자기 제동 현상 분석

2011012391 이동희
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주제 선정 배경

팀명 : 지하철

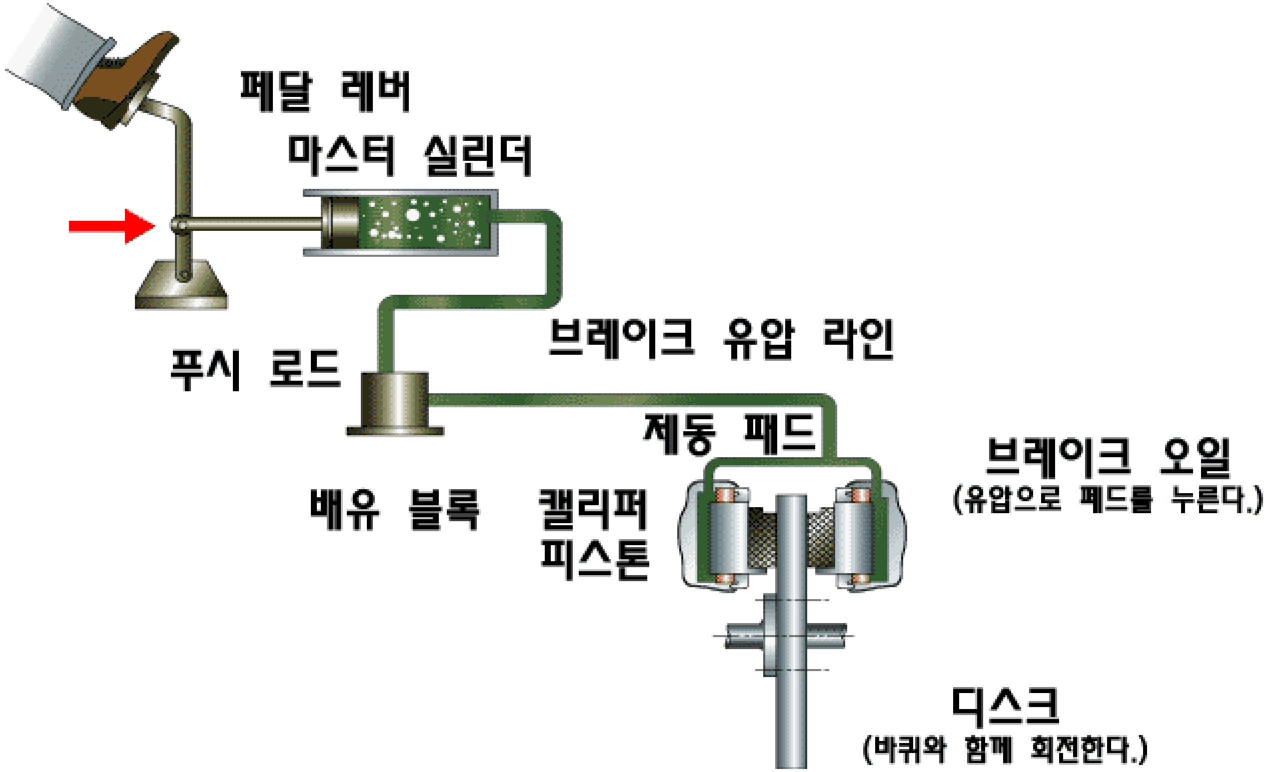
조원 : 이동희, 정규빈

특징 : 지하철 통학

지하철 제동방식에 대한 궁금증

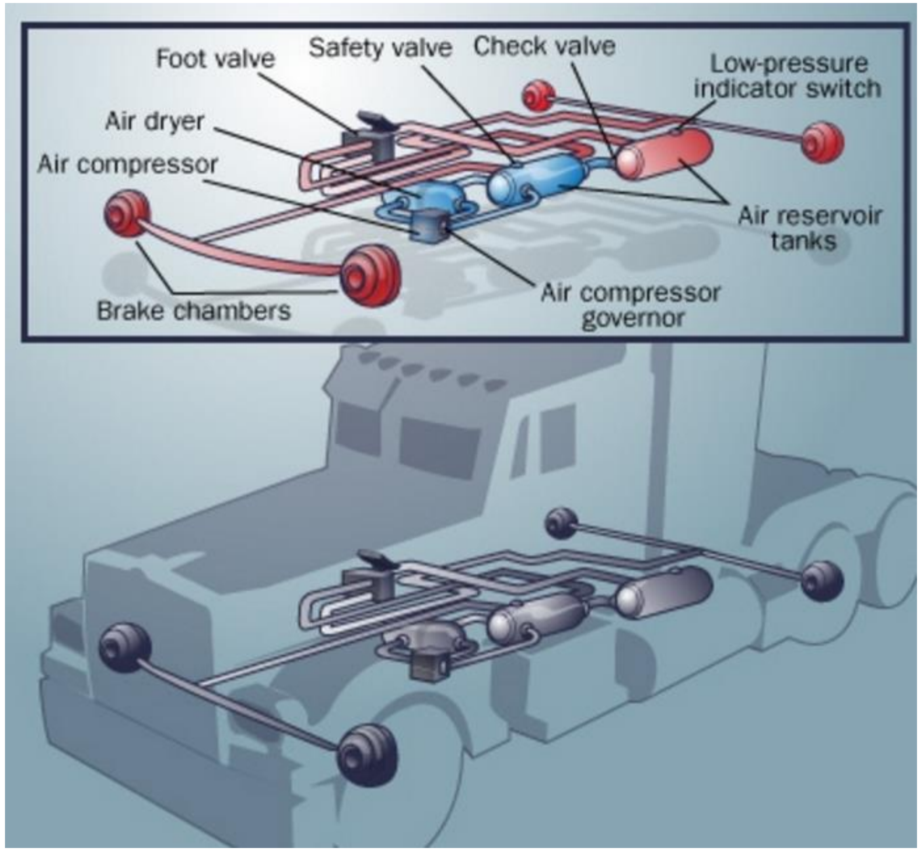
**-> 다양한 제동 방식 중
Magnetic brake를 주제로 선정**

유압 브레이크



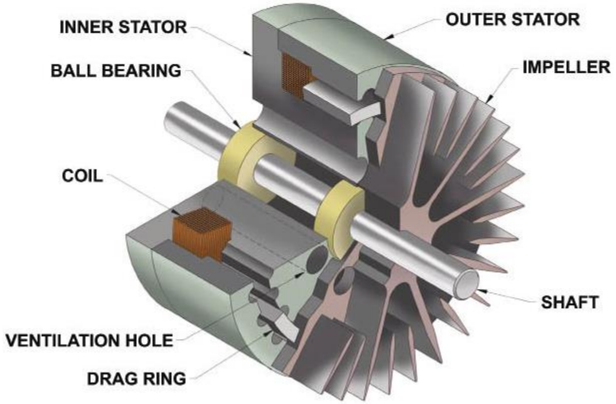
장점	단점
사용이 편리하다. (밟는 힘과 비례하여 제동력 발생) 소음이 적다	큰 제동력 발생 한계 베이퍼 록 현상

