간단한 건물 모델에 대한 내진효과 분석

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7. 아쉬운 점

비교 (4. Matlab ↔ 5. Comsol)

주제 선정 배경

경주 지진때 겪었던 경험

안전해질 수 있는 방법은 없을까?

내진 효과 분석

팀명 선정 배경

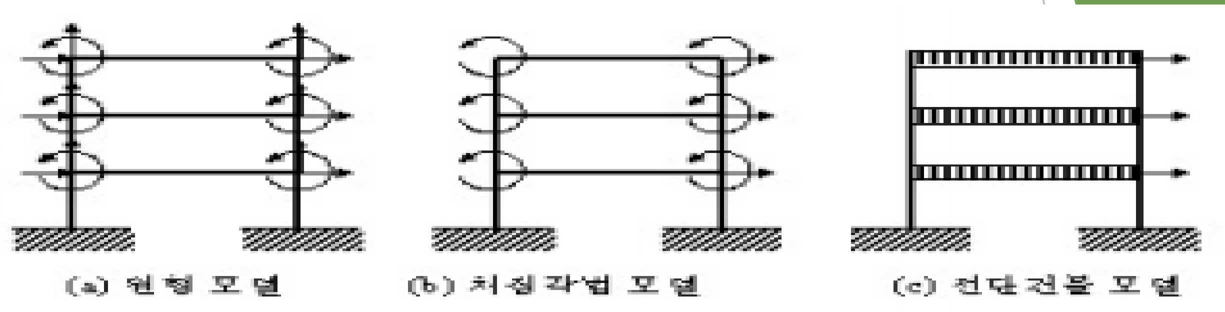
팀명: 지진희

지진(이/희)

일어나면 위험!

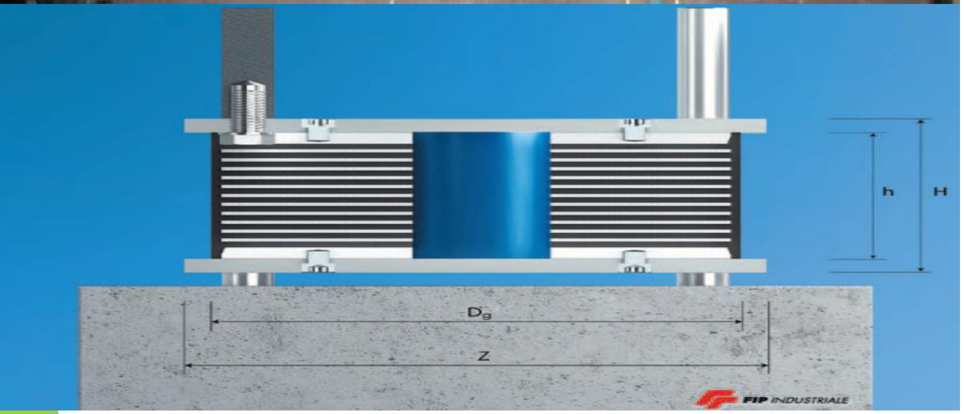
사진: 연예인 지진희

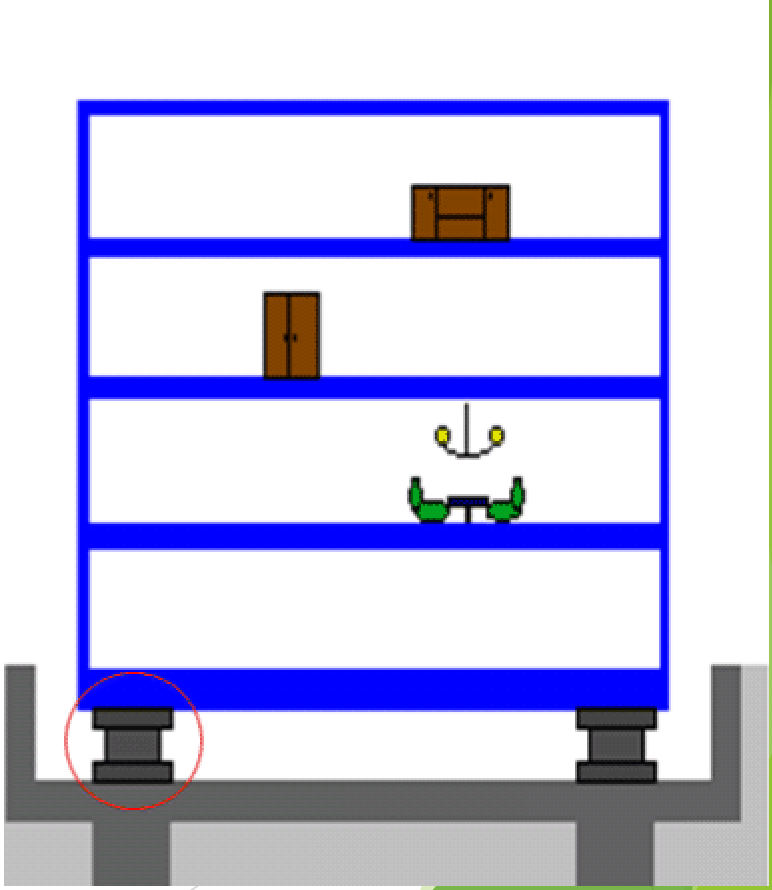
Governing equation



	원형모델	처짐각법 모델	전단건물 모델
절점 변위의 원인	모두 고려	부재의 휨변형	수평변위
3층건물 DOF	수평변위(3)+전단변형(3)+휨변형(6)+축변형(6)=18 DOF	수평변위(3)+휨변형(6)=9 DOF	수평변위(3) = 3DOF

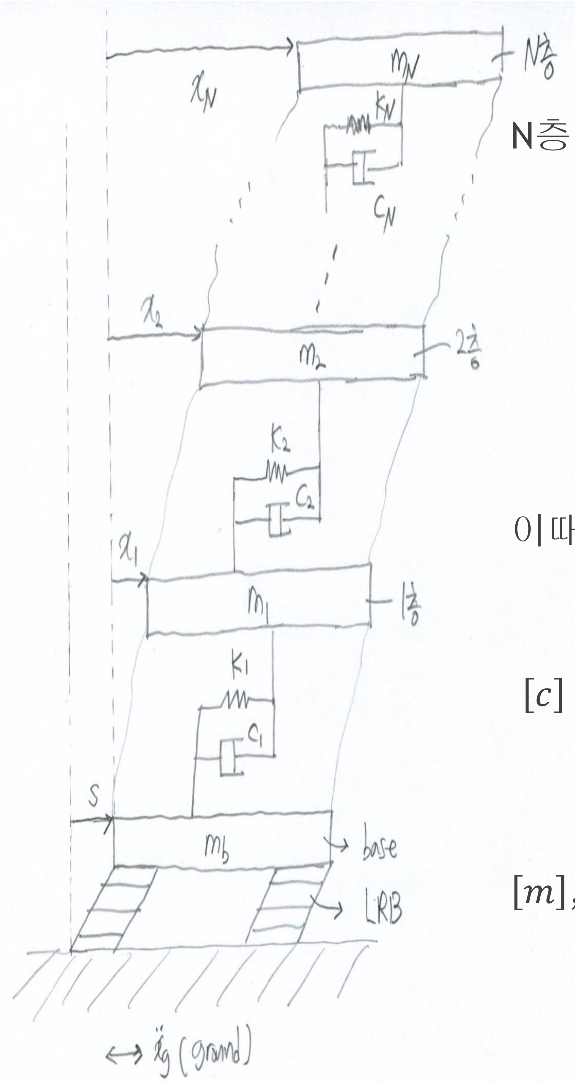
Lead Rubber Bearing(LRB)





Lead: 진동에너지의 감쇠 기능
Rubber: 수평방향의 강성 결정
Steel: 수직하중 견디도록

Governing equation



N층일 때 전단건물 모델에 대한 방정식

$$[\boldsymbol{m}][\ddot{\boldsymbol{x}}]+[\boldsymbol{c}][\dot{\boldsymbol{x}}]+[\boldsymbol{k}][\boldsymbol{x}]=\left(\frac{\boldsymbol{c_0\dot{s}+k_0 s}}{\boldsymbol{m_b}}-\frac{\boldsymbol{c_1\dot{x}_1+k_1x_1}}{\boldsymbol{m_b}}\right)[\mathrm{m}][1] \quad \ldots \text{(식2)}$$

이때 $[m]=\begin{pmatrix} m_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & m_N \end{pmatrix}$ $[1]=[1\ 1\ 1\ \ldots\ 1]^T$ $[x]=[x_1\ \ x_2\ \ x_3\ \ \ldots\ x_N]^T$

$$[c]=\begin{pmatrix} c_1+c_2 & -c_2 & & \\ -c_2 & c_2+c_3 & -c_3 & \\ & & \ddots & \\ & & -c_N & c_N \end{pmatrix} \qquad [k]=\begin{pmatrix} k_1+k_2 & -k_2 & & \\ -k_2 & k_2+k_3 & -k_3 & \\ & & \ddots & \\ & & -k_N & k_N \end{pmatrix}$$

$[m]$, $[c]$, $[k]$, $[x]$ 는 NxN 행렬이고 **[1]** 는 Nx1 행렬이다.

Governing equation

단순화를 위해 다음과 같은 가정 도입

첫째, base를 제외한 3층의 건물(N=3)으로 생각

둘째, 각 층의 질량과 base의 질량은 같음. 즉, $m_1 = m_2 = m_3 = m_b = m$

셋째, 층간의 stiffness와 damping 계수는 같음. 즉, $k_1 = k_2 = k_3 = k$, $c_1 = c_2 = c_3 = c$

이러한 가정하에 식1과 식2는 다음과 같음

$$\ddot{s} + \frac{c_0}{m}\dot{s} + \frac{k_0}{m}s = \frac{(c\dot{x}_1 + kx_1)}{m} - \ddot{x}_g \quad \text{... (변형된 식1)}$$

$$[m][\ddot{x}] + [c][\dot{x}] + [k][x] = \left(\frac{c_0\dot{s} + k_0 s}{m_0} - \frac{c_1\dot{x}_1 + k_1 x_1}{m_0}\right)[\mathrm{m}][1] \quad \text{... (변형된 식2)}$$

$$[m] = m\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix} \quad [1] = [1\ 1\ 1]^T \quad [\mathrm{c}] = \mathrm{c}\begin{pmatrix}2 & -1 & 0\\ -1 & 2 & -1\\ 0 & -1 & 1\end{pmatrix} \quad [\mathrm{k}] = \mathrm{k}\begin{pmatrix}2 & -1 & 0\\ -1 & 2 & -1\\ 0 & -1 & 1\end{pmatrix}$$

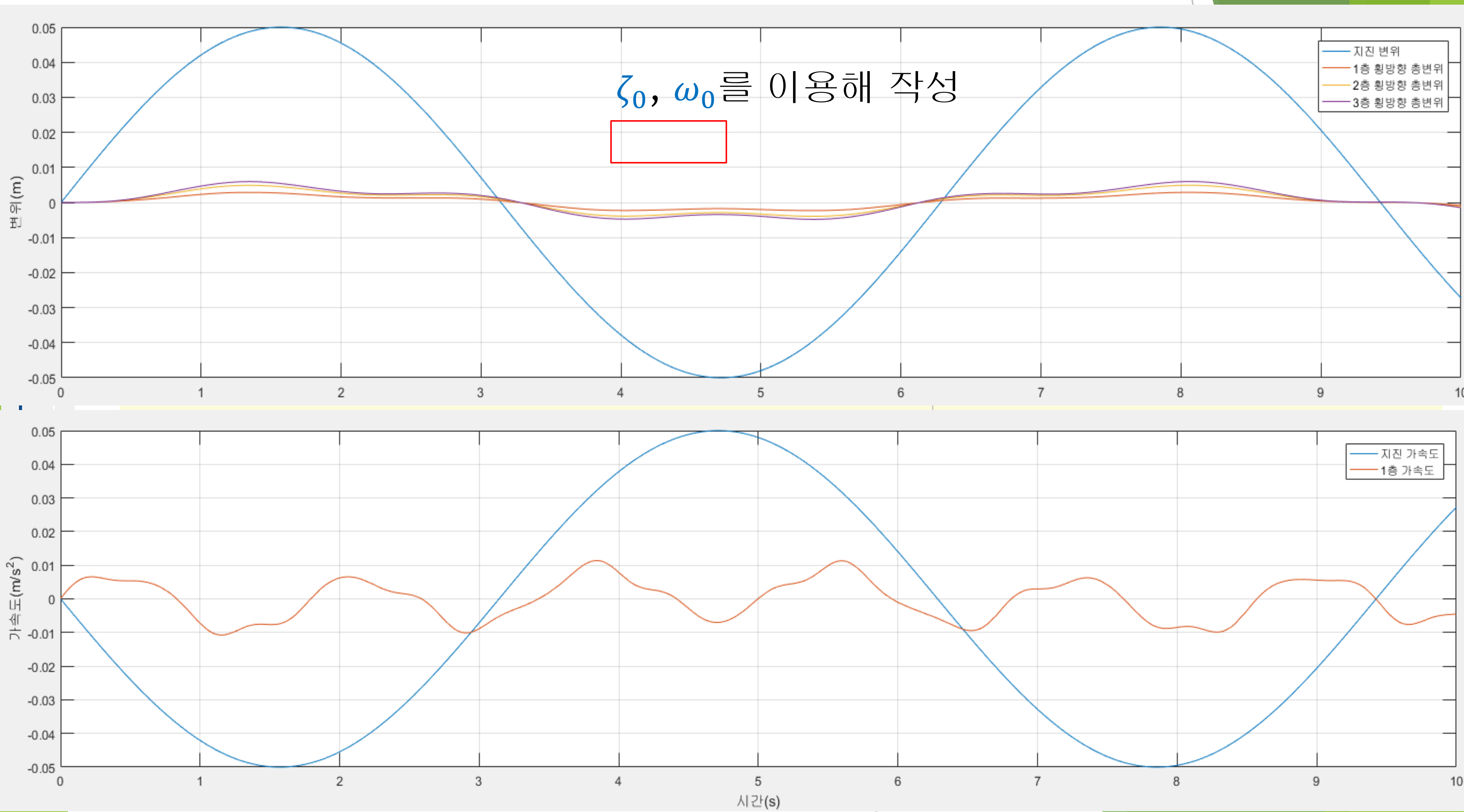
Matlab

Matlab의 ode45를 이용하기 위한 coupling equation

$$y_1 = x_1 \qquad \dot{y}_1 = y_2$$
$$y_2 = \dot{y}_1 \qquad m\dot{y}_2 = -(2cy_2 - cy_4 + 2ky_1 - ky_3) + \left(\frac{c_0}{m}y_8 + \frac{k_0}{m}y_7 - \frac{cy_2 + ky_1}{m}\right)m$$
$$y_3 = x_2 \qquad \dot{y}_3 = y_4$$
$$y_4 = \dot{y}_3 \qquad m\dot{y}_4 = -(cy_2 + 2cy_4 - cy_6 - ky_1 + 2ky_3 - ky_5) + \left(\frac{c_0}{m}y_8 + \frac{k_0}{m}y_7 - \frac{cy_2 + ky_1}{m}\right)m$$
$$y_5 = x_3 \qquad \dot{y}_5 = y_6$$
$$y_6 = \dot{y}_5 \qquad m\dot{y}_6 = -(-cy_4 + cy_6 - ky_3 + ky_5) + \left(\frac{c_0}{m}y_8 + \frac{k_0}{m}y_7 - \frac{cy_2 + ky_1}{m}\right)m$$
$$y_7 = s \qquad \dot{y}_7 = y_8$$
$$y_8 = \dot{y}_7 \qquad \dot{y}_8 = -\frac{c_0}{m}y_8 - \frac{k_0}{m}y_7 + \frac{cy_2 + ky_1}{m} - \ddot{x}_g$$

