

CozyMa

<서스펜션의 damper를 전자석과 코일로 대체할 시 효과 해석>

<CAE TEAM PROJECT>

2015020200 김현진

2015012915 최민석



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5. 결론 및 참고문헌
6. Q&A



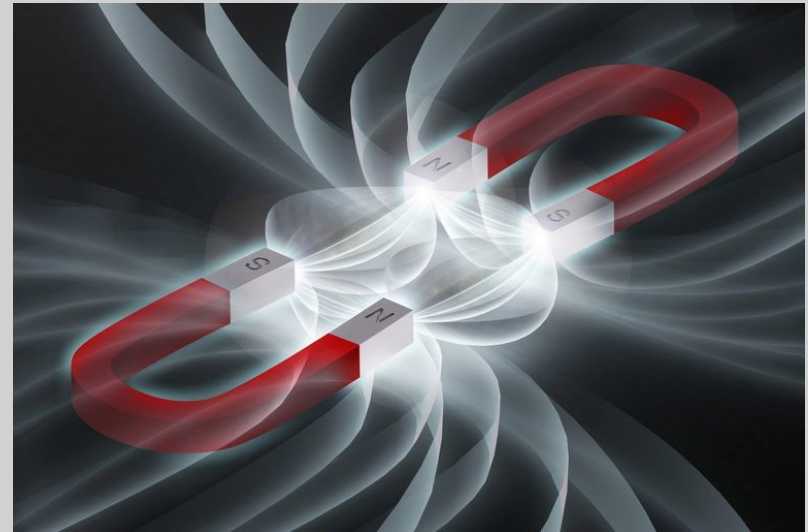
1. 팀명 소개 및 주제선정 배경

Cozy(편안한)



+

Magnetism(자기, 자성)

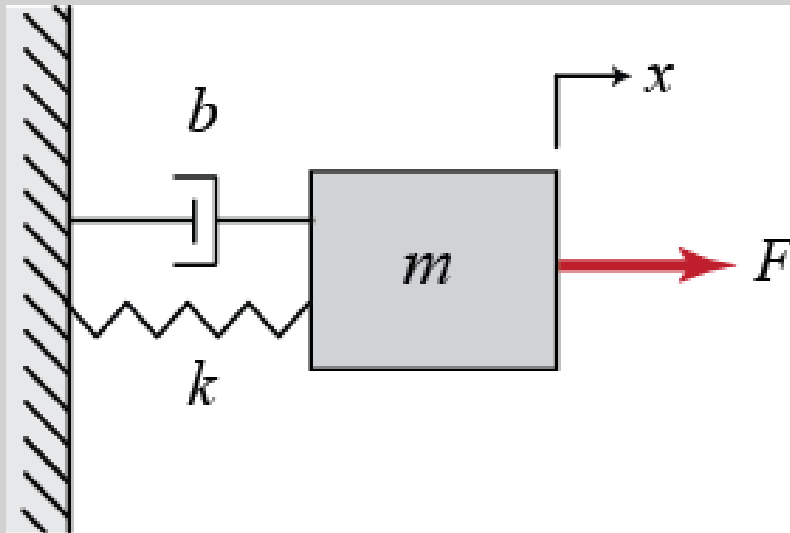


1. 팀명 소개 및 주제선정 배경

CozyMa

2. 기본 개념

Mass-Spring-Damper SYSTEM

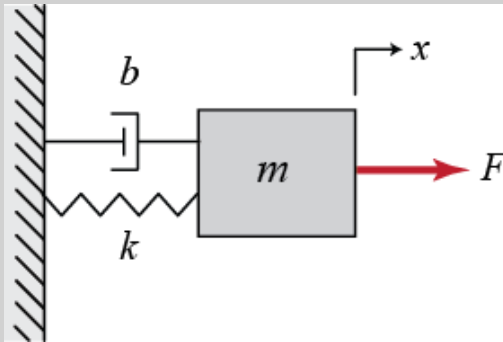


$$F_s = -Kx$$

$$F_d = -b\dot{x}$$

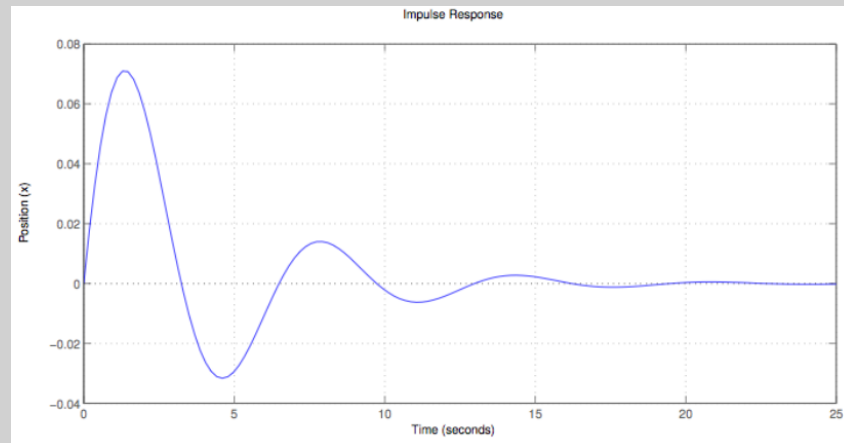
2. 기본 개념

Mass-Spring-Damper SYSTEM



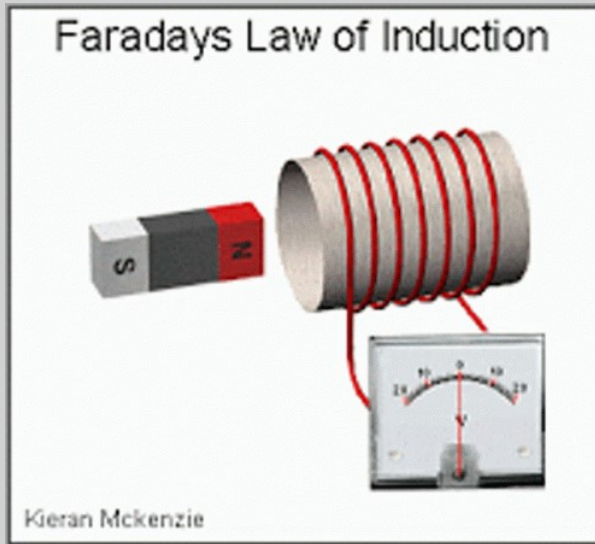
$$1) F = \delta(t)$$

$$2) m\ddot{x} = -kx - b\dot{x} + \delta(t)$$

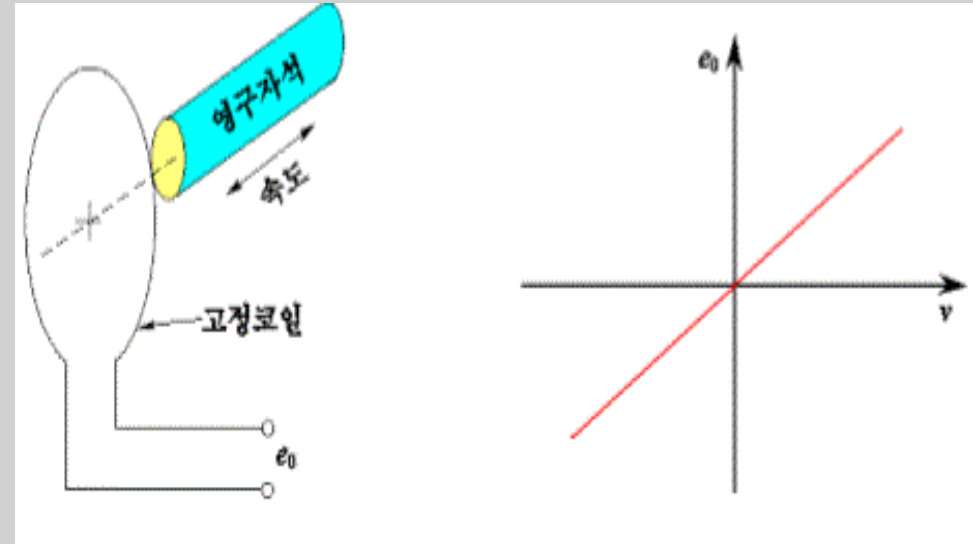


2. 기본 개념

Electromagnetic induction



$$V = -N \frac{d\phi}{dt}$$



자석의 **속도** \propto 유도된 **전압**

2. 기본 개념

Reluctance force

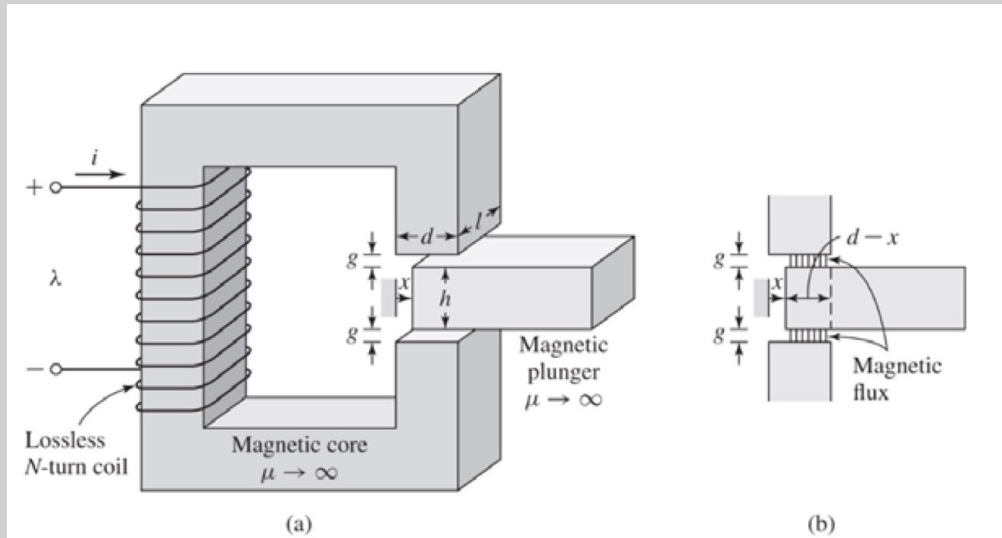


Figure 3.6 (a) Relay with movable plunger for Example 3.2 (b) Detail showing air-gap configuration with the plunger partially removed.

$$R = \frac{\mu l}{A}$$

$$L = \frac{N^2}{R_{eq}} = \frac{N^2}{R_{core} + R_{gap} + R_{plun}}$$

$$= \frac{\mu_0 N^2}{2g} A_{gap} = \frac{\mu_0 N^2}{2g} l(d-x)$$

$$\rightarrow \frac{dL}{dx} = - \frac{\mu_0 N^2 l}{2g}$$

$$F = \frac{I^2}{2} \cdot \frac{dL}{dx} = - \frac{\mu_0 N^2 l}{4g} I^2$$

3. COMSOL 해석

$$F = -\frac{\mu_0 N^2 l}{4g} I^2$$

1. 힘의 방향

2. I^2 에 비례

3. Plunger 변위와 무관

COMSOL-PARAMETER

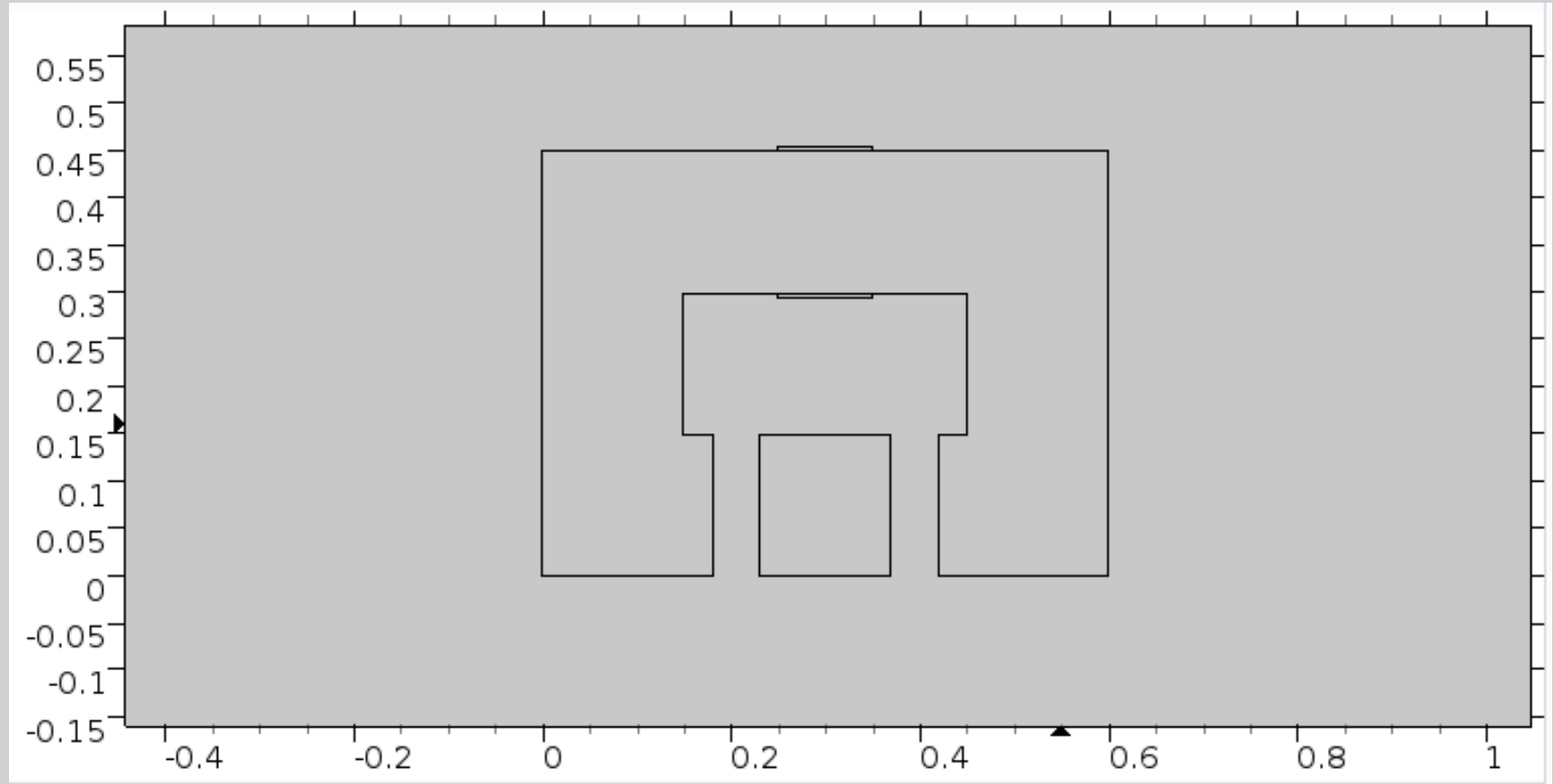
Parameters

Parameters

Name	Expression	Value	Description
wc	60[cm]	0.6 m	Core 폭
dc	45[cm]	0.45 m	Core 높이
l	15[cm]	0.15 m	Core 면 폭/높이
pc	3[cm]	0.03 m	Core 튀어나온 길이
lcoil	10[cm]	0.1 m	Coil 폭
dcoil	0.5[cm]	0.005 m	Coil 높이
N	5000	5000	Coil 감은수
lg	5[cm]	0.05 m	Air gap
mu	10000	10000	비투자율