에어 브레이크



장점	단점
베이퍼 록 발생 무관 자동차 중량에 상관 받지 않는다 (큰 제동력 발생)	구조가 복잡 가격이 높다 엔진 출력이 공기 압축기에 사용된다 소음 지속 사용 불가

마그네틱 브레이크



Magnetic brake를 적용한 신칸센 열차

장점	단점
베이퍼 록 발생 무관 기계적 접촉 부분이 없어 마모 x 브레이크 제어 용이	열 발산 유의 속도가 0일 때 제동력 발생 x

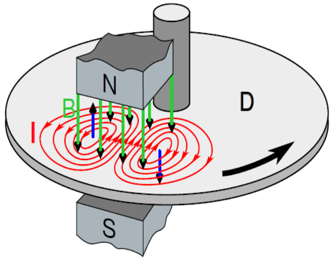
원리

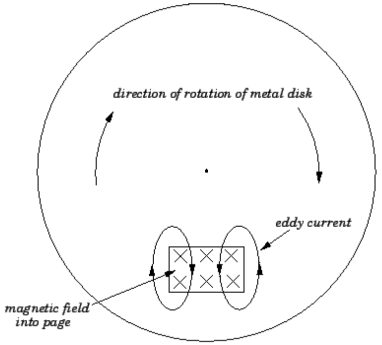
Lorentz force: $\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B})$

맴돌이 전류(eddy current) 생성

자기장 형성 (암페어 주회법칙)

제동력 발생





어플리케이션

낚시대

열차 브레이크

축 제동

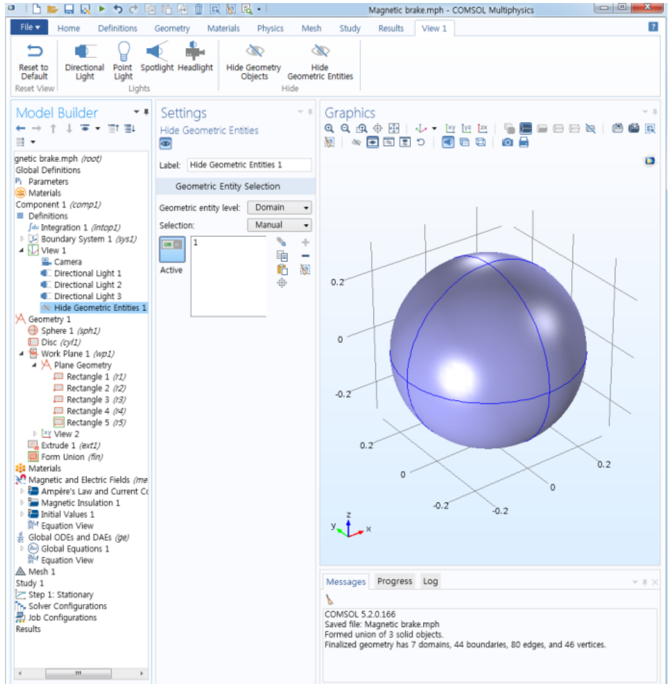
해석 방향

- Magnetic braking 원리

- Comsol model 해석을 통한 제동력과 속도 변화 확인

- 해결 결과에 따른 Magnetic 브레이크의 특징

모델링 과정(geometry)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Hide Geometric Entities
Label: Hide Geometric Entities 1
Geometric Entity Selection
Geometric entity level: Domain
Selection: Manual
1

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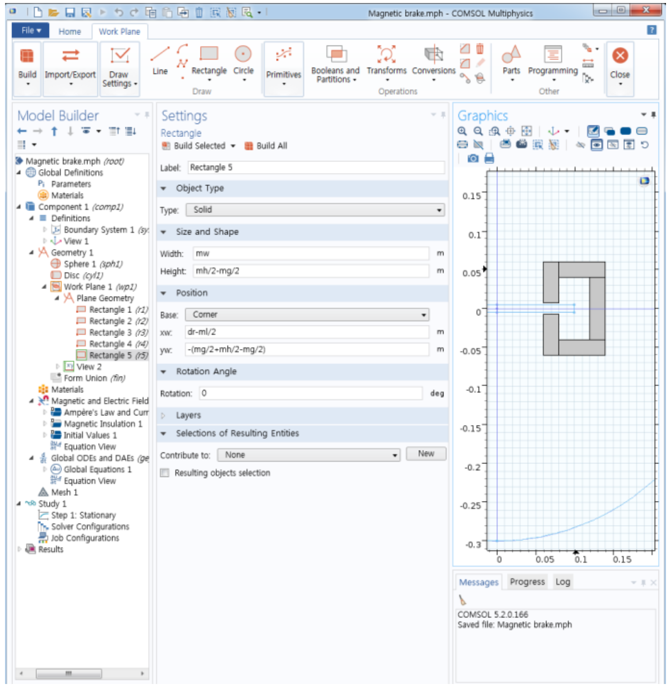
COMSOL 5.2.0.166
Saved file: Magnetic brake.mph
Formed union of 3 solid objects.
Finalized geometry has 7 domains, 44 boundaries, 80 edges, and 46 vertices.
```


Settings
Rectangle
Label: Rectangle 5
Object Type
Type: Solid
Size and Shape
Width: mw m
Height: mh/2-mg/2 m
Position
Base: Corner
xw: dr-ml/2 m
yw: -(mg/2+mh/2-mg/2) m
Rotation Angle
Rotation: 0 deg
Layers
Selections of Resulting Entities
Contribute to: None
☐ Resulting objects selection

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COMSOL 5.2.0.166
Saved file: Magnetic brake.mph
```
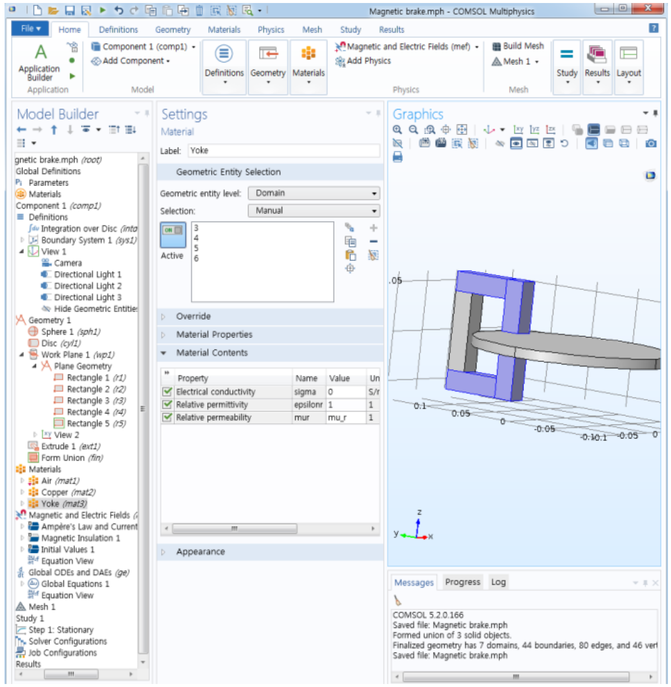


Settings
Material
Label: Yoke
Geometric Entity Selection
Geometric entity level: Domain
Selection: Manual
3
4
5
6
Override
Material Properties
Material Contents