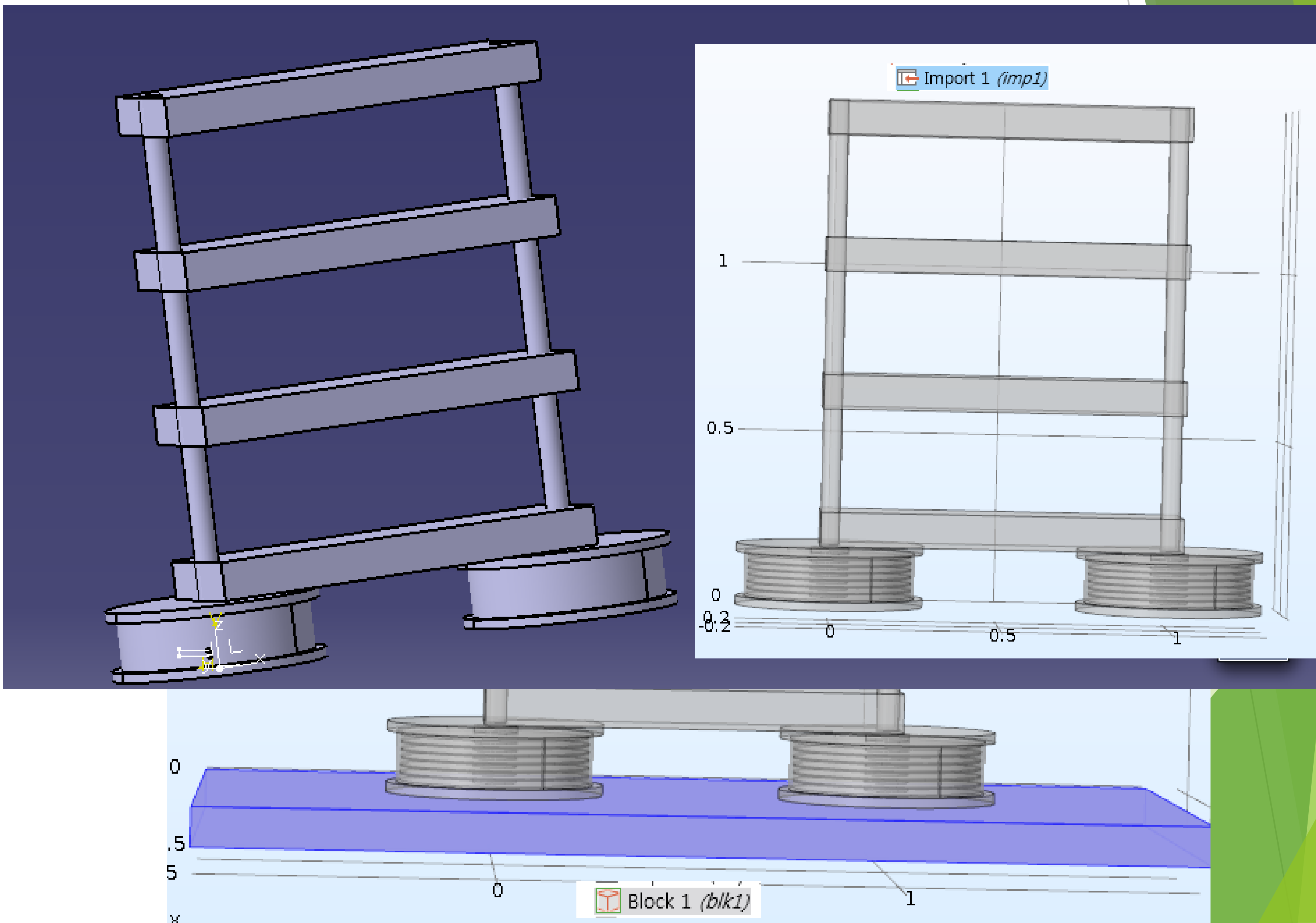
$2\zeta_0\omega_0 = \frac{c_0}{m}, \omega_0^2 = \frac{k_0}{m}$ -> 매트랩 코드에서 c_0, k_0 대신 ζ_0, ω_0를 이용해 작성

Matlab

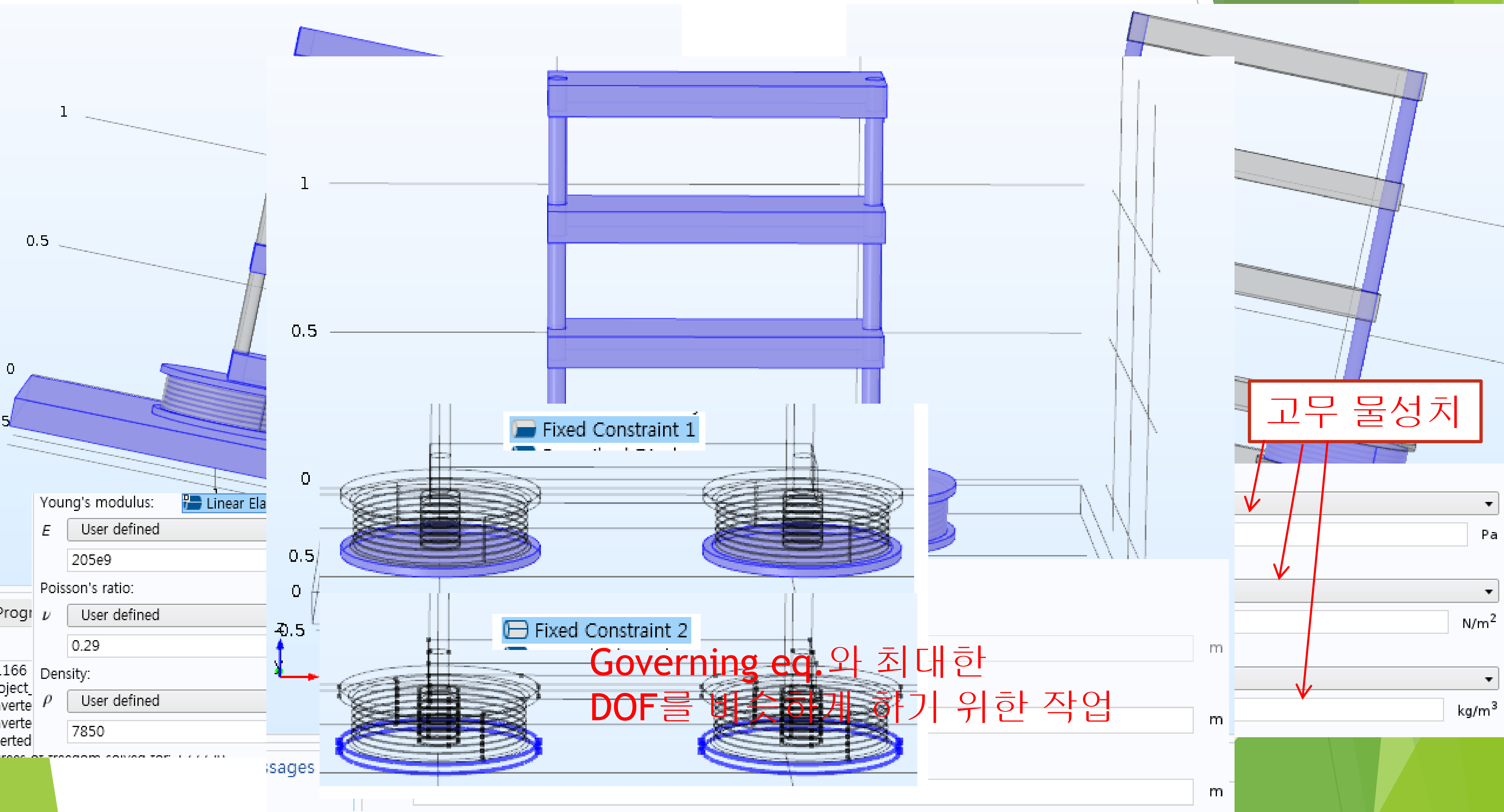


ζ0, ω0를 이용해 작성
변위(m)
지진 변위
1층 횡방향 총변위
2층 횡방향 총변위
3층 횡방향 총변위
가속도(m/s2)
지진 가속도
1층 가속도
시간(s)