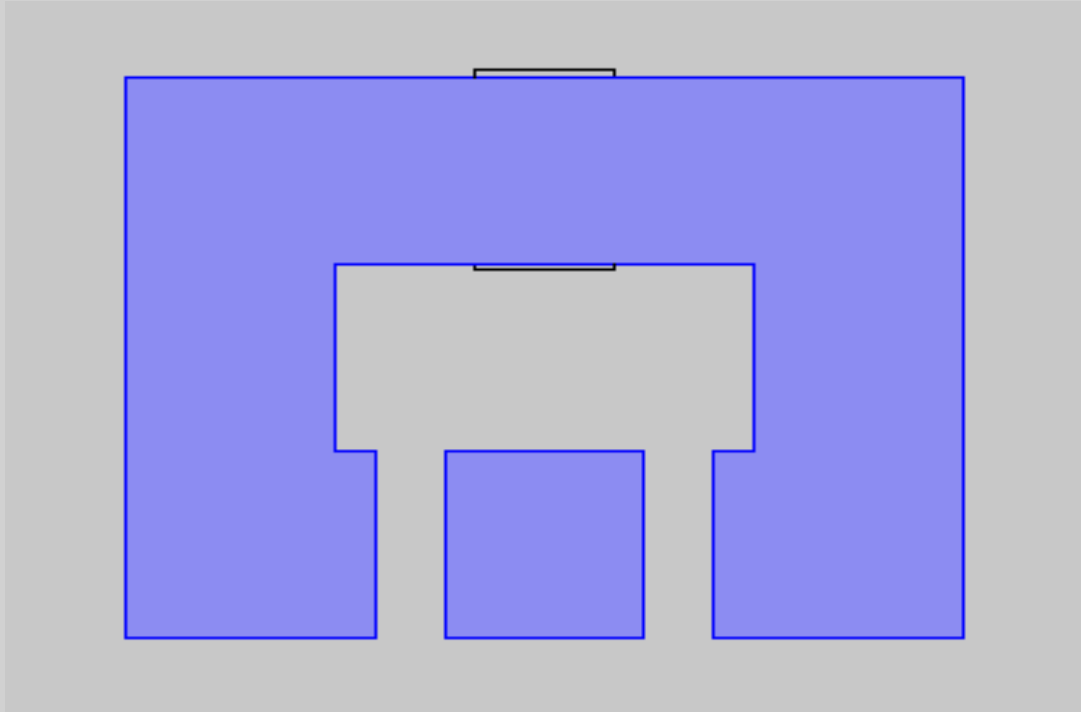
3. COMSOL - Geometry

- Geometry 1
 - Rectangle 1 (*r1*)
 - Rectangle 2 (*r2*)
 - Difference 1 (*dif1*)
 - Rectangle 3 (*r3*)
 - Rectangle 4 (*r4*)
 - Difference 2 (*dif2*)
 - Rectangle 5 (*r5*)
 - Rectangle 6 (*r6*)
 - Square 1 (*sq1*)
 - Form Union (*fin*)

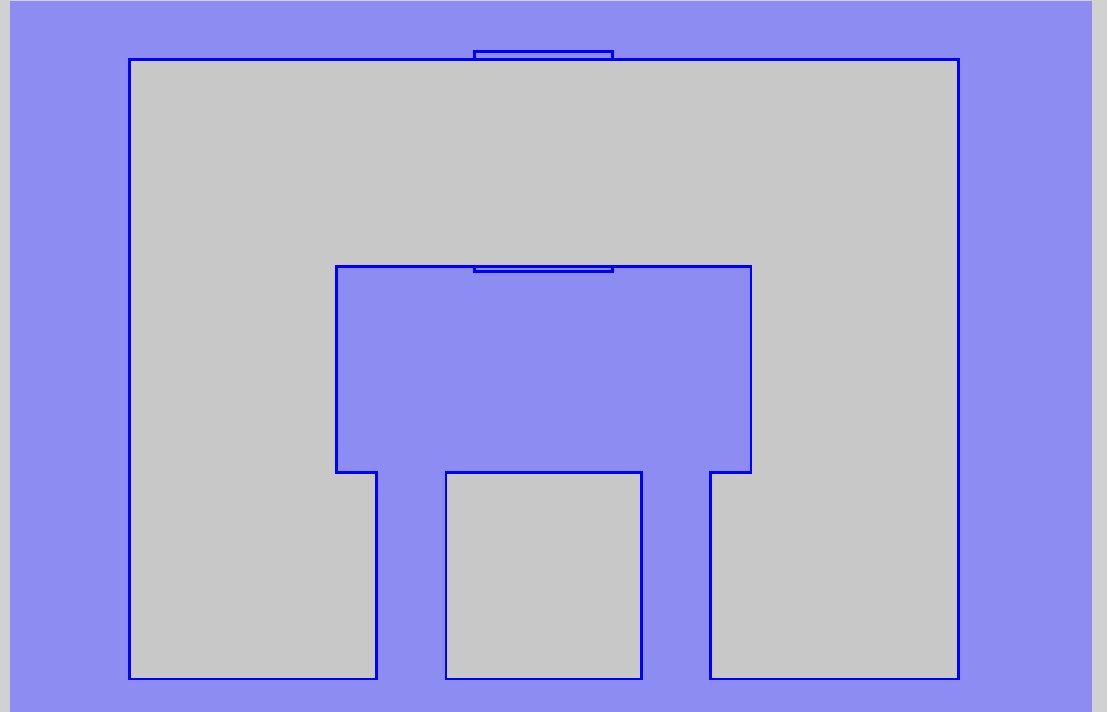


2D-AC/DC-Magnetic Fields -Stationary

3. COMSOL 해석 - Permeability

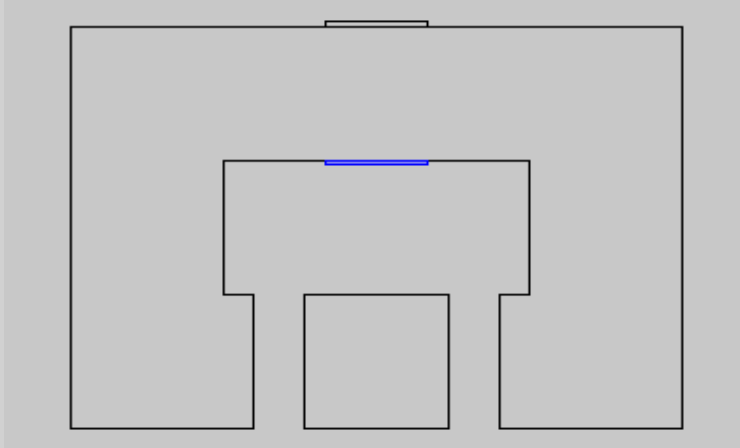


$B = \mu_0 \mu_r H$
Relative permeability:
 μ_r
 1

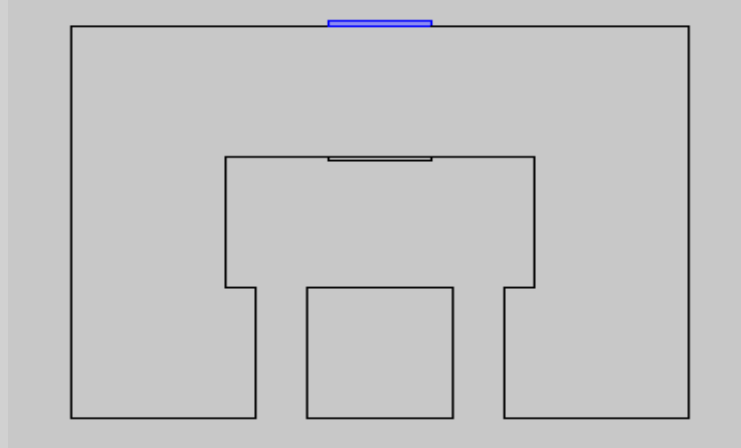


$B = \mu_0 \mu_r H$
Relative permeability:
 μ_r
 1

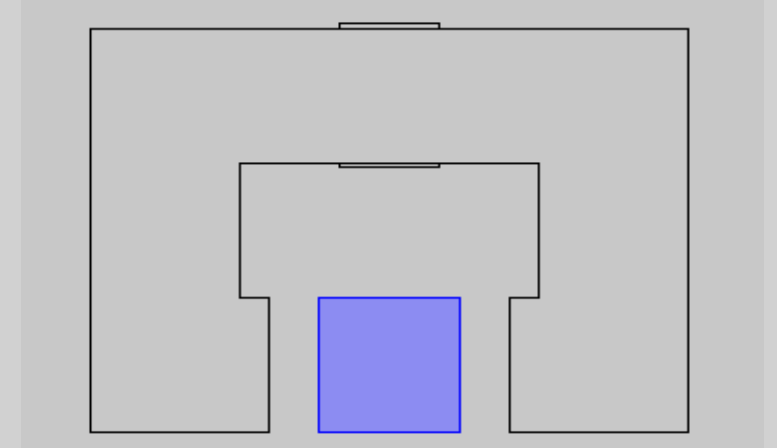
3. COMSOL 해석 - J,F



J_e	0	x	A/m ²
	0	y	
	$-I*N/(lcoil*dcoil)$	z	



J_e	0	x	A/m ²
	0	y	
	$I*N/(lcoil*dcoil)$	z	



- Ampère's Law 2
- External Current Density 1
- External Current Density 2
- Force Calculation 1

3. COMSOL 해석-Mesh

Mesh 1

Size

Element Size

Calibrate for:

General physics

Predefined Custom

Extremely fine

Free Triangular 1

Settings

Free Triangular

Build Selected Build All

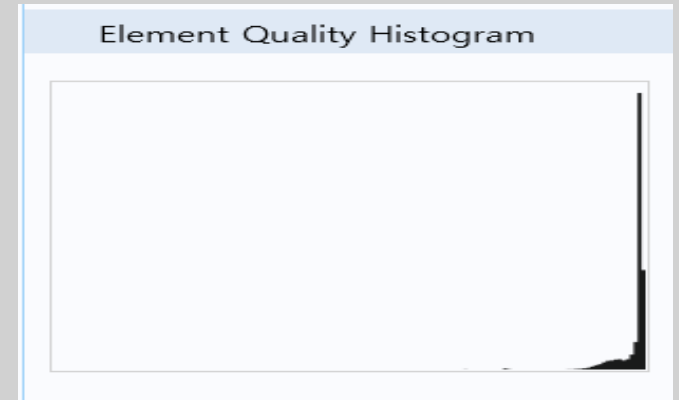
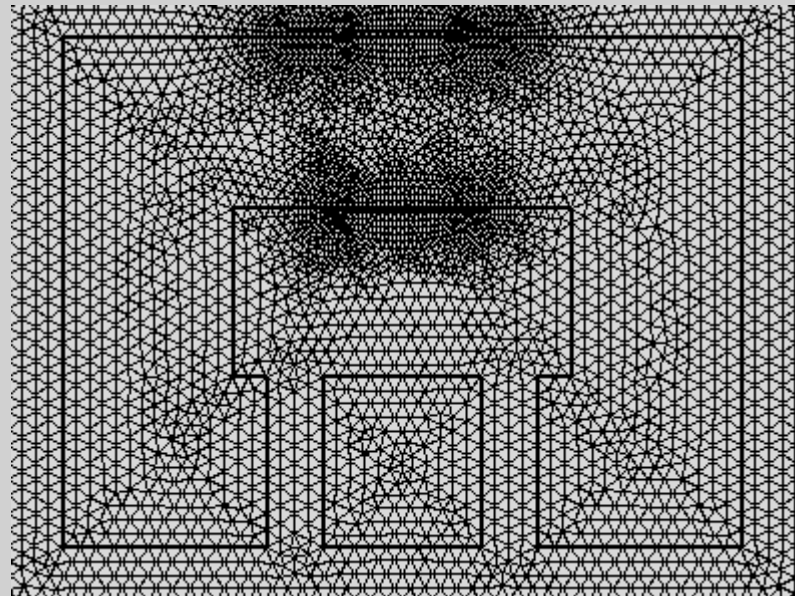
Label: Free Triangular 1