	Property	Name	Value	Un
☑	Electrical conductivity	sigma	0	S/r
☑	Relative permittivity	epsilonr	1	1
☑	Relative permeability	mur	mu_r	1

Appearance

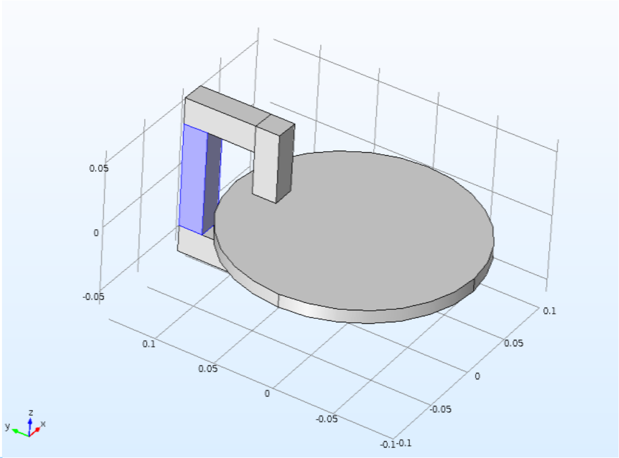
```
COMSOL 5.2.0.166
Saved file: Magnetic brake.mph
Formed union of 3 solid objects.
Finalized geometry has 7 domains, 44 boundaries, 80 edges, and 46 vert
Saved file: Magnetic brake.mph
```

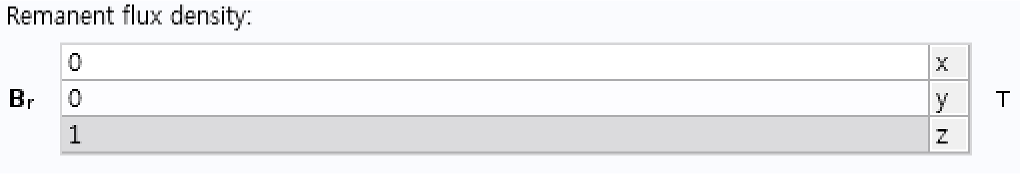
<구체 >

<영구자석, 디스크 >

모델링 과정(magnetic and electric field)

Permanent Magnet

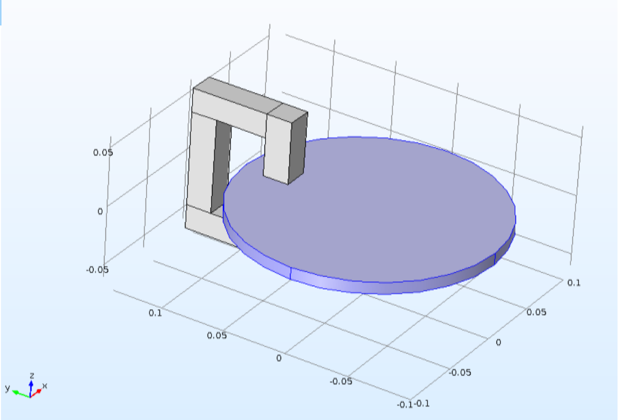




Remanent flux density:

$\mathbf{B}_r$	0	x	T
	0	y	
	1	z	

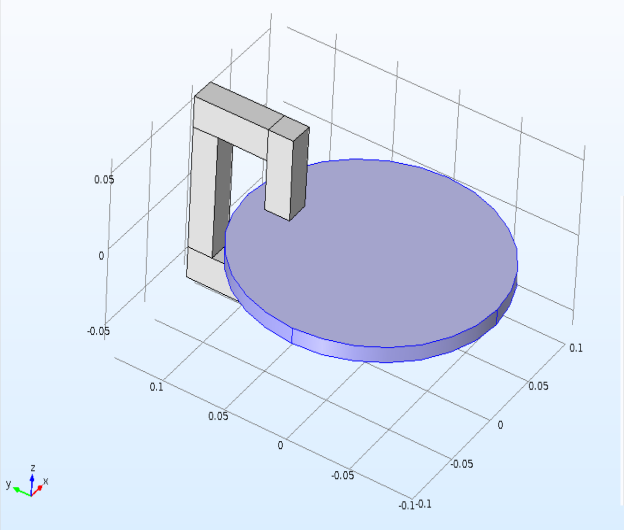
Force Calculation 1

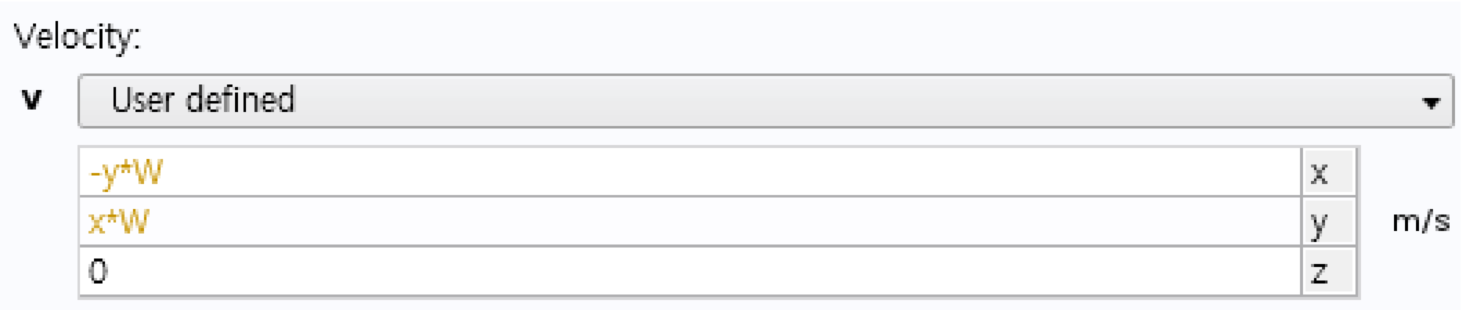


Torque axis:

$\mathbf{r}_{ax}$	0	x
	0	y
	1	z

Velocity (Lorentz Term) 1

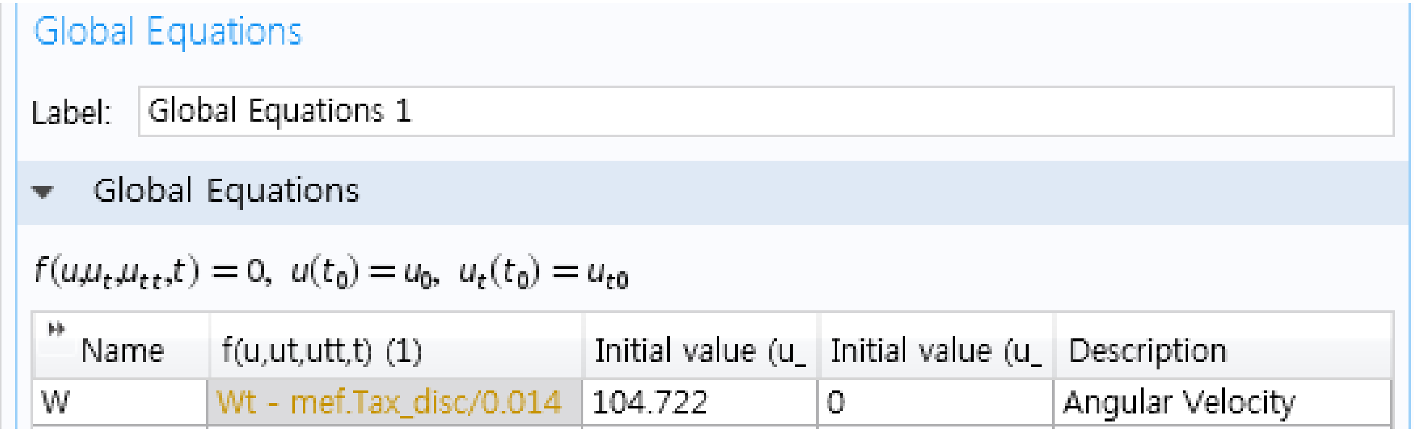




Velocity:

v User defined

-y*W	x	m/s
x*W	y	
0	z	



Global Equations

Label: Global Equations 1

Global Equations

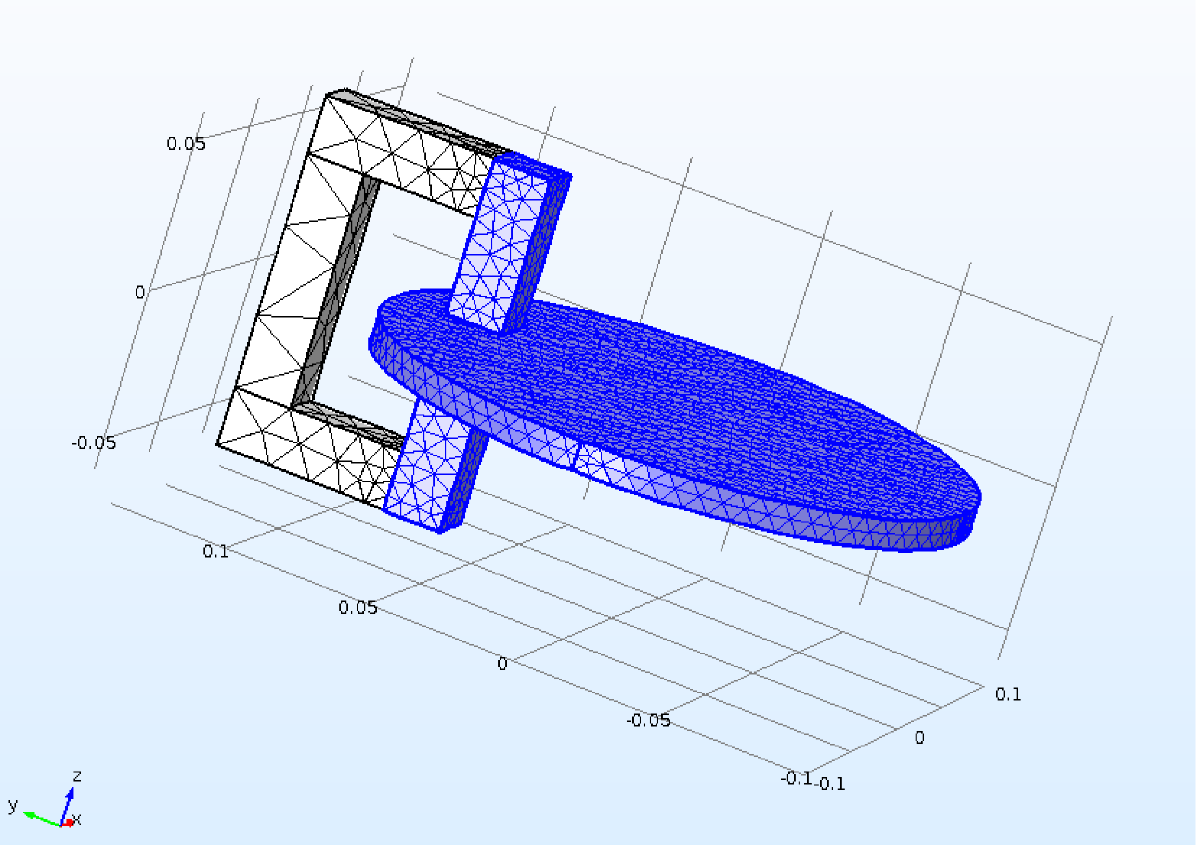
$f(u,u_t,u_{tt},t) = 0, \; u(t_0) = u_0, \; u_t(t_0) = u_{t0}$

Name	f(u,ut,utt,t) (1)	Initial value (u_	Initial value (u_	Description
W	Wt - mef.Tax_disc/0.014	104.722	0	Angular Velocity

