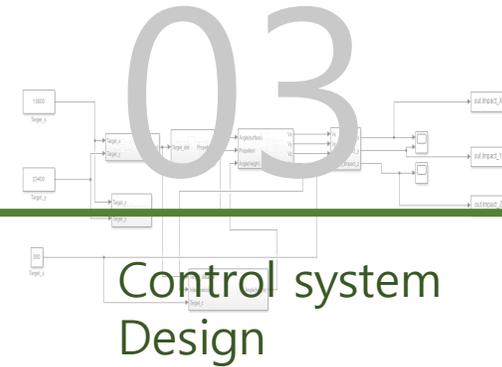
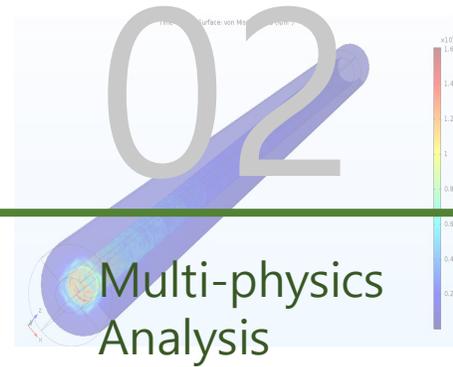


K-9 자주포 포신 해석 및 제어기 설계



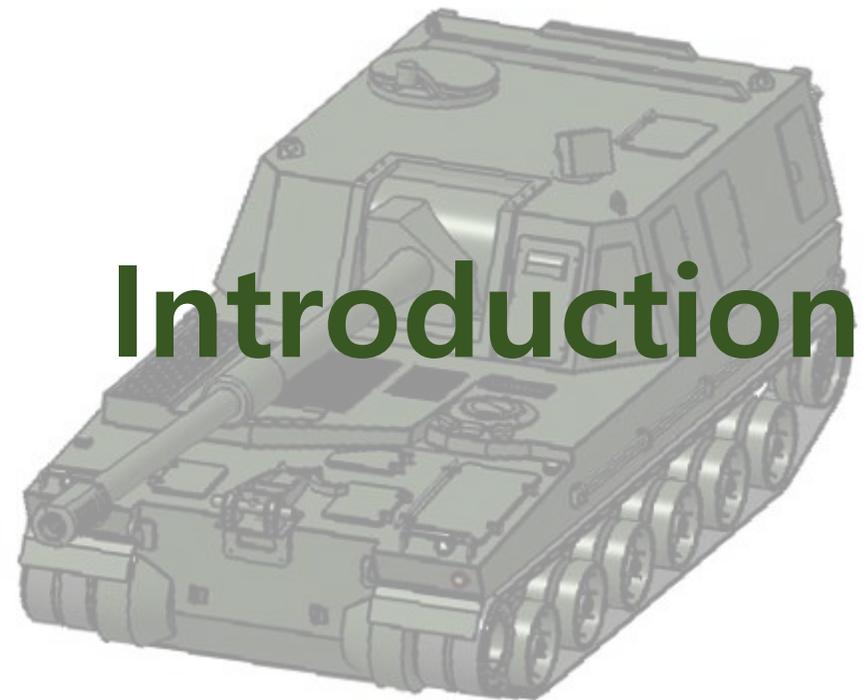
TEAM 포트리스
2019040873 이주섭
2022037083 최찬휘

Contents



04

Result



Introduction

Introduction

Goal



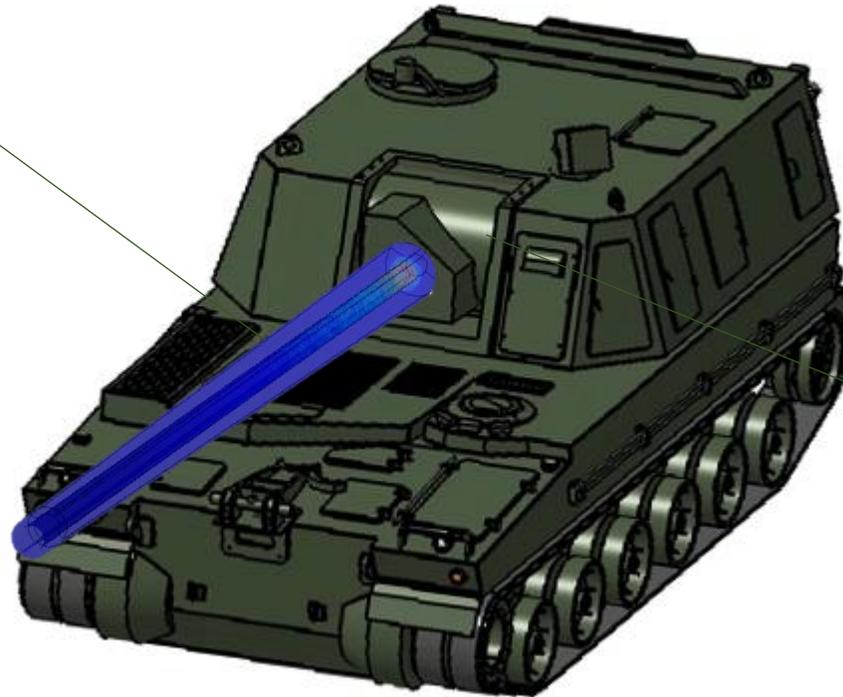
1. **COMSOL**을 이용해 발포 시 포신이 받는 **응력과 진동을 해석**하고, **진동을 최소화하는 방안**을 모색한다.
2. **Simulink**를 이용해 **자주포 조준 제어 시스템**을 설계한다.