Domain Selection

Geometric entity level: Entire geometry

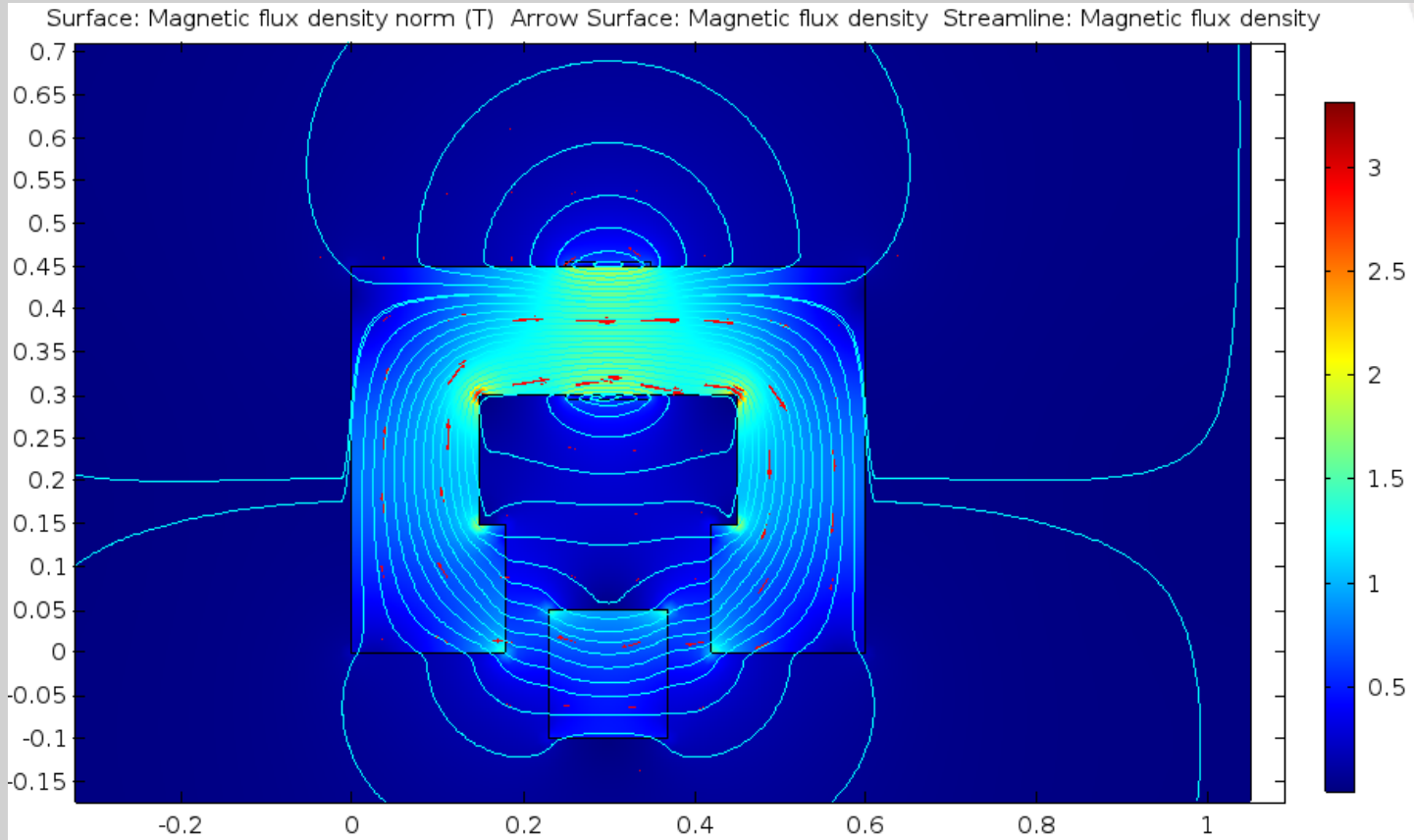
ON

Active



3. COMSOL 해석

- ▲ Magnetic Flux Density Norm (mf)
- Surface 1
- Arrow Surface 1
- Streamline 1



3. COMSOL 해석

검증1 - 힘의 방향

방법 : x에 따른 flux data 추출

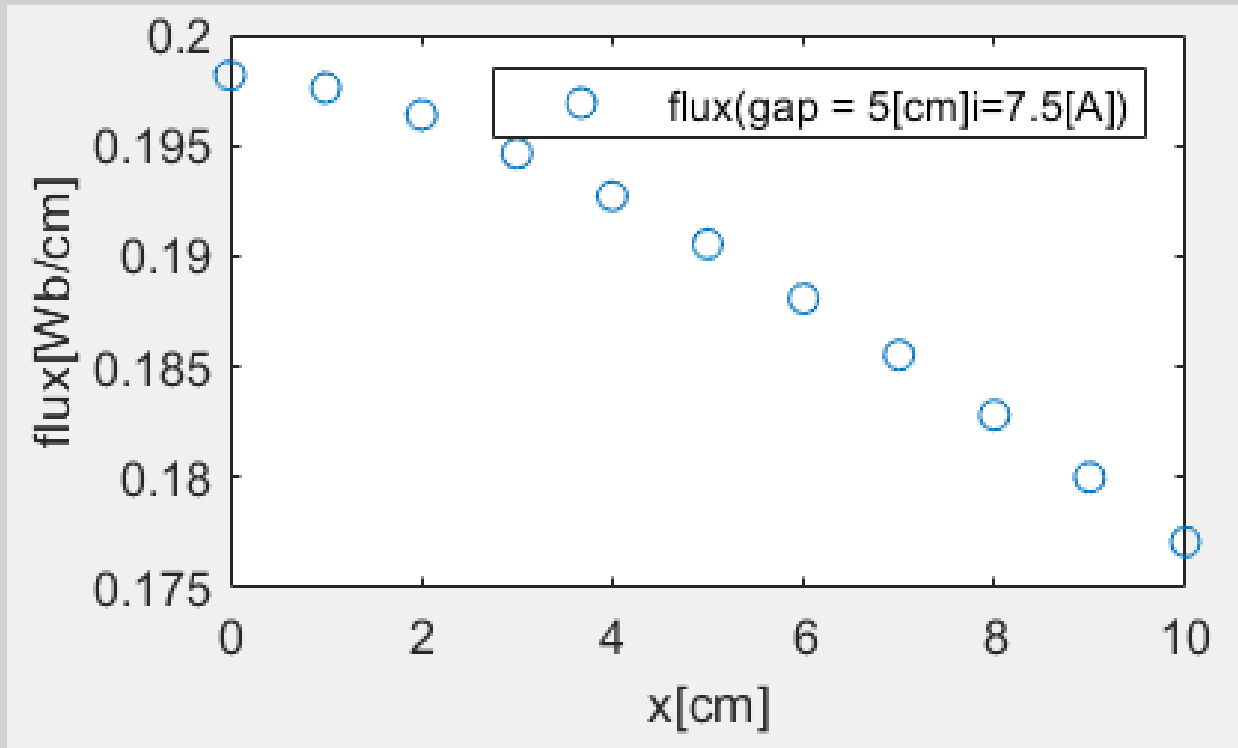
The screenshot illustrates the workflow in COMSOL for extracting flux data. In the 'Results' tree, the 'Derived Values' node is expanded, and '철심자속' (Core Flux) is selected. An arrow indicates the next step is to view the 'Tables' section, where 'fluxdata' is highlighted. A central diagram shows a magnetic core with a red arrow pointing up and a green arrow pointing left. A bottom window titled 'fluxdata' displays a table of magnetic flux density values.

Magnetic flux density, x component (Wb/m)	Magnetic flux density, x component (Wb/m)	Magnetic f
0.19758	0.19638	0.19465

3. COMSOL 해석

검증1 - 힘의 방향

방법 : x에 따른 flux data 추출



$$x \uparrow \rightarrow \Phi \downarrow \rightarrow R \uparrow \rightarrow L \downarrow$$

힘의 방향은 변위의 반대

3. COMSOL 해석

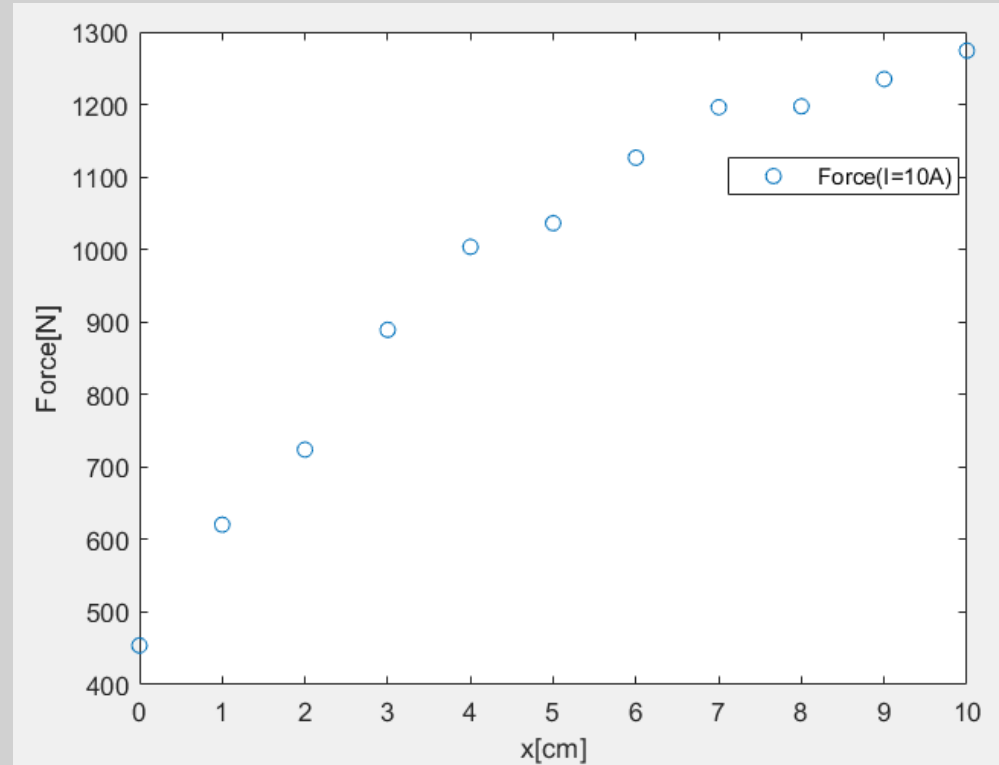
검증2 - x와 무관

I=10A, x에 따른 force data 추출



I=10A

Electromagnetic force, y component (N)	Electromagnetic force, y componen
453.90	620.51



