

# Suspension Battery Charging System

Team: 티끌 모아 충전

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## 1 프로젝트 선정 배경

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## Chapter 01

# 프로젝트 선정 배경

## 1. 프로젝트 선정 배경

- 소비자가 원하는 전기차의 주행 가능 거리가 증가함에 따라 제조사도 전기차의 주행 가능 거리를 늘리고자 함
- 하지만 배터리 용량을 늘리면 제조원가 상승 및 차량 무게 증가로 인해 전비 측면에서 손해를 봄
- 따라서 배터리 용량을 무작정 늘리기 보단 낭비되는 에너지를 최대한 회수하여 활용하는 전략이 필요
- 회생제동 브레이크 시스템처럼 서스펜션의 운동에너지를 회수하고 배터리를 충전하여 낭비되는 에너지를 최소화 할 수 있을 것

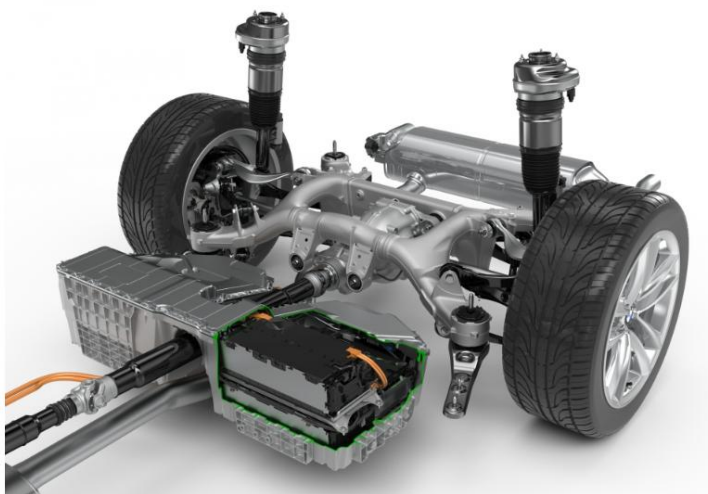
# 1. 프로젝트 선정 배경

HOME > 자동차 > 뉴스

## BMW의 신박한 전기차 특허...'서스펜션으로 배터리 충전'

차 박종준 | © 승인 2022.12.08 14:25

BMW가 서스펜션의 운동에너지로 배터리를 충전하는 기술 특허를 독일에서 출원한 것으로 전해졌다.



BMW 7시리즈 PHEV 배터리팩과 후륜 서스펜션 구조 (사진은 기사 내용과 무관)

이번 특허는 서스펜션에서 발생하는 진동을 전기로 전환하는게 핵심이다. 스테빌라이저에 부착된 발전기가 주행 중 발생하는 진동을 동력으로 전환하고, 만들어진 전기를 배터리에 저장한다.

차체 진동을 분산시키는 기존 서스펜션의 역할과 전혀 다른 개념이다. 서스펜션이 축소했다 이완되는 과정에서 발전기 내부의 플라이 휠이 회전하는 운동 에너지를 공급한다. 스트로크가 반복될수록 발전기 회전 속도가 점차 빨라지며 전기가 생성되는 것이다.

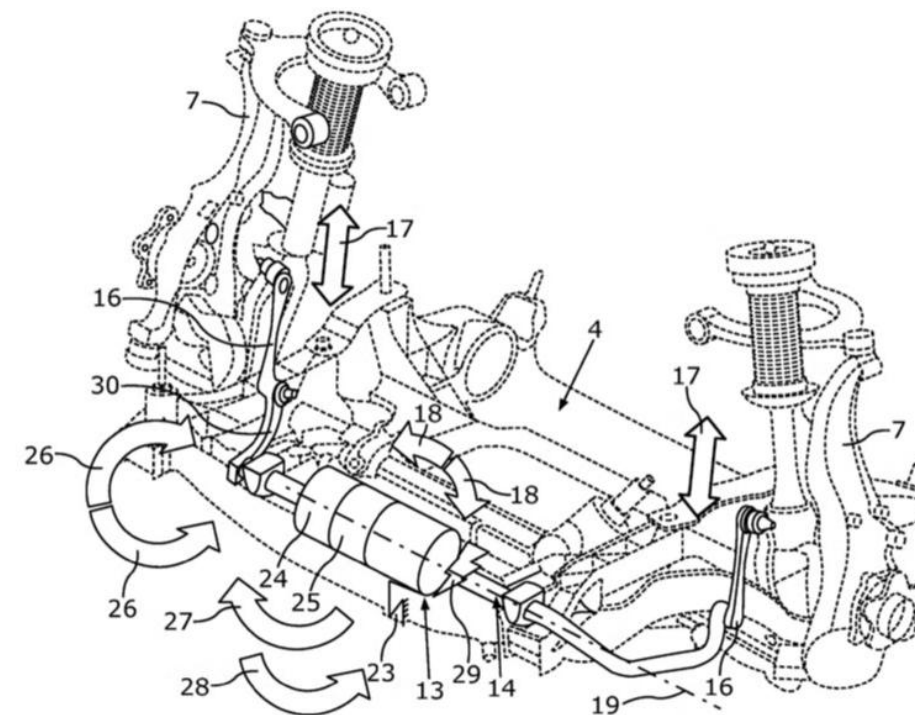


Fig.3

서스펜션의 상하 직선 운동(힘) → 회전운동(토크) → 모터(발전기) → 배터리 충전

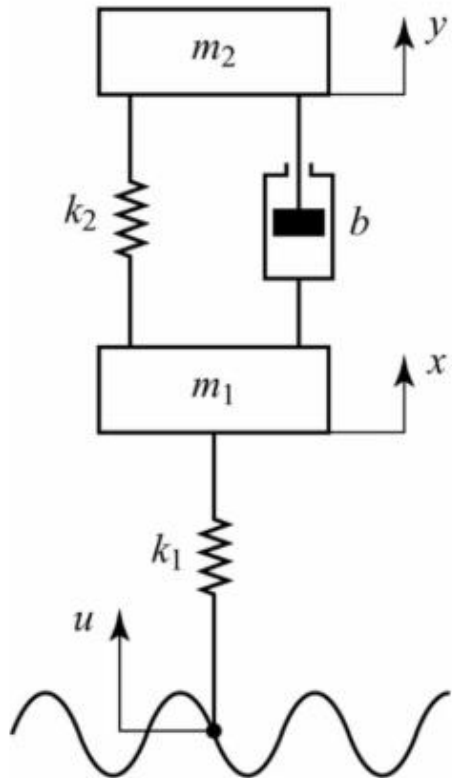
# 1. 프로젝트 선정 배경

- 불규칙한 거친 노면을 차량의 바퀴에 인가하였을 때 배터리 SOC변화를 Simulink로 확인
- 상하 직선 운동을 회전 운동으로 바꾸기 위한 서스펜션의 추가적인 빔 구조를 모델링 및 COMSOL로 해석

## Chapter 02

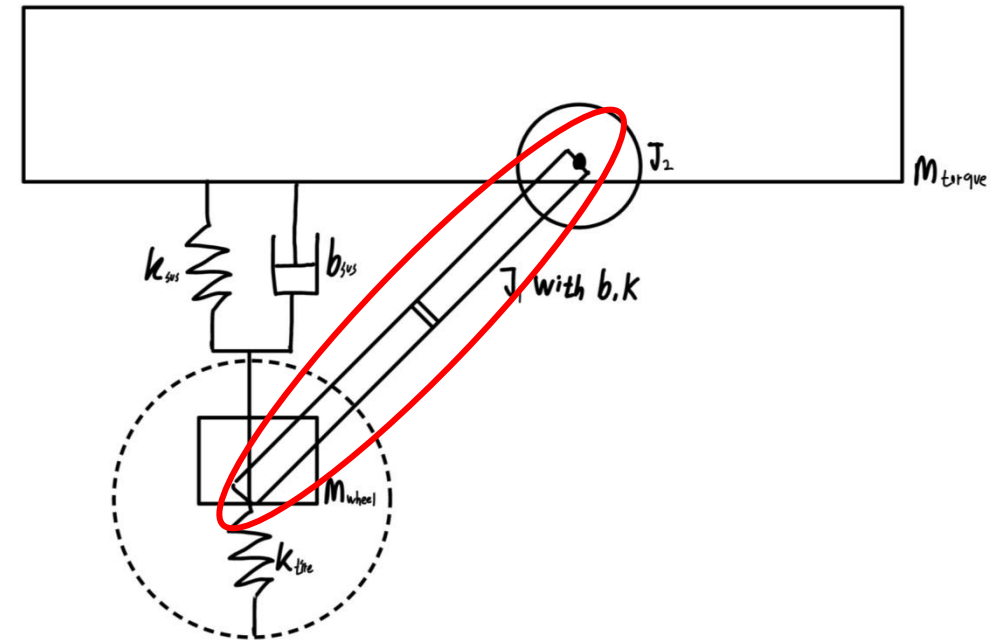
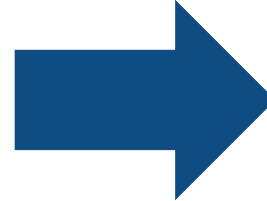
# 서스펜션 모델링

## 2. 서스펜션 모델링



$$m_1 \ddot{x} + b\dot{x} + (k_1 + k_2)x = b\dot{y} + k_2y + k_1u$$

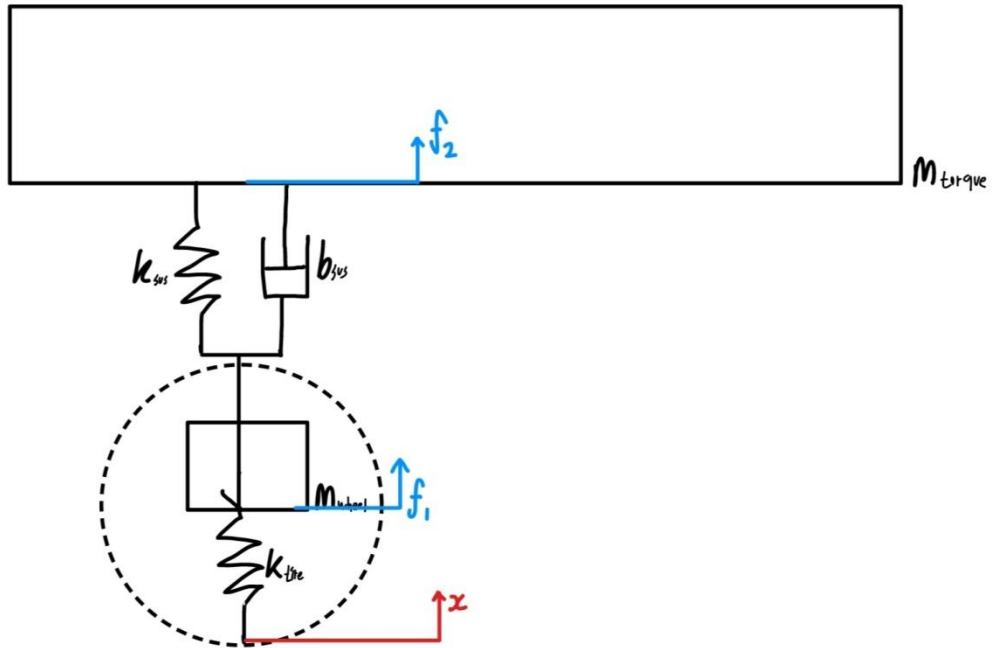
$$m_2 \ddot{y} + b\dot{y} + k_2y = b\dot{x} + k_2x$$