Comsol

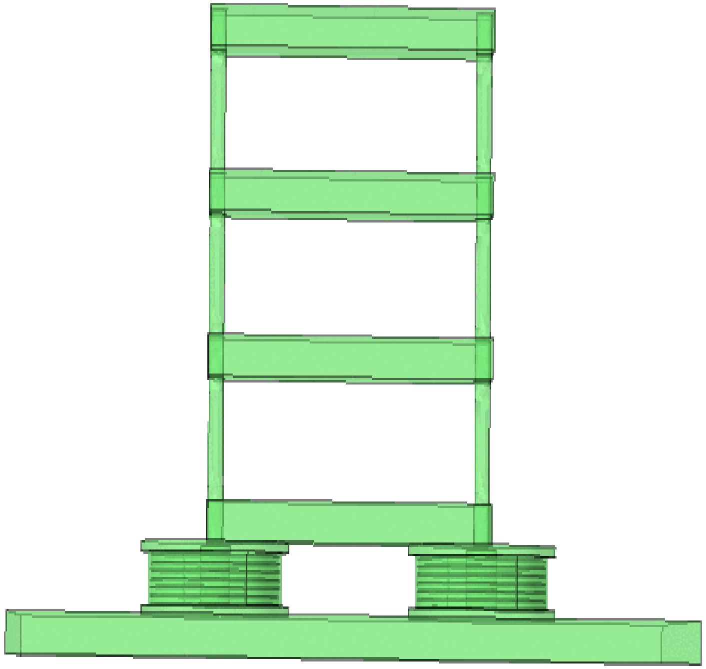


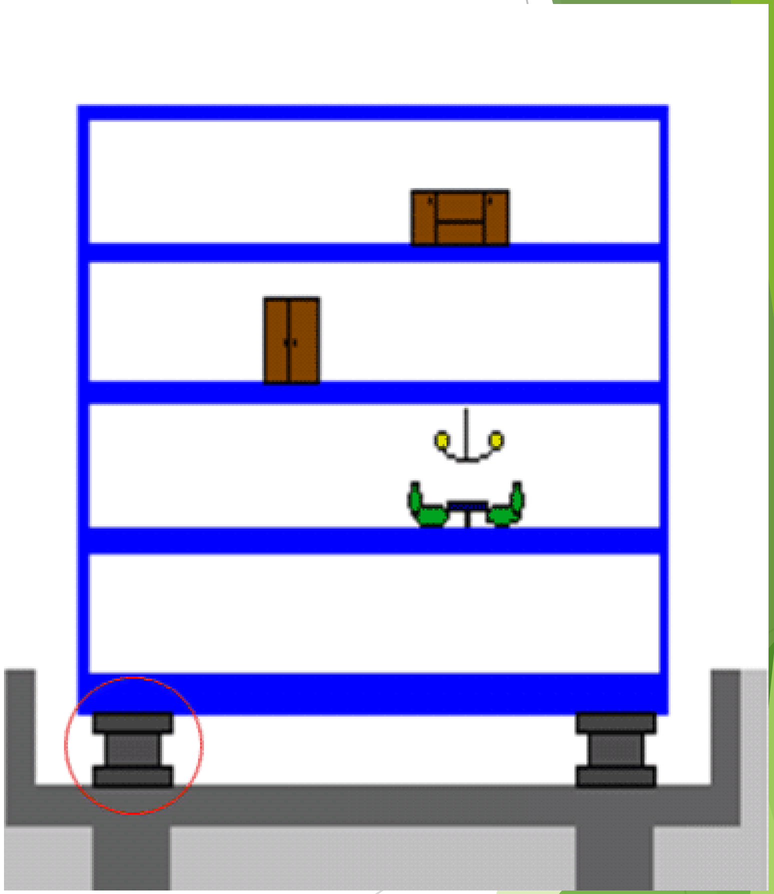
Comsol



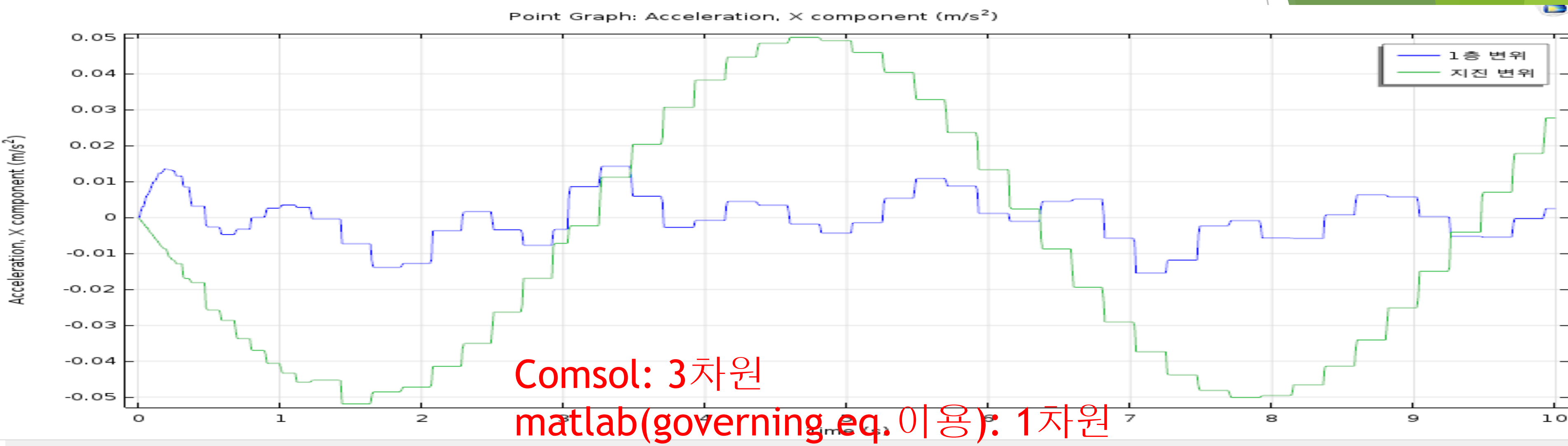
Young's modulus:
Linear Ela
E
User defined
205e9
Poisson's ratio:
ν
User defined
0.29
Density:
ρ
User defined
7850
Fixed Constraint 1
Fixed Constraint 2
고무 물성치
Governing eq.와 최대한
DOF를 비슷하게 하기 위한 작업
Pa
N/m²
kg/m³
m

Comsol 영상

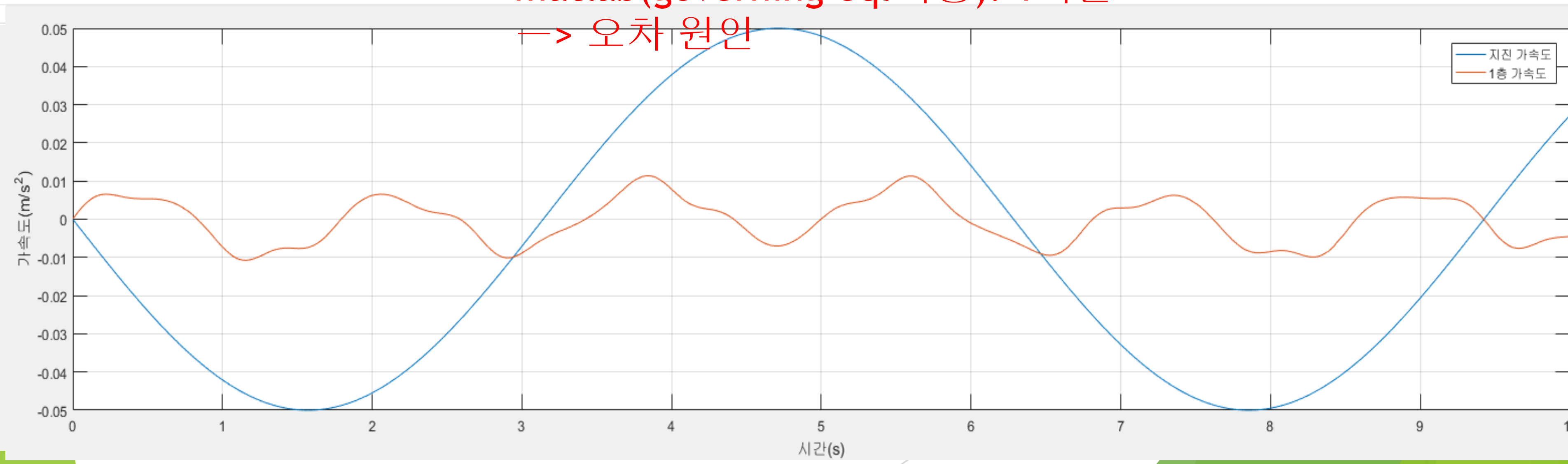




Matlab 결과와 유사성



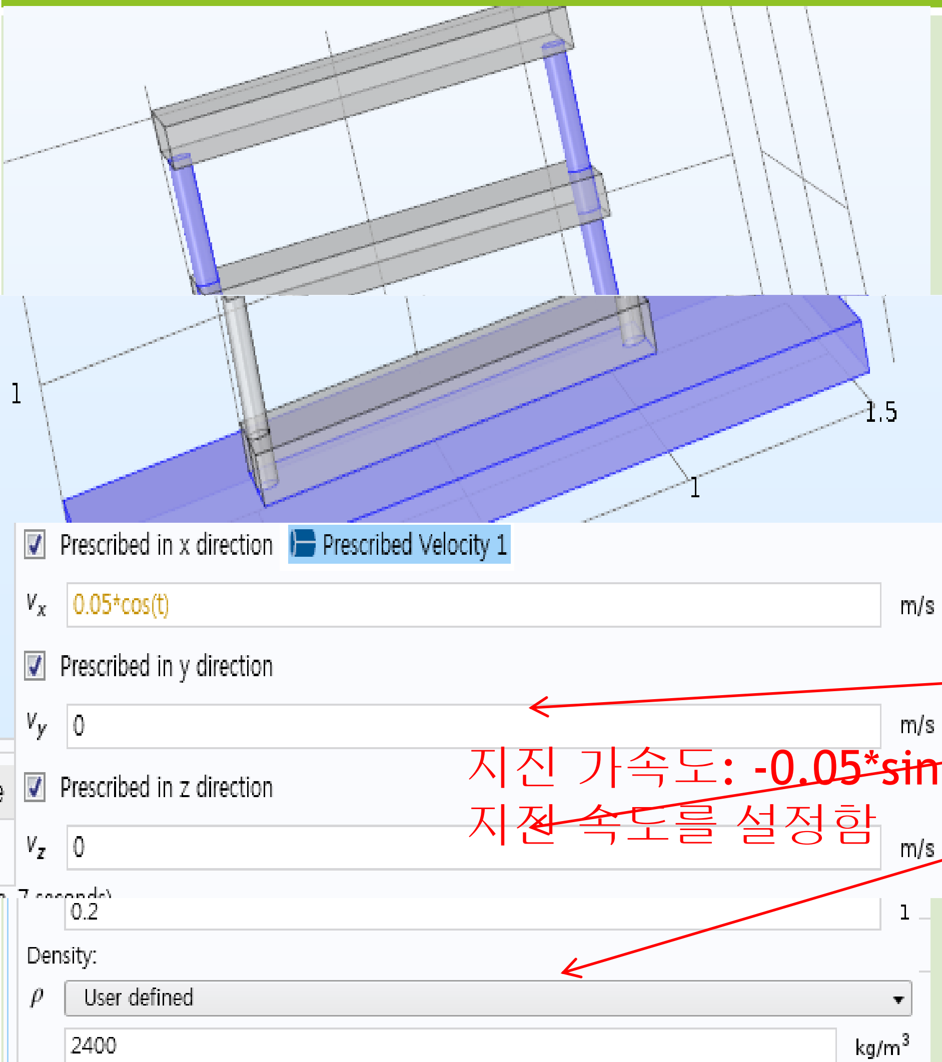
Comsol: 3차원
matlab(governing eq. 이용): 1차원
—> 오차 원인



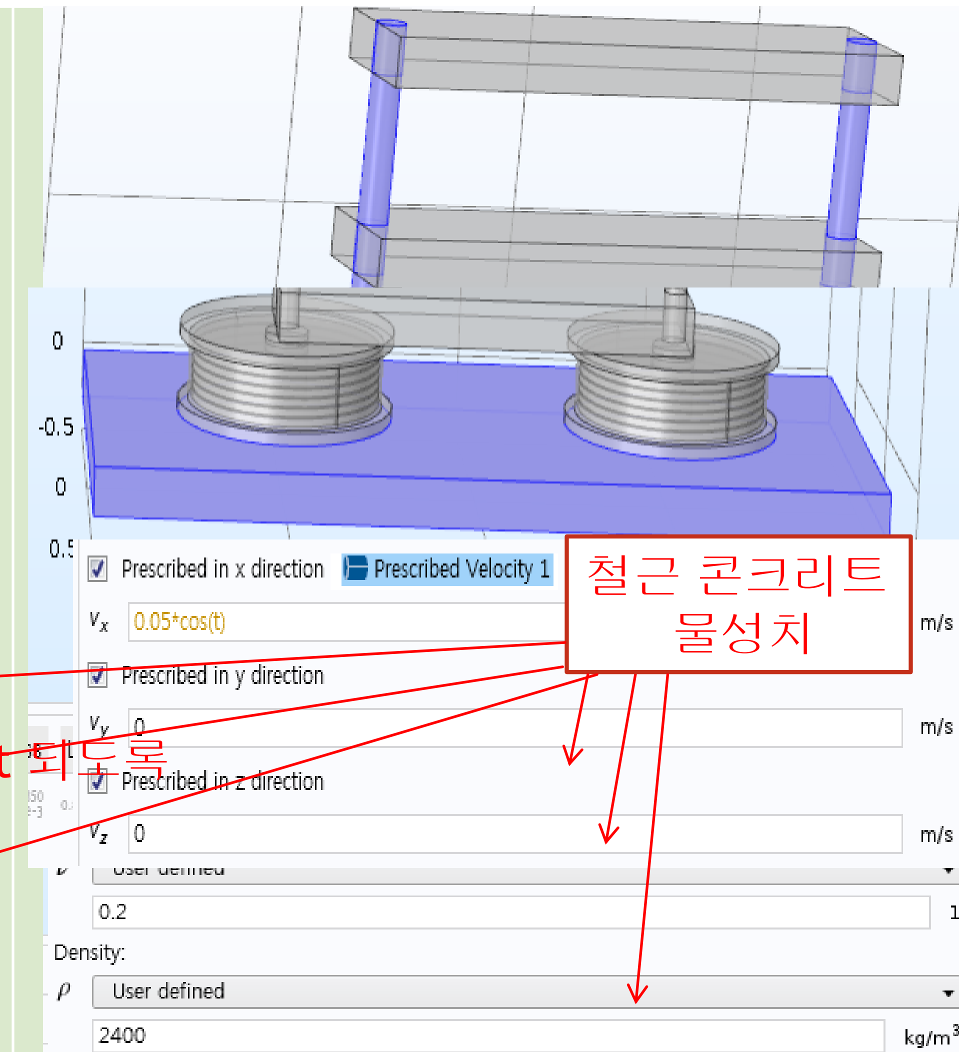
RC: Reinforced Concrete (철근 콘크리트)

Comsol(RC사용)