3. COMSOL 해석

검증3 - I^2 에 비례

$x=10\text{cm}$, I 에 따른 force data 추출

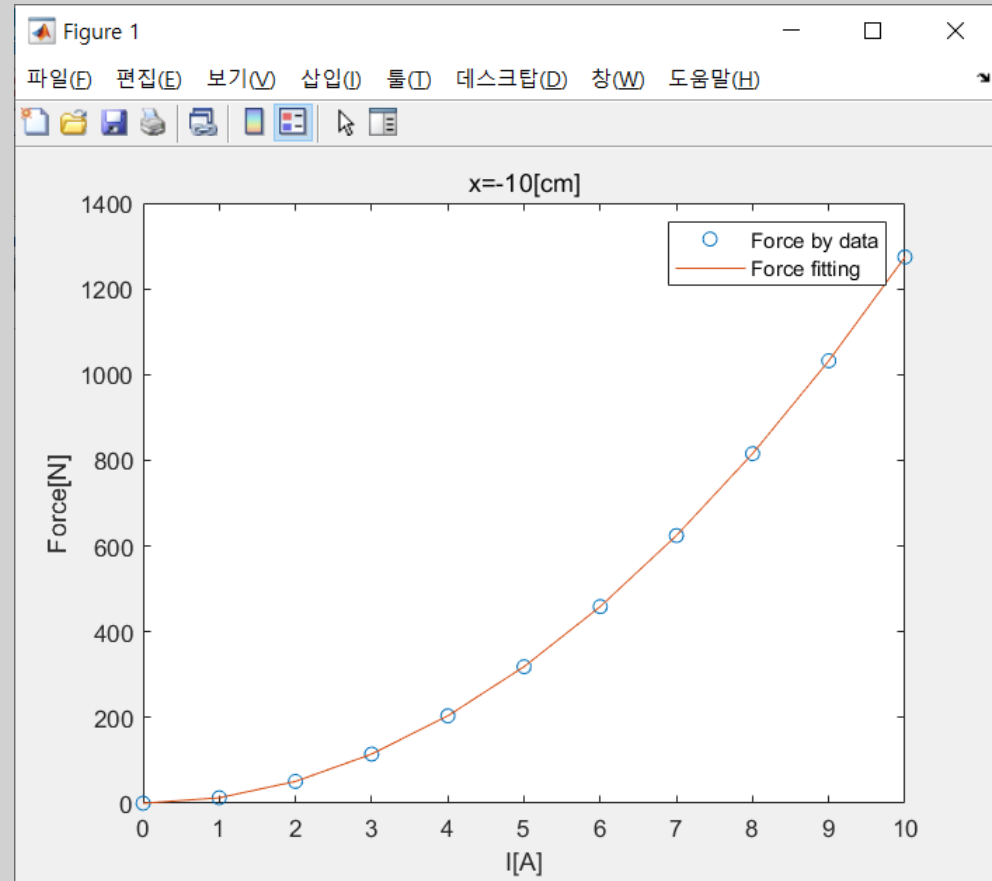
Derived Values

- 철심자속
- 공극자속
- force**



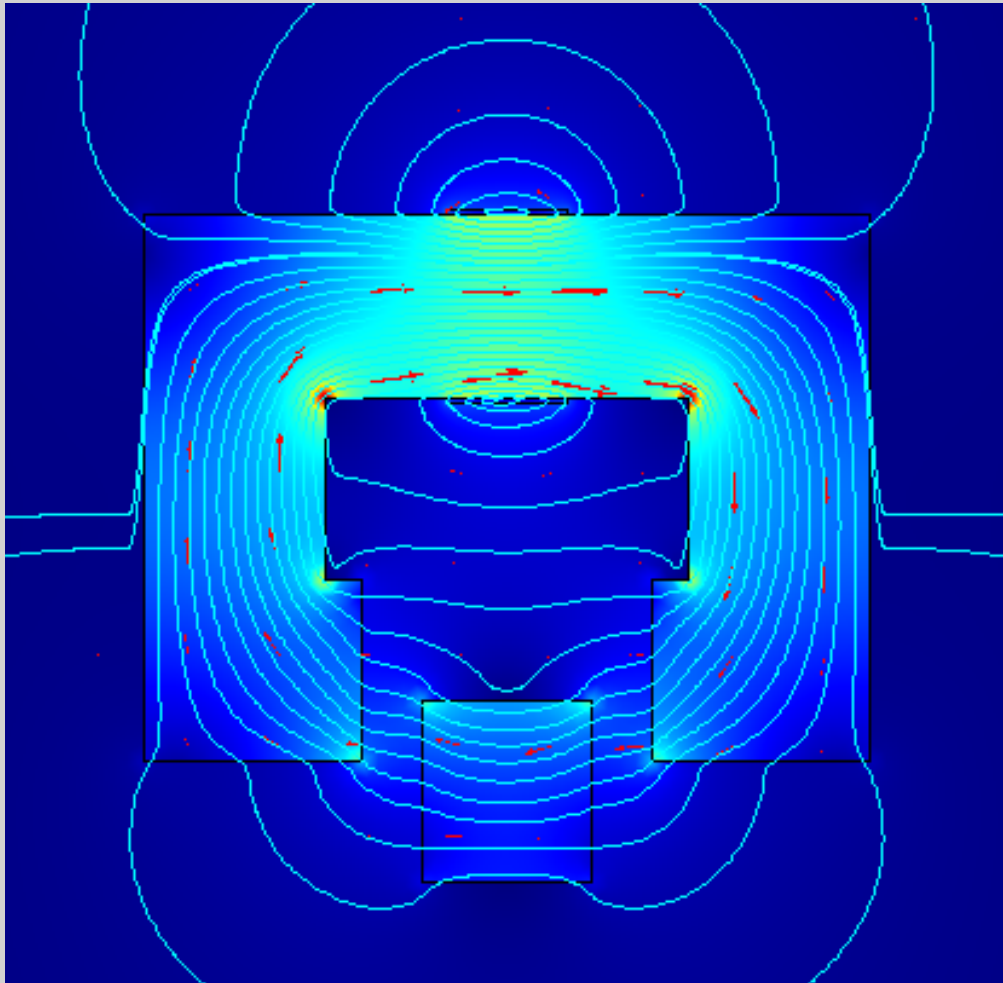
$x=-10$

Electromagnetic force, y component (N)	Electromagnetic force, y componen
12.743	50.973



3. COMSOL 해석

오차 원인



1. $\mu_{core} = \mu_{plunger} = 10,000 (R_{eq} \neq R_{gap})$

$$L = \frac{N^2}{R_{eq}} = \frac{N^2}{R_{core} + R_{gap} + R_{plun}}$$

2. Fringing effect & Leakage flux

$$A_{gap} \neq l(d - x)$$

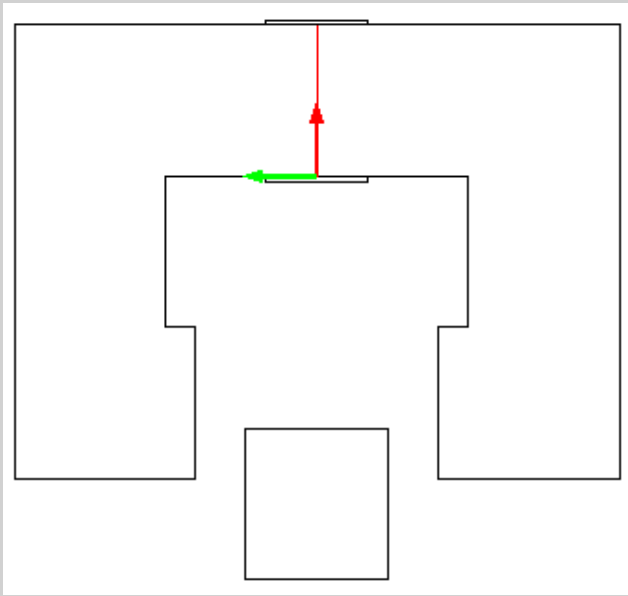
→ **Nonlinear function of x**

$$\therefore F = \frac{I^2}{2} \cdot \frac{dL}{dx} \neq -\frac{\mu_0 N^2 l}{4g} I^2$$

3. COMSOL 해석

오차 원인

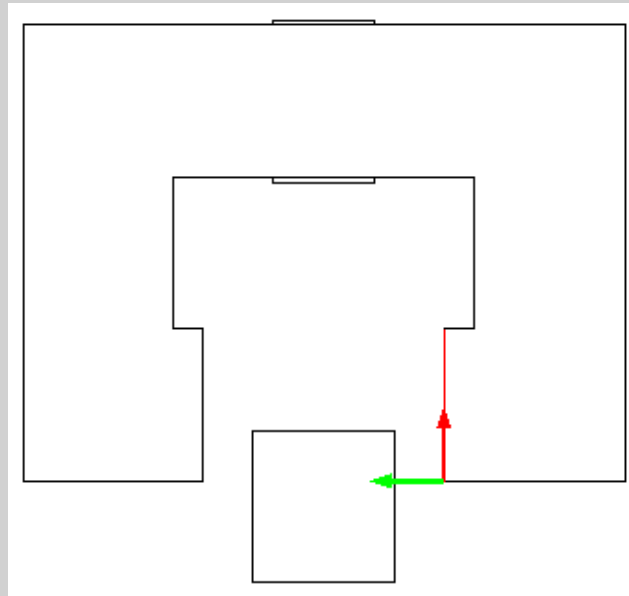
<철심 자속>



Magnetic flux density, x component (Wb/m)

0.24154

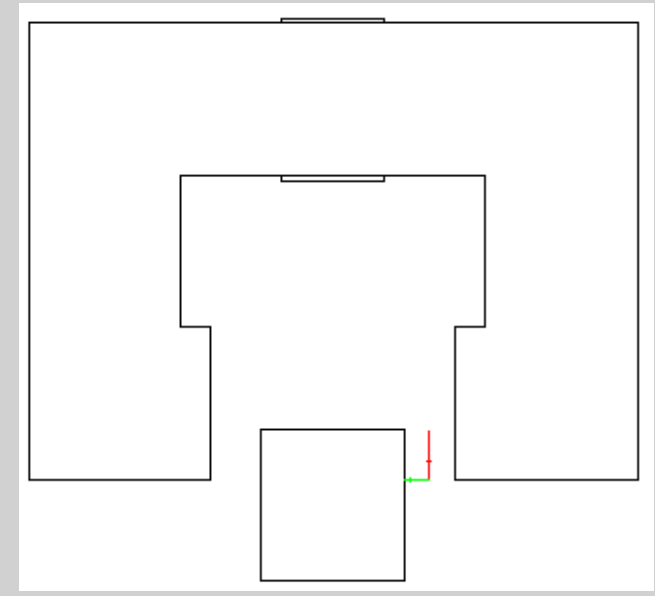
<철심 끝 자속>



Magnetic flux density, x component (Wb/m)

-0.075883

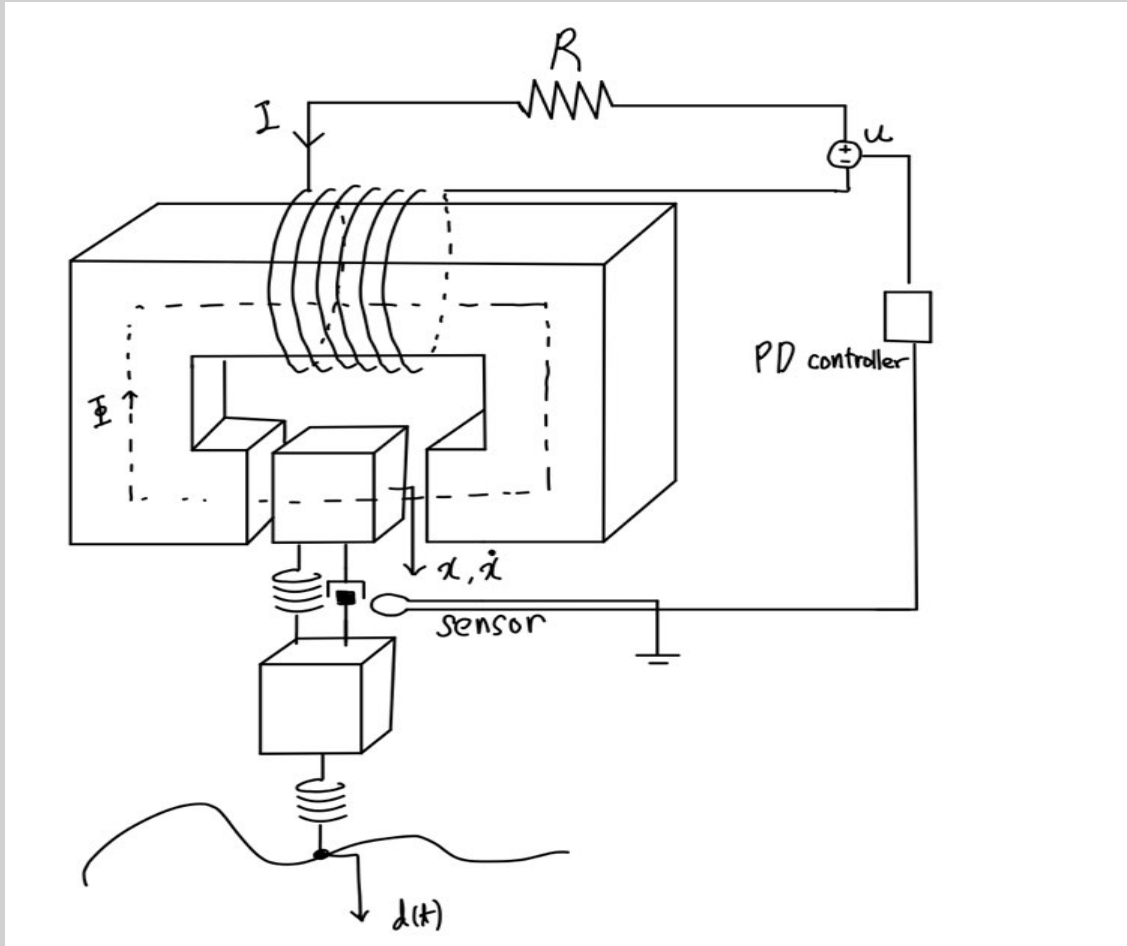
<공극 자속>



Magnetic flux density, x component (Wb/m)

-0.029932

4. SIMULINK 분석



```
K_sus=30e3;  
C_sus=1950;  
K_tire=3.4e5;  
m_body=2065;  
m_wheel=48.3;  
V=20;  
mu0=4*pi*10^-7;  
g=0.05;  
h=0.15;  
L=0.15;  
N=5000;  
alpha=mu0*L*N^2/(2*g);  
R=20;  
Ce=200;
```

4. SIMULINK 분석

※ 전체 system

$$1) m_b \ddot{x}_b = -k_s(x_b - x_w) - c_s(\dot{x}_b - \dot{x}_w) + F_r$$

$$2) m_w \ddot{x}_w = -k_s(x_w - x_b) - c_s(\dot{x}_w - \dot{x}_b) + k_t(x_w - d)$$

$$3) V = Ri + \frac{d(L(x_b) \cdot i)}{dt} = Ri + \frac{\partial L(x_b)}{\partial x_b} \frac{dx_b}{dt} i + \frac{di}{dt} L(x_b)$$