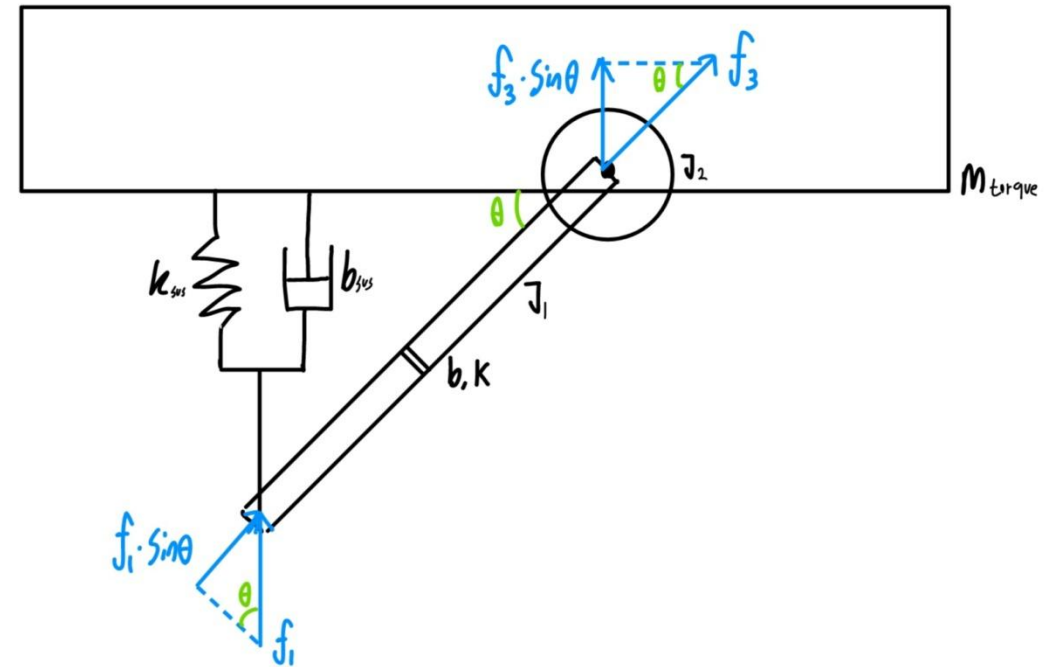
상하 직선 운동 → 회전운동으로 바꿀  
추가적인 Beam 장착



## 2. 서스펜션 모델링

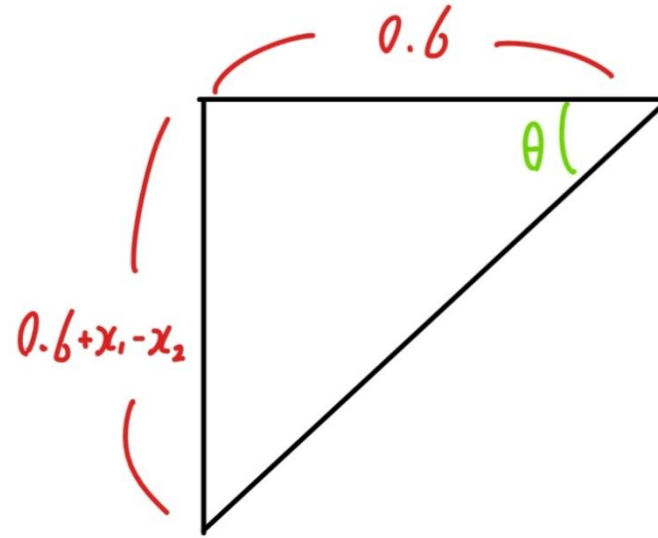
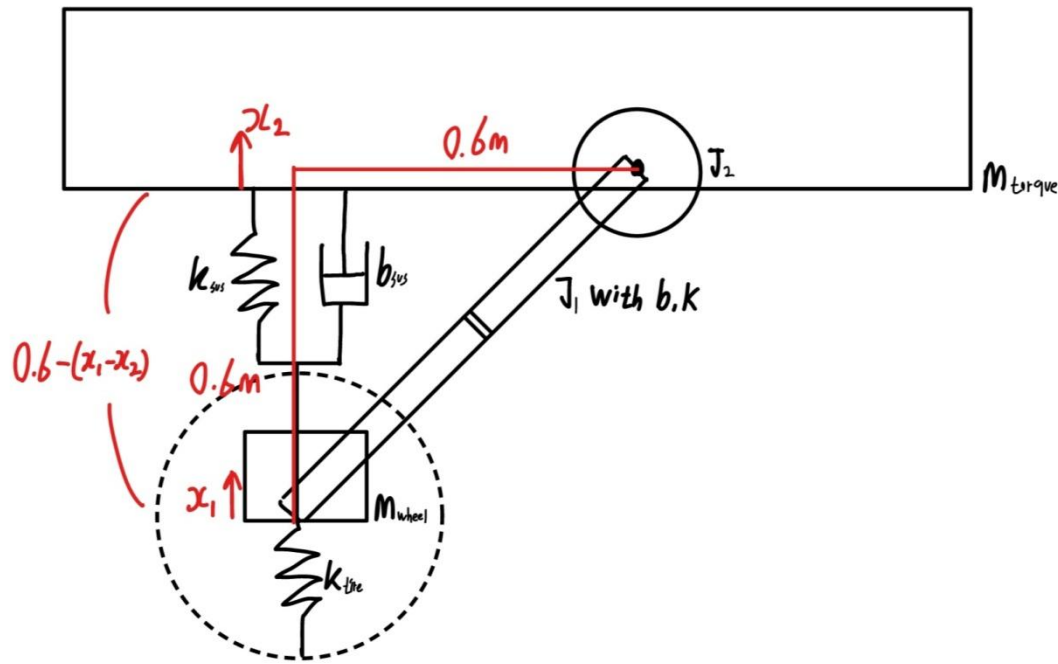


Beam이 없을 때 변위와 힘



Beam 에 작용하는  $f_1$ 의 y방향의 힘

## 2. 서스펜션 모델링

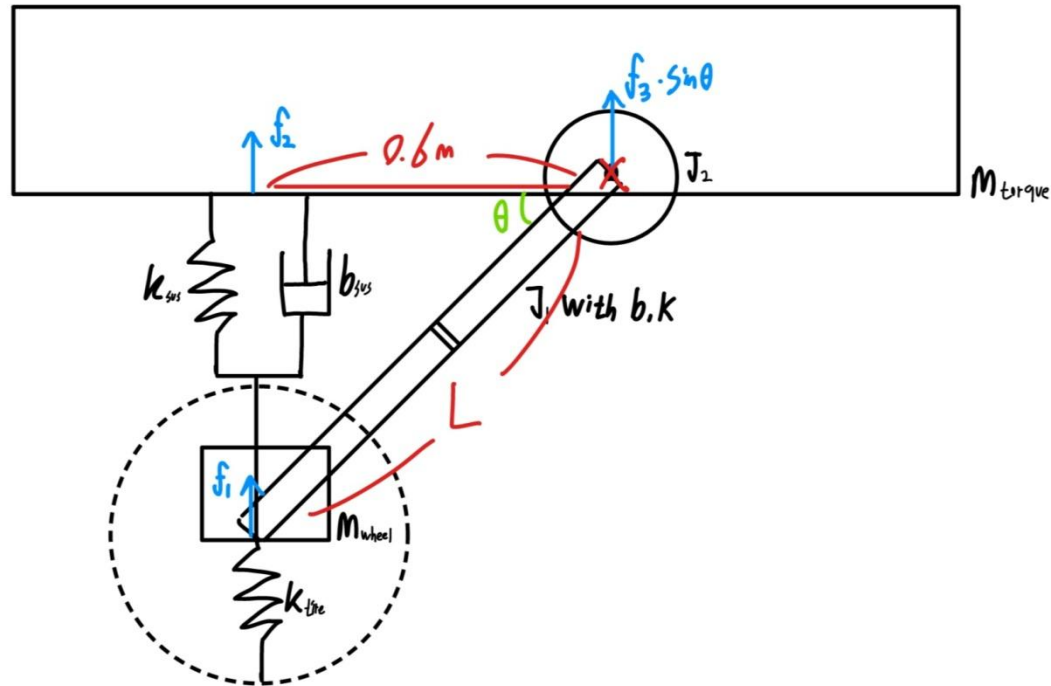


$$\tan \theta = \frac{0.6 + x_1 - x_2}{0.6}$$

$$\theta = \tan^{-1} \left( \frac{0.6 + x_1 - x_2}{0.6} \right)$$

wheel에서의 변위( $x_1$ )와 quarter mass의 변위( $x_2$ )에 따른 각도 계산

## 2. 서스펜션 모델링



$$T_{total} = 0.6 \cdot f_1$$

$$T_{motor} = T_{total} \times \frac{J_2}{J_1 + J_2}$$

$$J_2 = \frac{1}{2} m r^2$$

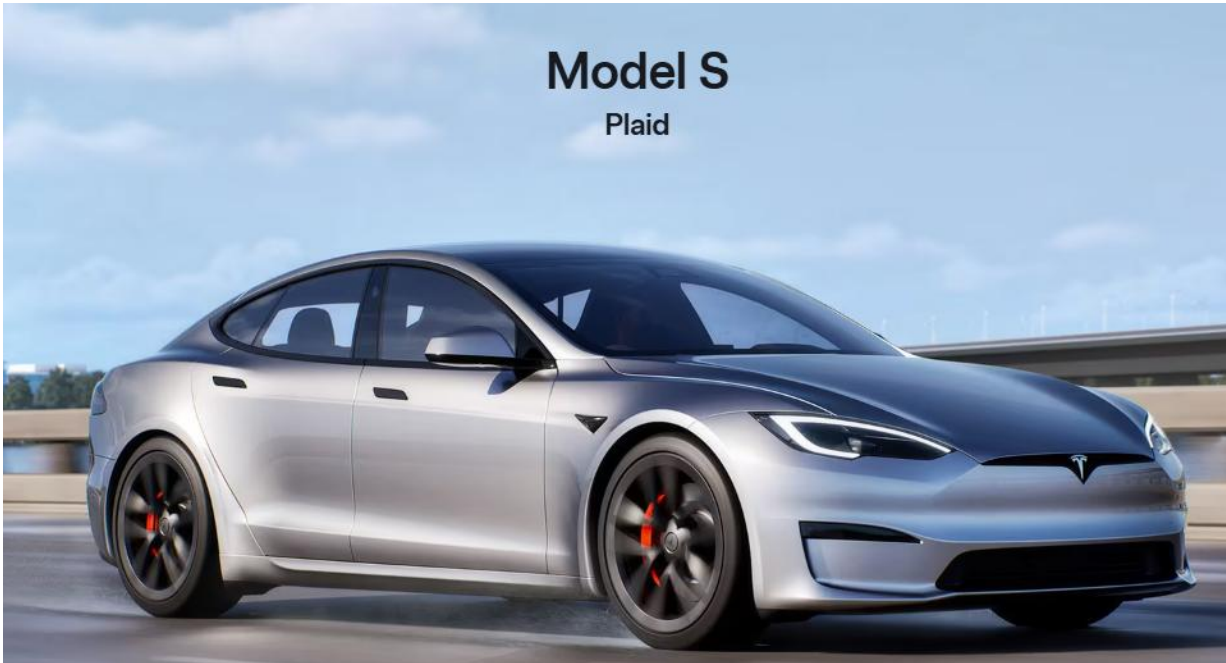
$$J_1 = \frac{1}{3} m L^2, \quad L = 0.6 \text{ Sec} \theta$$

$$= \frac{1}{3} m \left( 0.6 \cdot \frac{1}{\cos \theta} \right)^2$$

각도에 따라 변화하는 beam의 관성 모멘트와 모터에 인가되는 토크 계산

### 3. 서스펜션 & SOC 충전 시뮬레이션

#### TESLA Model S



21" Tesla Model S Twin Turbine Wheel

This wheel was the last wheel option available when ordering a Tesla Model S in 2020. It came in a staggered set up. This wheel was available with a set of lug nut covers that only first this wheel design. The 21" Turbine was available in silver or gray color.