LRB 없을 때



LRB 있을 때



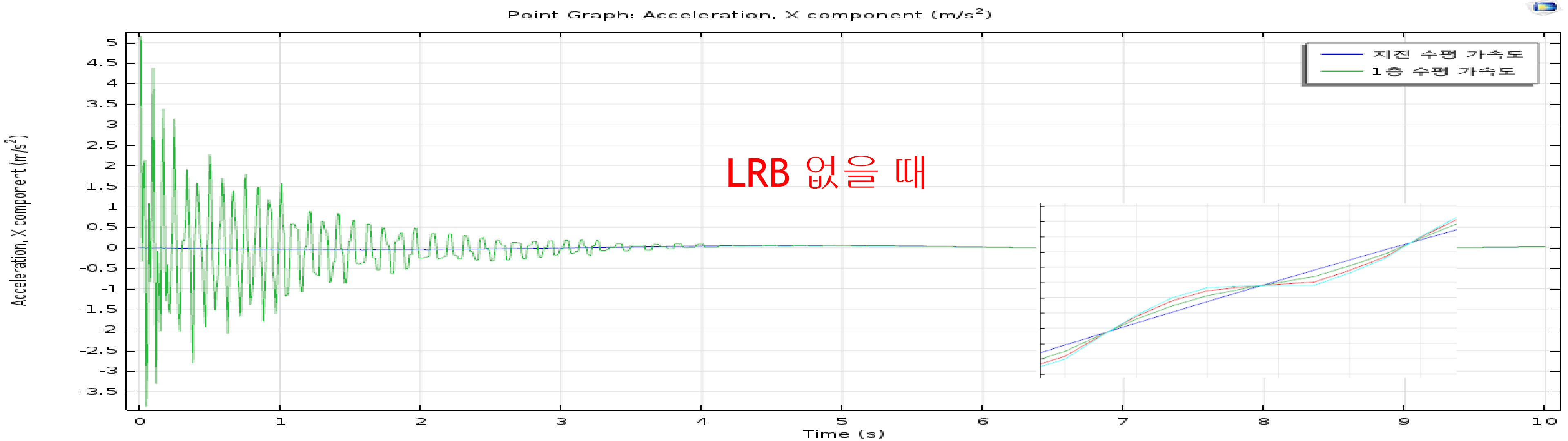
철근 콘크리트 물성치

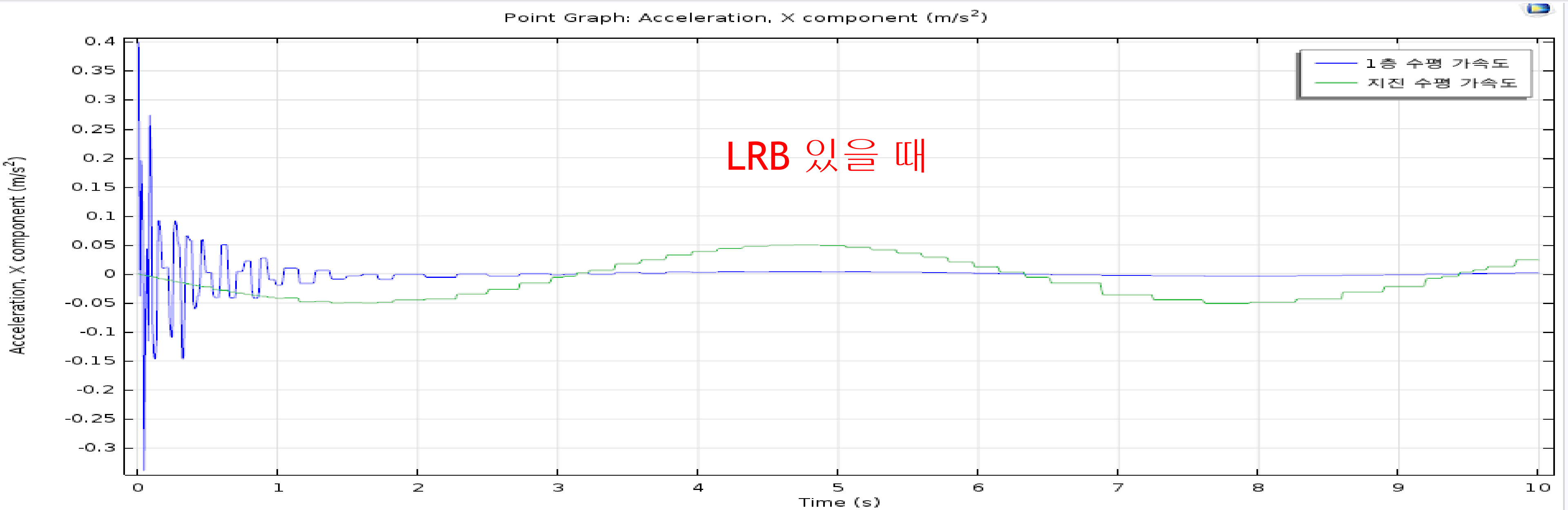
지진 가속도: -0.05*sint 되도록 지진 속도를 설정함

RC: Reinforced Concrete (철근 콘크리트)

Comsol(RC사용)

지진가속도 : 0.05*sint





RC: Reinforced Concrete (철근 콘크리트)

Comsol(RC사용)

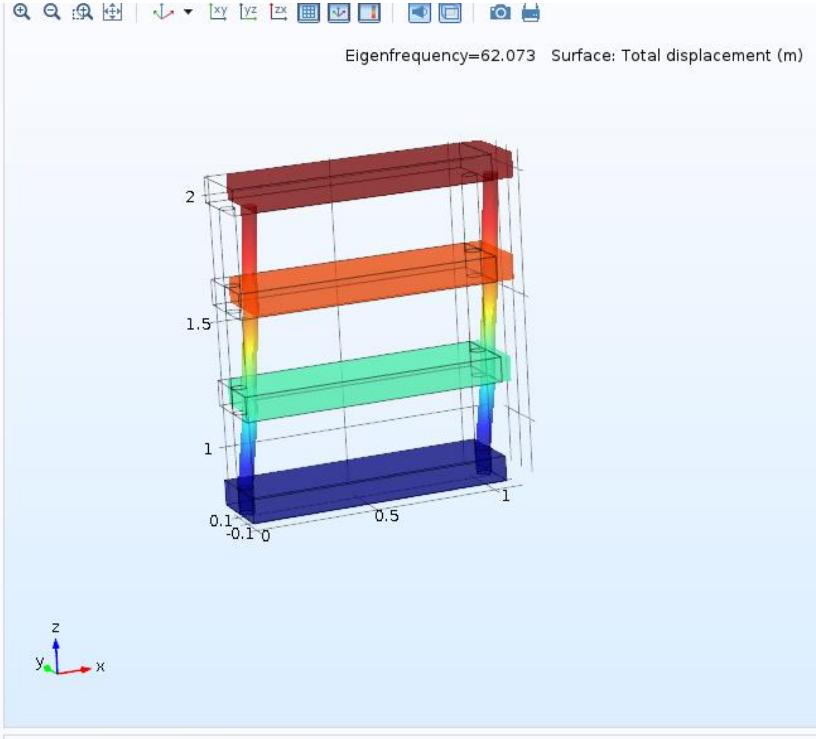
```
model.result.table.remove('tbl1');
model.result.table.remove('tbl2');
model.result.table.create('tbl1', 'Table');
model.result.table('tbl1').comments('Point Evaluation 1 (u)');
model.result.numerical('pev1').set('table', 'tbl1');
model.result.numerical('pev1').setResult;
model.result.table.create('tbl2', 'Table');
model.result.table('tbl2').comments('Point Evaluation 2 (solid.u_ttX)');
model.result.numerical('pev2').set('table', 'tbl2');
model.result.numerical('pev2').setResult;

with_disp=model.result.table('tbl1').getReal;
with_accel=model.result.table('tbl2').getReal;
n=length(with_disp); sum_disp=0; sum_accel=0;
for i=1:n-1
    sum_disp=sum_disp+with_disp(i,2)^2*(with_disp(i+1,1)-with_disp(i,1));
    sum_accel=sum_accel+with_accel(i,2)^2*(with_accel(i+1,1)-with_accel(i,1));
end
rms_disp=sqrt(sum_disp/10)
rms_accel=sqrt(sum_accel/10)
```

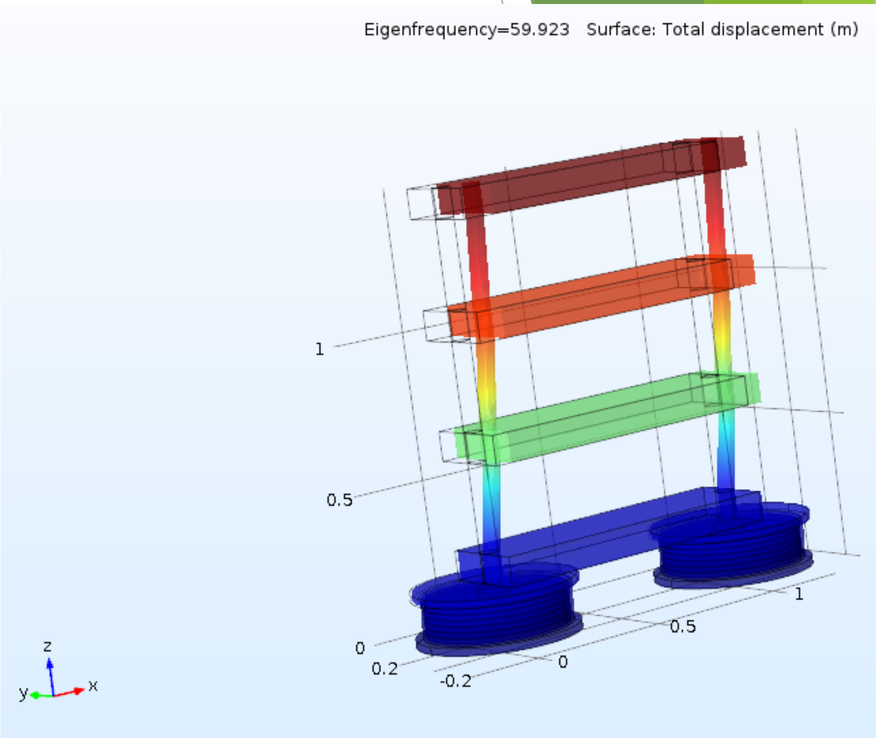
지진변위 최대 진폭 0.05m 일 때

1층에 대해	LRB 사용 X	LRB 사용 O
10초동안 변위 rms	0.0346m	0.0026m
10초동안 가속도 rms	0.5340m/s^2	0.0300m/s^2

Eigen frequency



고유진동수 감소



실제 건물 진동수는 5층이 약 2hz,3층은 약2.3hz

Eigen frequency

규모6이하의 지진의 진동수는 **2.5~5hz** → 고유진동수가 낮아야 안전

MR(Magneto-Rheological) Damper

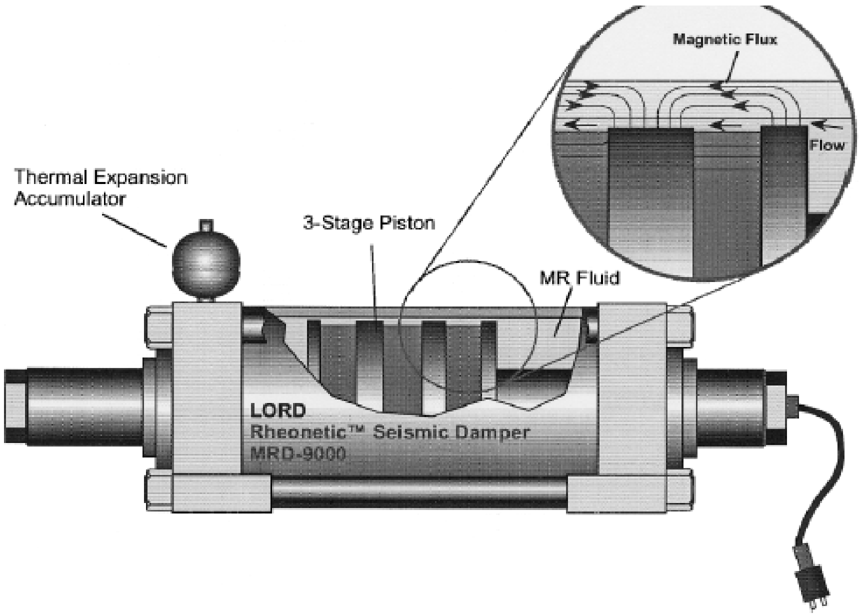
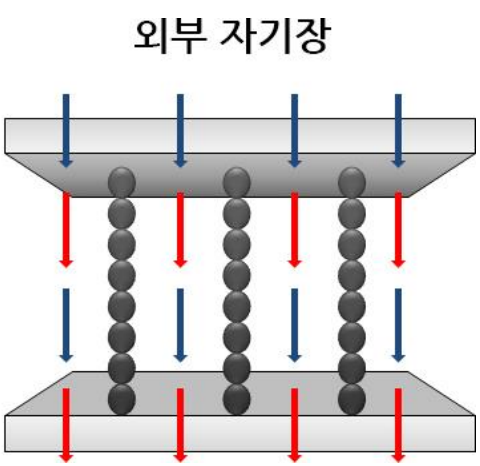
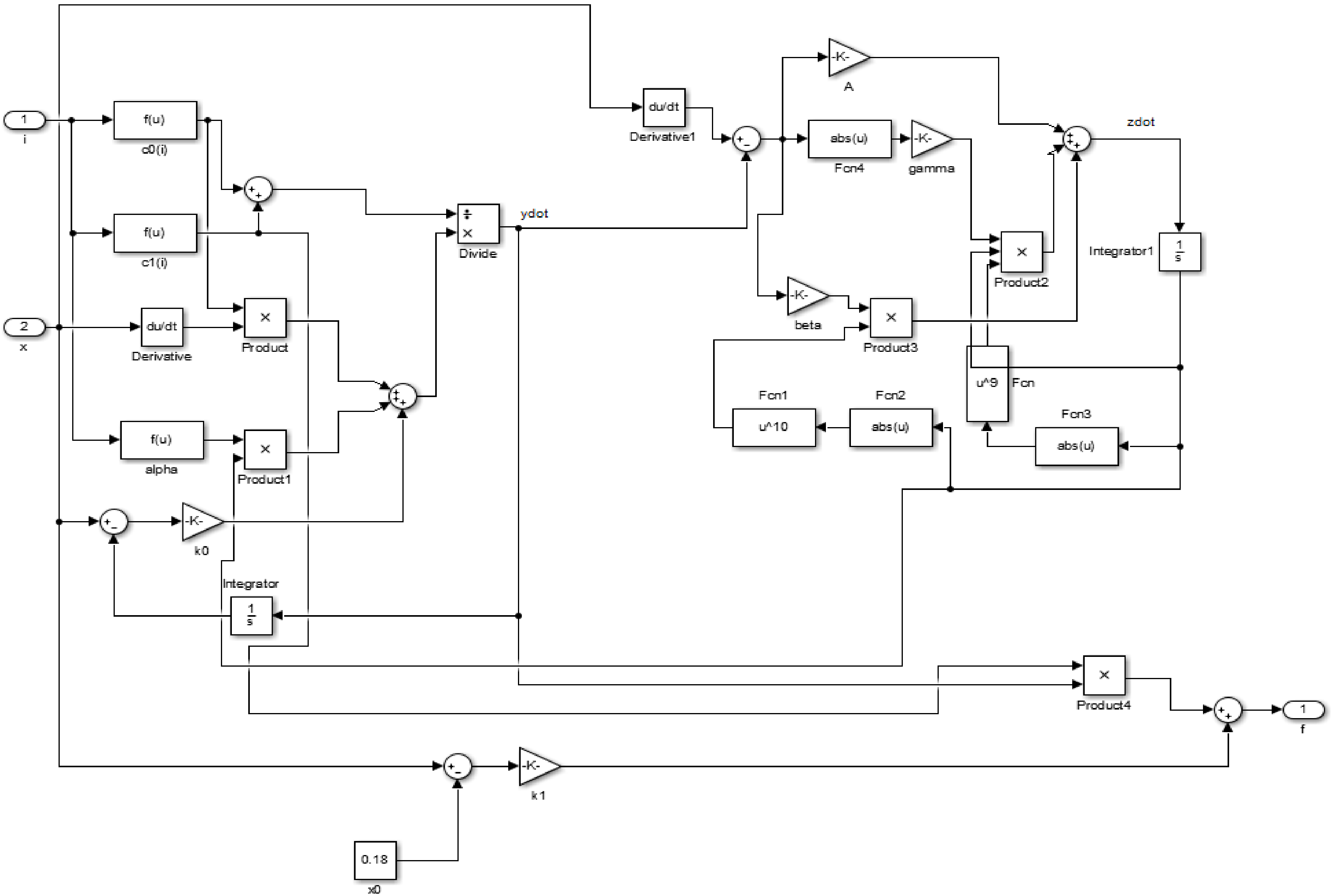


Fig. 2. Schematic of the large-scale 20-ton MR fluid damper.