$$4) N_c Bl \frac{dx_b}{dt} = V$$

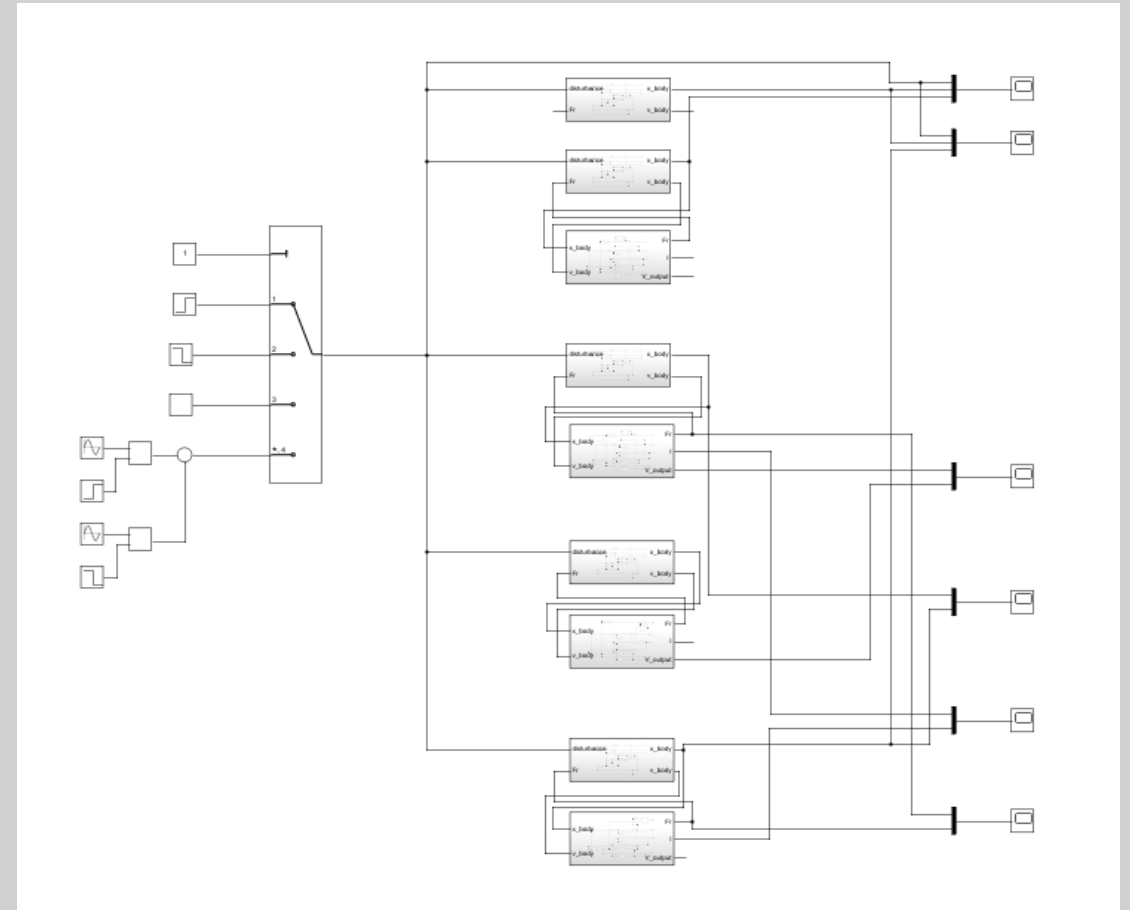
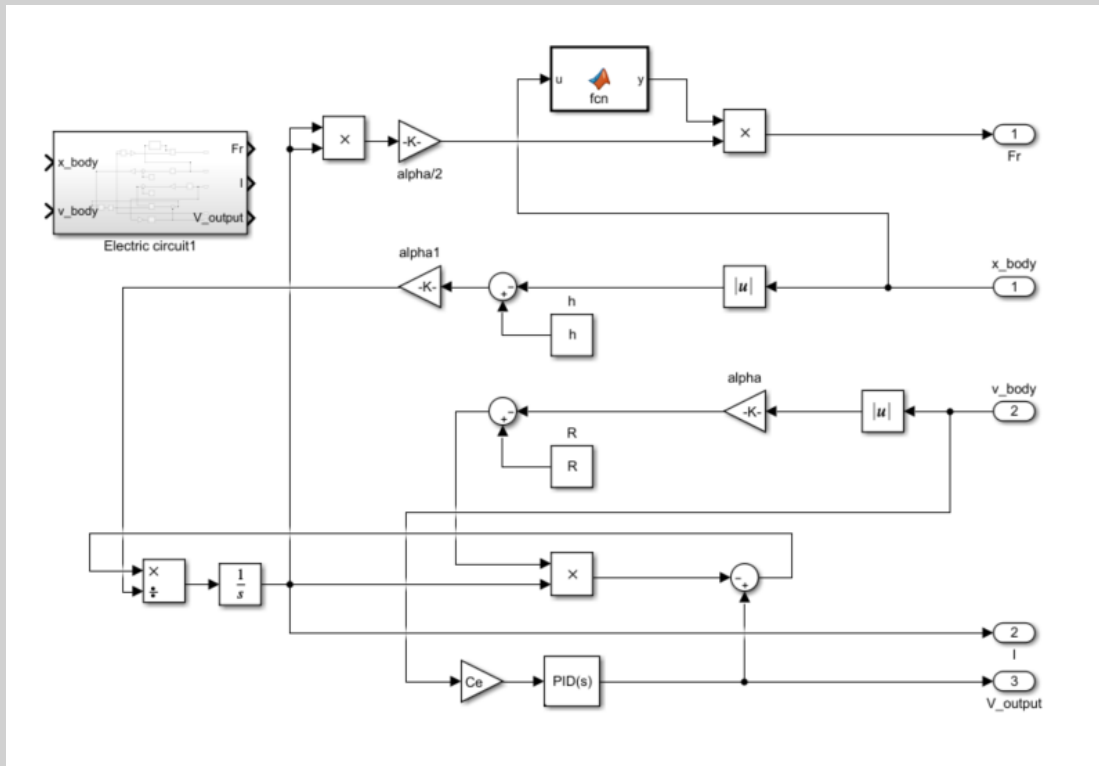
$$5) F_r = -\frac{\mu_0 N^2 l}{4g} i^2$$

1), 2) : mass, spring, damper system

3), 4), 5) : **electromagnetic system**

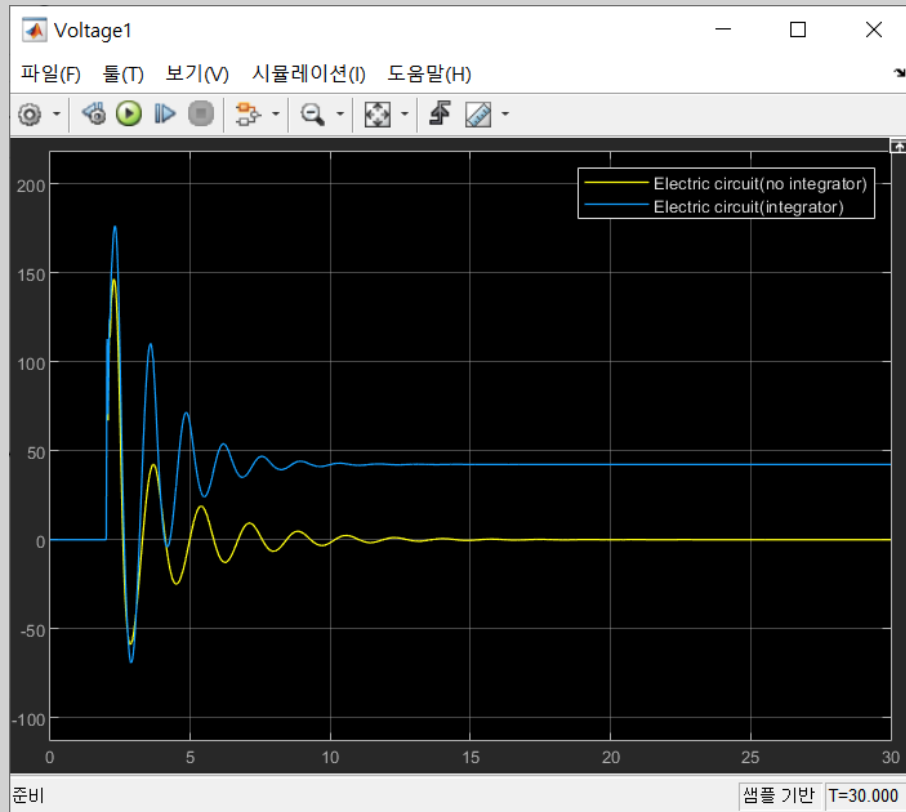
4. SIMULINK 분석

※ 전체 system



4. SIMULINK 분석

※ PD 제어를 사용한 이유



Integrator사용시



이전 step의 속도의 적분 값을 다음 step에 반영



즉, Plunger의 변위 값이 전압에 영향을 끼침



e_{ss} 발생!!

4. SIMULINK 분석

※ 이론 값 VS Comsol data

$$F_r = -\frac{\mu_0 N^2 l}{4g} i^2$$



<가정>

1. Core 및 Plunger의 상대 투자율 : ∞
2. 공극에서의 **Fringing effect 무시**

4. SIMULINK 분석

※ 이론 값 VS Comsol data

Lookup Table Editor: y1_1/Electric circuit_comsol/2-D Lookup Table1

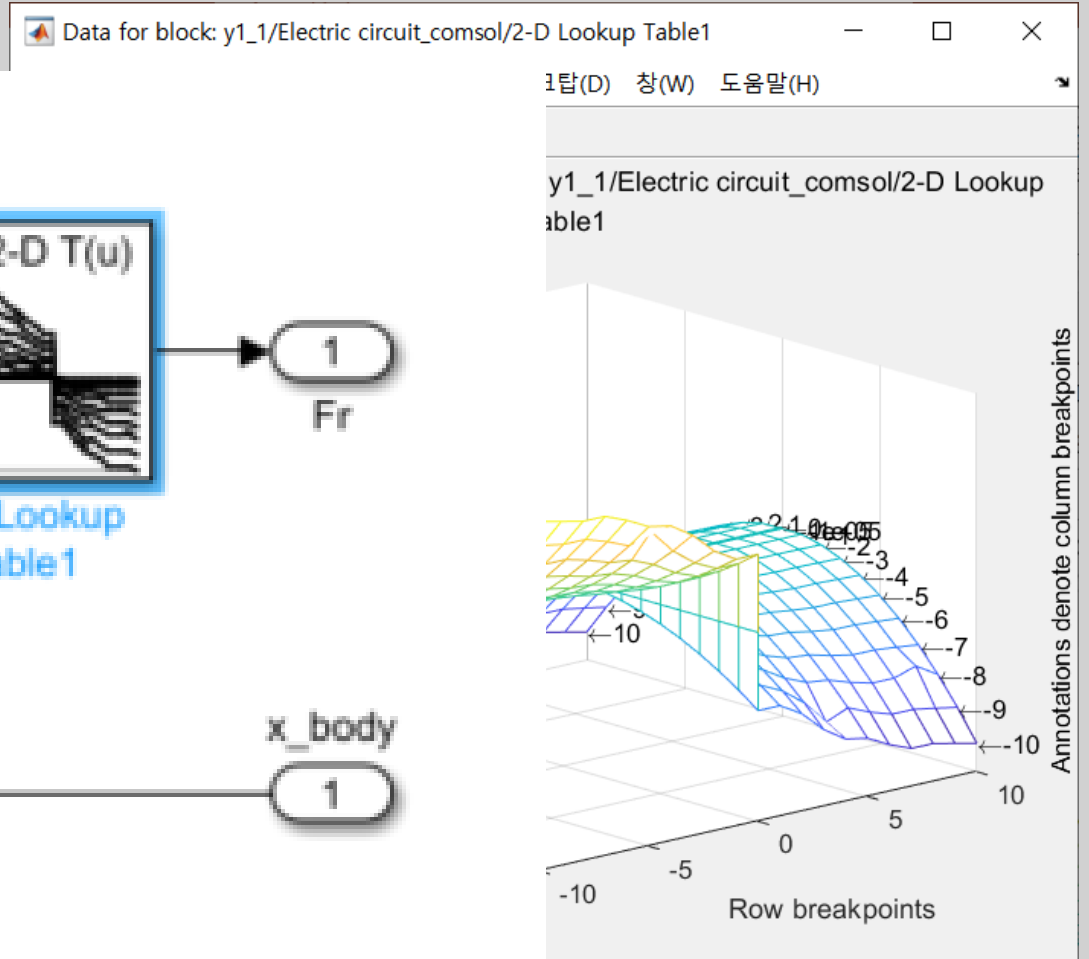
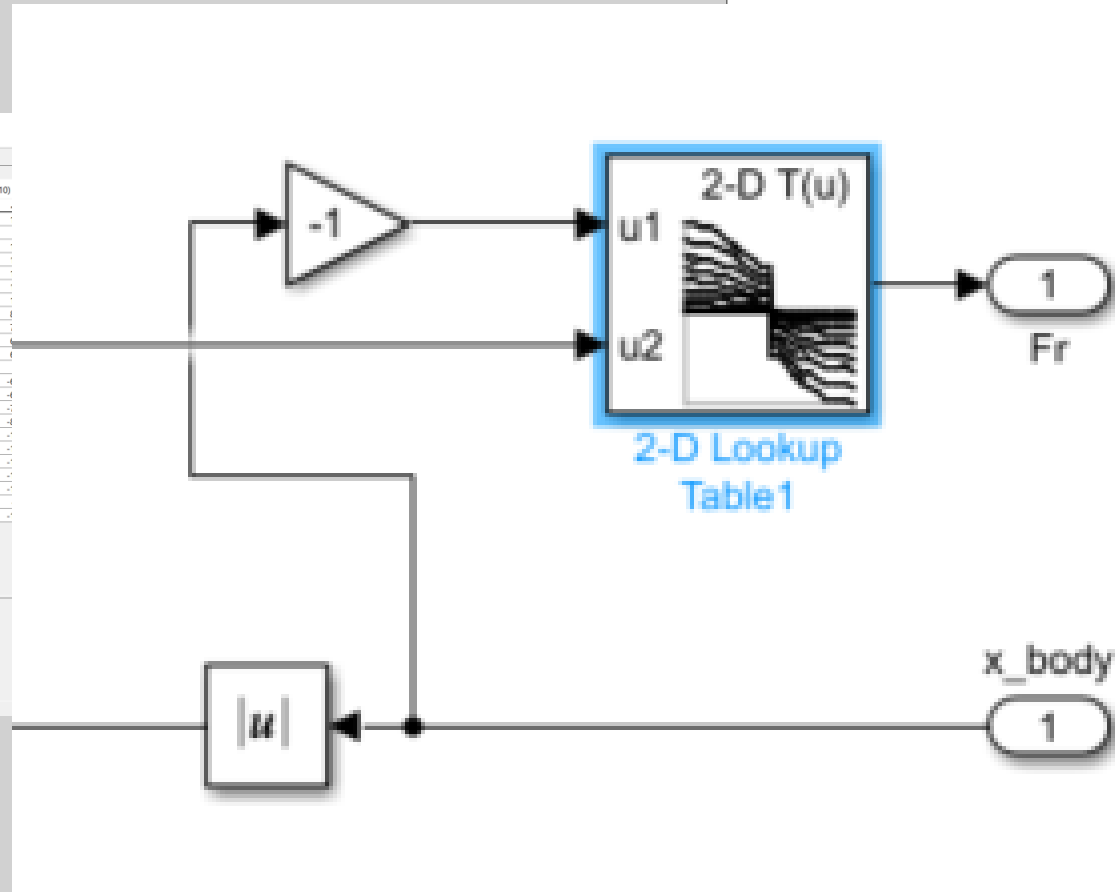
Viewing "n-D Lookup Table" block data [T.C.]:

Row	Column	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1)	-10	1274.3	1032.2	815.56	624.42	458.75	318.58	203.89	114.69	50.973	-
(2)	-9	1235	1000.3	709.39	605.15	444.6	308.75	197.6	111.15	49.4	-
(3)	-8	1197.5	969.95	766.38	586.76	431.09	299.37	191.59	107.77	47.899	-
(4)	-7	1196.2	968.91	765.55	586.13	430.62	299.04	191.39	107.66	47.847	-
(5)	-6	1126.6	912.55	721.03	552.04	405.58	281.65	180.26	101.39	45.064	-
(6)	-5	1036.3	839.38	663.22	507.78	373.06	259.07	165.8	93.265	41.451	-
(7)	-4	1003.7	912.98	642.35	491.8	361.32	250.92	160.59	90.331	40.147	-
(8)	-3	889.27	720.31	569.14	435.74	320.14	222.32	142.28	80.035	35.571	-
(9)	-2	724.01	586.45	463.37	354.76	260.64	181	115.84	65.161	28.96	-
(10)	-1	620.51	502.61	397.12	304.05	223.38	155.13	99.281	55.846	24.82	-
(11)	0	620.51	502.61	397.12	304.05	223.38	155.13	99.281	55.846	24.82	-
(12)	1	0	0	0	0	0	0	0	0	0	-
(13)	1e-05	-620.51	-502.61	-397.12	-304.05	-223.38	-155.13	-99.281	-55.846	-24.82	-
(14)	1	-620.51	-502.61	-397.12	-304.05	-223.38	-155.13	-99.281	-55.846	-24.82	-
(15)	2	-724.01	-586.45	-463.37	-354.76	-260.64	-181	-115.84	-65.161	-28.96	-
(16)	3	-889.27	-720.31	-569.14	-435.74	-320.14	-222.32	-142.28	-80.035	-35.571	-
(17)	4	-1003.7	-912.98	-642.35	-491.8	-361.32	-250.92	-160.59	-90.331	-40.147	-
(18)	5	-1036.3	-839.38	-663.22	-507.78	-373.06	-259.07	-165.8	-93.265	-41.451	-
(19)	6	-1126.6	-912.55	-721.03	-552.04	-405.58	-281.65	-180.26	-101.39	-45.064	-
(20)	7	-1196.2	-968.91	-765.55	-586.13	-430.62	-299.04	-191.39	-107.66	-47.847	-
(21)	8	-1197.5	-969.95	-766.38	-586.76	-431.09	-299.37	-191.59	-107.77	-47.899	-
(22)	9	-1235	-1000.3	-709.39	-604.15	-444.6	-308.75	-197.6	-111.15	-49.4	-
(23)	10	-1274.3	-1032.2	-815.56	-624.42	-458.75	-318.58	-203.89	-114.69	-50.973	-

Data Type: Row: double Column: double Table: double

Dimension Selector: Dimension size: 23 23 Select 2-D slice: All All

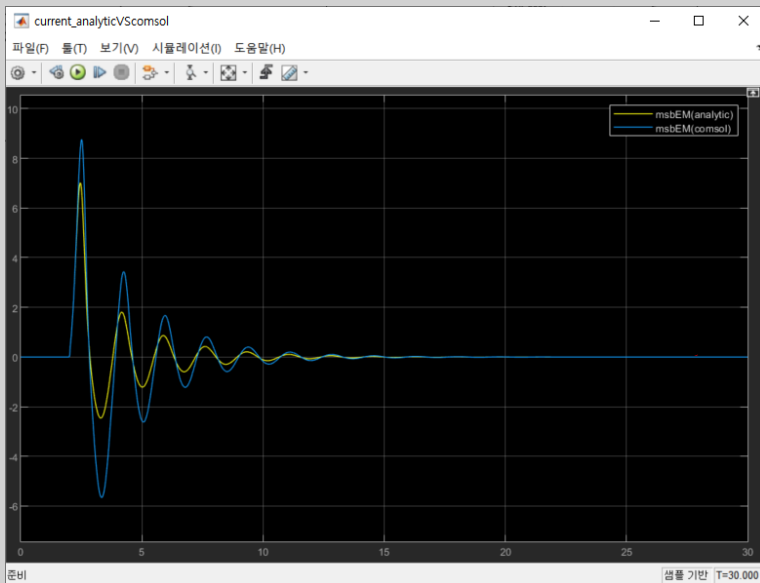
Transpose display



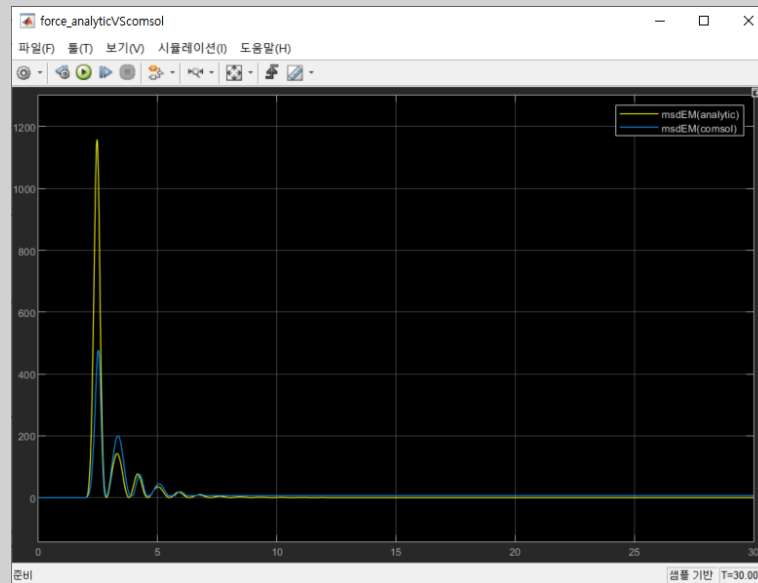
4. SIMULINK 분석

※ 이론 값 VS Comsol data

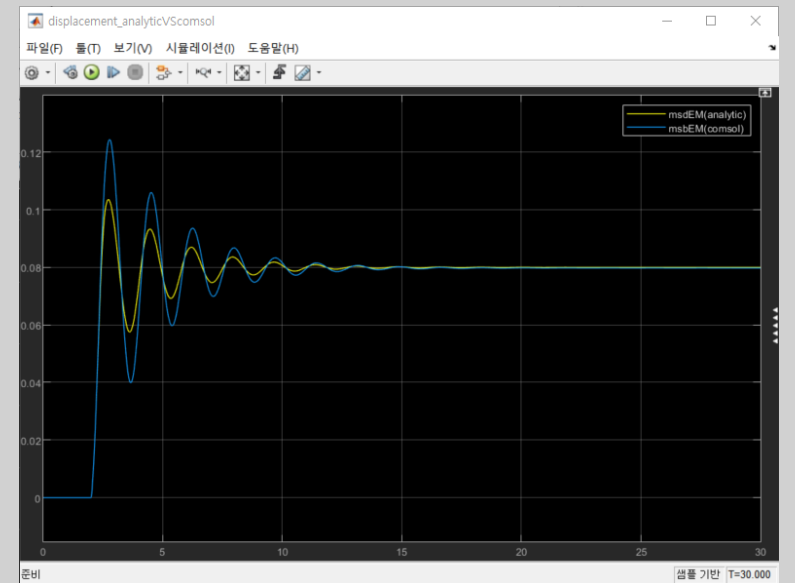
<Current>



<Force>



<Displacement>

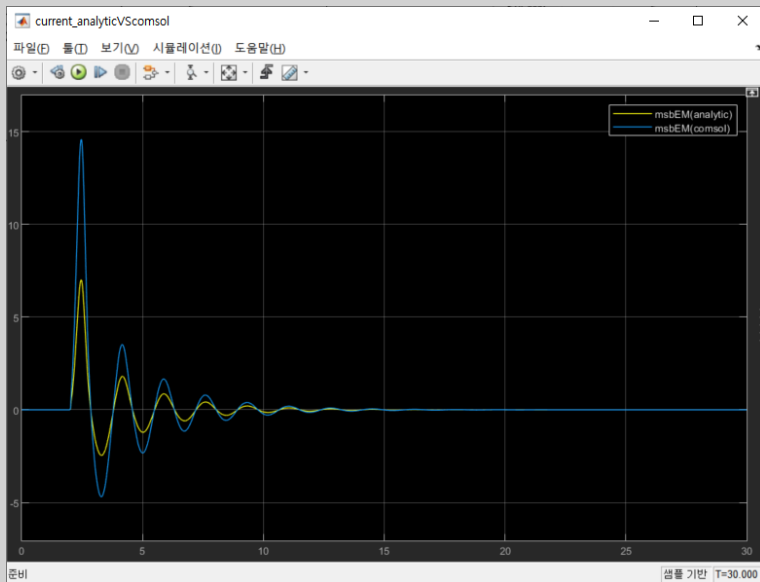


PID parameter : $P=3$, $D=0.05$ ($N=100$)

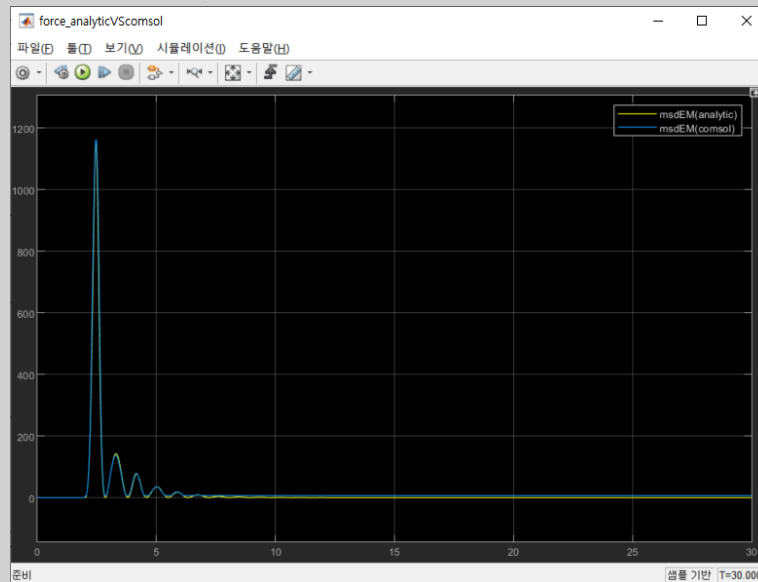
4. SIMULINK 분석

※ 이론 값 VS Comsol data

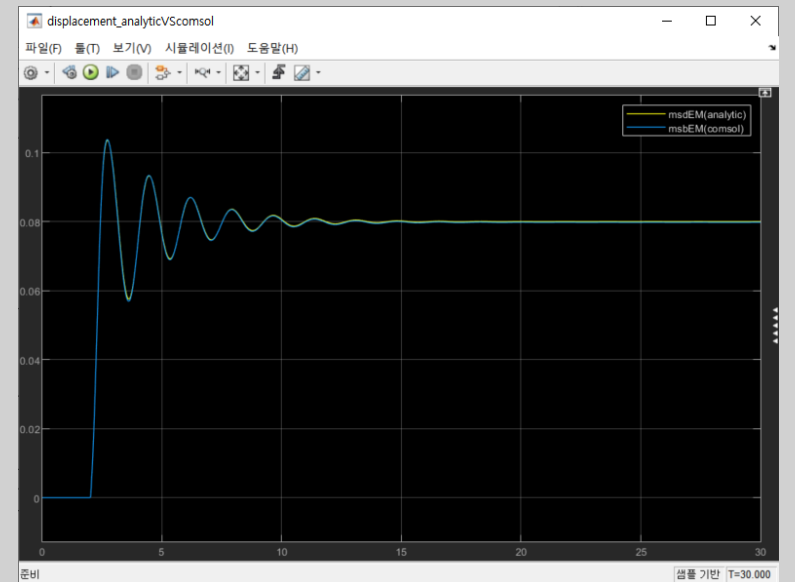
<Current>



<Force>



<Displacement>



PID parameter : $P=6.35$, $D=0.05$ ($N=100$)

