C***

$$F = BiL = \left(\frac{B_r h}{2\pi r}\right)\left(\frac{B_r h}{\mu_0\mu_r}\right)L = \frac{(1.2T)(0.1m) * (1.2T)(0.1m)}{2\pi(0.3m) * (4\pi\times10^{-7}H/m)(1.05)}(1m)$$

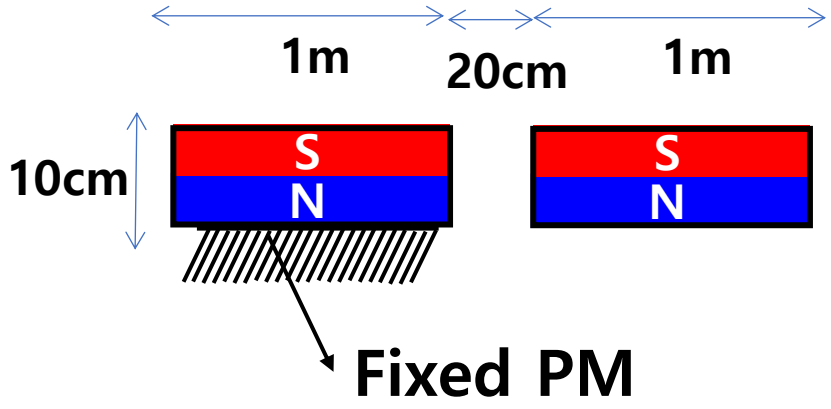
$$= 5{,}796\ (N)$$

$\therefore\ \boldsymbol{F_{total} = 4F = 23{,}184(N)}$

2 dimensional calculation = $2F$ =11,592 (N)

Ref. : 9,318 N by FEM calculation (see page 6)

5. Simple Calculation Example



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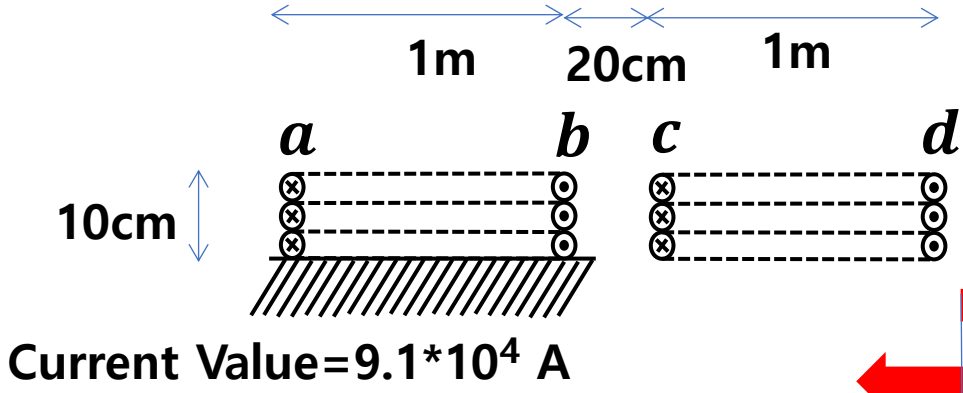
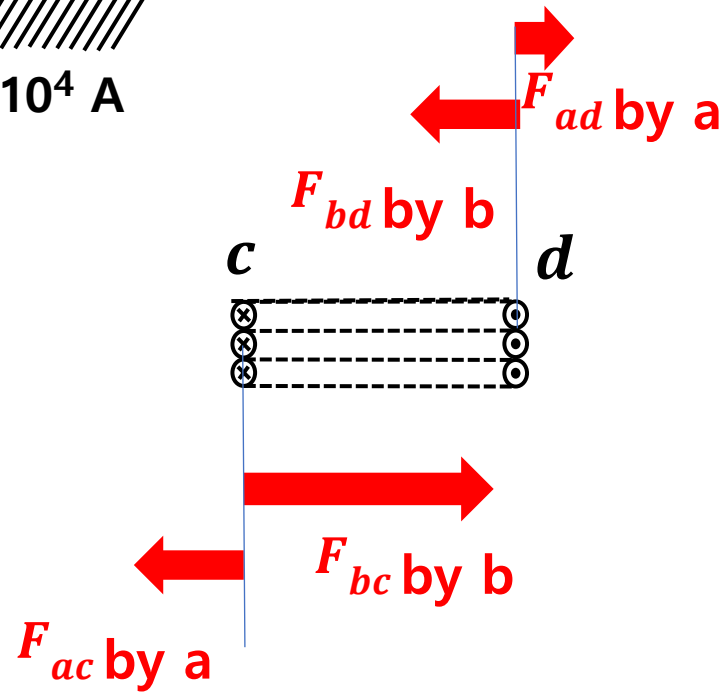