$$I\alpha = T$$

$$w' - \frac{T}{I_z} = 0$$

Mesh



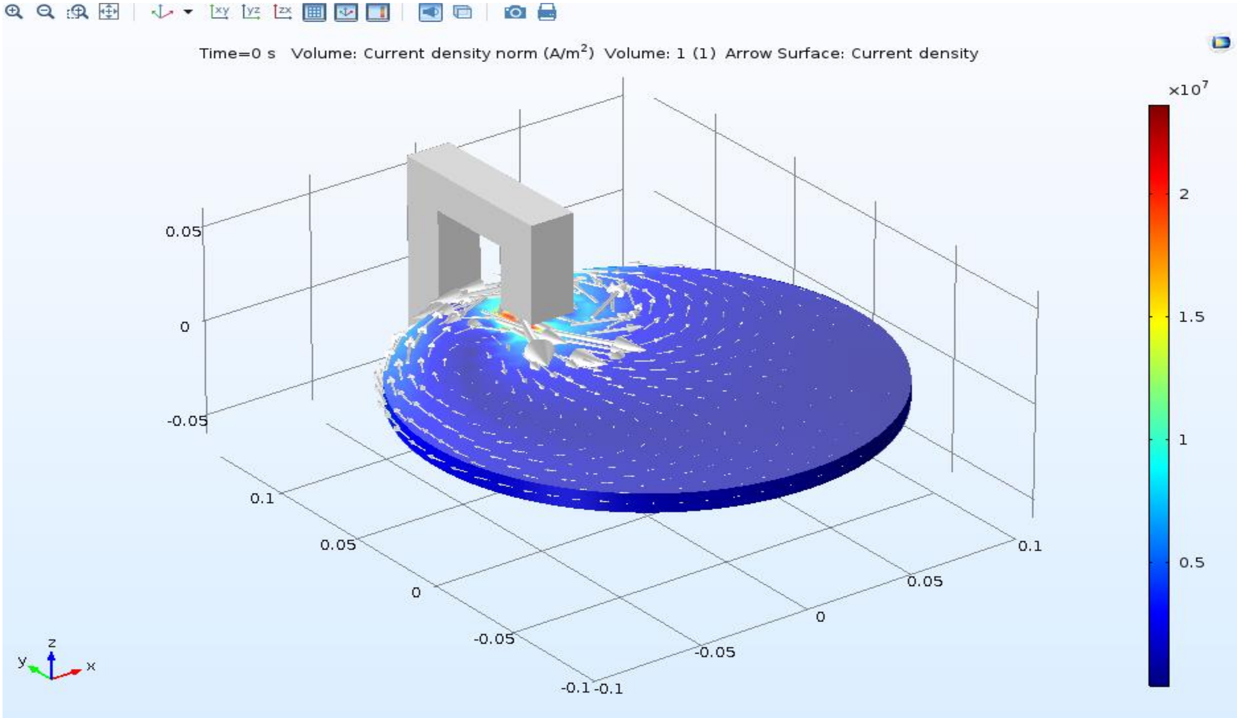
<SIZE>

Extremely fine

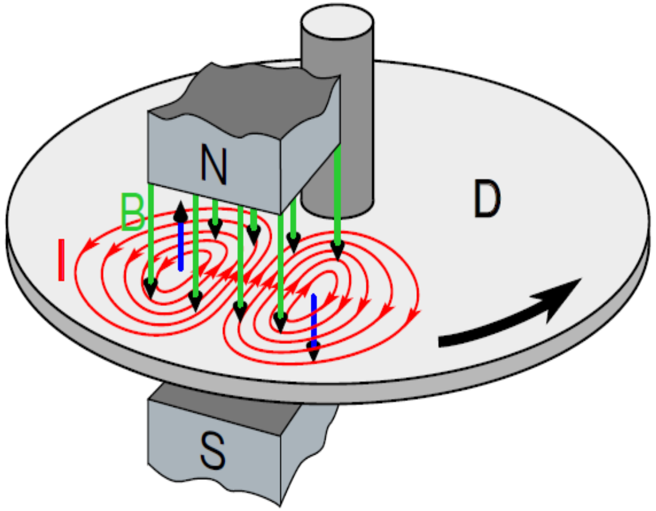
Coarser

해석 결과

<Eddy current flow>

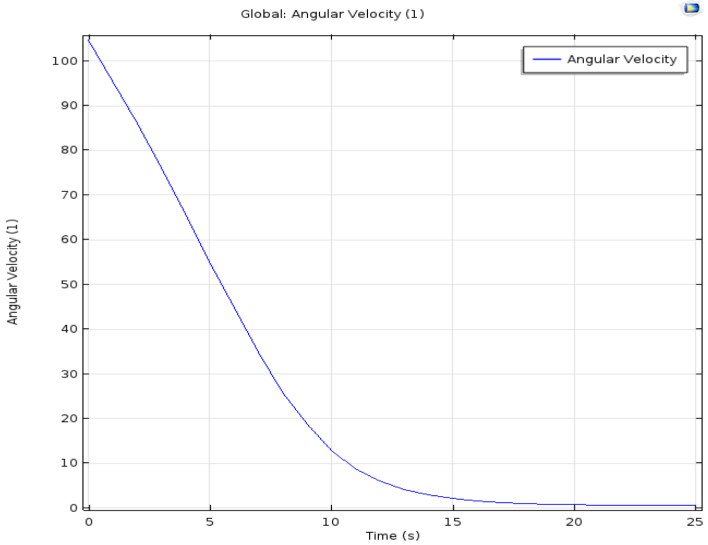


회전을 억제하는 자기장을 발생시키는 방향으로 eddy current 형성



입력변화에 따른 감속비교

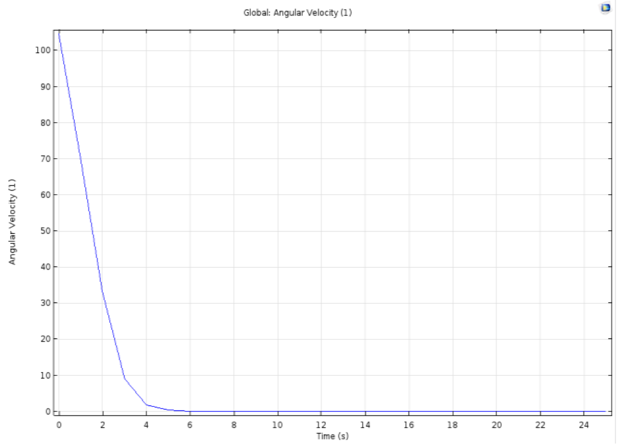
입력1) 기자력 변화(전자석구동시)
입력2) 공극 간격 조절



영구자석을 입력으로 줌

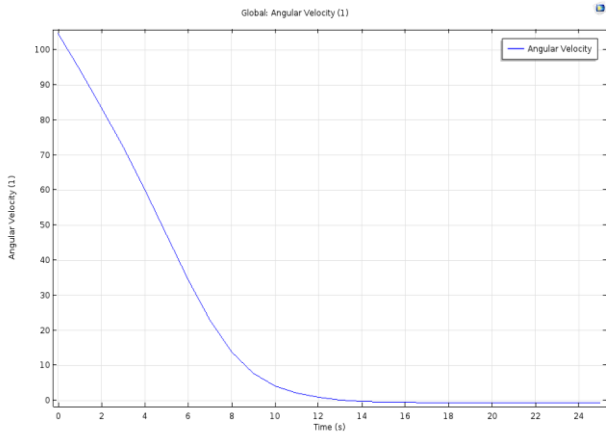
Br=1T ,공극 간격:1.5cm

정지까지 10~15초



Br=2T , 공극 간격: 1.5cm =>4초대

자속밀도 증가
->디스크에서의 자속밀도증가
->Eddy current 증가
->회전 감속 효과

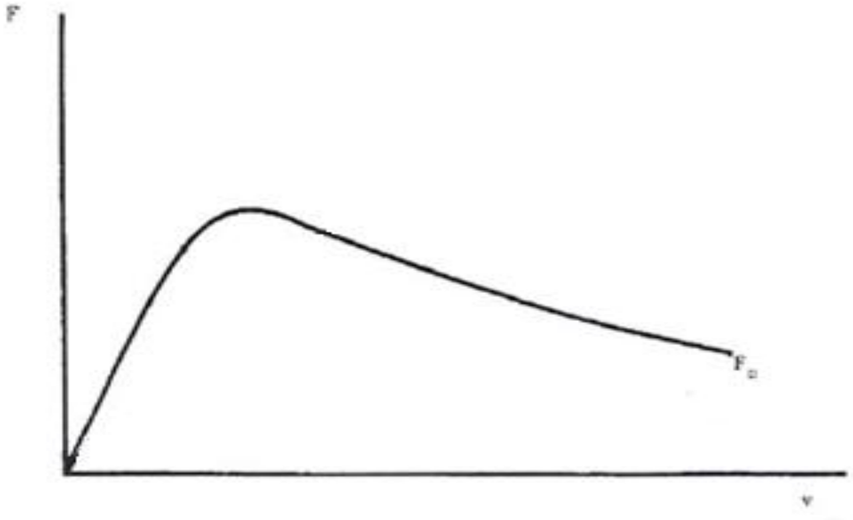


Br=1T, 공극 간격: 1.25cm =>8~10초대

공극 간격 감소
-> 총 자기저항 감소, flux양 증가
-> 디스크에서의 자속 밀도 증가

속도에 따른 Drag Force 비교

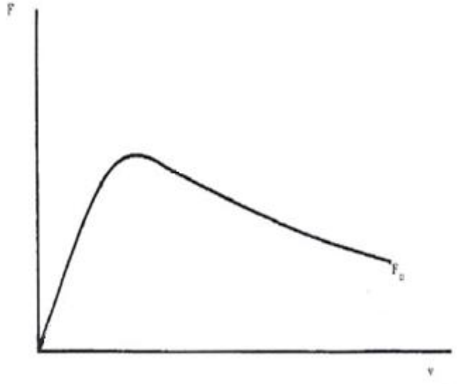
As the velocity increases, however, the magnetic drag force reaches the maximum (referred to as the drag peak) and then decreases as 1/*v.*