Tesla Model S AWD Rear Shock Absorber (Left Or Right)  
1015620-05 Dual Motor

**타이어의 stiffness(K): 190,000 N/m**

**휠 무게(21인치) : 35.8lbs**

**타이어 (Pirelli P Zero 275/35R21  
103W XL) 무게: 31.31lbs**

**서스펜션(스프링 + 댐퍼) 무게: 8.4kg**

### 3. 서스펜션 & SOC 충전 시뮬레이션

#### Tesla model S

- Capacity: 232Ah
- 18650 Li-ion
- 96 series, 74 parallel

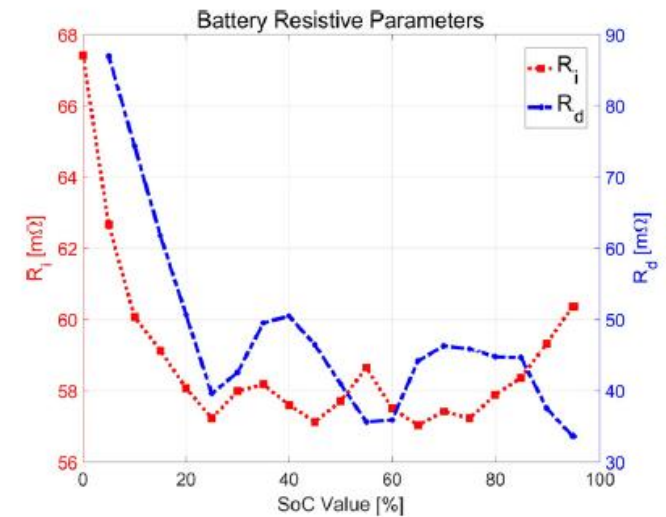
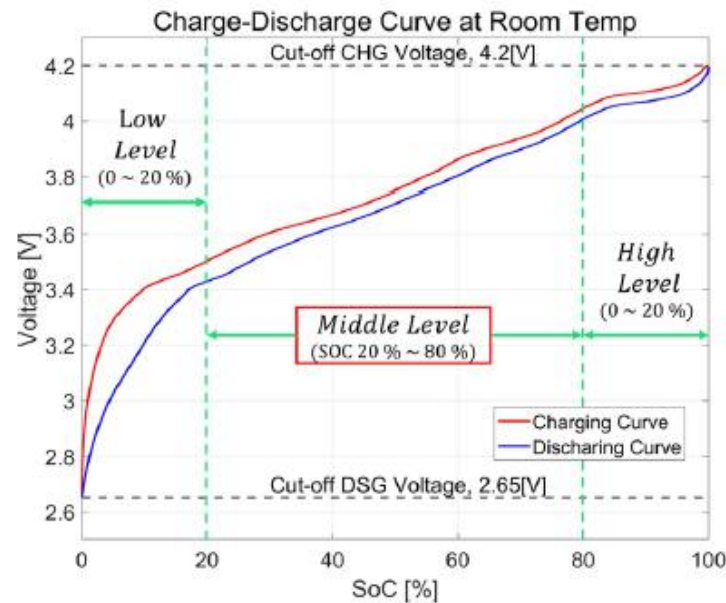
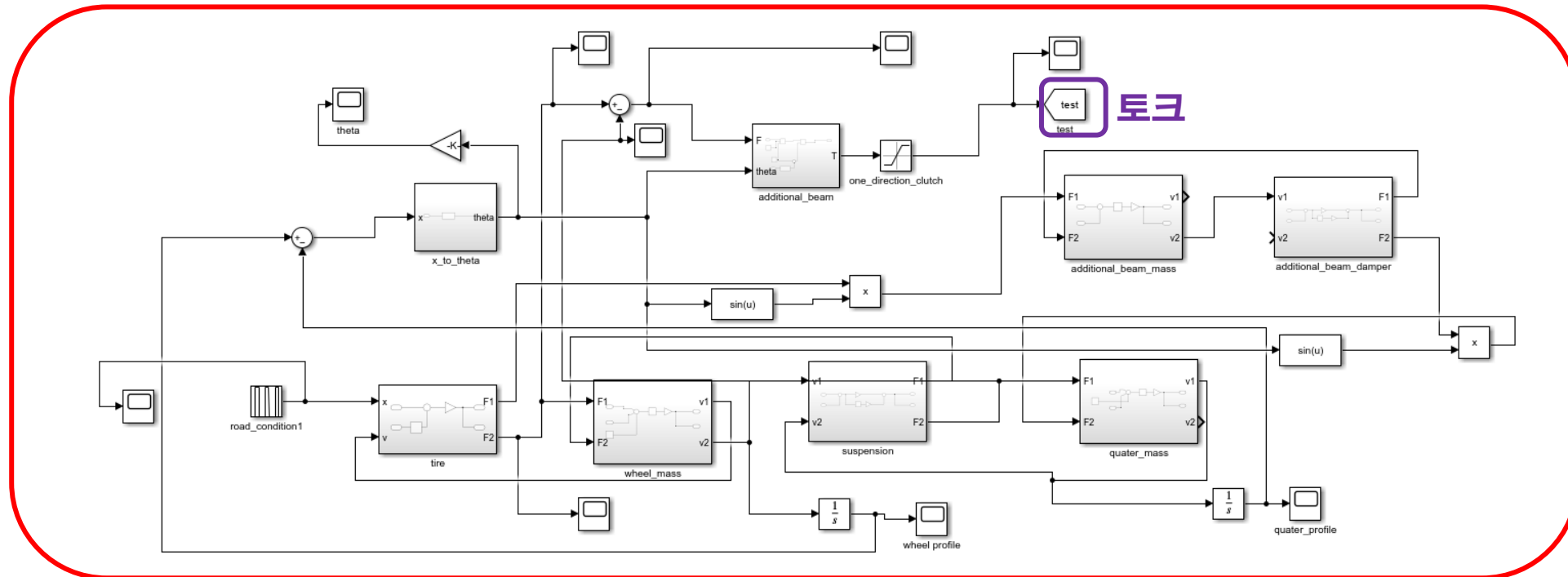
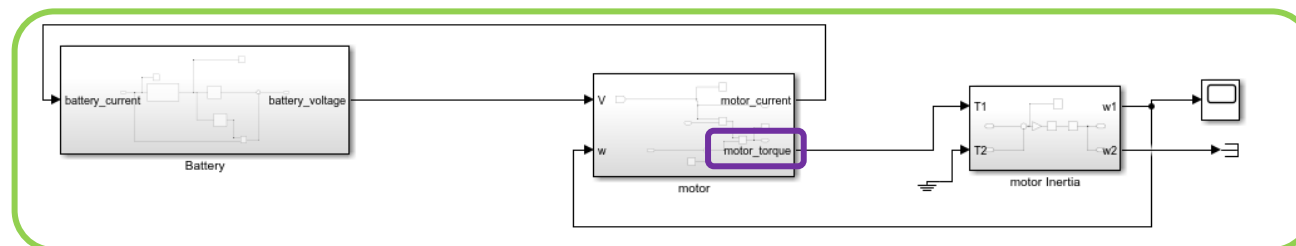


Fig. 10. Parameter extraction results of resistive parameters

### 3. 서스펜션 & SOC 충전 시뮬레이션



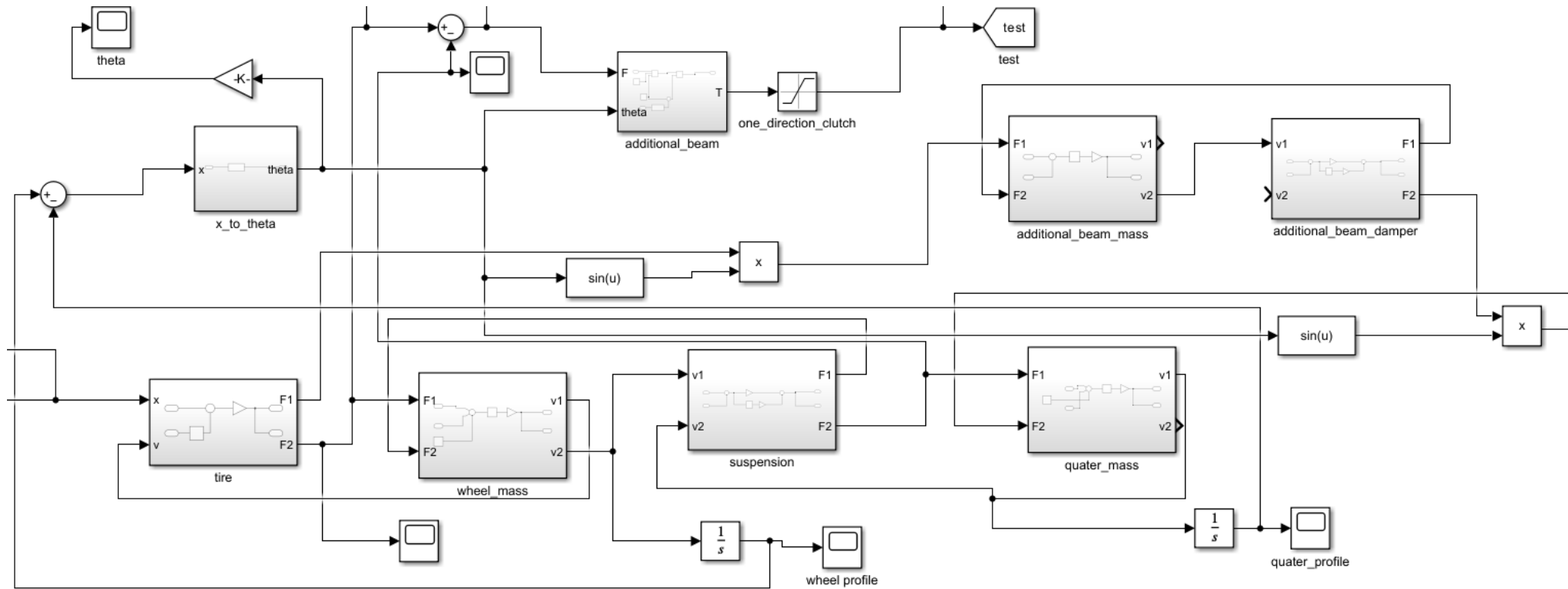
## 서스펜션



## 모터, 배터리

## 서스펜션 모델링을 바탕으로 만든 시뮬레이션 모델

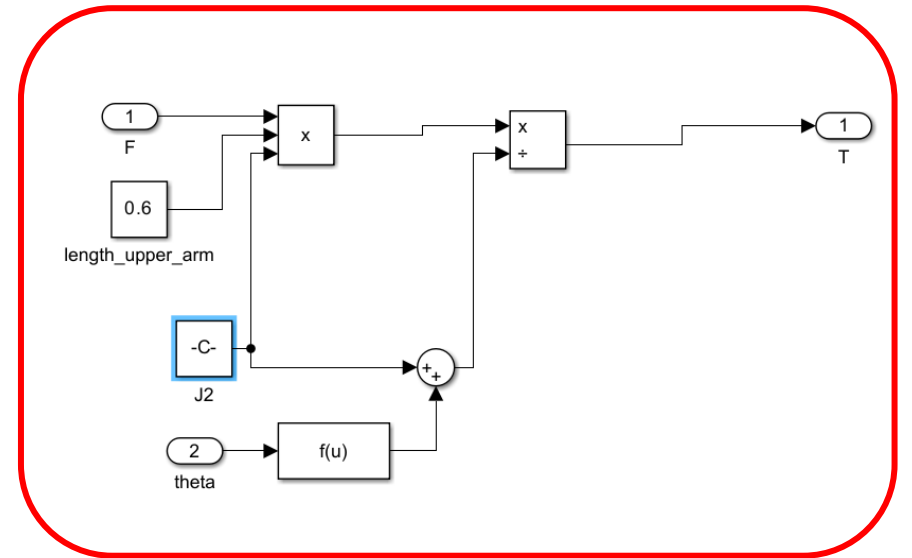
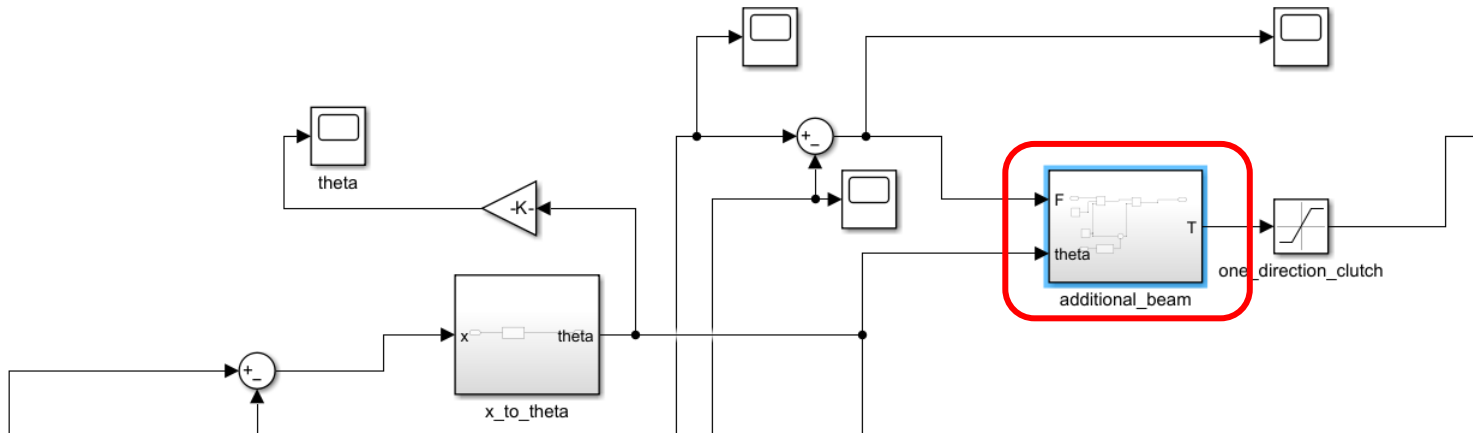
### 3. 서스펜션 & SOC 충전 시뮬레이션