- **Magnetic Flux Density B in line c by line b**

$$B = \mu_0\mu_r H = \mu_0\mu_r \frac{\mathcal{F}_{PM}}{2\pi r} = \mu_0\mu_r \frac{1}{2\pi r}\frac{B_r}{\mu_0\mu_r}h = \frac{B_r}{2\pi r}h$$

- **Force in line c by B and $\mathcal{F}_{PM}$ in line c**

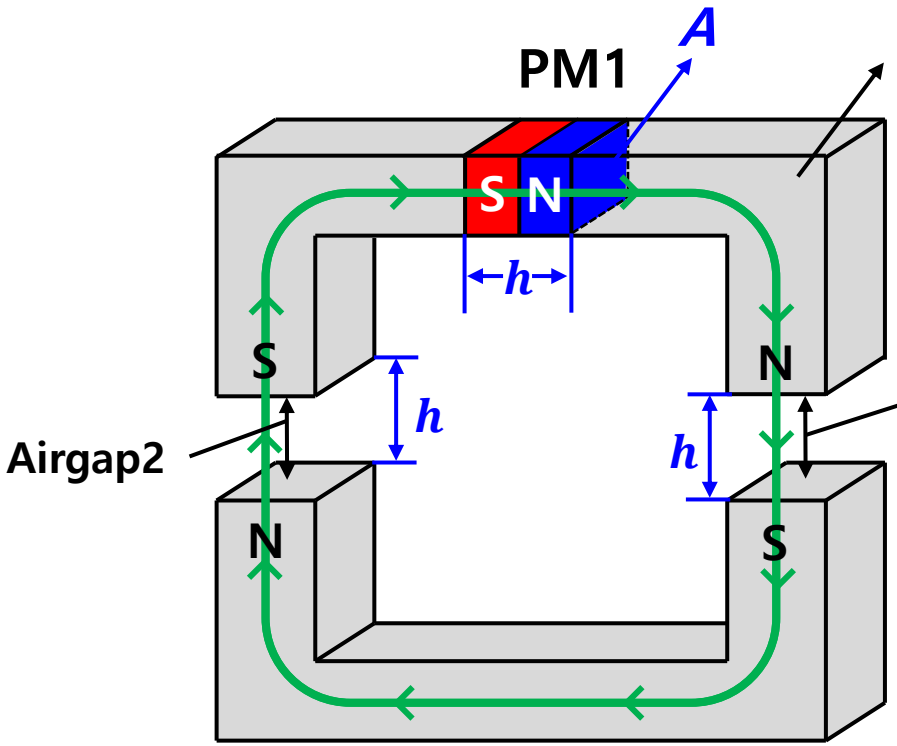
$$\mathbf{F}_{bc} = BiL = \left(\frac{B_r h}{2\pi r}\right)\left(\frac{B_r h}{\mu_0\mu_r}\right)L = \frac{(1.2T)(0.1m)*(1.2T)(0.1m)}{2\pi(0.2m)*(4\pi\times10^{-7}H/m)(1.05)}(1m) = 8{,}684\text{N}$$

$$\mathbf{F}_{ad} = 789\text{ N}, \quad \mathbf{F}_{ac} = 1447\text{ N} \quad \mathbf{F}_{bd} = 1{,}447\text{ N}$$

$$\mathbf{F}_{total} = 8684 + 789 - 1447 - 1447 = \mathbf{6{,}579\ N}$$

Ref. : 6,742N by FEM calculation(see page 9)