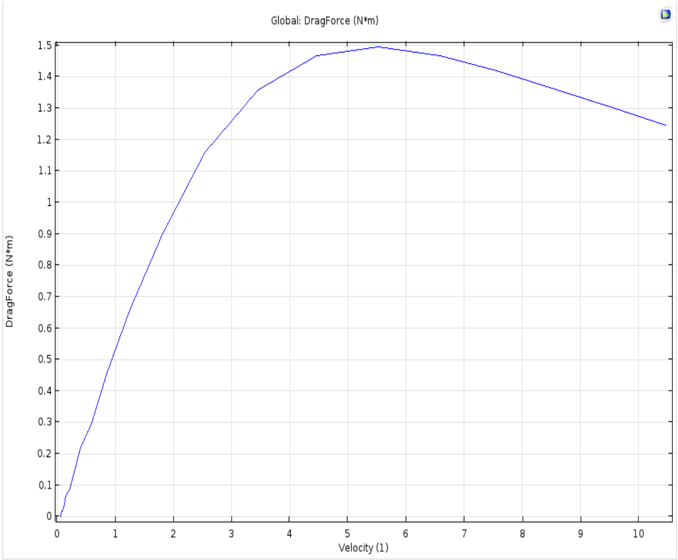
Velocity dependence of magnetic lift force F_L and magnetic drag force F_D

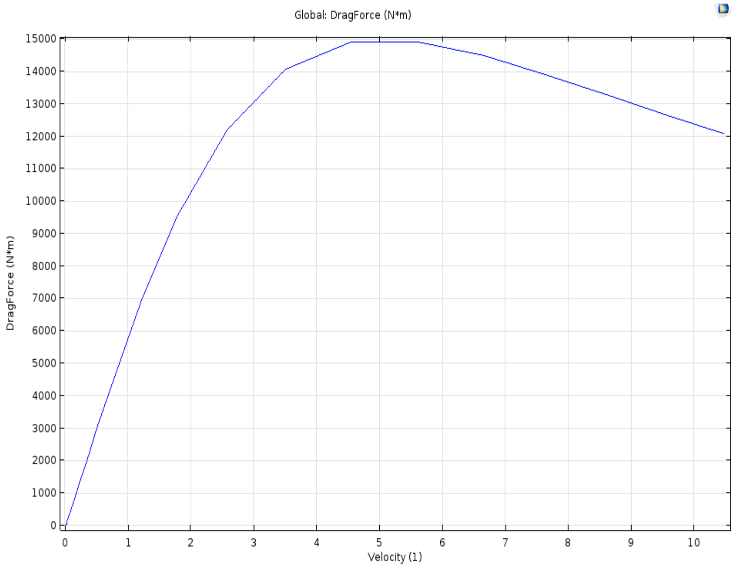
<analytic>

속도에 따른 Drag Force 비교



Velocity dependence of magnetic lift force F_L and magnetic drag force F_D





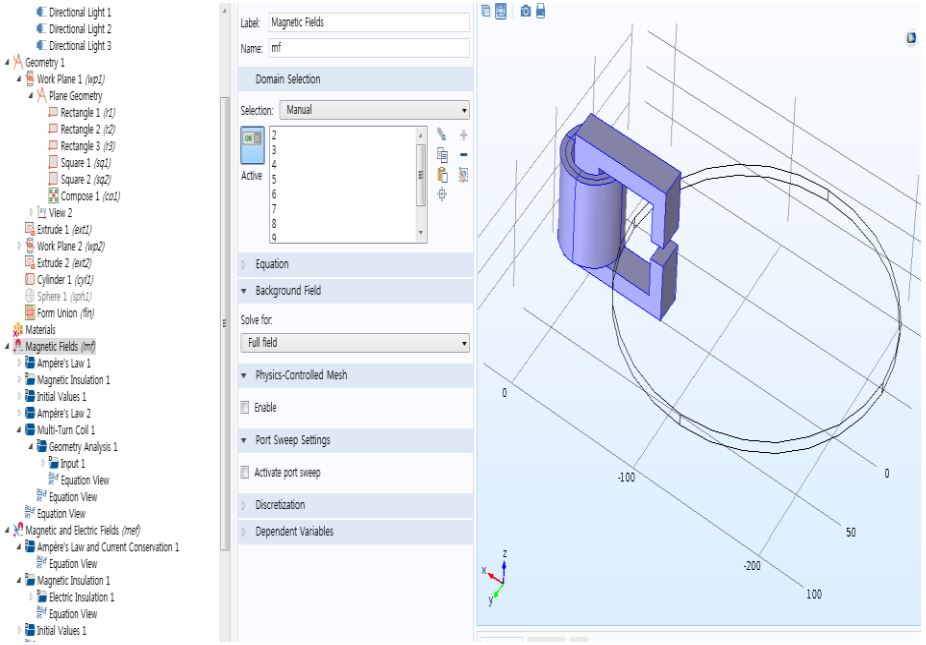
입력 변화

<analytic>

<comsol 결과>


Q
&
A

전자석 (3D multi-turn coil x)