- 내부에 미세한 철가루가 혼합된 오일을 충전
- 전류가 흐르면 코일에서 자기장 발생
- 발생된 자기장에 의해 철가루가 정렬되면서 내부 유체가 굳어버리면서 viscocity 증가.

MR(Magneto-Rheological) Damper 시뮬링크 모델

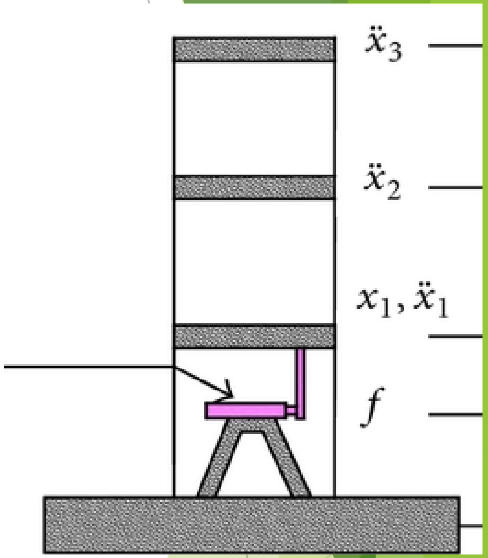


MR(Magneto-Rheological) Damper

- $M\ddot{X}+C_d\dot{X}+K_sX=-MJa-Hf$ M, C_d, K_s :mass, damping, stiffness matrix

>> $\ddot{X}=-M^{-1}K_sX-M^{-1}C_d\dot{X}-Ja-M^{-1}Hf$

$\hat{X}=\begin{bmatrix}X\\ \dot{X}\end{bmatrix}$를 이용하여
state-space equation 만들자



J=$\begin{bmatrix}1\\1\\1\end{bmatrix}$ H=$\begin{bmatrix}1\\0\\0\end{bmatrix}$ X=$\begin{bmatrix}x_1\\x_2\\x_3\end{bmatrix}$ a=지진 가속도 f=댐퍼의 힘

$\hat{X}=\begin{bmatrix}X\\ \dot{X}\end{bmatrix}$ $\dot{\hat{X}}=\begin{bmatrix}\dot{X}\\ \ddot{X}\end{bmatrix}$

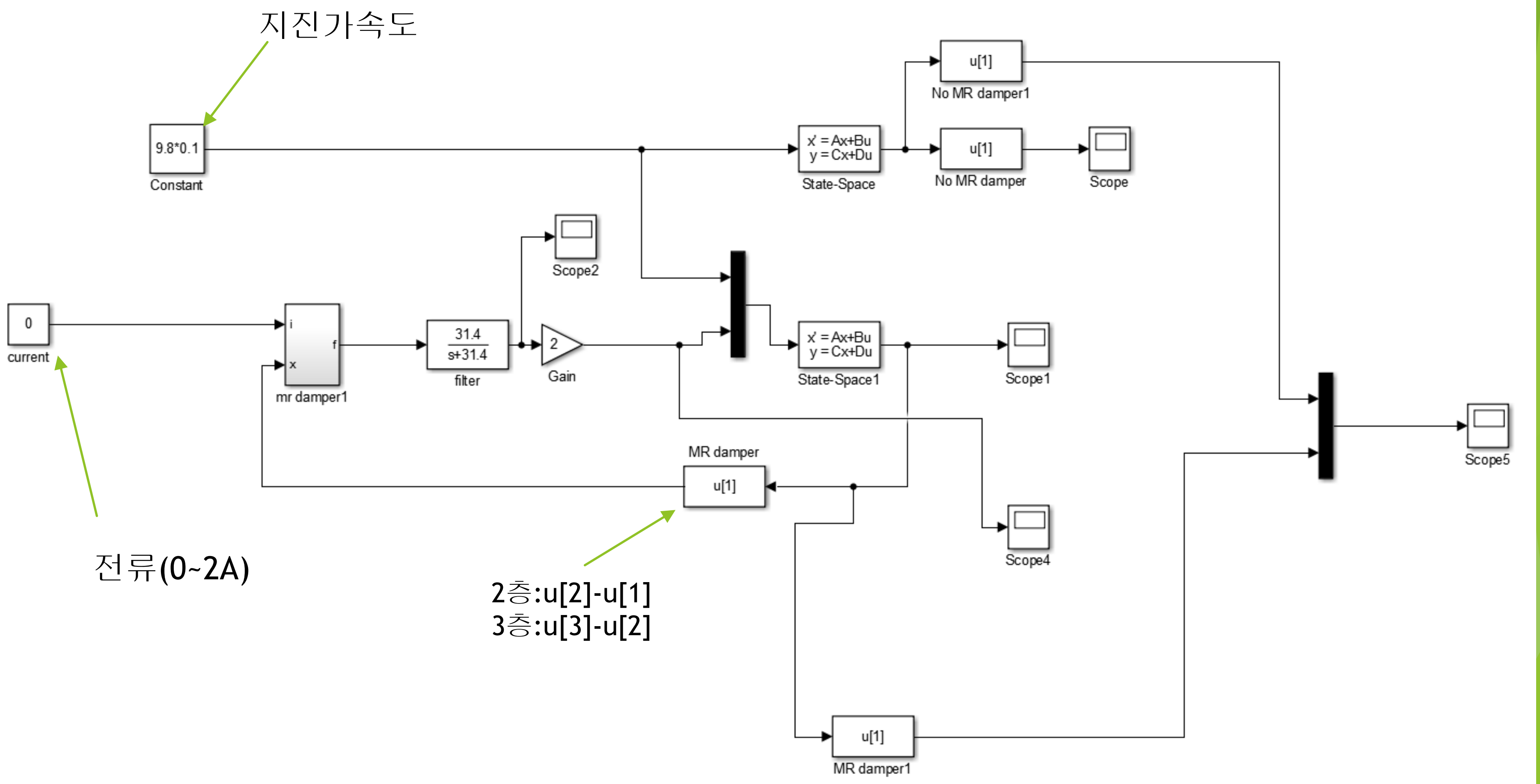
Y=$\begin{bmatrix}X\\ \dot{X}\\ \ddot{X}\end{bmatrix}$