4. SIMULINK 분석

※ 비교 분석

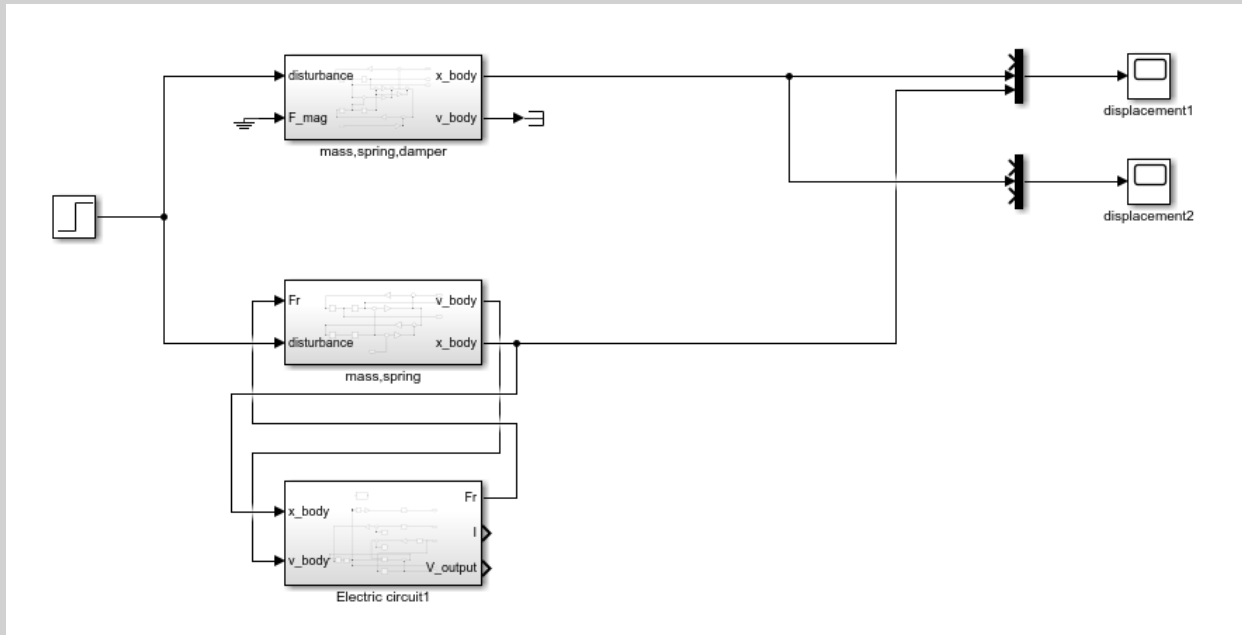
Mass, Spring, Damper system

VS

Mass, Spring, **Electromagnetic system**

4. SIMULINK 분석

※ 비교 분석



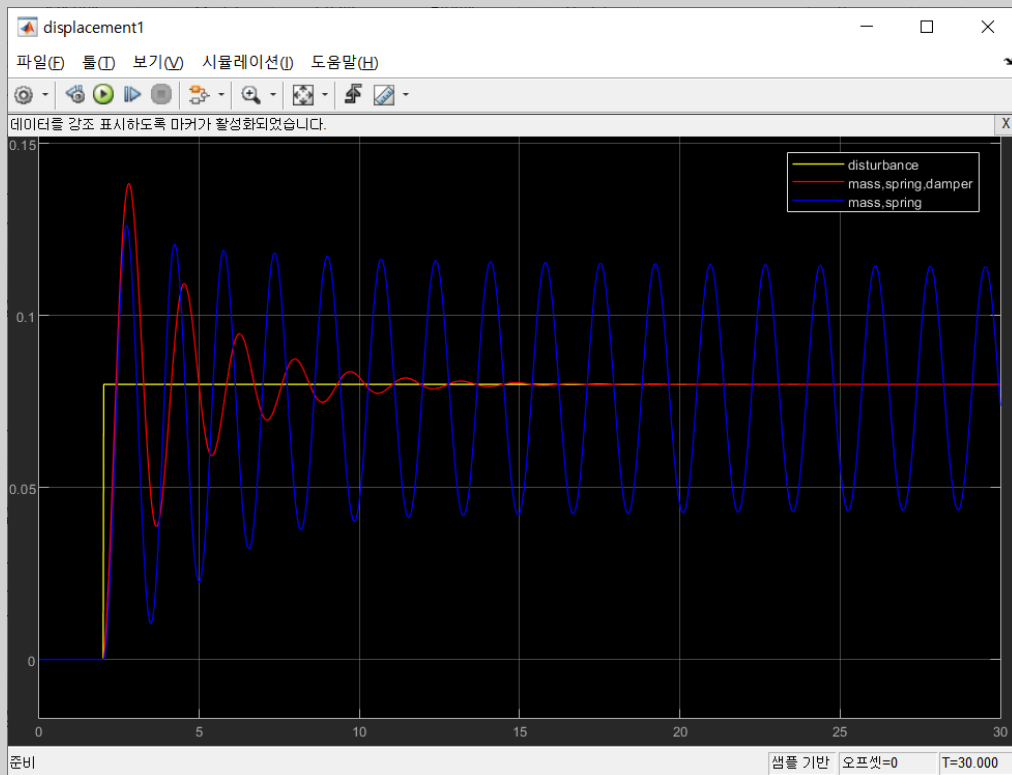
Input source : 갑작스러운 톱(step input)

Step time : 2sec

Final value : 0.08m

4. SIMULINK 분석

※ 비교 분석



결과 : 진동을 **제어하지 못함**

원인 분석

	Damper	EM
힘을 발생시키는 input	속도	속도
output	속도	변위

4. SIMULINK 분석

※ 비교 분석

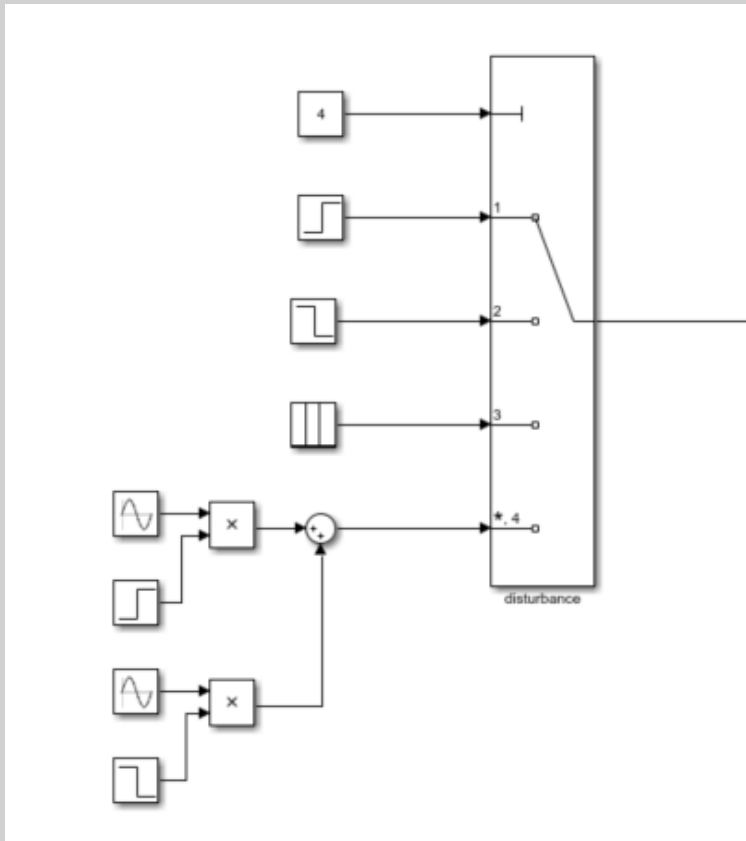
Mass, Spring, Damper system

VS

Mass, Spring, Damper, **Electromagnetic system**

4. SIMULINK 분석

※ 비교 분석

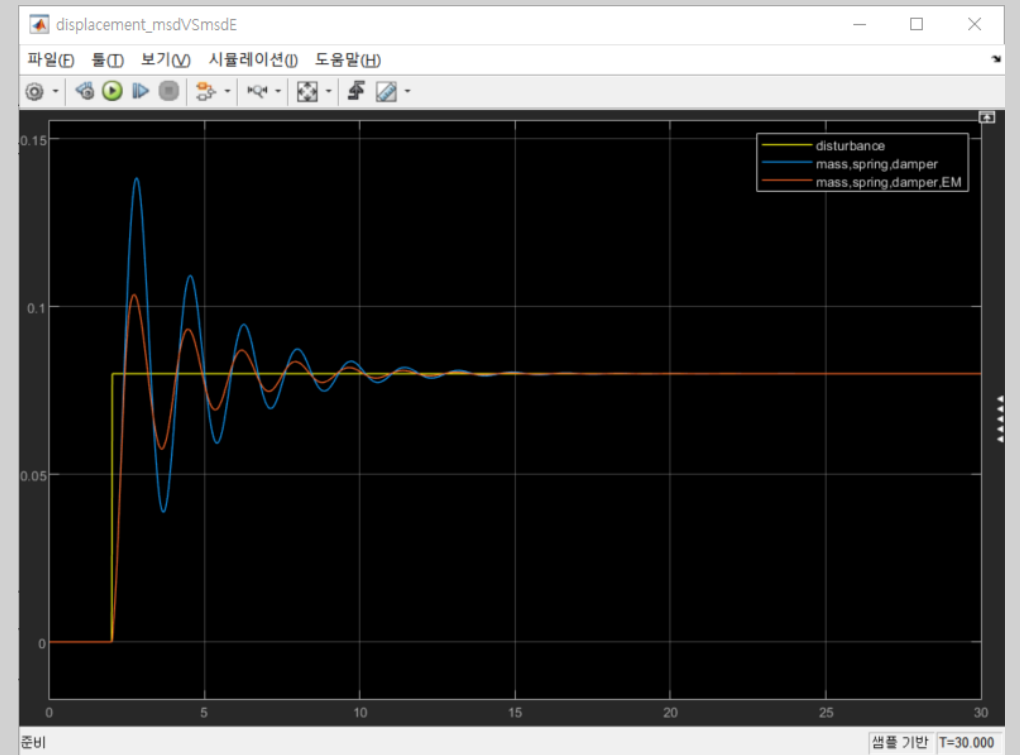
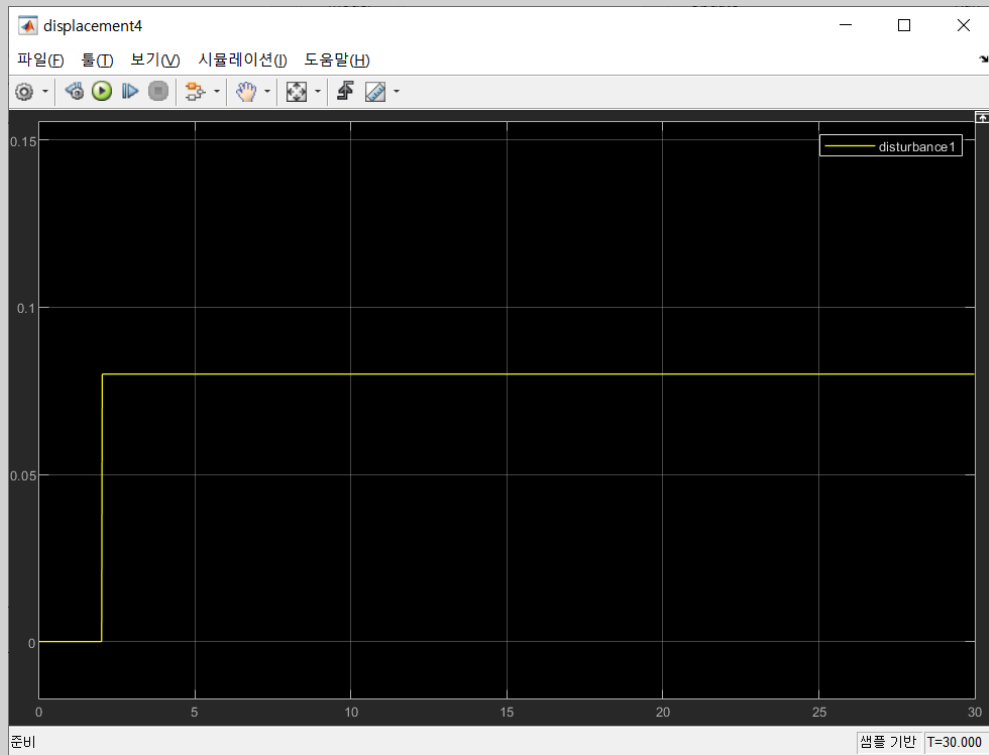


<Disturbance>

1. 갑작스러운 턱(0.08m)
2. 갑작스러운 움덩이(-0.08m)
3. 과속방지턱(0.08m)
4. 자갈밭(sine wave, ± 0.01 m)

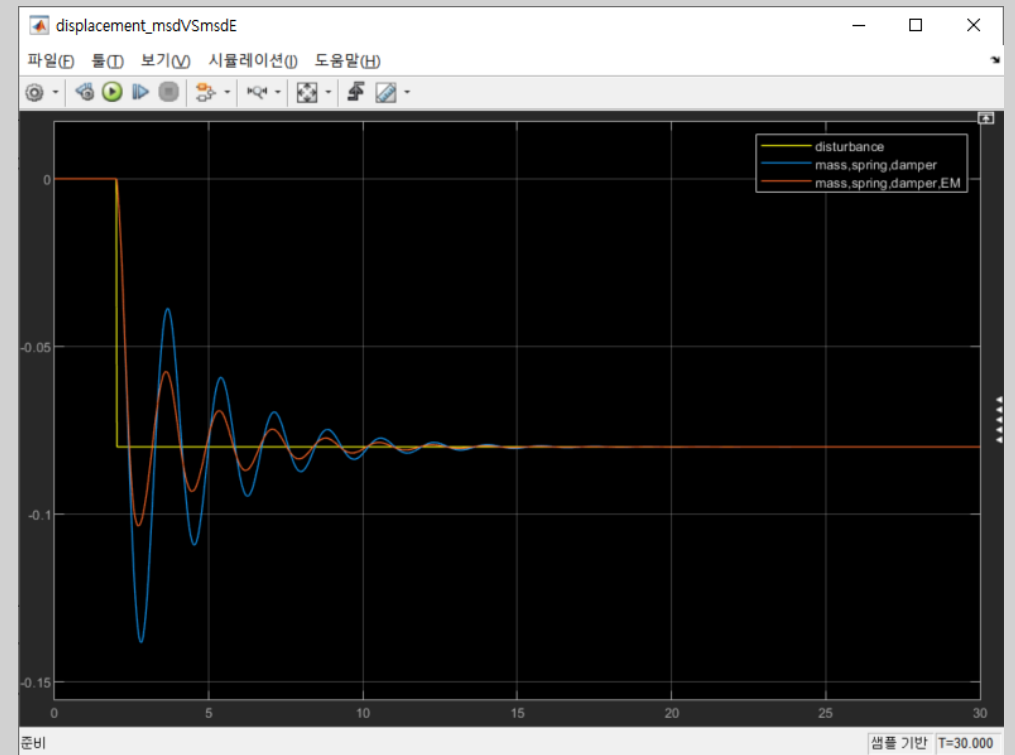
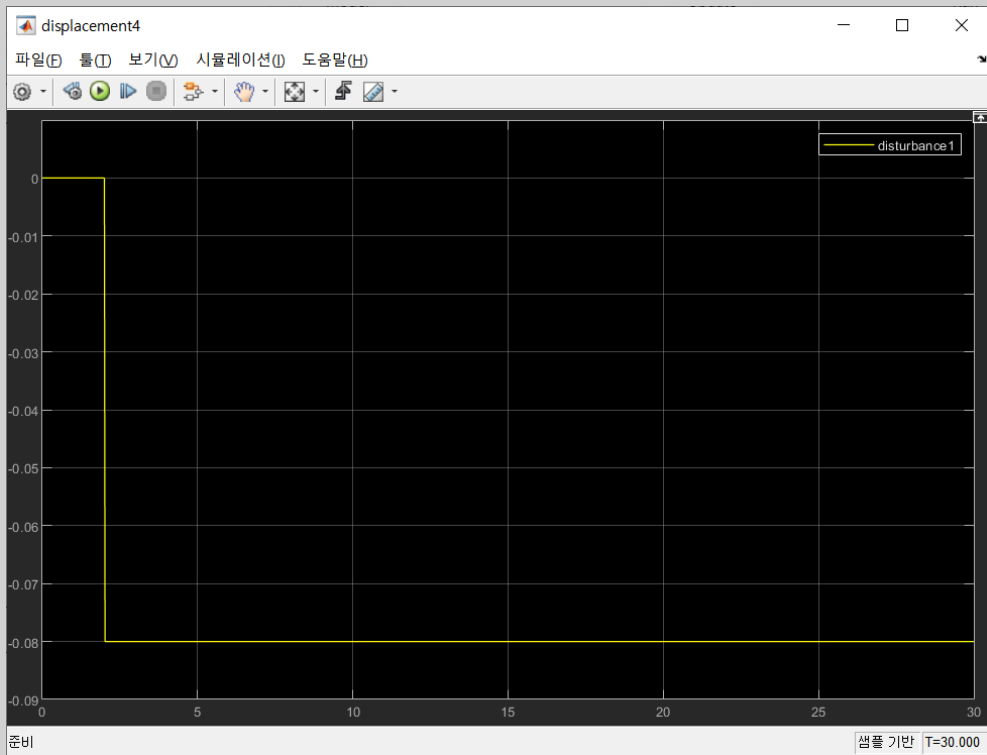
4. SIMULINK 분석