수식 기반 서스펜션 모델링 → Simulink 구성



### 3. 서스펜션 & SOC 충전 시뮬레이션



- 서스펜션 변위 → 각도
- 힘과 각도 → 발전기 토크

$$T_{total} = 0.6 \cdot f_1$$

$$T_{motor} = T_{total} \times \frac{J_2}{J_1 + J_2}$$

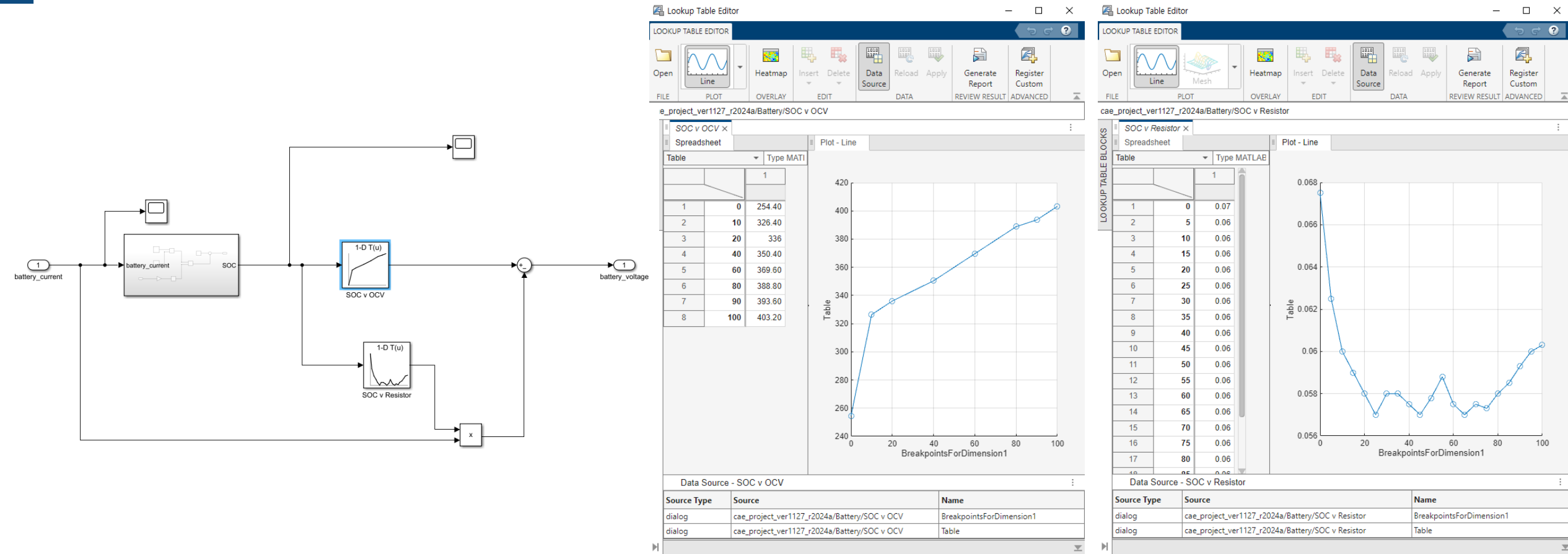
$$J_2 = \frac{1}{2} m r^2$$

$$J_1 = \frac{1}{3} m L^2, \quad L = 0.6 \sec \theta$$

$$= \frac{1}{3} m \left( 0.6 \cdot \frac{1}{\cos \theta} \right)^2$$



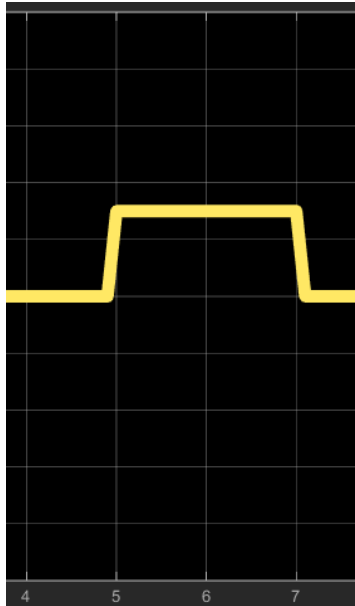
### 3. 서스펜션 & SOC 충전 시뮬레이션



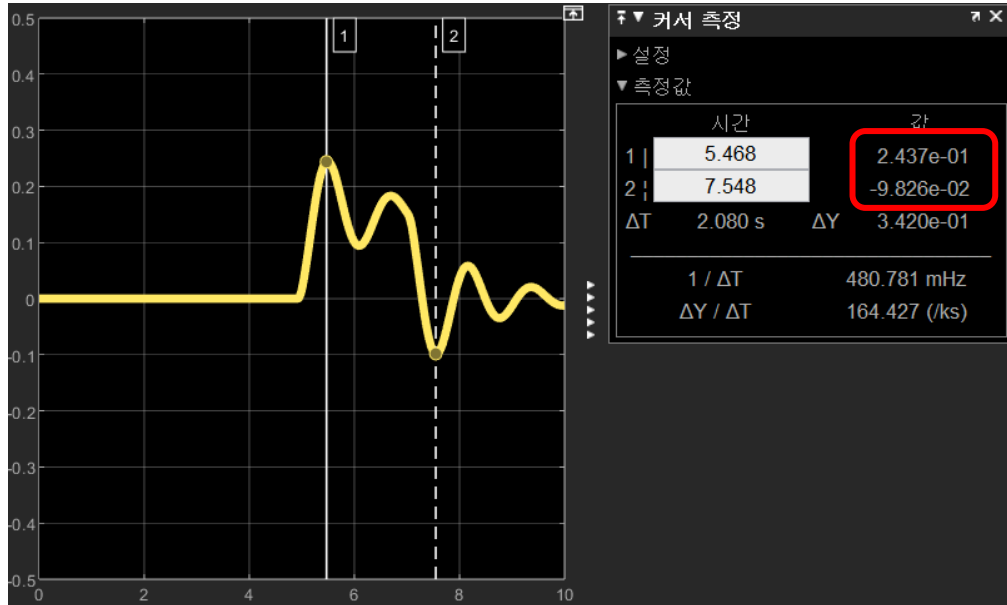
18650 Li-ion battery(96 series) SOC v Open-Circuit Voltage , SOC v  $R_{in}$  커브 반영

### 3. 서스펜션 & SOC 충전 시뮬레이션

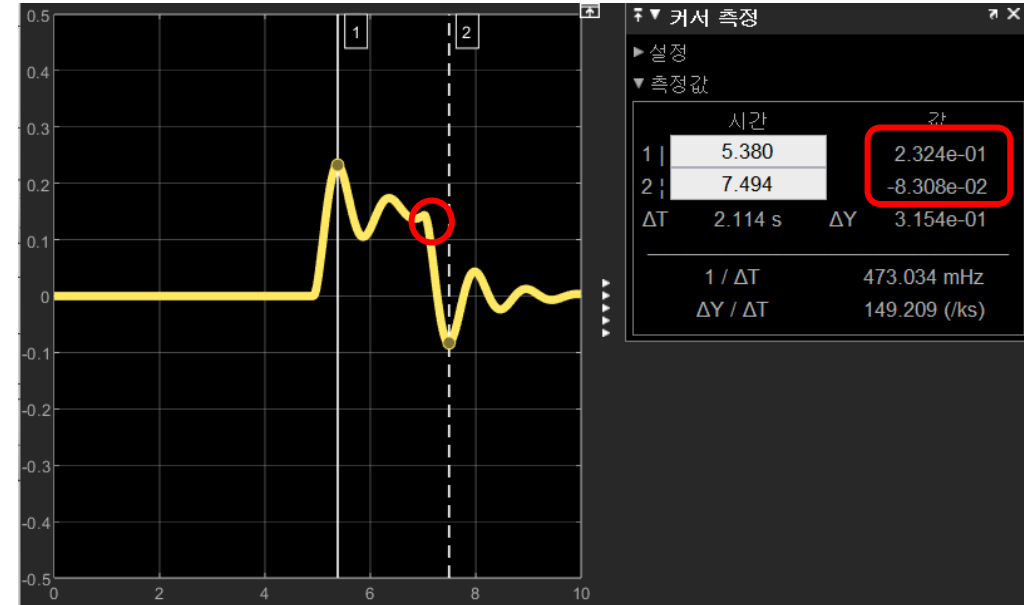
- 승차감 분석



방지턱 상황



기본 서스펜션 모델

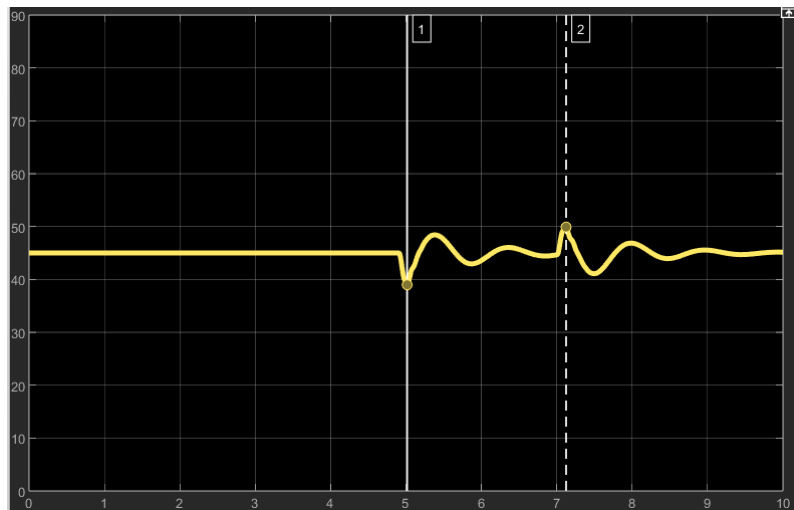


발전기가 정착된 서스펜션 모델

발전기를 장착한 서스펜션 모델이 overshoot가 더 작고 빠르게 회복되나  
미세하게 튀는 구간 존재

### 3. 서스펜션 & SOC 충전 시뮬레이션

- Beam 각도, 힘, 토크 분석



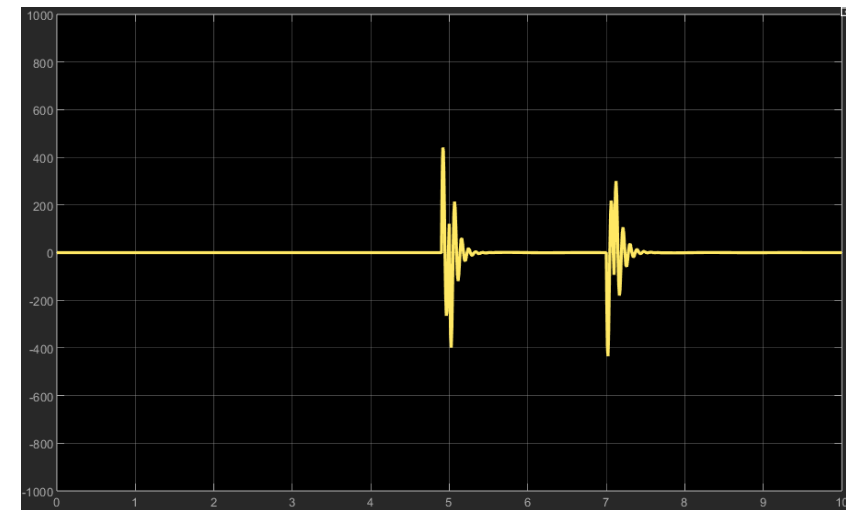
Value  
3.898e+01  
4.988e+01

Beam 각도: 49.88도 ~ 38.98도



Value  
2.989e+03  
-2.982e+03

Beam에 가해지는 최대 힘: 2989N

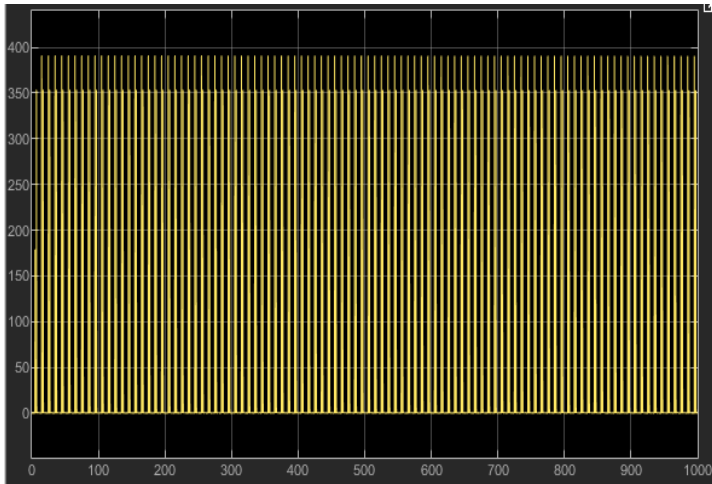


Value  
4.322e+02  
-4.251e+02

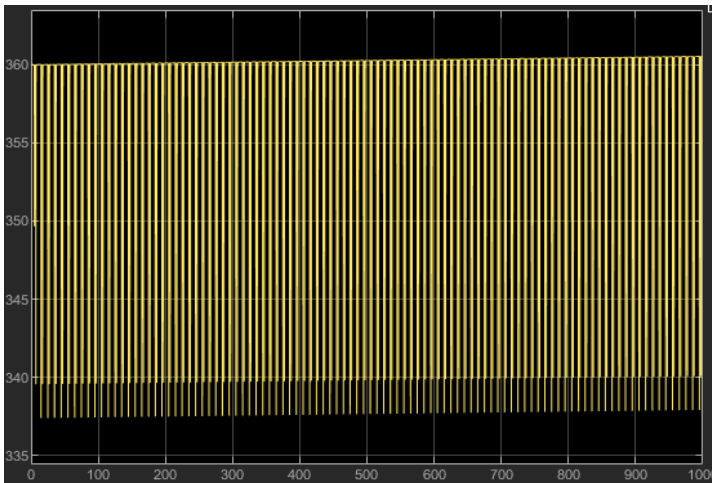
발전기에 인가되는 최대 토크: 432N\*m

### 3. 서스펜션 & SOC 충전 시뮬레이션

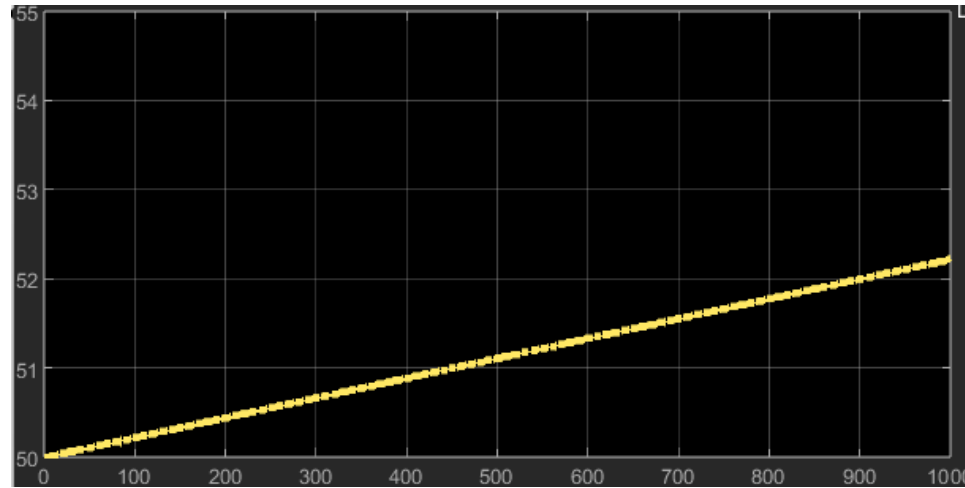
- SOC 충전량 분석 (방지턱 100개)