6. Permanent Magnet Circuit in Iron Core



Attractive Force

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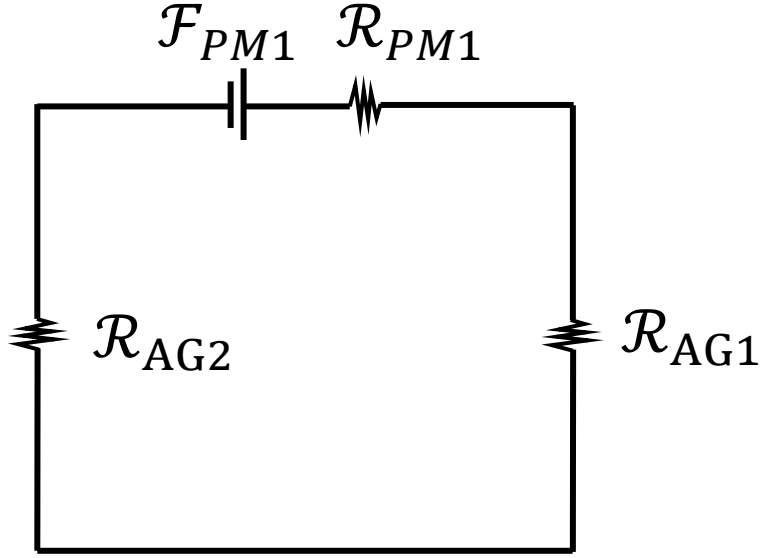
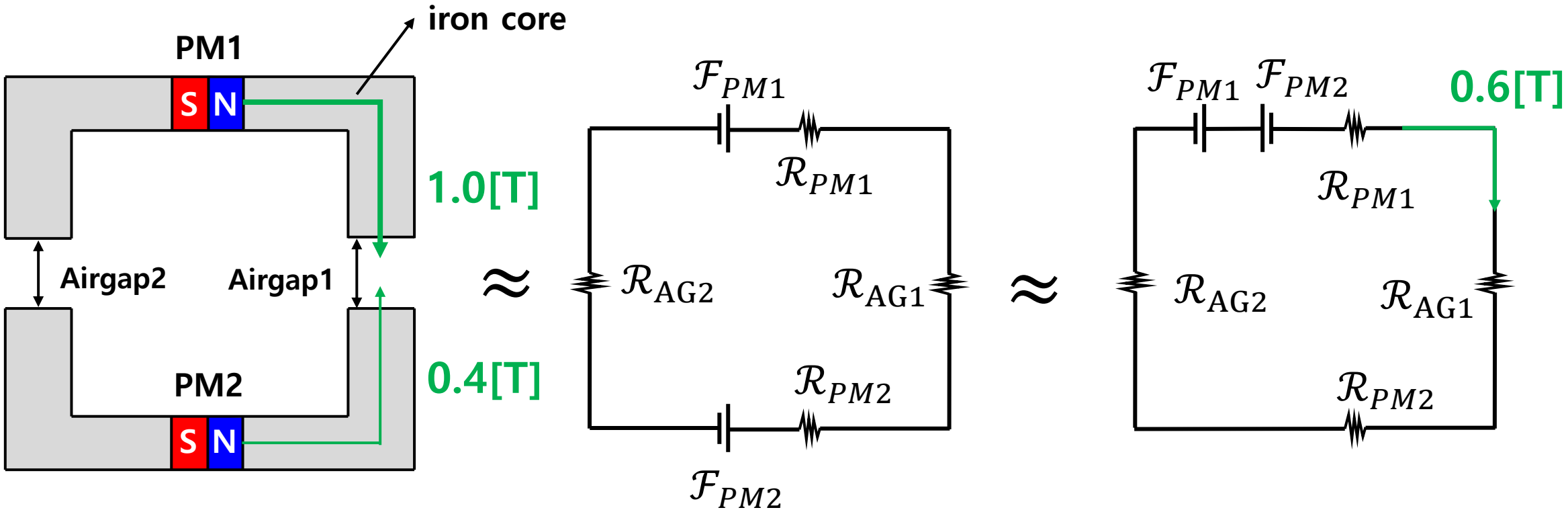