Label: Magnetic Fields

Name: mf

Selection: Manual

2
3
4
5
6
7
8
9

Solve for: Full field

☐ Enable

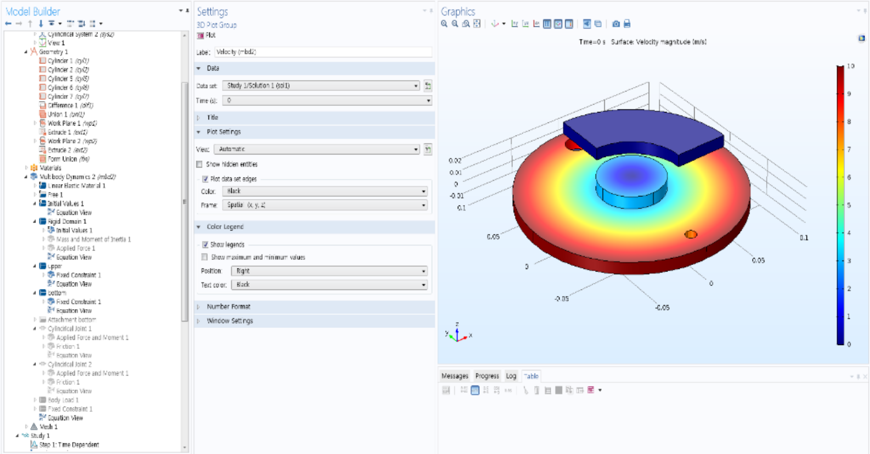
☐ Activate port sweep

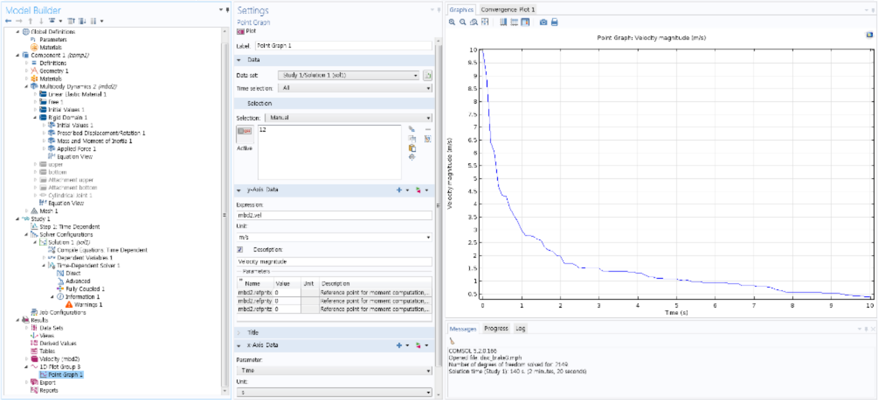
- 전자석을 설계하여 전류의 세기에 따라 자속이 생성되는 것을 시도

- Electric circuit을 통해 실제 전자석 브레이크의 전류에 따른 직관적인 해석이 가능

- 전류에 의한 자속이 공극을 통과하는 방법을 해결하지 못함

Multibody Dynamics





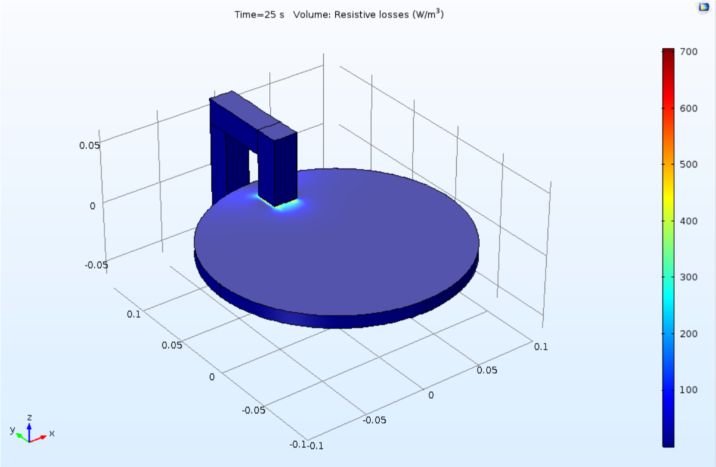
```
COMSOL 5.2.0.166
Opened file: disc_brake3.mph
Number of degrees of freedom solved for: 2149
Solution time (Study 1): 140 s. (2 minutes, 20 seconds)
```

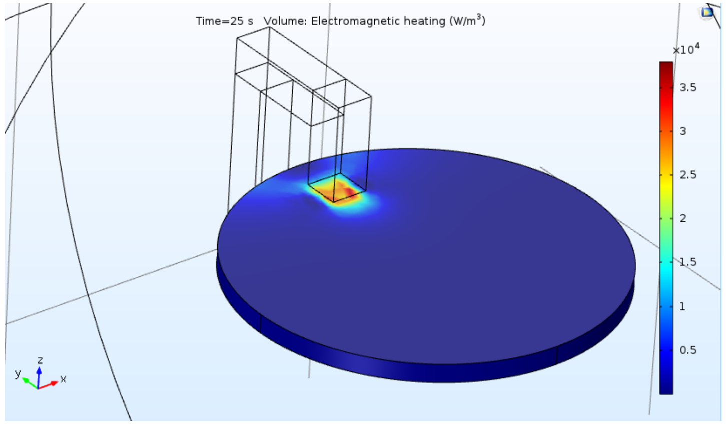
- Multi Dynamics를 이용하여 유압브레이크를 설계

- 같은 지오메트리를 가진 디스크 브레이크 거동과 Magnetic 브레이크의 거동을 시각적 비교 가능

- 브레이크를 설계하여 디스크를 회전하고 normal force를 가했으나, 이론과는 다른 해석 불가능한 데이터 생성

Heating 해석



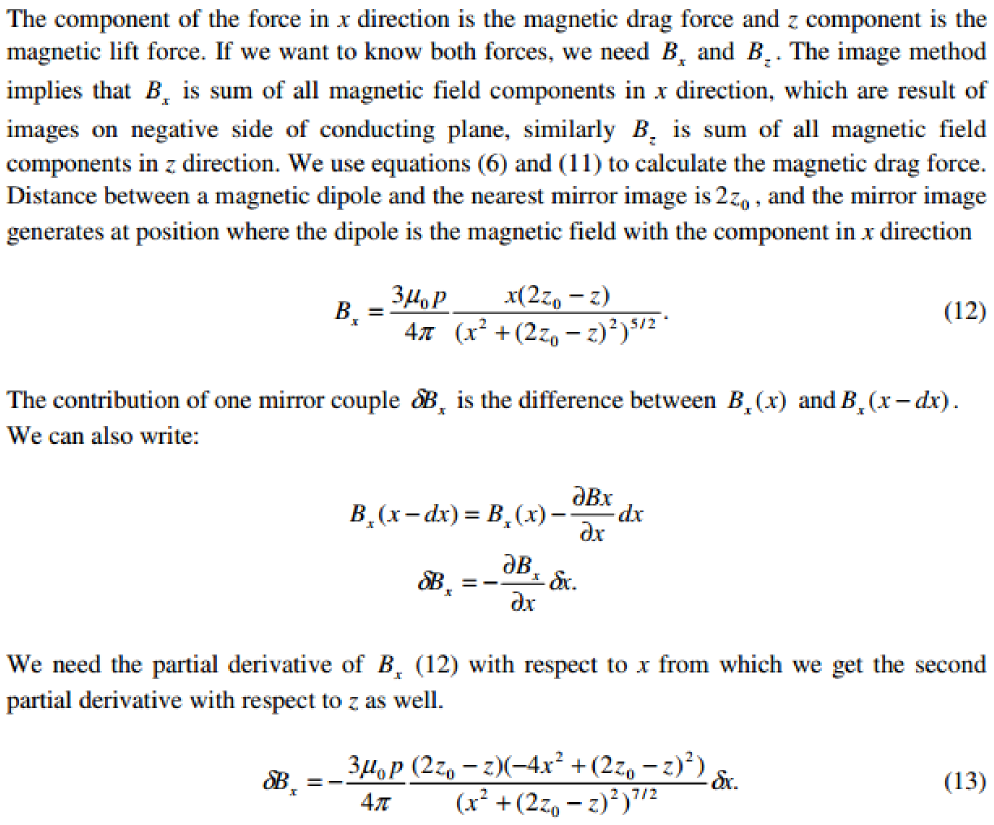


- 저항으로 인한 열 손실 분석을 통해 자속 밀도가 증가 할수록 발생하는 열이 커짐을 확인

- 전자석에는 철심 부분의 발열이 적음을 확인

- 유압 브레이크와 비교하여 패드 부분의 발열로 인한 베이퍼 록 현상이 마그네틱 브레이크에서는 관계 없음을 확인

Drag force 이론



The component of the force in x direction is the magnetic drag force and z component is the magnetic lift force. If we want to know both forces, we need B_x and B_z. The image method implies that B_x is sum of all magnetic field components in x direction, which are result of images on negative side of conducting plane, similarly B_z is sum of all magnetic field components in z direction. We use equations (6) and (11) to calculate the magnetic drag force. Distance between a magnetic dipole and the nearest mirror image is $2z_0$, and the mirror image generates at position where the dipole is the magnetic field with the component in x direction

$$B_x = \frac{3\mu_0 p}{4\pi}\frac{x(2z_0 - z)}{(x^2 + (2z_0 - z)^2)^{5/2}}. \tag{12}$$