전류

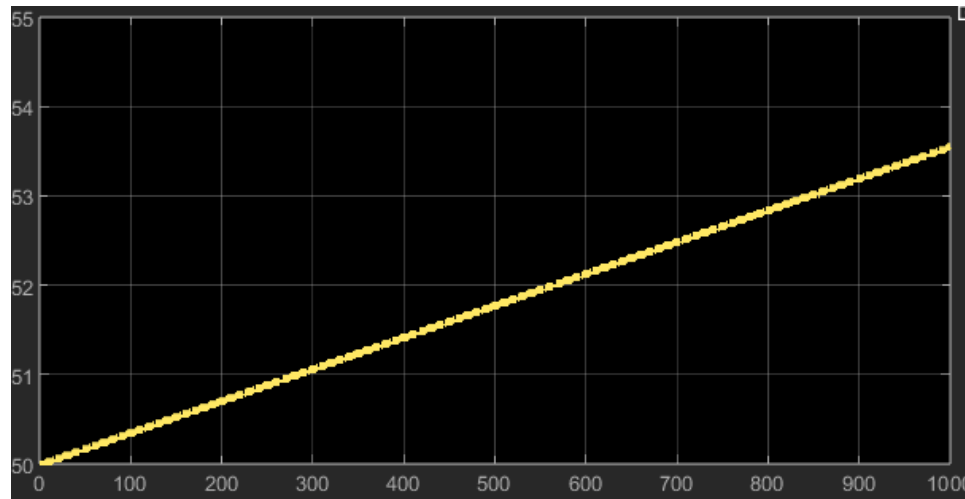


전압



- 모터 최대 토크 330Nm
- 모터 최대 속도 400rpm

SOC: 2.25%  
상승

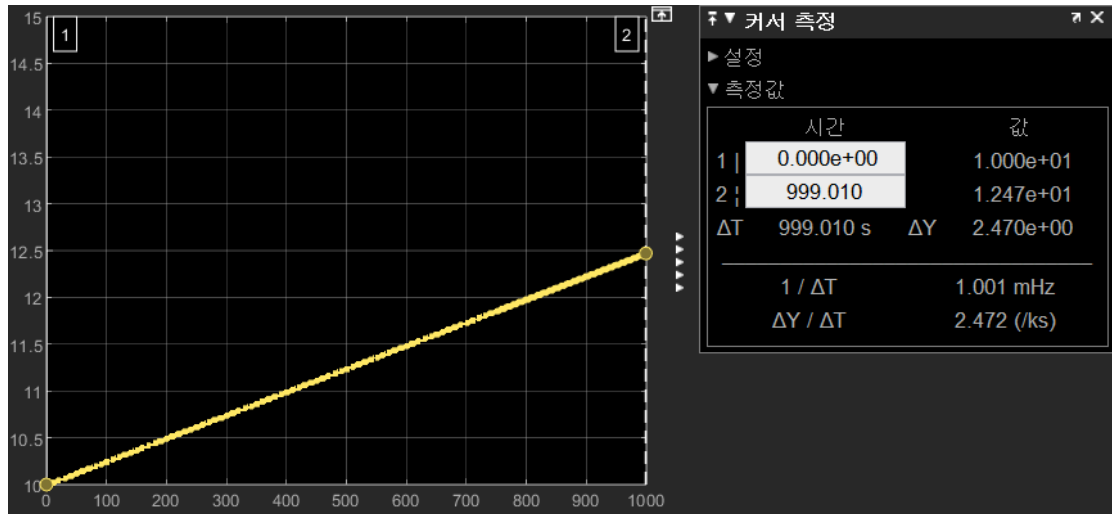


- 모터 최대 토크 450Nm
- 모터 최대 속도 600rpm

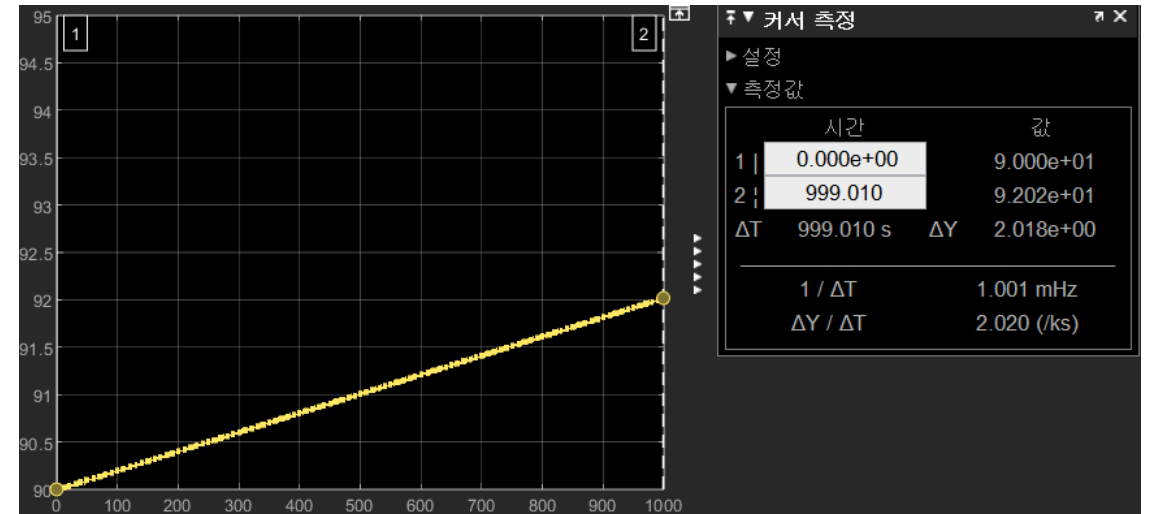
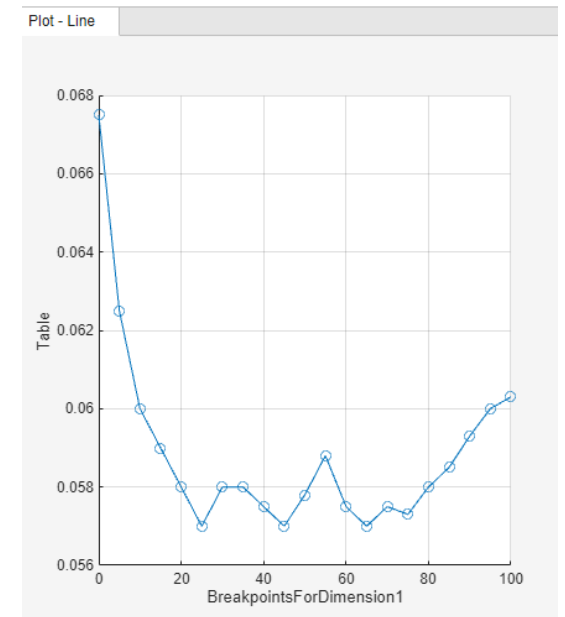
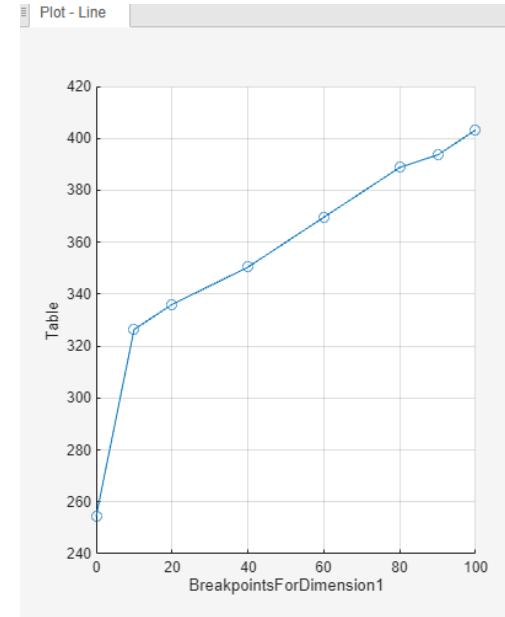
SOC: 3.51%  
상승

### 3. 서스펜션 & SOC 충전 시뮬레이션

- 배터리 충전 상태에 따른 충전량
- SOC에 따른 OCV,  $R_{in}$  특성에 의해 현재 SOC 상태에 따라 충전되는 정도의 차이 존재



• 10% → 12.5%

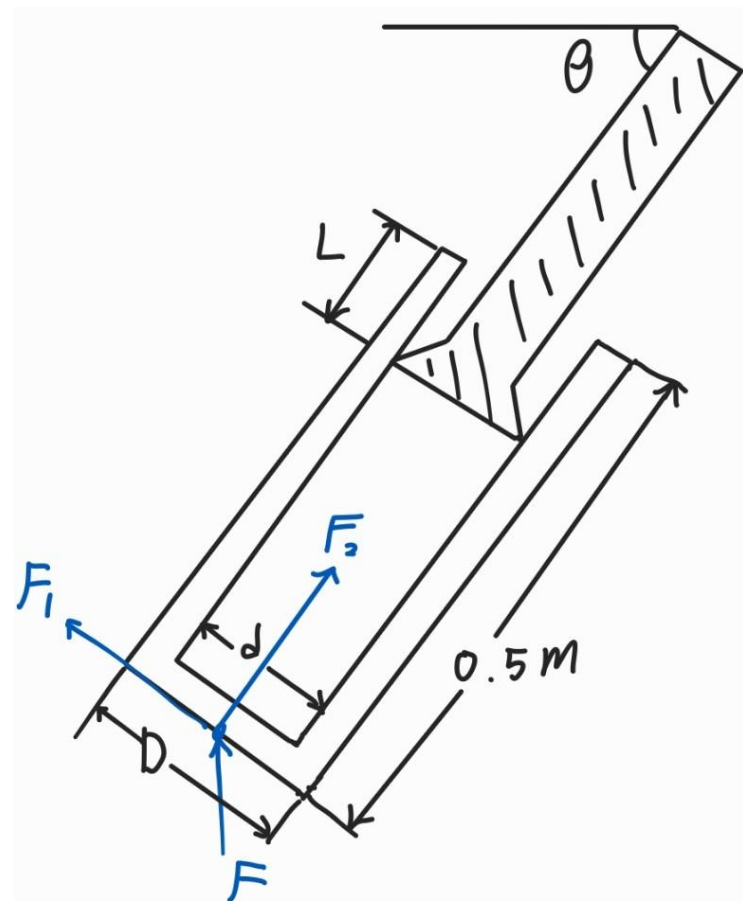
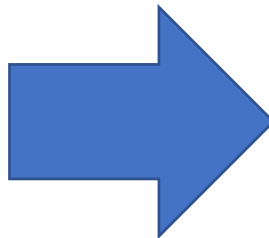
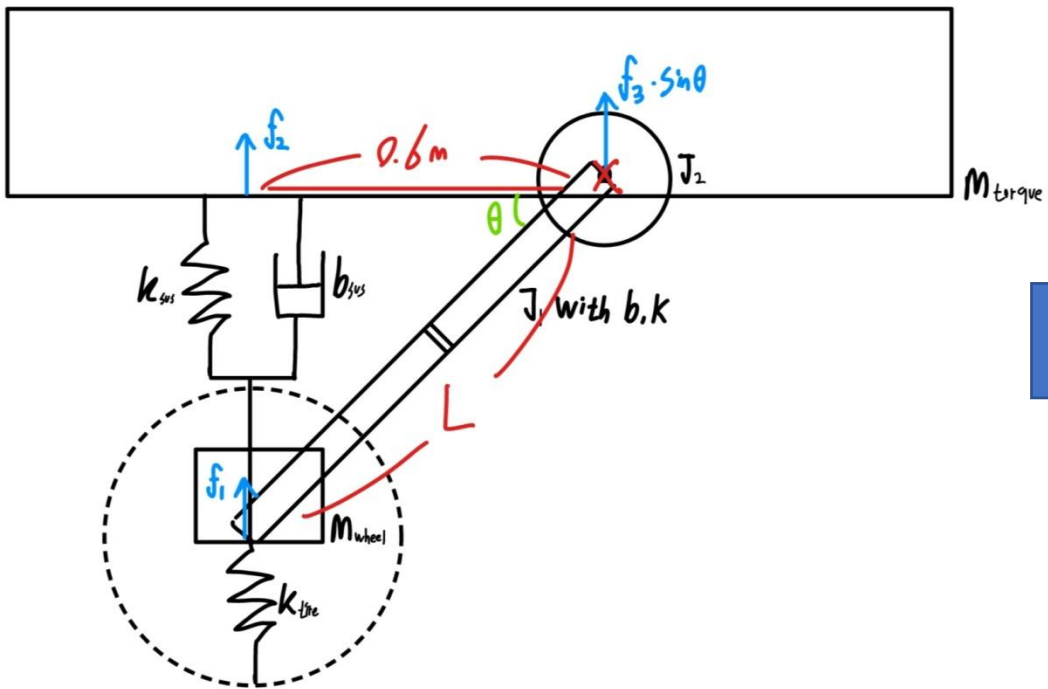