Magnetomotive Force of PM $\mathcal{F}_{PM} = \frac{B_r}{\mu_0 \mu_r} h$

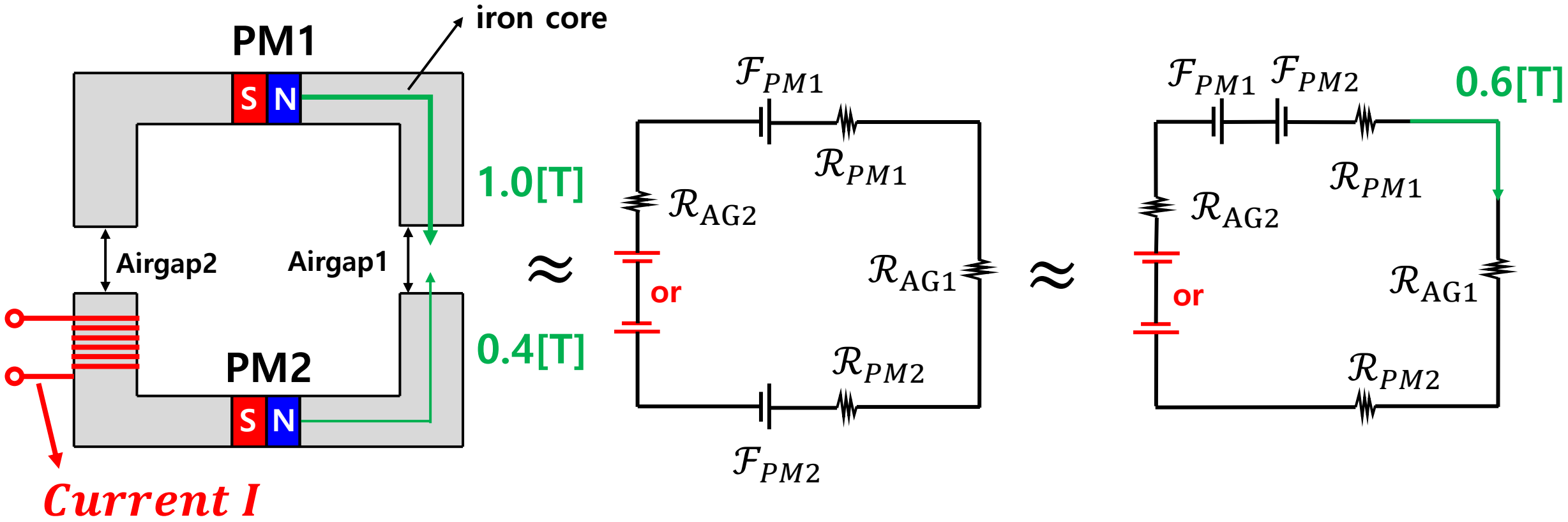
Magnetic Resistance of PM $\mathcal{R}_{PM} = \frac{h}{\mu_0 \mu_r A}$