$\dot{\hat{X}}$=A$\hat{X}$+Bu

Y=C$\hat{X}$ + Du

state-space equation

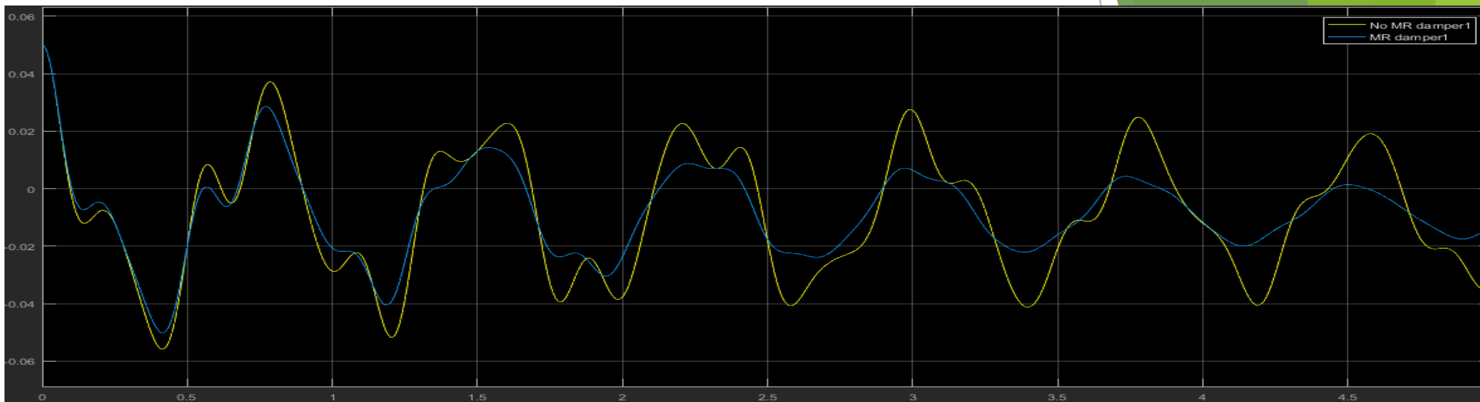
MR(Magneto-Rheological) Damper



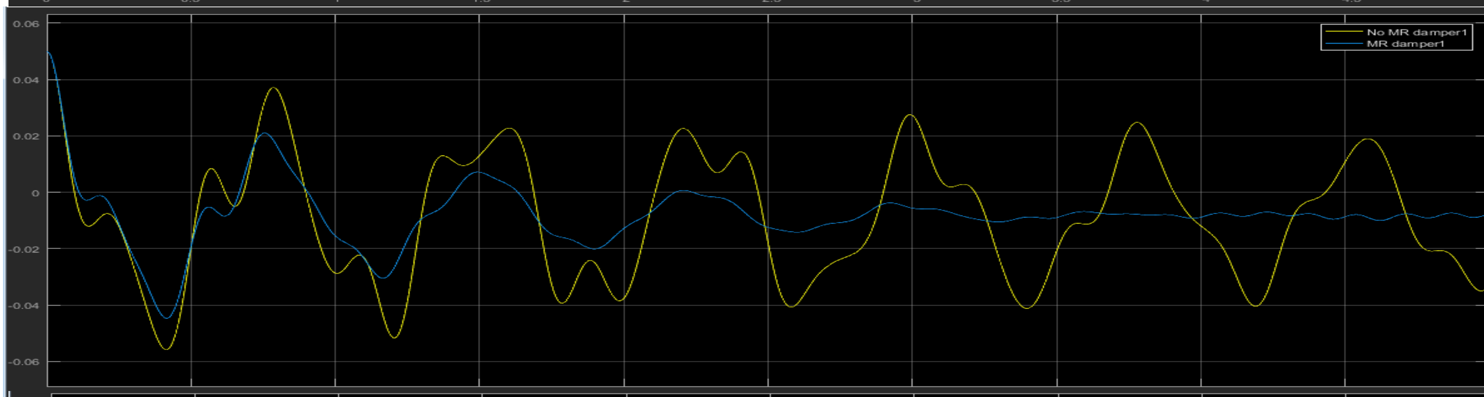
MR(Magneto-Rheological) Damper

1층에 damper 놓은 경우

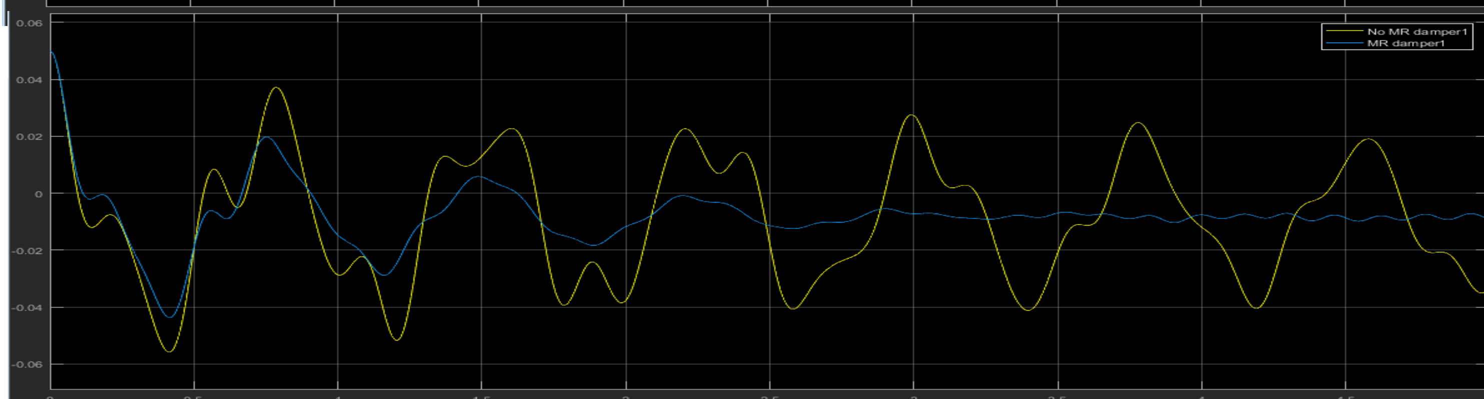
전류 0A



전류 1A

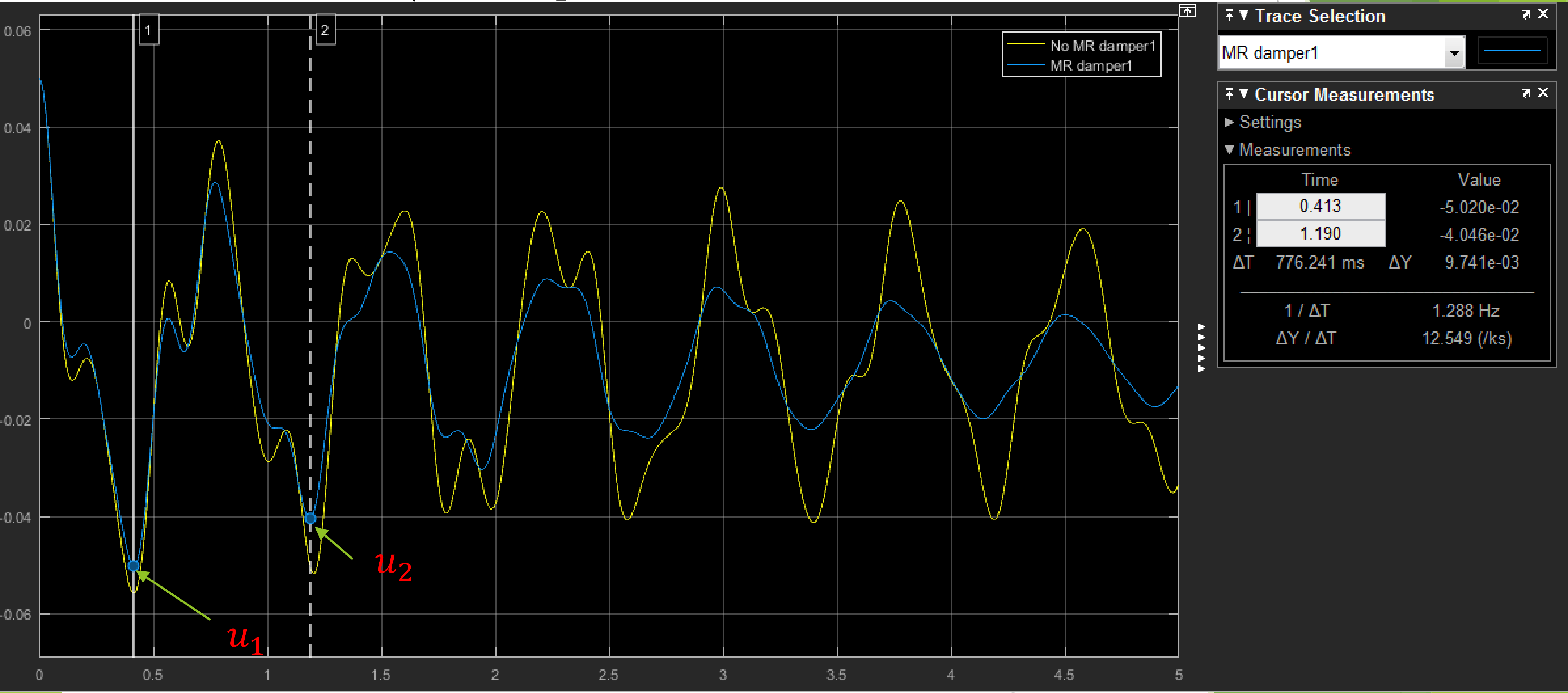


전류 2A



MR(Magneto-Rheological) Damper

- $\xi = \frac{ln\frac{u_1}{u_2}}{\sqrt{4\pi^2 + \left(ln\frac{u_1}{u_2}\right)^2}}$(system dynamics by ogata(8-15) 참조)



MR(Magneto-Rheological) Damper

```
clc;
% x=[nodamper 0A 1A 2A]
%% 1층
x1=[5.585 5.020 4.468 4.371];
x2=[5.176 4.406 3.046 2.883]; n=length(x1);
for i=1:n
    damping_ratio(i)=log(x1(i)/x2(i))/sqrt(4*pi^2+(log(x1(i)/x2(i)))^2);
end
damping_ratio_1=damping_ratio*100
%% 2층
x1=[5.585 5.483 5.261 5.215];
x2=[5.176 4.270 3.592 3.489]; n=length(x1);
for i=1:n
    damping_ratio(i)=log(x1(i)/x2(i))/sqrt(4*pi^2+(log(x1(i)/x2(i)))^2);
end
damping_ratio_2=damping_ratio*100
%% 3층
x1=[5.585 5.046 4.753 4.728];
x2=[5.176 4.004 3.244 3.147]; n=length(x1);
for i=1:n
    damping_ratio(i)=log(x1(i)/x2(i))/sqrt(4*pi^2+(log(x1(i)/x2(i)))^2);
end
damping_ratio_3=damping_ratio*100
```

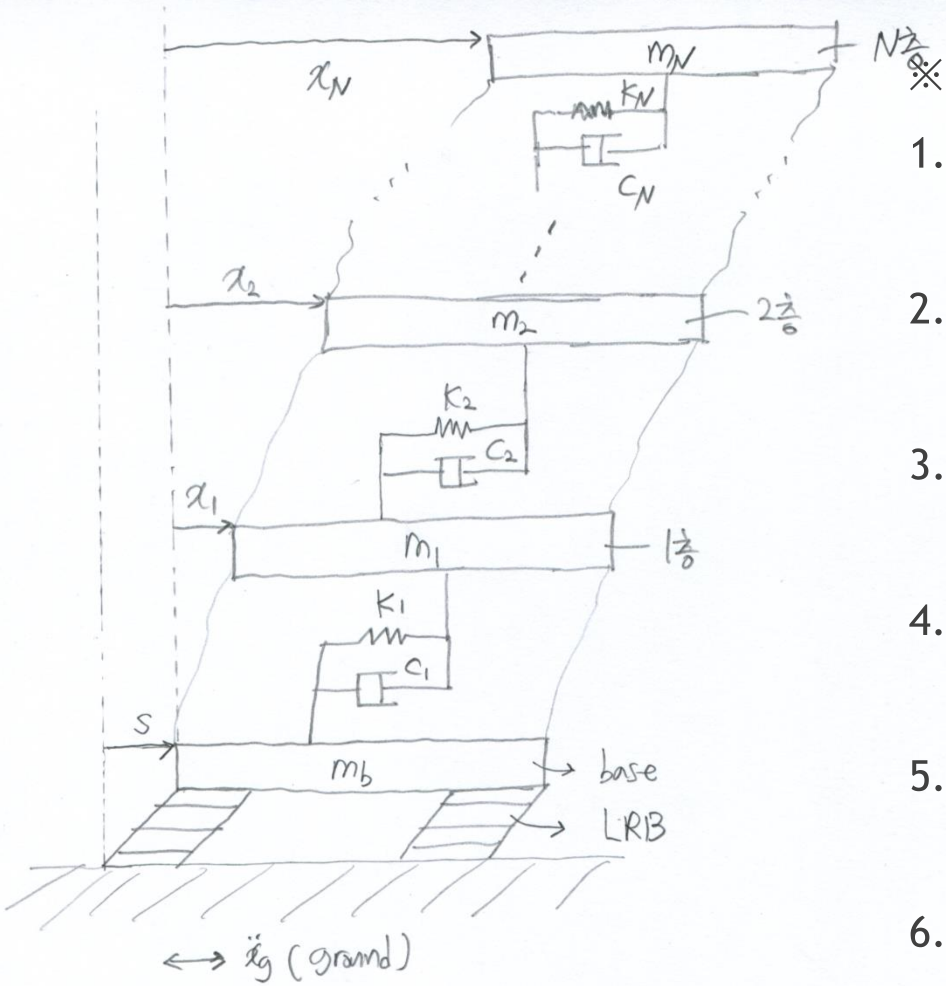
		no damper	0A	1A	2A
1층	damping_ratio_1 =	1.2103	2.0759	6.0861	6.6089
2층	damping_ratio_2 =	1.2103	3.9763	6.0624	6.3838
3층	damping_ratio_3 =	1.2103	3.6788	6.0680	6.4649

1층에 설치하는 것이 가장 효과적

Q&A

Governing equation

전단건물 모델



※ Governing equation을 구할 때 가정들

1. 강체로 가정 -> 전단변형 무시

2. 기둥의 축변형 무시

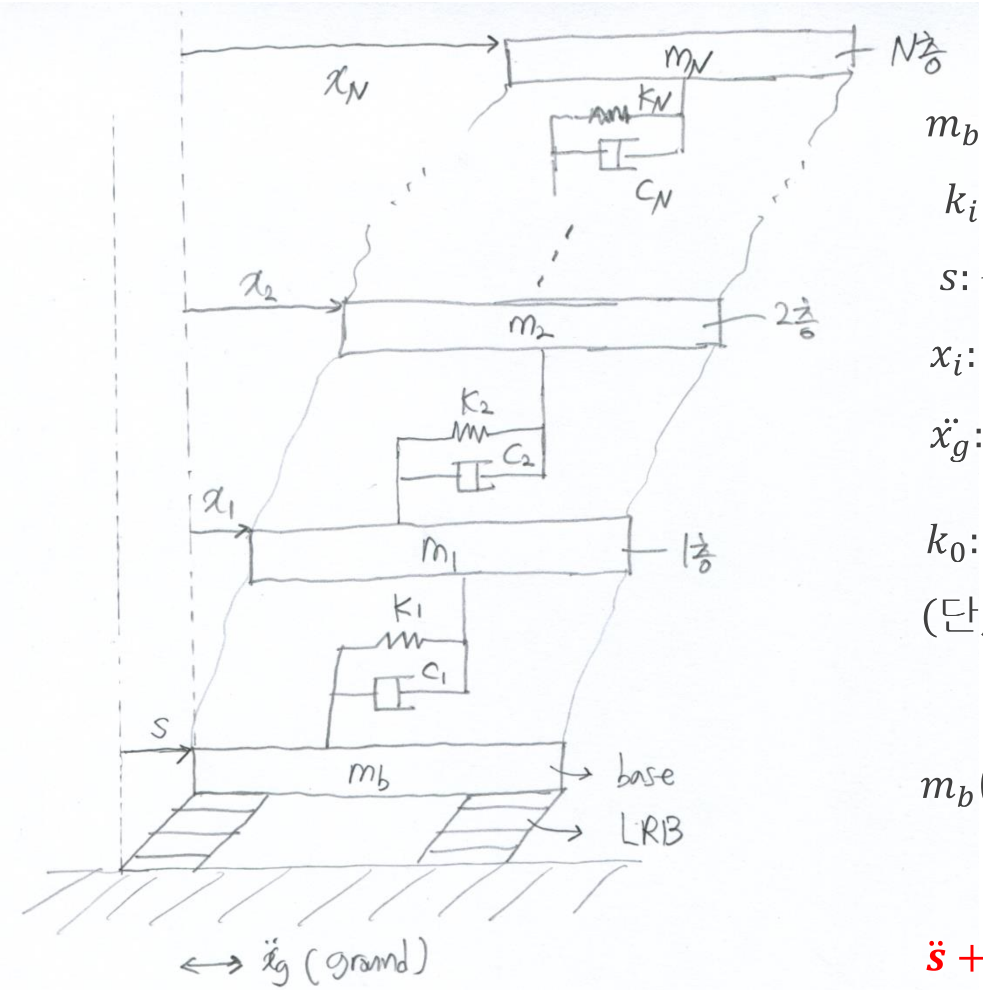
3. 절점의 회전 무시

4. 기둥은 오직 stiffness, damping만 존재

5. 각 층은 질량만 존재

6. LRB -> spring과 damper로 간주(effective)

Governing equation



m_b: 베이스의 질량, m_i: 각 층의 질량

k_i: 각 층 사이의 $stiffness$, c_i: 각 층 사이의 $damping$

s: 건물의 베이스와 땅간의 수평 상대 변위,

x_i: 건물의 베이스와 각 층간의 수평 상대 변위

$\ddot{x_g}$: 땅의 수평 가속도

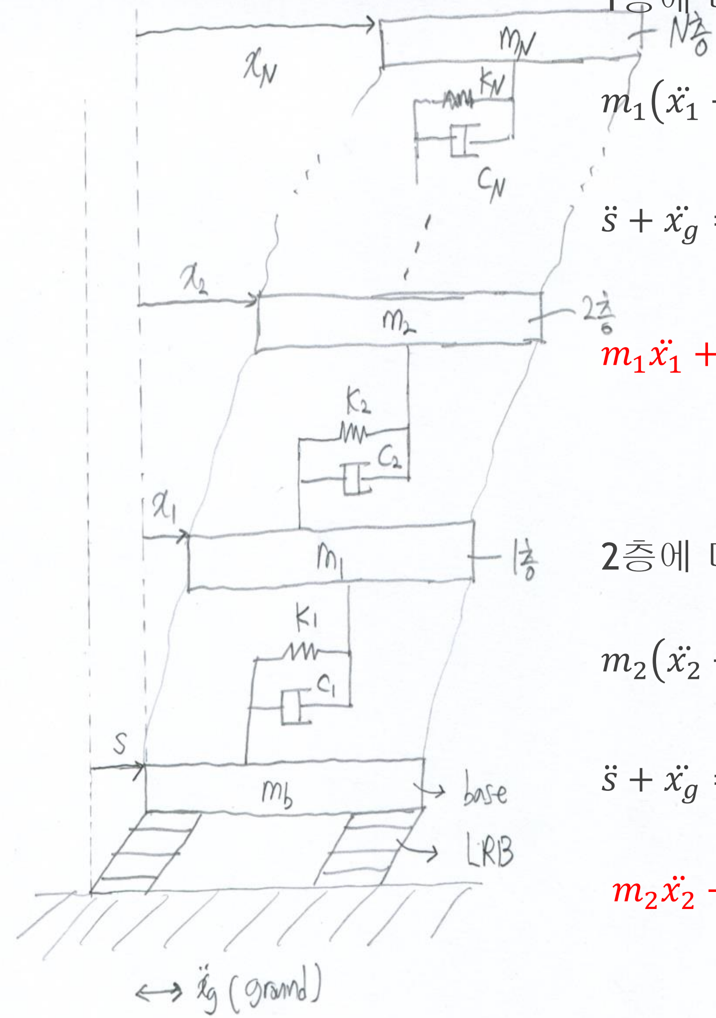
k_0: LRB의 수평 $stiffness$, c_0: LRB의 수평 $damping$