• 90% → 92.0%

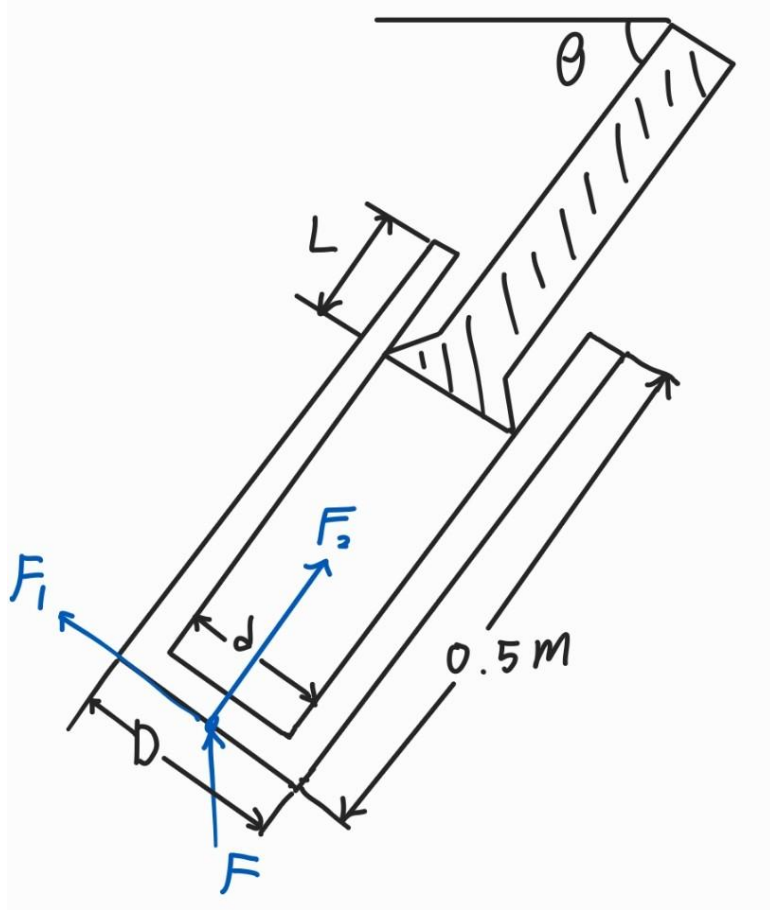
## Chapter 04

# Additional beam 해석 및 설계

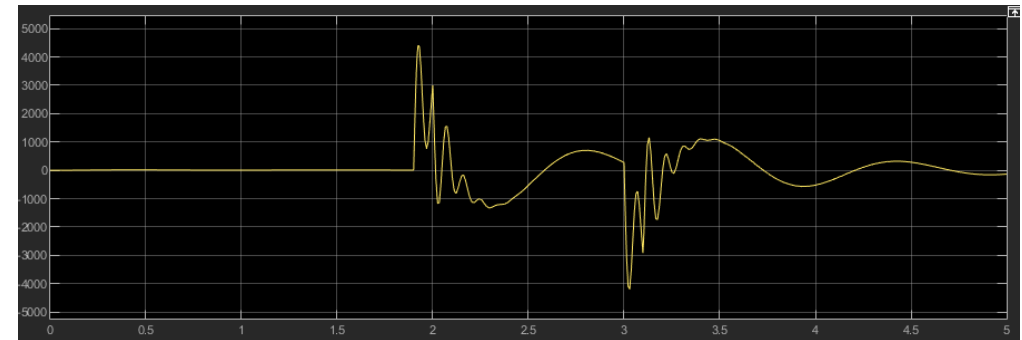
## 4. Additional beam 해석 및 설계



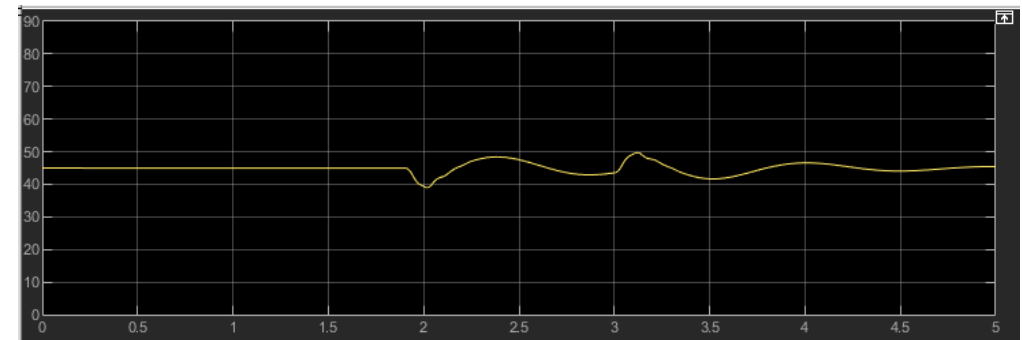
## 4. Additional beam 해석 및 설계



〈Simulink data〉



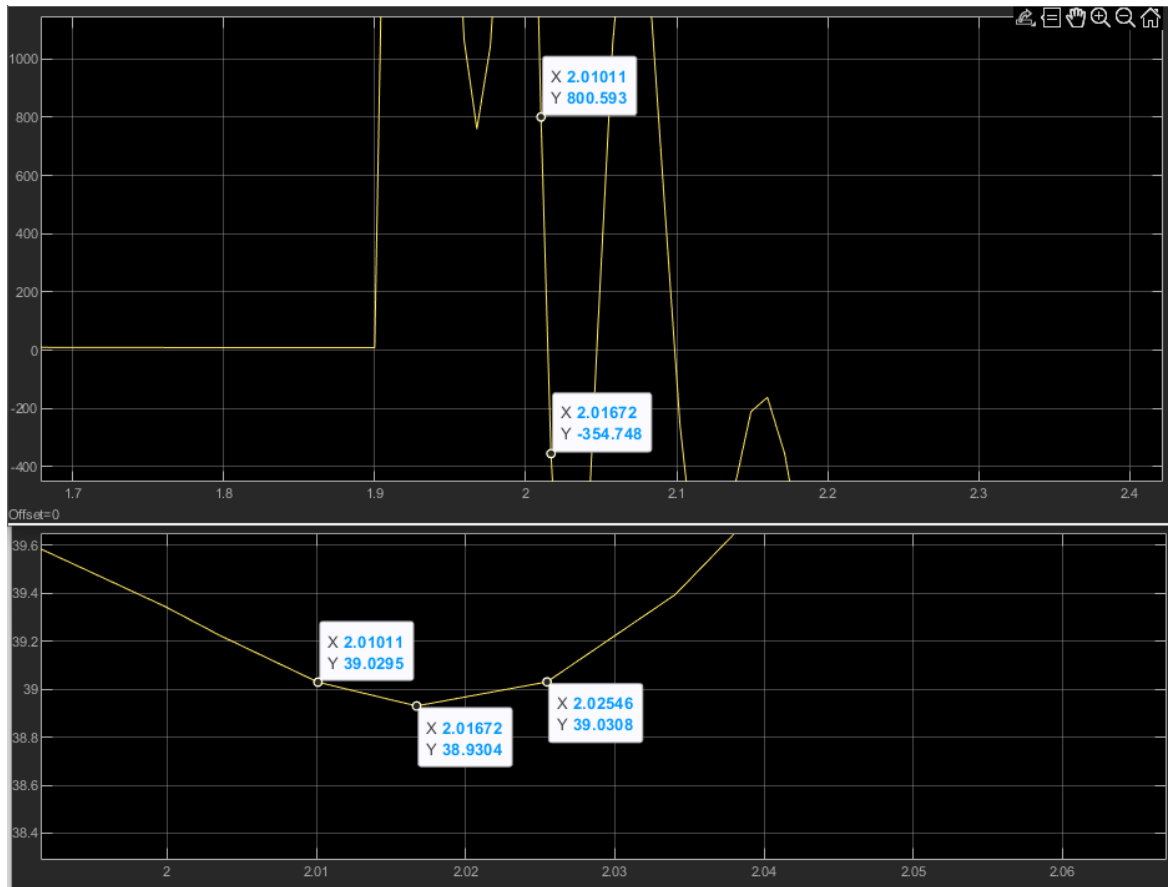
F (인가 되는 힘)



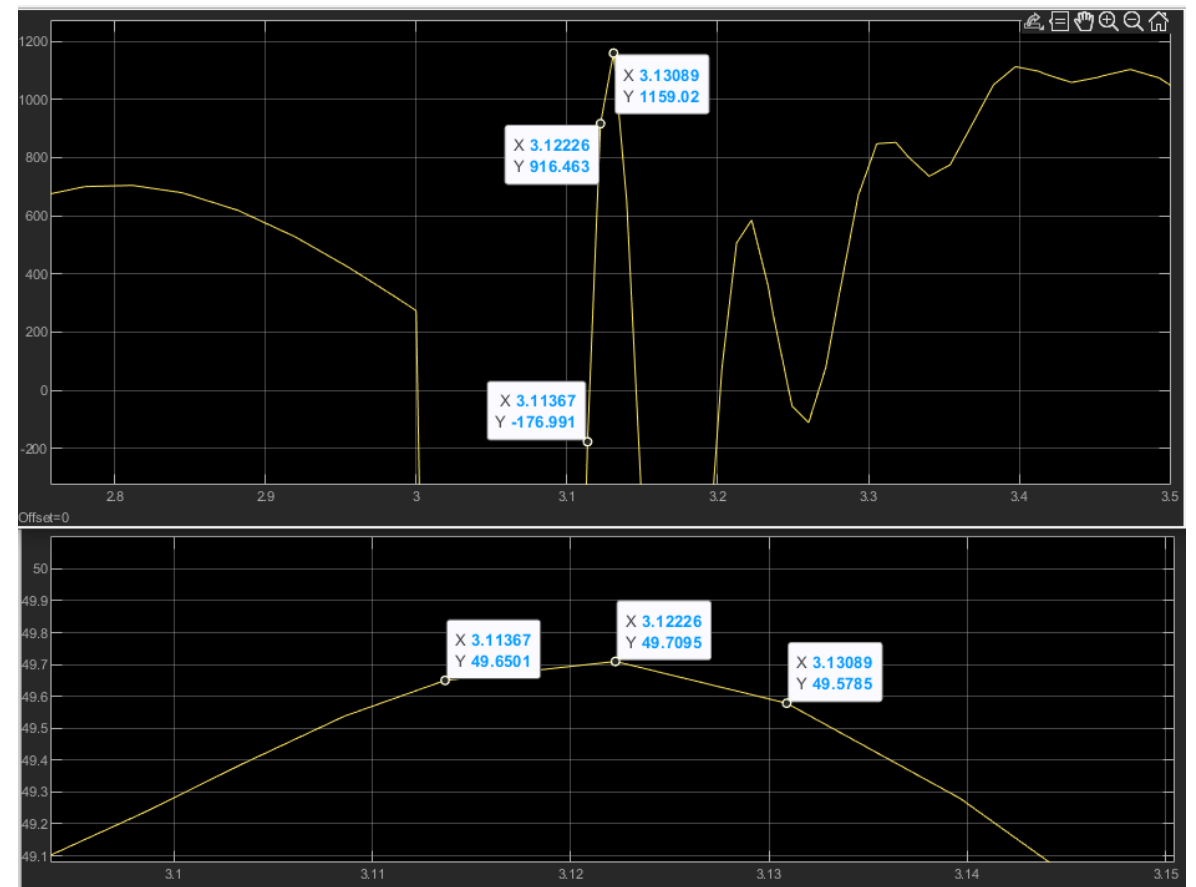
$\theta$  (Additional beam 의 각도)



## 4. Additional beam 해석 및 설계

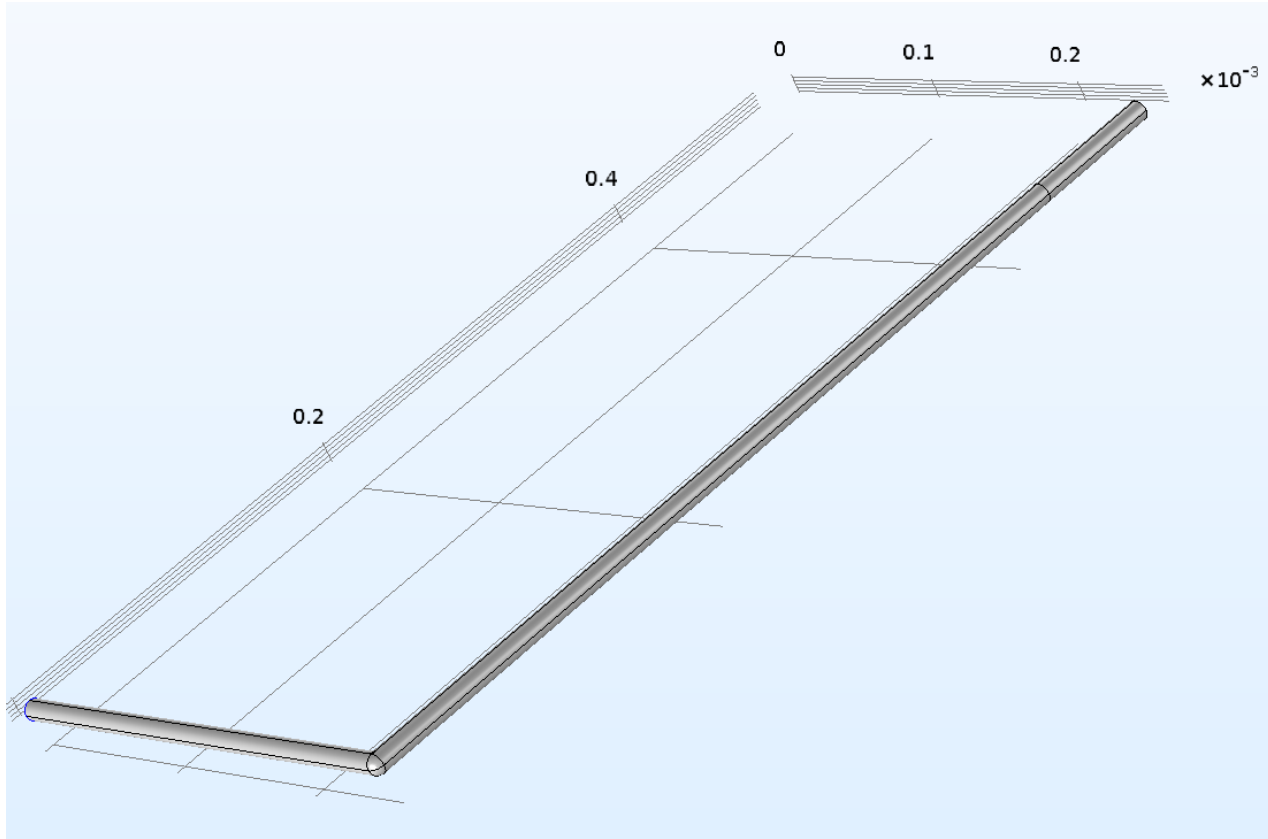


$\theta$  최소일 때 힘



$\theta$  최대일 때 힘

## 4. Additional beam 해석 및 설계



### AISI 1020 cold drawn steel

Young's modulus:

$E$  User defined  
210e9 Pa

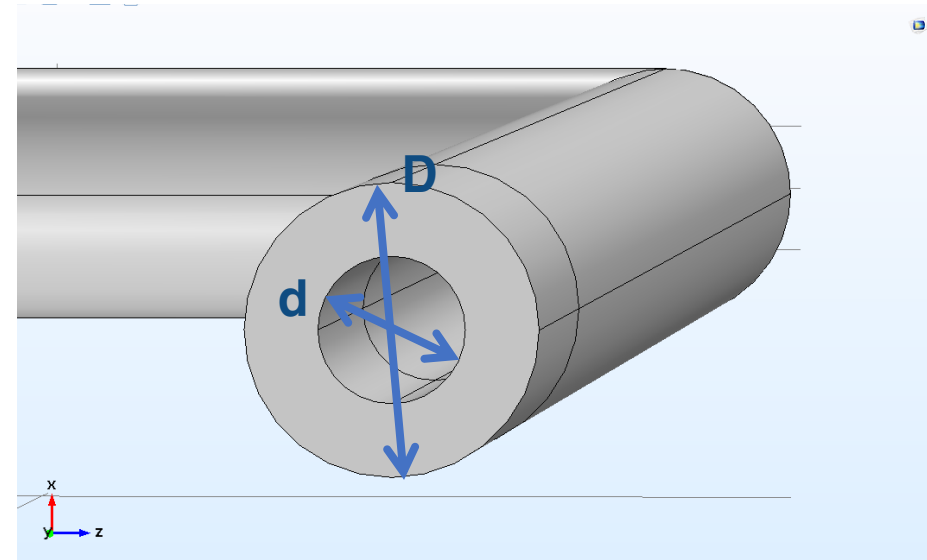
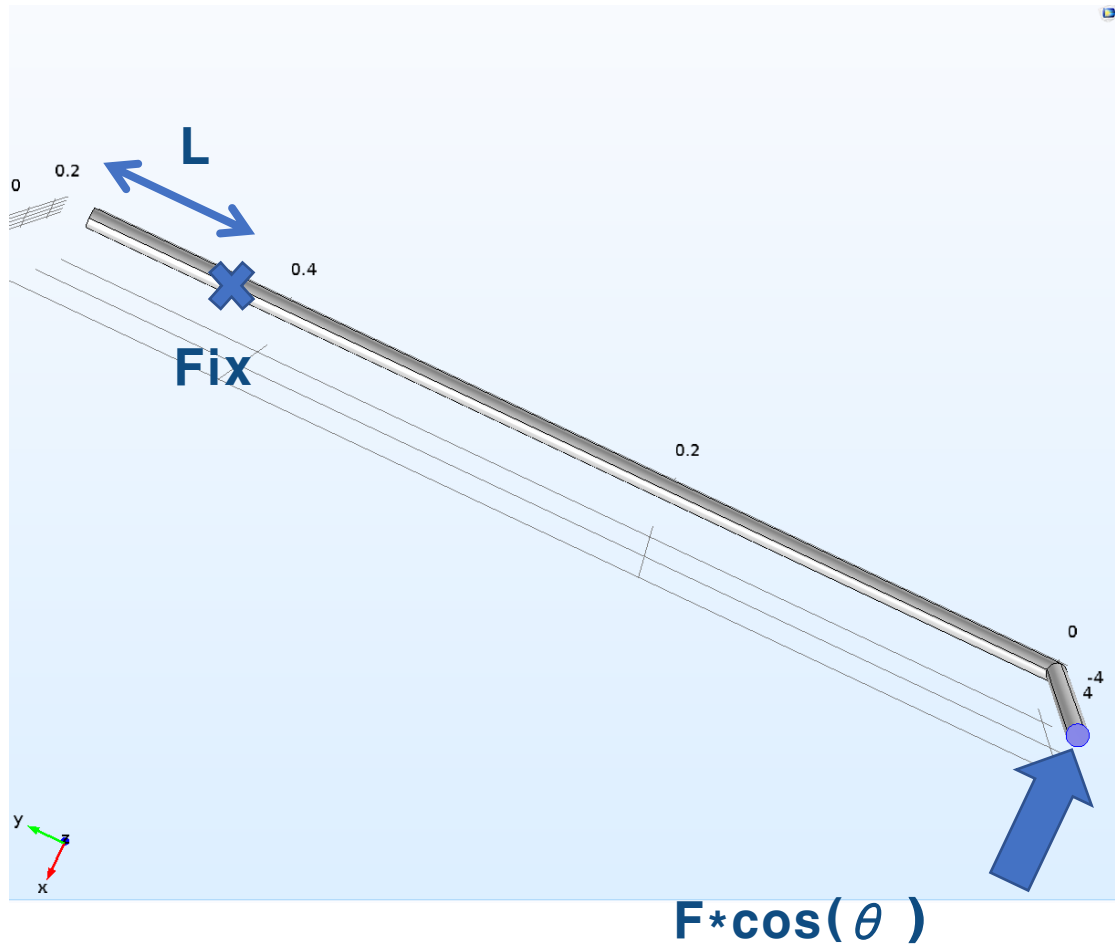
Poisson's ratio:

$\nu$  User defined  
0.3 1

Density:

$\rho$  User defined  
0 kg/m<sup>3</sup>

## 4. Additional beam 해석 및 설계



### Parameters

Name	Expression	Value
L	68.7[mm]	0.0687 m
F	100[N]	100 N
D	3[mm]	0.003 m
d	2[mm]	0.002 m

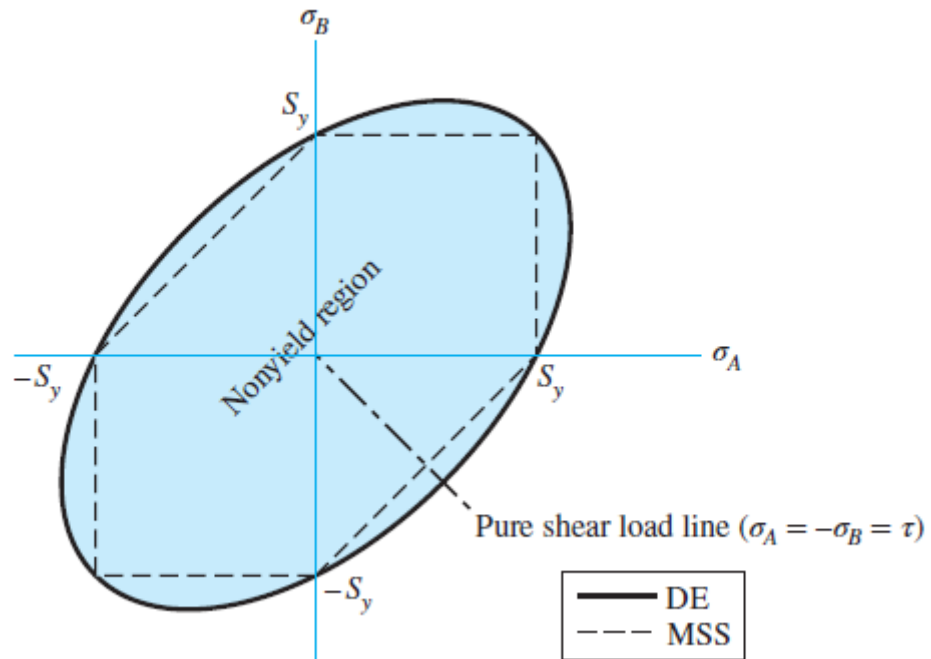
### Component 1 (comp1)

#### Definitions

- von mises (bnd7)
- First principal stress (bnd11)
- Third principal stress (bnd13)
- Boundary System 1 (sys1)
- View 1

## 4. Additional beam 해석 및 설계

- Von Mises stress



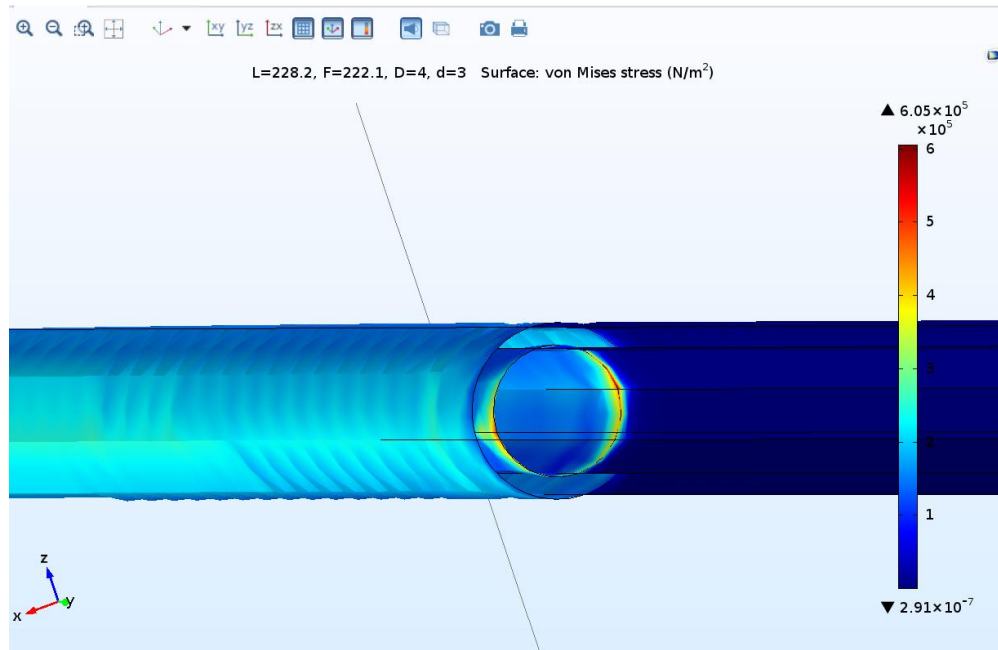
- Von Mises stress

$$\sigma' = \left[ \frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2}{2} \right]^{1/2}$$

- For yield

$$\sigma' \geq S_y$$

## 4. Additional beam 해석 및 설계



L	F	D	d	von Mises stress (N/m <sup>2</sup> ), von mises
228.20E-3	222.10	4.0000E-3	3.0000E-3	1.6991E6
68.700E-3	-699.10	4.0000E-3	3.0000E-3	16.653E6
228.20E-3	222.10	3.0000E-3	2.0000E-3	4.6563E6
68.700E-3	-699.10	3.0000E-3	2.0000E-3	15.549E6
228.20E-3	222.10	2.0000E-3	1.0000E-3	1.2430E6
68.700E-3	-699.10	2.0000E-3	1.0000E-3	10.830E6