Airgap Magnetic Resistance of PM $\mathcal{R}_{PM} = \frac{h}{\mu_0 A}$

6. Permanent Magnet Circuit in Iron Core



6. Permanent Magnet Circuit in Iron Core

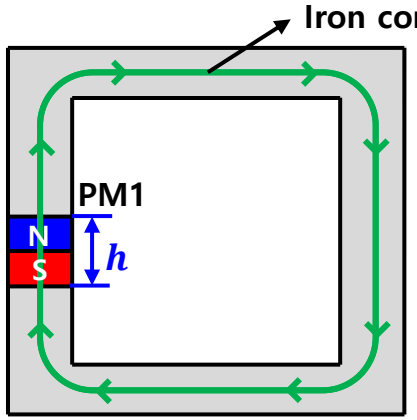


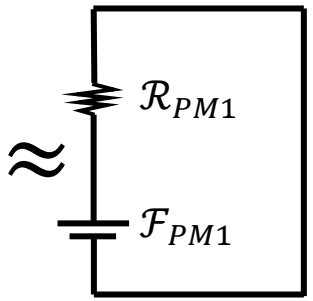
When a current flows in coil, MMF by current is generated in Iron Core!

6. Permanent Magnet Circuit in Iron Core

Value Added Mechatronics

· Point A Magnetic Density 1.2 [T]



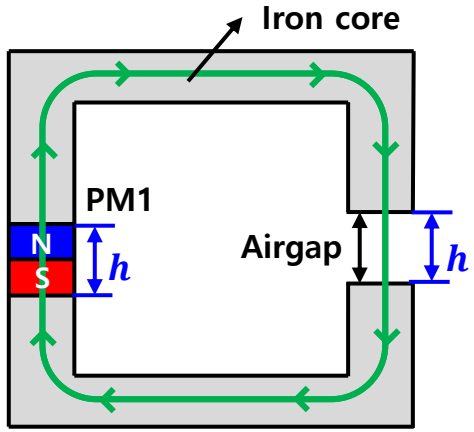


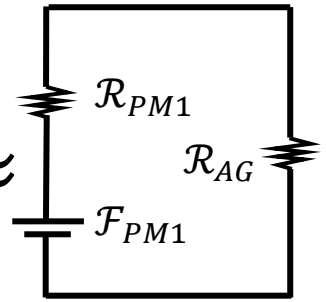
$$\mathcal{F}_{PM} = \phi \mathcal{R}_{PM}$$

$$\phi = \frac{\mathcal{F}_{PM}}{\mathcal{R}_{PM}} = \frac{\frac{B_r}{\mu_0 \mu_r} h}{\frac{h}{\mu_0 \mu_r A}} = B_r A$$

$$B = \frac{\phi}{A} = \frac{B_r A}{A} = B_r = 1.2\ [T]$$

· Point B Magnetic Density 0.6 [T]



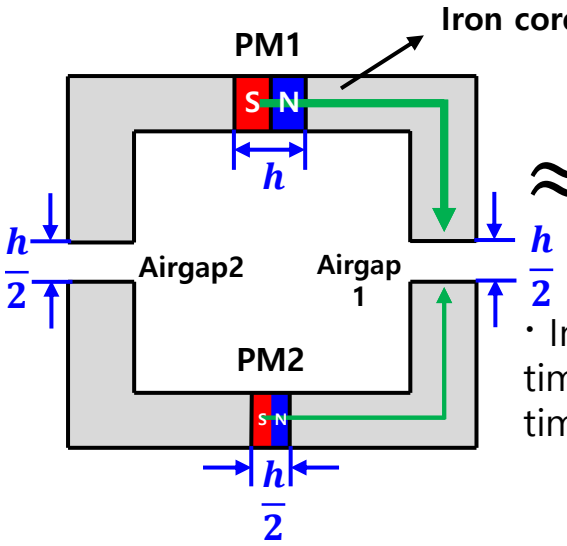


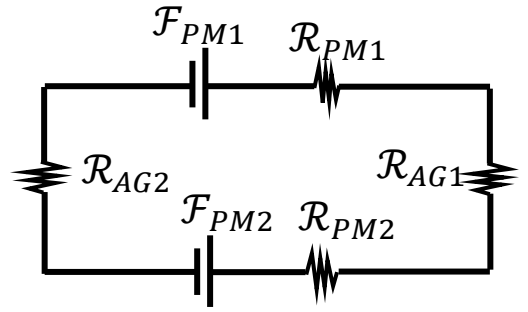
$$\mathcal{R}_{AG} = \frac{h}{\mu_0 \mu_r A}$$