(단, $i = 1,2,\dots,N$)

$$m_b(\ddot{s} + \ddot{x_g}) = -c_0\dot{s} - k_0 s + c_1\dot{x_1} + k_1 x_1$$

$$\ddot{s} + \frac{c_0}{m_b}\dot{s} + \frac{k_0}{m_b}s = \frac{(c_1\dot{x_1} + k_1 x_1)}{m_b} - \ddot{x_g} \quad \dots \text{(식1)}$$

Governing equation



1층에 대하여,

1층 기준으로
base와 1~2층 사이의 운동 방정식

$m_1(\ddot{x}_1 + \ddot{s} + \ddot{x}_g) = -c_1\dot{x}_1 + c_2(\dot{x}_2 - \dot{x}_1) - k_1x_1 + k_2(x_2 - x_1)$ 이고

$\ddot{s} + \ddot{x}_g = -\frac{c_0\dot{s}+k_0s}{m_b} + \frac{c_1\dot{x}_1+k_1x_1}{m_b}$ 이므로 정리하면(by 식(1))

$m_1\ddot{x}_1 + (c_1 + c_2)\dot{x}_1 - c_2\dot{x}_2 + (k_1 + k_2)x_1 - k_2x_2 = m_1(\frac{c_0\dot{s}+k_0s}{m_b} - \frac{c_1\dot{x}_1+k_1x_1}{m_b})$

2층에 대하여,

2층 기준으로
1~3층 사이의 운동 방정식

$m_2(\ddot{x}_2 + \ddot{s} + \ddot{x}_g) = -c_2(\dot{x}_2 - \dot{x}_1) + c_3(\dot{x}_3 - \dot{x}_2) - k_2(x_2 - x_1) + k_3(x_3 - x_2)$ 이고

$\ddot{s} + \ddot{x}_g = -\frac{c_0\dot{s}+k_0s}{m_b} + \frac{c_1\dot{x}_1+k_1x_1}{m_b}$ 이므로 정리하면 (by 식(1))

$m_2\ddot{x}_2 - c_2\dot{x}_1 + (c_2 + c_3)\dot{x}_2 - c_3\dot{x}_3 - k_2x_1 + (k_2 + k_3)x_2 - k_3x_3 =$

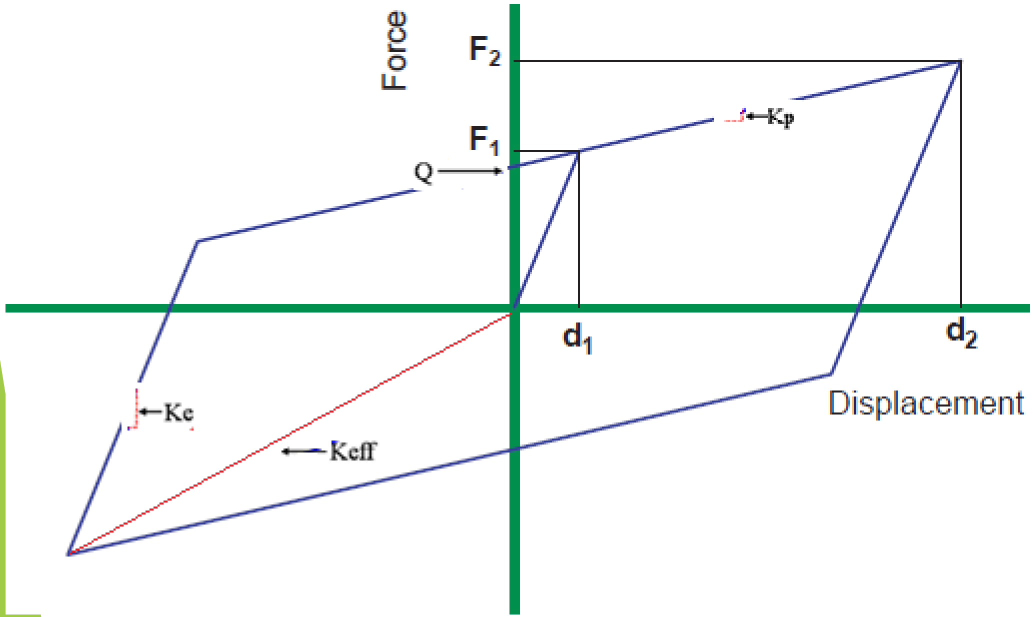
$m_2(\frac{c_0\dot{s} + k_0s}{m_b} - \frac{c_1\dot{x}_1 + k_1x_1}{m_b})$

Matlab

$2\zeta_0\omega_0 = \frac{c_0}{m}, \omega_0^2 = \frac{k_0}{m}$ -> 매트랩 코드에서 c_0, k_0 대신 ζ_0, ω_0를 이용해 작성

ζ_0: bearing의 effective damping ratio ω_0: bearing의 natural frequency

ζ_0와 k_0는 LRB의 bilinear 모델의 Hysteresis loop을 통해 구함



$$k_e = \frac{F_1}{d_1}$$

$$k_p = \frac{F_2 - F_1}{d_2 - d_1}$$

$$\boldsymbol{k_0} = \boldsymbol{k_{eff}} = \frac{\boldsymbol{F_2}}{\boldsymbol{d_2}}$$

$$Q = F_1 - k_p d_1$$

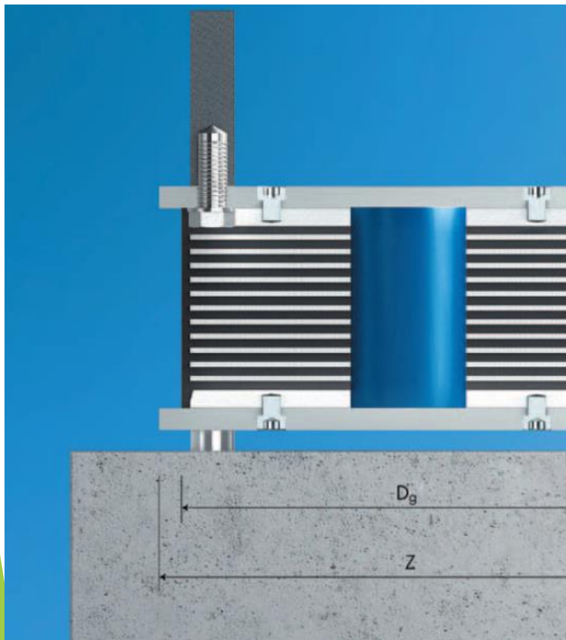
$$A = 4Q(d_2 - d_1)$$

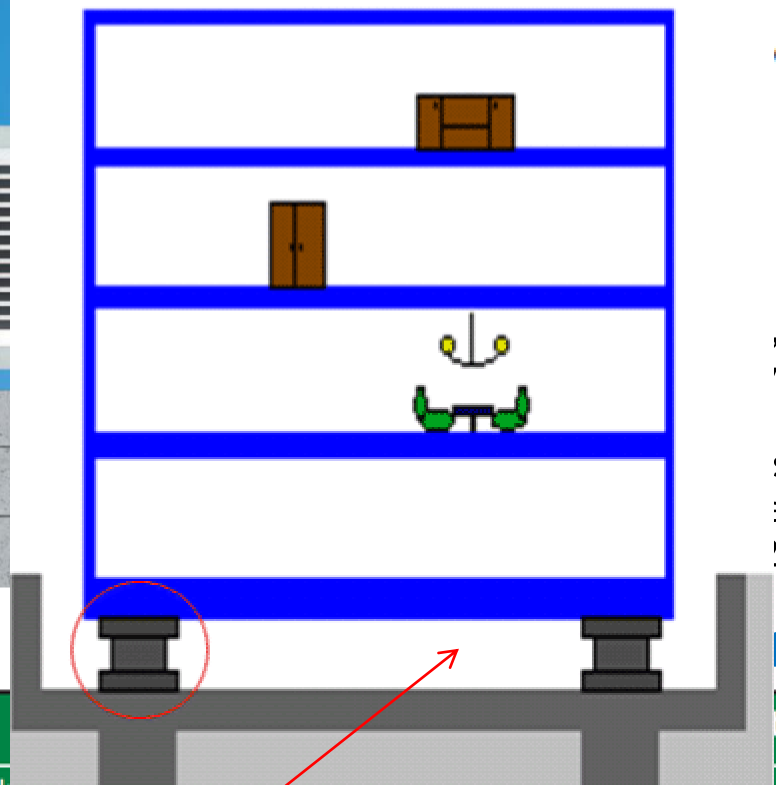
$$\zeta_0 = \frac{A}{2\pi k_{eff} d_2^2} = \frac{\boldsymbol{2}}{\boldsymbol{\pi}}\left(\frac{\boldsymbol{F_1}}{\boldsymbol{F_2}} - \frac{\boldsymbol{d_1}}{\boldsymbol{d_2}}\right)$$

elastic stiffness (K_e) , post-yield stiffness (K_p)
yield displacement (d_1), yield force (F_1)
maximum displacement (d_2), corresponding force (F_2)
hysteretic loop area (A), effective stiffness ($\boldsymbol{k_{eff}}$)

Matlab

모델링한 LRB





ıe top and bottom
rolled carbon steel
ı A709 Grade 36

NR, as per ASTM

purity of 99.9 %

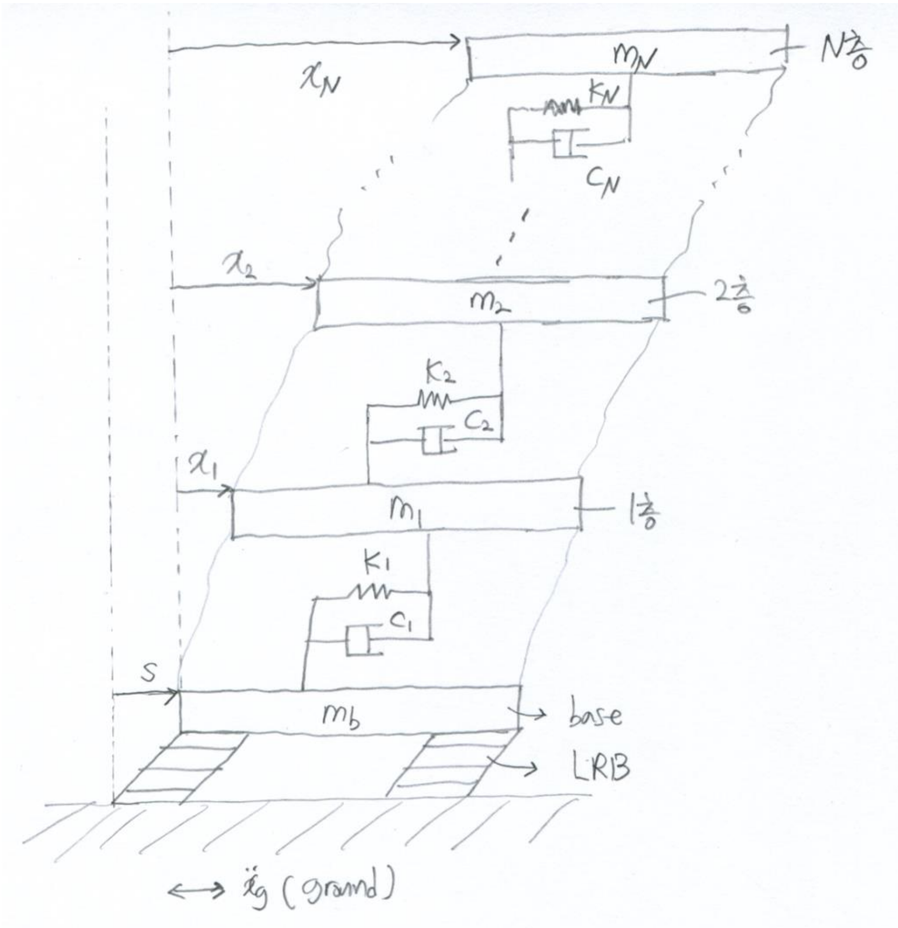
, v=0.29, Density=7850kg/m^3
'=0.4999
m^3 E=2G(1+v)=1.1992MPa
sity=11340kg/m^3
ː):
ː400kg/m^3

ı.94e6 N/m

실제 제품의 사양

LRB-S	V	F_{zd}								t_e	h	H	Z
	kN	kN	kN/mm	%	kN	KN	mm	kN/mm	mm	mm	mm	mm	mm
			At d_2 = 83 mm										
LRB-S 500/100-110	2700	3630	1.94	35	162	106	8	1164	500	100	197	247	550

고층건물일수록 고유진동수가 감소하는 이유



- 각 층의 스프링은 서로 직렬로 결합되어 있다.
- $k_{eq} = \frac{k_1 k_2}{k_1 + k_2} < k_1$
- K가 추가될수록 전체 탄성계수값은 낮아짐
- $2\pi f = \sqrt{\frac{k}{m}}$ 고층일수록 f감소

고층건물일수록 고유진동수가 감소하는 이유

K∝ $\frac{I}{l^3}$, I=$\frac{bh^3}{12}$ K=a$\frac{I}{l^3}$(a=상수)=a $\frac{bh^3}{12l^3}$

$\sqrt{\frac{k}{m}}$=$\sqrt{\frac{a}{12}\frac{bh^3}{ml^3}}$

만약 직육면체의 각 길이가 일정하게 줄어들고 부피가 $\frac{1}{8}$배가 되면 길이는 $\frac{1}{2}$배 ⟶ $\frac{bh^3}{l^3}$은 $\frac{1}{2}$배,m은$\frac{1}{8}$배가 되어 $\sqrt{\frac{k}{m}}$증가.