1) 갑작스러운 톱(step input)



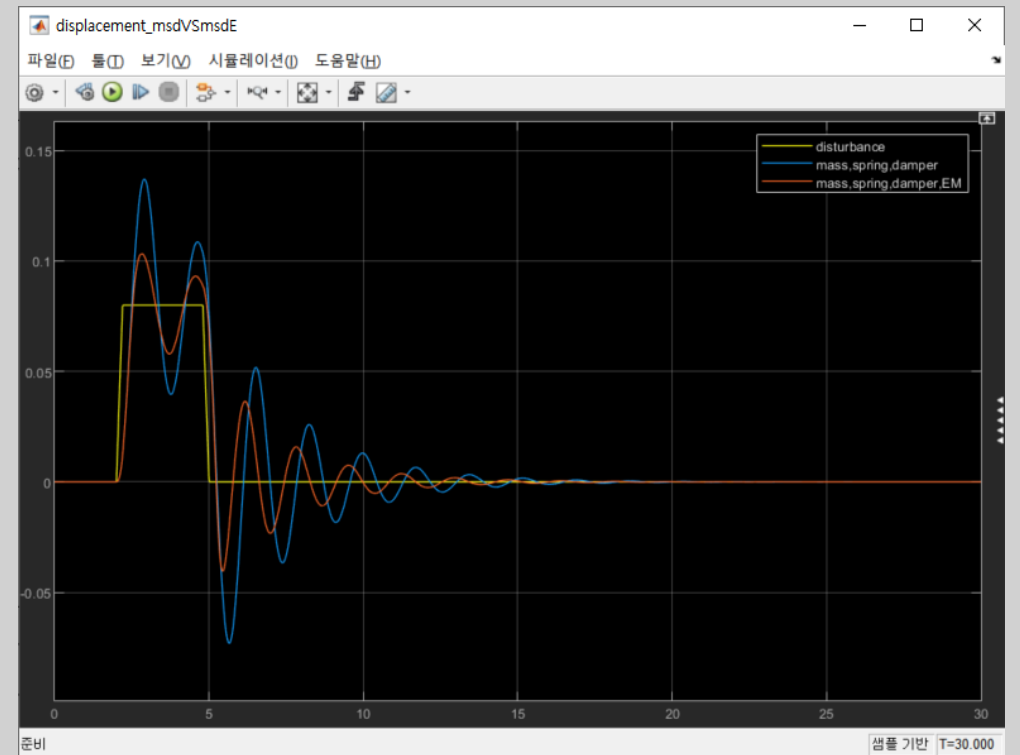
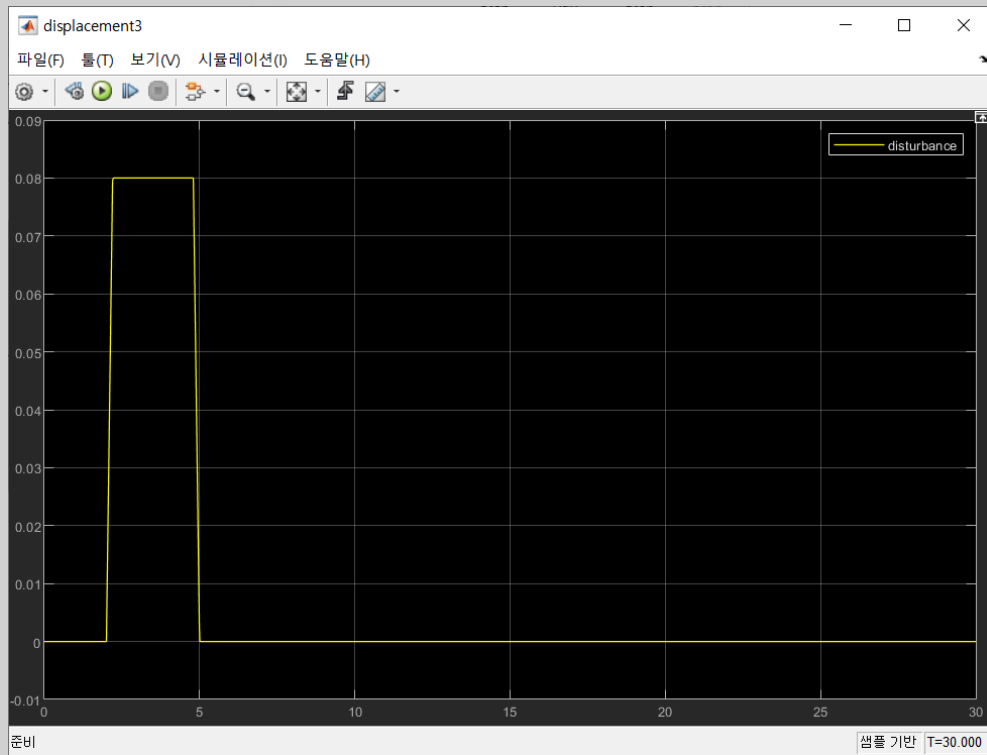
4. SIMULINK 분석

2) 갑작스러운 응덩이(step input2)



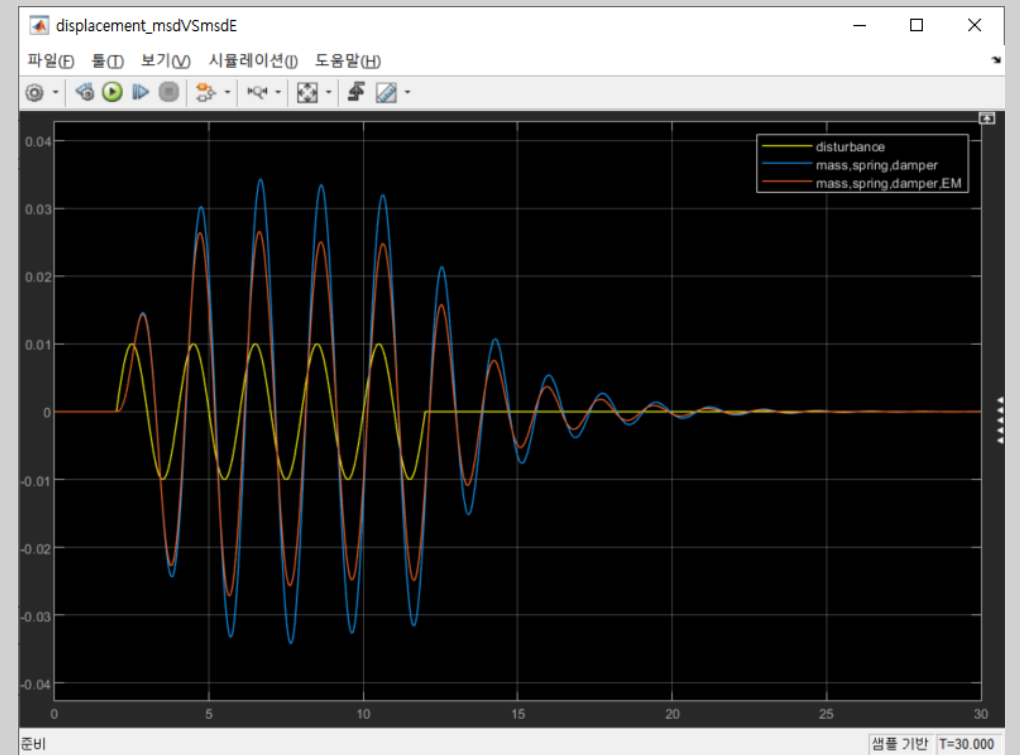
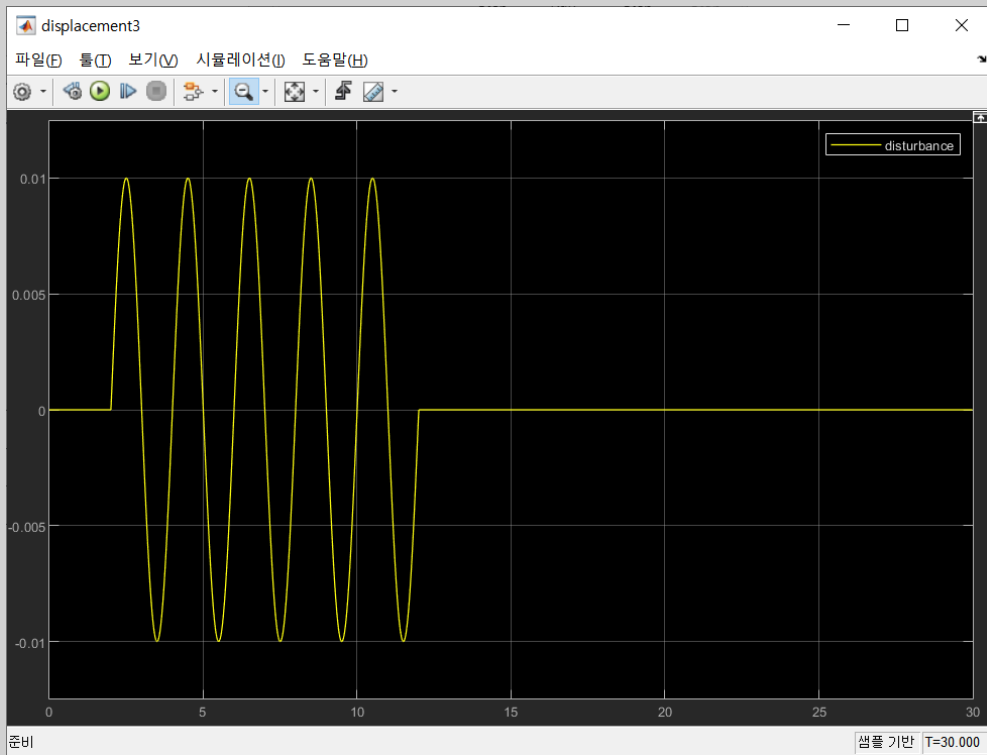
4. SIMULINK 분석

3) 과속방지턱(step size : 0.08m)



4. SIMULINK 분석

4) 자갈발(Amplitude : 0.01m)



5. 결과 및 고찰

	턱	응덩이	과속방지턱	자갈밭	평균 overshoot 감소 정도(%)	평균 settling time 감소정도(%)
System	Electromagnetic system(X)				$\frac{msd - msd_{EM}}{msd} \times 100(\%)$	
	Electromagnetic system(O)					
Overshoot(m)	0.058	-0.058	0.057/-0.073	0.024		
	0.024	-0.024	0.023/-0.041	0.016		
Settling time(sec)	13.71	13.71	14.02	22.64		
	8.483	8.483	11.80	21.68		
Overshoot 감소 정도(%)	58.62	58.62	59.65/43.84	33.33	50.81	
Settling time 감소 정도(%)	38.13	38.13	15.83	4.24		19.27

5. 결론 및 참고문헌

1. Comsol에서 얻은 데이터를 사용했을 때와 이론식을 사용해 얻은 결과값은 진폭의 크기는 달랐으나 **파형은 일치했다.**
2. Damper를 제외하여 모델링한 system은 진동을 제어하지 못했다.
3. 변위의 disturbance가 일시적으로 일어났을 때보다 연속적으로 일어날 때 maximum overshoot와 settling time이 줄어든 비율이 더 작았다.
4. Electromagnetic system을 사용했을 때 의 maximum overshoot와 settling time 은 사용하지 않았을 때 보다 평균적으로 **각각 50.81%, 19.27%가 줄어들었다.**

5. 결론 및 참고문헌

1. Fitzgerald & Kingsley's Electric Machinery - 7th Edition, Stephen D. Umans, McGRAW – HILL
2. Robust Controller Design for Magnetic Suspension System, Im Kyu-Mann, So Kyung-Young, Journal of KIIT. Vol. 11, No. 12, pp. 35-41, Dec. 31, 2013. pISSN 1598-8619, eISSN 2093-757

Question

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Answer