$$\phi = \frac{\mathcal{F}_{PM}}{\mathcal{R}_{PM} + \mathcal{R}_{AG}} = \frac{B_r A}{2}$$

$$B = \frac{\phi}{A} = \frac{B_r}{2} = 0.6\ [T]$$

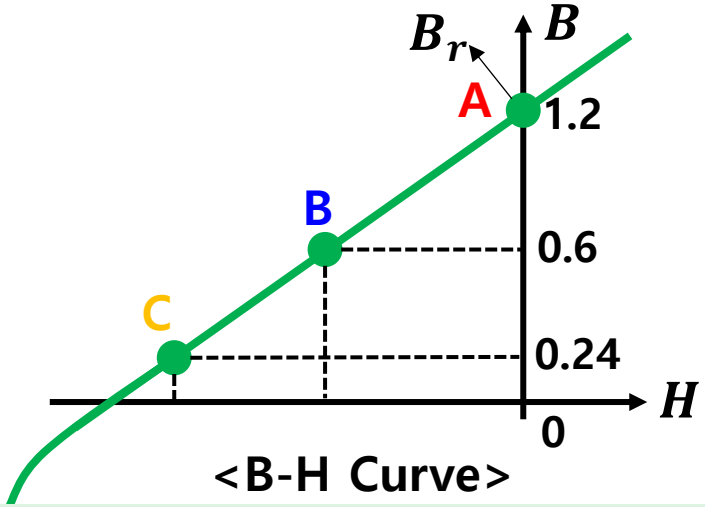
· Point C Magnetic Density 0.24 [T]





· In this case, $\mathcal{F}_{PM}$ decreases by 0.5 times and $\mathcal{R}_{PM}$ increases by 2.5 times in comparison to Point A