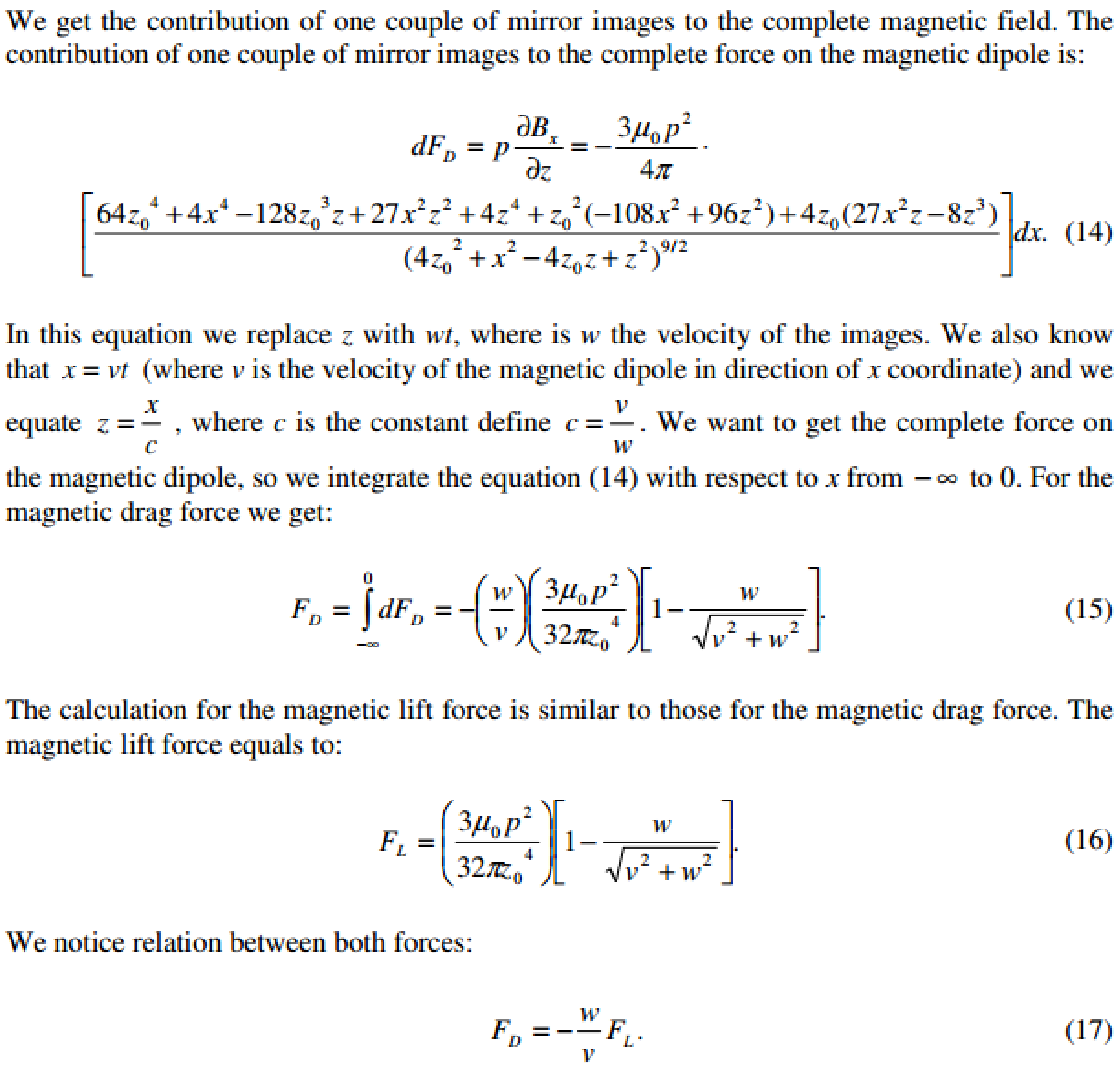
The contribution of one mirror couple δB_x is the difference between $B_x(x)$ and $B_x(x - dx)$. We can also write:

$$B_x(x - dx) = B_x(x) - \frac{\partial Bx}{\partial x}dx$$

$$\delta B_x = -\frac{\partial B_x}{\partial x}\delta x.$$

We need the partial derivative of B_x (12) with respect to x from which we get the second partial derivative with respect to z as well.

$$\delta B_x = -\frac{3\mu_0 p}{4\pi}\frac{(2z_0 - z)(-4x^2 + (2z_0 - z)^2)}{(x^2 + (2z_0 - z)^2)^{7/2}}\delta x. \tag{13}$$



We get the contribution of one couple of mirror images to the complete magnetic field. The contribution of one couple of mirror images to the complete force on the magnetic dipole is:

$$dF_D = p\frac{\partial B_x}{\partial z} = -\frac{3\mu_0 p^2}{4\pi}\cdot \left[\frac{64z_0^4 + 4x^4 - 128z_0^3 z + 27x^2z^2 + 4z^4 + z_0^2(-108x^2 + 96z^2) + 4z_0(27x^2z - 8z^3)}{(4z_0^2 + x^2 - 4z_0 z + z^2)^{9/2}}\right]dx. \tag{14}$$

In this equation we replace z with wt, where is w the velocity of the images. We also know that $x = vt$ (where v is the velocity of the magnetic dipole in direction of x coordinate) and we equate $z = \frac{x}{c}$, where c is the constant define $c = \frac{v}{w}$. We want to get the complete force on the magnetic dipole, so we integrate the equation (14) with respect to x from $-\infty$ to 0. For the magnetic drag force we get:

$$F_D = \int_{-\infty}^{0} dF_D = -\left(\frac{w}{v}\right)\left(\frac{3\mu_0 p^2}{32\pi z_0^4}\right)\left[1 - \frac{w}{\sqrt{v^2 + w^2}}\right]. \tag{15}$$

The calculation for the magnetic lift force is similar to those for the magnetic drag force. The magnetic lift force equals to:

$$F_L = \left(\frac{3\mu_0 p^2}{32\pi z_0^4}\right)\left[1 - \frac{w}{\sqrt{v^2 + w^2}}\right]. \tag{16}$$

We notice relation between both forces:

$$F_D = -\frac{w}{v}F_L. \tag{17}$$

참고 자료

- ECAD 전동기 응용 강의 자료

- MMC 차량 동역학 강의 자료

- 마그네틱 브레이크 이론 자료 URL
  http://mafija.fmf.uni-lj.si/seminar/files/2007_2008/BRAKING_MAGNETIC.pdf