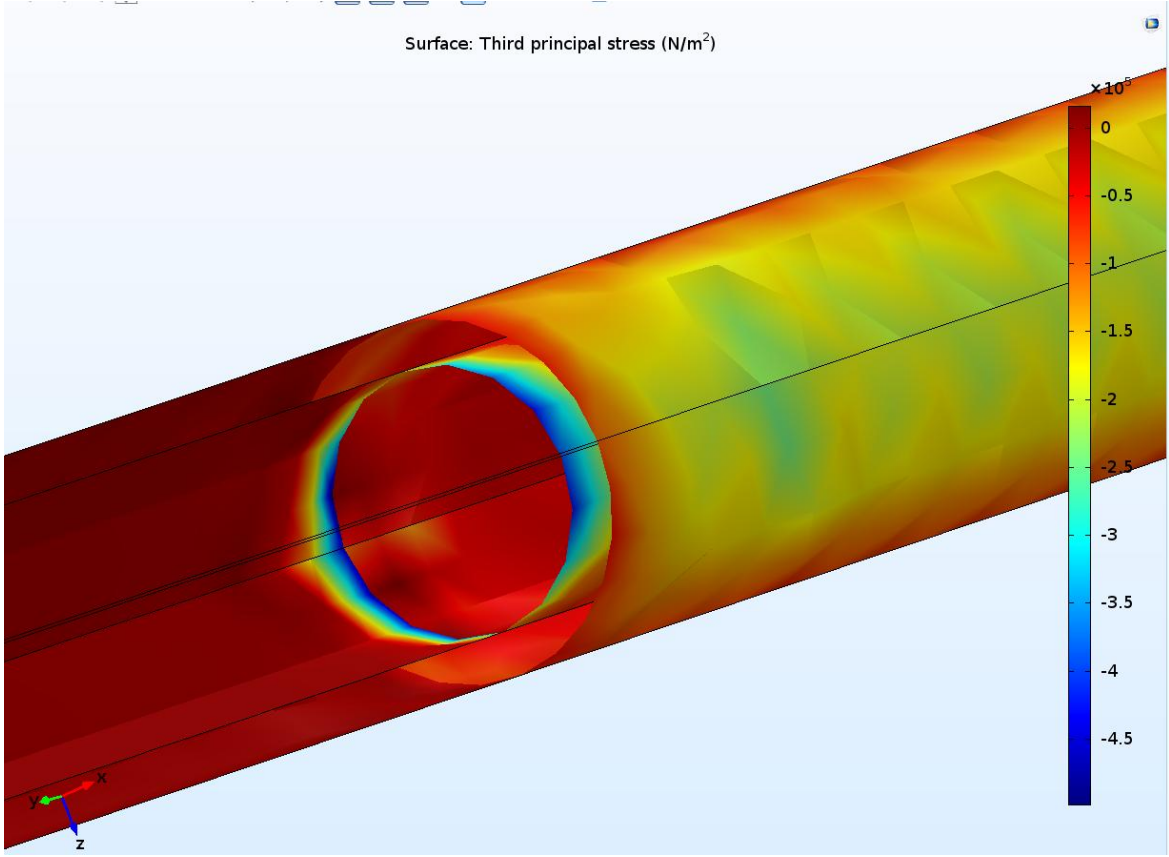
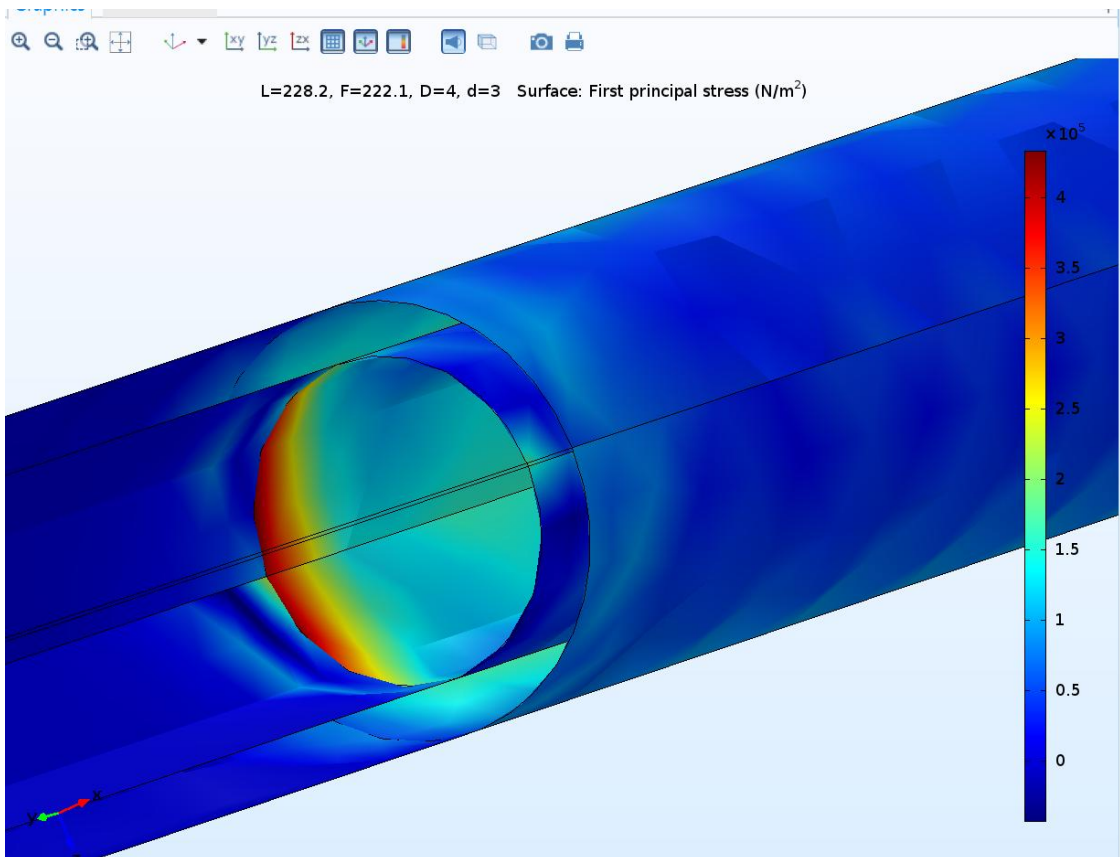
**Table A-20** Deterministic ASTM Minimum Tensile and Yield Strengths for Some Hot-Rolled (HR) and Cold-Drawn (CD) Steels

[The strengths listed are estimated ASTM minimum values in the size range 18 to 32 mm ( $\frac{3}{4}$  to  $1\frac{1}{4}$  in). These strengths are suitable for use with the design factor defined in Sec. 1-10, provided the materials conform to ASTM A6 or A568 requirements or are required in the purchase specifications. Remember that a numbering system is not a specification.]

1 UNS No.	2 SAE and/or AISI No.	3 Process- ing	4 Tensile Strength, MPa (kpsi)	5 Yield Strength, MPa (kpsi)	6 Elongation in 2 in, %	7 Reduction in Area, %	8 Brinell Hardness
G10060	1006	HR	300 (43)	170 (24)	30	55	86
		CD	330 (48)	280 (41)	20	45	95
G10100	1010	HR	320 (47)	180 (26)	28	50	95
		CD	370 (53)	300 (44)	20	40	105
G10150	1015	HR	340 (50)	190 (27.5)	28	50	101
		CD	390 (56)	320 (47)	18	40	111
G10180	1018	HR	400 (58)	220 (32)	25	50	116
		CD	440 (64)	370 (54)	15	40	126
G10200	1020	HR	380 (55)	210 (30)	25	50	111
		CD	470 (68)	390 (57)	15	40	131
G10300	1030	HR	470 (68)	260 (37.5)	20	42	137
		CD	520 (76)	440 (64)	12	35	149
G10350	1035	HR	500 (72)	270 (39.5)	18	40	143
		CD	550 (80)	460 (67)	12	35	163
G10400	1040	HR	520 (76)	290 (42)	18	40	149
		CD	590 (85)	490 (71)	12	35	170
G10450	1045	HR	570 (82)	310 (45)	16	40	163
		CD	630 (91)	530 (77)	12	35	179
G10500	1050	HR	620 (90)	340 (49.5)	15	35	179
		CD	690 (100)	580 (84)	10	30	197
G10600	1060	HR	680 (98)	370 (54)	12	30	201
G10800	1080	HR	770 (112)	420 (61.5)	10	25	229
G10950	1095	HR	830 (120)	460 (66)	10	25	248

Source: Data from 1986 SAE Handbook, p. 2.15.

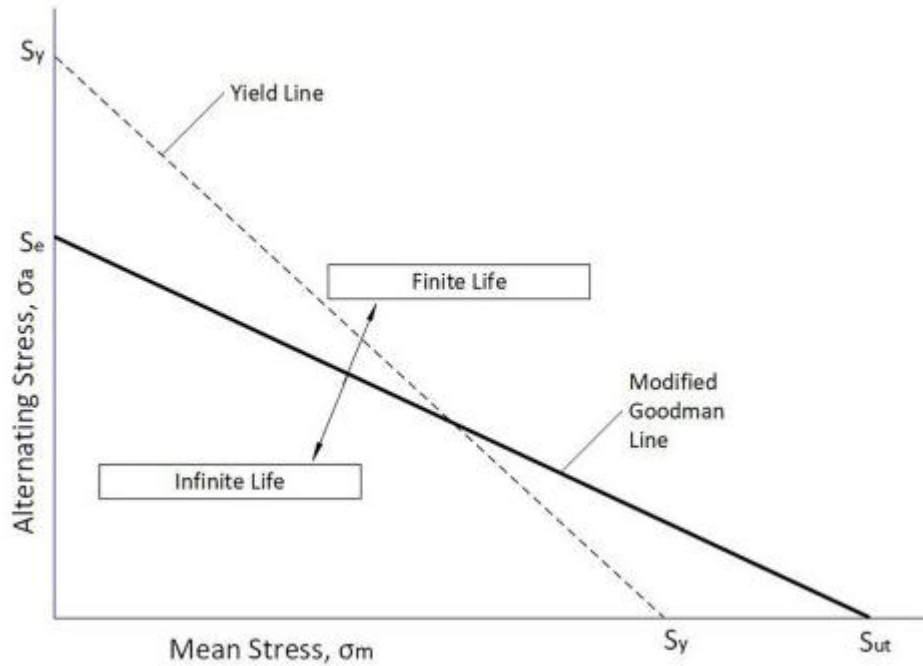
# 4. Additional beam 해석 및 설계



L	F	D	d	First principal stress (N/m <sup>2</sup> ), First principal stress	Thirh principal stress (N/m <sup>2</sup> ), Third principal stress
228.20E-3	222.10	4.0000E-3	3.0000E-3	1.6451E6	-717.95E3
68.700E-3	-699.10	4.0000E-3	3.0000E-3	4.3412E6	-16.364E6

## 4. Additional beam 해석 및 설계

- Fatigue Failure Criteria
  - Goodman line



Failure criterion:

$$\frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} = 1$$

Design equation:

$$n_f = \left( \frac{\sigma_a}{S_e} + \frac{\sigma_m}{S_{ut}} \right)^{-1} \quad \sigma_m \geq 0$$



## 4. Additional beam 해석 및 설계

1 UNS No.	2 SAE and/or AISI No.	3 Process- ing	4 Tensile Strength, MPa (kpsi)
G10060	1006	HR	300 (43)
		CD	330 (48)
G10100	1010	HR	320 (47)
		CD	370 (53)
G10150	1015	HR	340 (50)
		CD	390 (56)
G10180	1018	HR	400 (58)
		CD	440 (64)
G10200	1020	HR	380 (55)
		CD	470 (68)

$$S_e = k_a k_b k_c k_d k_e S'_e$$

$k_a$  = surface factor

$k_b$  = size factor

$k_c$  = load factor

$k_d$  = temperature factor

$k_e$  = reliability factor

$S'_e$  = rotary-beam test specimen endurance limit

$S_e$  = endurance limit at the critical location of a machine part in the geometry and condition of use

$$S'_e = \begin{cases} 0.5S_{ut} & S_{ut} \leq 200 \text{ kpsi (1400 MPa)} \\ 100 \text{ kpsi} & S_{ut} > 200 \text{ kpsi} \\ 700 \text{ MPa} & S_{ut} > 1400 \text{ MPa} \end{cases}$$

$$S'_e = 235, \text{ MPa}$$

$$k_a = 0.383, k_b = 0.692, k_c = 1.0, k_d = 1.0, k_e = 0.897$$

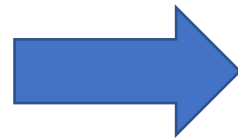


## 4. Additional beam 해석 및 설계

$$S'_e = 235, \text{MPa}$$

$$k_a = 0.383, k_b = 0.692, k_c = 1.0, k_d = 1.0, k_e = 0.897$$

First principal stress (N/m <sup>2</sup> ), First principal stress	Third principal stress (N/m <sup>2</sup> ), Third principal stress
1.6451E6	-717.95E3
4.3412E6	-16.364E6



- $\sigma_{max} = 4.34, \text{MPa}$
- $\sigma_{min} = -16.36, \text{MPa}$

## 5. Conclusion

$$S_e = 235 \cdot 0.383 \cdot 0.692 \cdot 1.0 \cdot 1.0 \cdot 0.897$$

$$S_e \approx 235 \cdot 0.237 \approx 55.7 \text{ MPa}$$

$$\sigma_{mean} = \frac{\sigma_{max} + \sigma_{min}}{2}, \quad \sigma_a = \frac{\sigma_{max} - \sigma_{min}}{2}$$

$$\sigma_{mean} = -6.01 \text{ MPa}$$

$$\sigma_a = 10.35 \text{ MPa}$$

$$\therefore \frac{\sigma_a}{S_e} + \frac{\sigma_{mean}}{S_{ut}} = 0.173$$

$$n = 5.78$$

## 5. Conclusion

### 해석 결과

- 서스펜션 발전기를 장착한 차량은 전반적으로 롤과 피치가 더 적지만 불쾌한 진동을 줄 가능성 존재함
- 배터리 용량이 큰 BEV는 서스펜션에 의한 배터리 충전량이 다소 적음 → HEV, PHEV와 같이 배터리 용량이 비교적 적은 차량에 적용될 시 더욱 극적인 효과
- Beam에 가해지는 힘에 대해 Von Mises Stress와 Goodman 선도 분석을 통해 설계의 안전성 검증.

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**Q&A**