$$B = 1.2 \frac{0.5}{2.5} = 0.24\ [T]$$

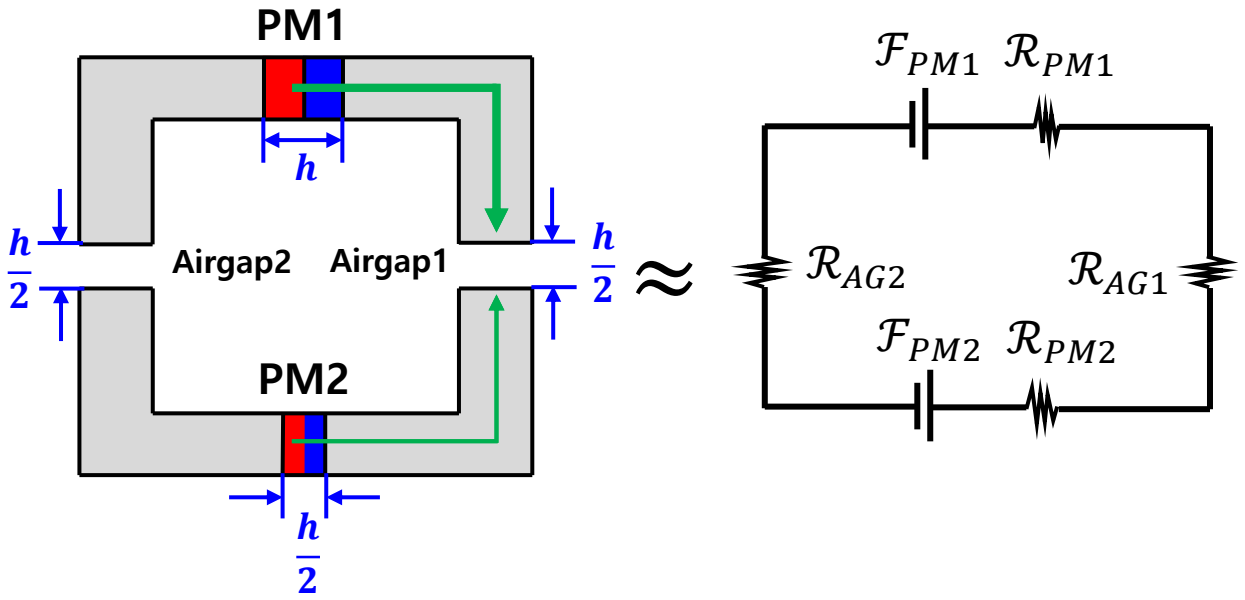


<B-H Curve>

6. Permanent Magnet Circuit in Iron Core

Value Added Mechatronics

· **Point C : Magnetic Density 0.24[T]**



$$\mathcal{F}_{PM1} = \phi_1 \mathcal{R}_{PM1} \qquad \mathcal{F}_{PM2} = \phi_2 \mathcal{R}_{PM2}$$

$$\mathcal{F}_{PM1} = \frac{B_r}{\mu_0 \mu_r} h \qquad \mathcal{F}_{PM2} = \frac{B_r}{\mu_0 \mu_r} \frac{h}{2} \qquad \mathcal{R}_{AG1} = \frac{h/2}{\mu_0 \mu_r A}$$

$$\mathcal{R}_{PM1} = \frac{h}{\mu_0 \mu_r A} \qquad \mathcal{R}_{PM2} = \frac{h/2}{\mu_0 \mu_r A} \qquad \mathcal{R}_{AG2} = \frac{h/2}{\mu_0 \mu_r A}$$

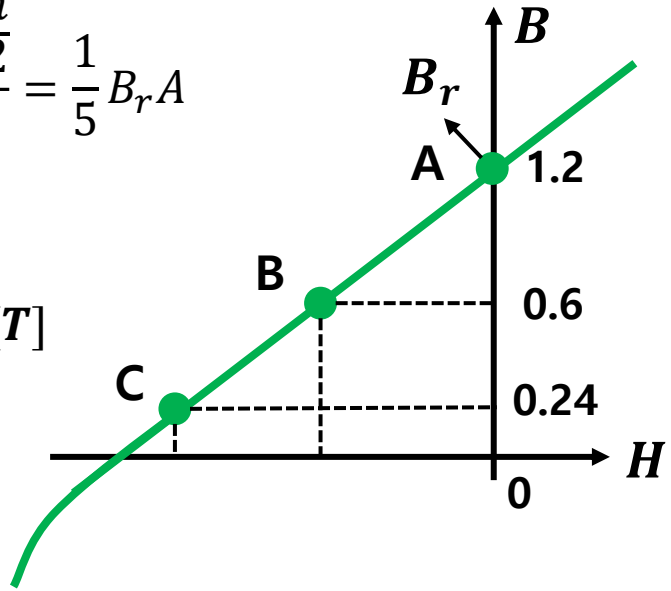
$$\mathcal{R}_{tot} = \mathcal{R}_{PM1} + \mathcal{R}_{PM2} + \mathcal{R}_{AG1} + \mathcal{R}_{AG2}$$

$$= \frac{h}{\mu_0 \mu_r A} + \frac{h/2}{\mu_0 \mu_r A} + \frac{h/2}{\mu_0 \mu_r A} + \frac{h/2}{\mu_0 \mu_r A} = \frac{5}{2} \frac{h}{\mu_0 \mu_r A}$$

$$\phi_{tot} = \frac{\mathcal{F}_{tot}}{\mathcal{R}_{tot}} = \frac{\mathcal{F}_{PM1} - \mathcal{F}_{PM2}}{\mathcal{R}_{tot}}$$

$$= \frac{\frac{B_r h}{\mu_0 \mu_r} - \frac{B_r}{\mu_0 \mu_r} \frac{h}{2}}{\frac{5}{2} \frac{h}{\mu_0 \mu_r A}} = \frac{1}{5} B_r A$$

$$\therefore \; \boldsymbol{B = \frac{\phi_{tot}}{A} = \frac{B_r}{5} = 0.24\ [T]}$$



<B-H Curve>