즉, 사이즈가 작아지면 고유진동수 증가

MR(Magneto-Rheological) Damper의 수학적 모델과 표현공식

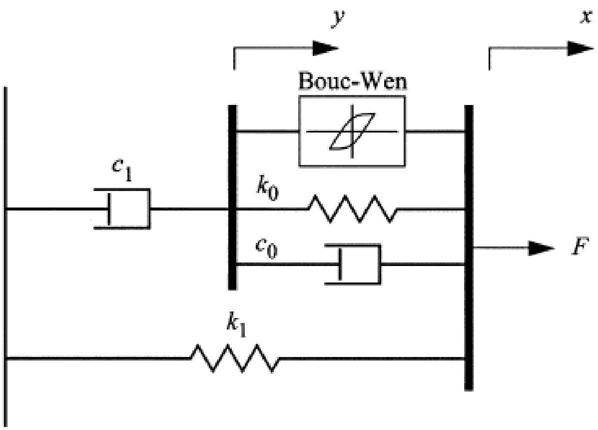


Fig. 11. Mechanical model of MR damper [14].

MR damper의 수학적 모델

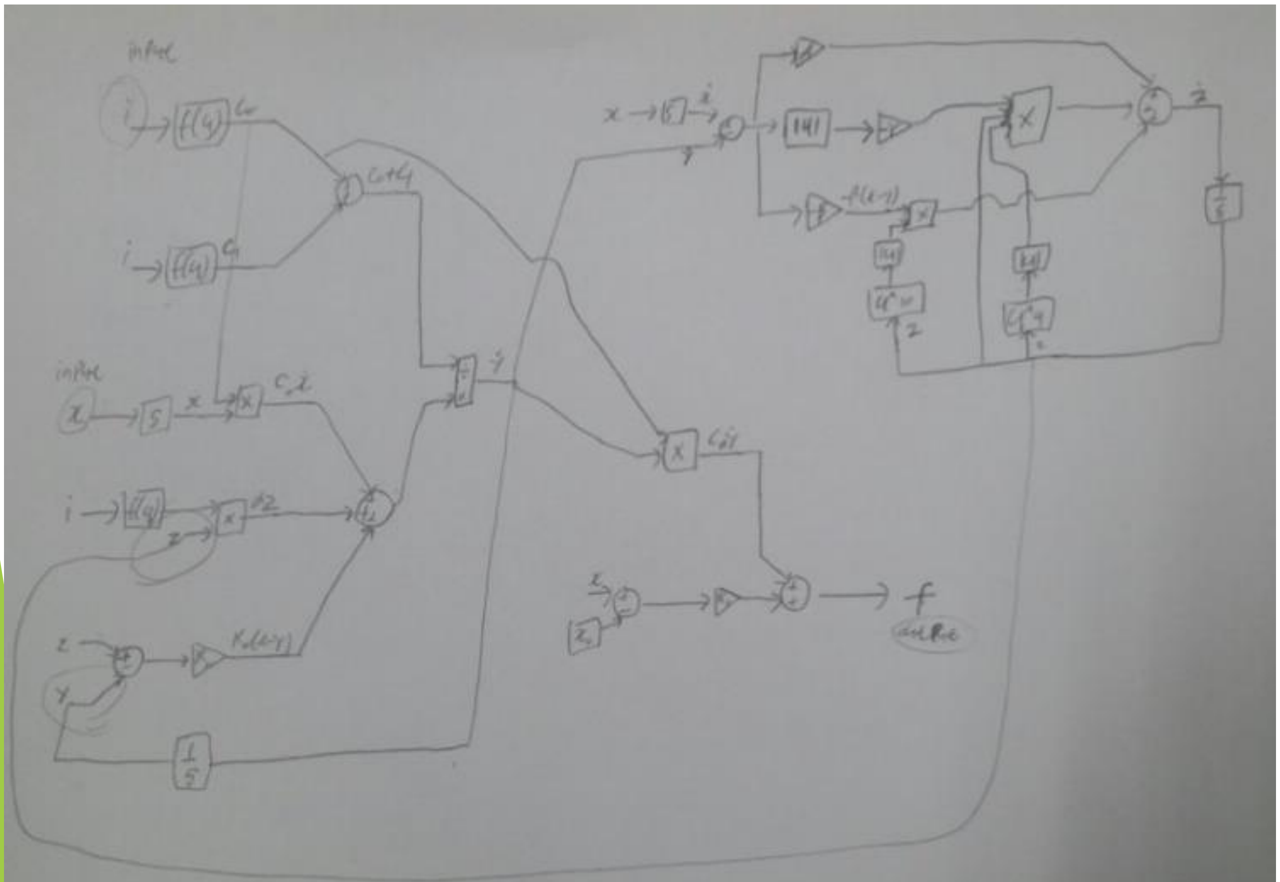
$$F=\alpha z+c_0(\dot{x}-\dot{y})+k_0(x-y)+k_1(x-x_0)=c_1\dot{y}+k_1(x-x_0)$$

$$\dot{z}=-\gamma|\dot{x}-\dot{y}|z|z|^{n-1}-\beta(\dot{x}-\dot{y})|z|^{n}+A(\dot{x}-\dot{y})$$

$$\dot{y}=\frac{1}{c_0+c_1}\{\alpha z+c_0\dot{x}+k_0(x-y)\}$$

- F=댐퍼로부터 나오는 힘
- z=hysteresis loop에서의 x축(자기장의 세기)

MR(Magneto-Rheological) Damper 시뮬링크 모델



- Mr damper 에 대한 시뮬링크 모델 작성

MR(Magneto-Rheological) Damper A B C D 계수행렬 계산

댐퍼가 없을 경우 ⟶ ***H=0***

$\dot{\hat{X}}$=A$\hat{X}$+Bu

A=$\begin{bmatrix} zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}$ B=$\begin{bmatrix} \text{zeros}(3,1) \\ -\text{ones}(3,1) \end{bmatrix}$

Y=C$\hat{X}$ + **Du**

u=a=$\ddot{x_g}$

C=$\begin{bmatrix} eye(3) & zeros(3,3) \\ zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}$ D=$\begin{bmatrix} \text{zeros}(3,1) \\ \text{zeros}(3,1) \\ -\text{ones}(3,1) \end{bmatrix}$

Pf) A$\hat{X}$=$\begin{bmatrix} zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}\begin{bmatrix} X \\ \dot{X} \end{bmatrix}$ =$\begin{bmatrix} \dot{X} \\ -M^{-1}K_sX - M^{-1}C_d\dot{X} \end{bmatrix}$: 6x1 벡터

Bu=$\begin{bmatrix} \text{zeros}(3,1) \\ -\text{ones}(3,1) \end{bmatrix}\ddot{x_g}$=$[0 \;\; 0 \;\; 0 \;\; -\ddot{x}_g \;\; -\ddot{x_g} \;\; -\ddot{x_g}]^T$: 6x1 벡터

A$\hat{X}$+Bu= $\begin{bmatrix} \dot{X} \\ -M^{-1}K_sX - M^{-1}C_d\dot{X} - Ja \end{bmatrix}$ = $\begin{bmatrix} \dot{X} \\ \ddot{X} \end{bmatrix}$ = $\dot{\hat{X}}$

($\because$ $\ddot{X}$=$-M^{-1}K_sX - M^{-1}C_d\dot{X} - Ja$)

C$\hat{X}$ = $\begin{bmatrix} eye(3) & zeros(3,3) \\ zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}\begin{bmatrix} X \\ \dot{X} \end{bmatrix}$= $\begin{bmatrix} X \\ \dot{X} \\ -M^{-1}K_sX - M^{-1}C_d\dot{X} \end{bmatrix}$: 9x1벡터

Du = $\begin{bmatrix} \text{zeros}(3,1) \\ \text{zeros}(3,1) \\ -\text{ones}(3,1) \end{bmatrix}\ddot{x_g}$=$[0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; 0 \;\; -\ddot{x}_g \;\; -\ddot{x_g} - \ddot{x_g}]^T$: 9x1벡터

C$\hat{X}$ + Du = $\begin{bmatrix} X \\ \dot{X} \\ -M^{-1}K_sX - M^{-1}C_d\dot{X} - Ja \end{bmatrix}$ =$\begin{bmatrix} X \\ \dot{X} \\ \ddot{X} \end{bmatrix}$= Y

($\because$ $\ddot{X}$=$-M^{-1}K_sX - M^{-1}C_d\dot{X} - Ja$)

MR(Magneto-Rheological) Damper
A B C D 계수행렬 계산

댐퍼가 있을 경우 ⟶ $H=\begin{bmatrix}1\\0\\0\end{bmatrix}$ (1층) , $H=\begin{bmatrix}0\\1\\0\end{bmatrix}$ (2층) , $H=\begin{bmatrix}0\\0\\1\end{bmatrix}$ (3층)

$\dot{\hat{X}}=A\hat{X}+Bu$

$$B=\begin{bmatrix} zeros(3,1) & zeros(3,1) \\ -ones(3,1) & -M^{-1}H \end{bmatrix}$$

$Y=C\hat{X}+Du$

$$u=\begin{bmatrix}a\\f\end{bmatrix}=\begin{bmatrix}\ddot{x}_g\\f\end{bmatrix}$$

$$D=\begin{bmatrix} zeros(3,1) & zeros(3,1) \\ zeros(3,1) & zeros(3,1) \\ -ones(3,1) & -M^{-1}H \end{bmatrix}$$

Pf) $A\hat{X}=\begin{bmatrix} zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}\begin{bmatrix}X\\\dot{X}\end{bmatrix}=\begin{bmatrix}\dot{X}\\-M^{-1}K_sX-M^{-1}C_d\dot{X}\end{bmatrix}$: 6x1 벡터

$Bu=\begin{bmatrix} zeros(3,1) & zeros(3,1) \\ -ones(3,1) & -M^{-1}H \end{bmatrix}\begin{bmatrix}\ddot{x}_g\\f\end{bmatrix}=\begin{bmatrix} zeros(3,1) \\ [-\ddot{x}_g\ -\ddot{x}_g\ -\ddot{x}_g]^T-M^{-1}Hf \end{bmatrix}$

: 6x1 벡터

$A\hat{X}+Bu=\begin{bmatrix}\dot{X}\\-M^{-1}K_sX-M^{-1}C_d\dot{X}-Ja-M^{-1}Hf\end{bmatrix}=\begin{bmatrix}\dot{X}\\\ddot{X}\end{bmatrix}=\dot{\hat{X}}$

$(\because \ddot{X}=-M^{-1}K_sX-M^{-1}C_d\dot{X}-Ja-M^{-1}Hf)$

$C\hat{X}=\begin{bmatrix} eye(3) & zeros(3,3) \\ zeros(3,3) & eye(3) \\ -M^{-1}K_s & -M^{-1}C_d \end{bmatrix}\begin{bmatrix}X\\\dot{X}\end{bmatrix}=\begin{bmatrix}X\\\dot{X}\\-M^{-1}K_sX-M^{-1}C_d\dot{X}\end{bmatrix}$: 9x1벡터

$Du=\begin{bmatrix} zeros(3,1) & zeros(3,1) \\ zeros(3,1) & zeros(3,1) \\ -ones(3,1) & -M^{-1}H \end{bmatrix}\begin{bmatrix}\ddot{x}_g\\f\end{bmatrix}=\begin{bmatrix} zeros(3,1) \\ zeros(3,1) \\ [-\ddot{x}_g\ -\ddot{x}_g\ -\ddot{x}_g]^T-M^{-1}Hf \end{bmatrix}$

: 6x1 벡터

$C\hat{X}+Du=\begin{bmatrix}X\\\dot{X}\\-M^{-1}K_sX-M^{-1}C_d\dot{X}-Ja-M^{-1}Hf\end{bmatrix}=\begin{bmatrix}X\\\dot{X}\\\ddot{X}\end{bmatrix}=Y$

$(\because \ddot{X}=-M^{-1}K_sX-M^{-1}C_d\dot{X}-Ja-M^{-1}Hf)$

MR(Magneto-Rheological) Damper 건물 물성치 계산

$$M = 10^5 \times \begin{bmatrix} 3.456 & 0 & 0 \\ 0 & 3.456 & 0 \\ 0 & 0 & 3.456 \end{bmatrix} kg$$

$$K = 10^8 \times \begin{bmatrix} 2.4 & -1.2 & 0 \\ -1.2 & 2.4 & -1.2 \\ 0 & -1.2 & 1.2 \end{bmatrix} N/m$$

$$[M]\{\ddot{x}\} + [K]\{x\} = 0$$

$$([K] - \omega^2[M])\{\Phi\} = 0 \ , \quad \det([K] - \omega^2[M]) = 0$$

ω^2: eigenvalue ω: eigenfrequency   {: }: eigen vector

mode shape matrix

Modal mass matrix

$$[\phi]^t [M] [\phi] = \begin{bmatrix} \ddots & & \\ & m & \\ & & \ddots \end{bmatrix}$$

감쇠비
ξ=0.01로 가정

$$C_g = \mathrm{diag}[\, 2\xi_i \omega_i \, M_i \,]$$

generalized damping matrix

$$[\phi]^t [C] [\phi] = \begin{bmatrix} \ddots & & \\ & c & \\ & & \ddots \end{bmatrix}$$

Dampig matrix
(구하고자 하는것)

건물 특성: active control of earthquake responses
Using fuzzy supervisory control technique 참조
Park et al

```
M=[345600,0,0;0,345600,0;0,0,345600];
KS=[240000000,-120000000,0;-120000000,240000000,-120000000;0,-120000000,120000000];
% PI=mode shape matrix, M=mass matrix, Mm=modal mass matrix
% Cm=modal damping matrix, Cd=damping matrix
[PI,square_freq]=eig(KS,M);
Zeta=ones(1,n)*0.01;
natural_freq=sqrt(diag(square_freq));
Mm=(PI')*M*PI;
for j=1:n
 c(j)=[2*Zeta(j)*natural_freq(j)*Mm(j,j)];
end
Cm=diag(c);
Cd=inv(PI')*Cm*inv(PI);
```

Damping matrix
Cd 구하는 과정

아쉬운 점

1. Governing equation을 구할 때의 여러 가지 가정
2. Comsol에서 고무의 특성을 linear로 가정