Introduction

Role

COMSOL

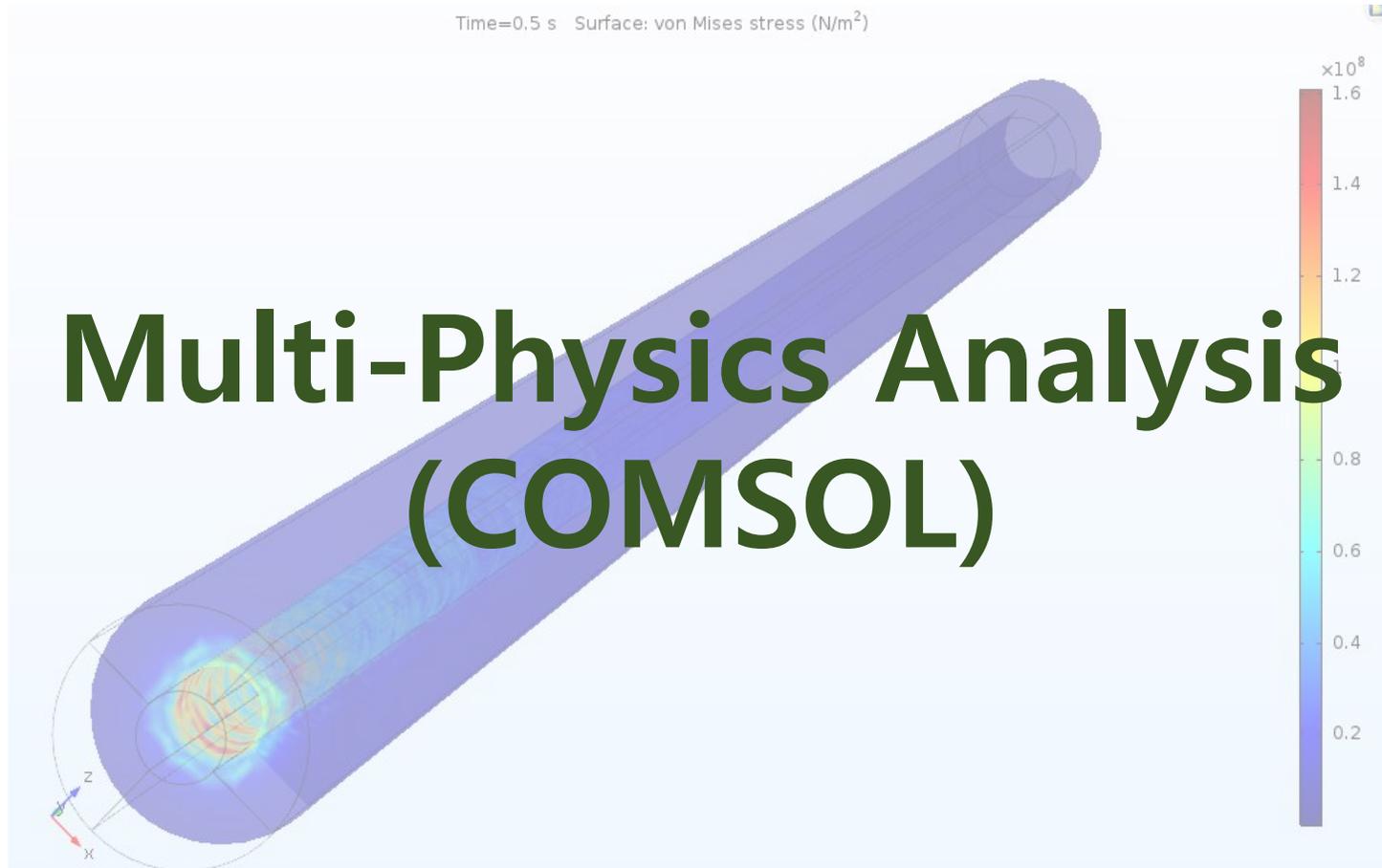
포신 내부의
Multi-Physic해석
PPT 제작



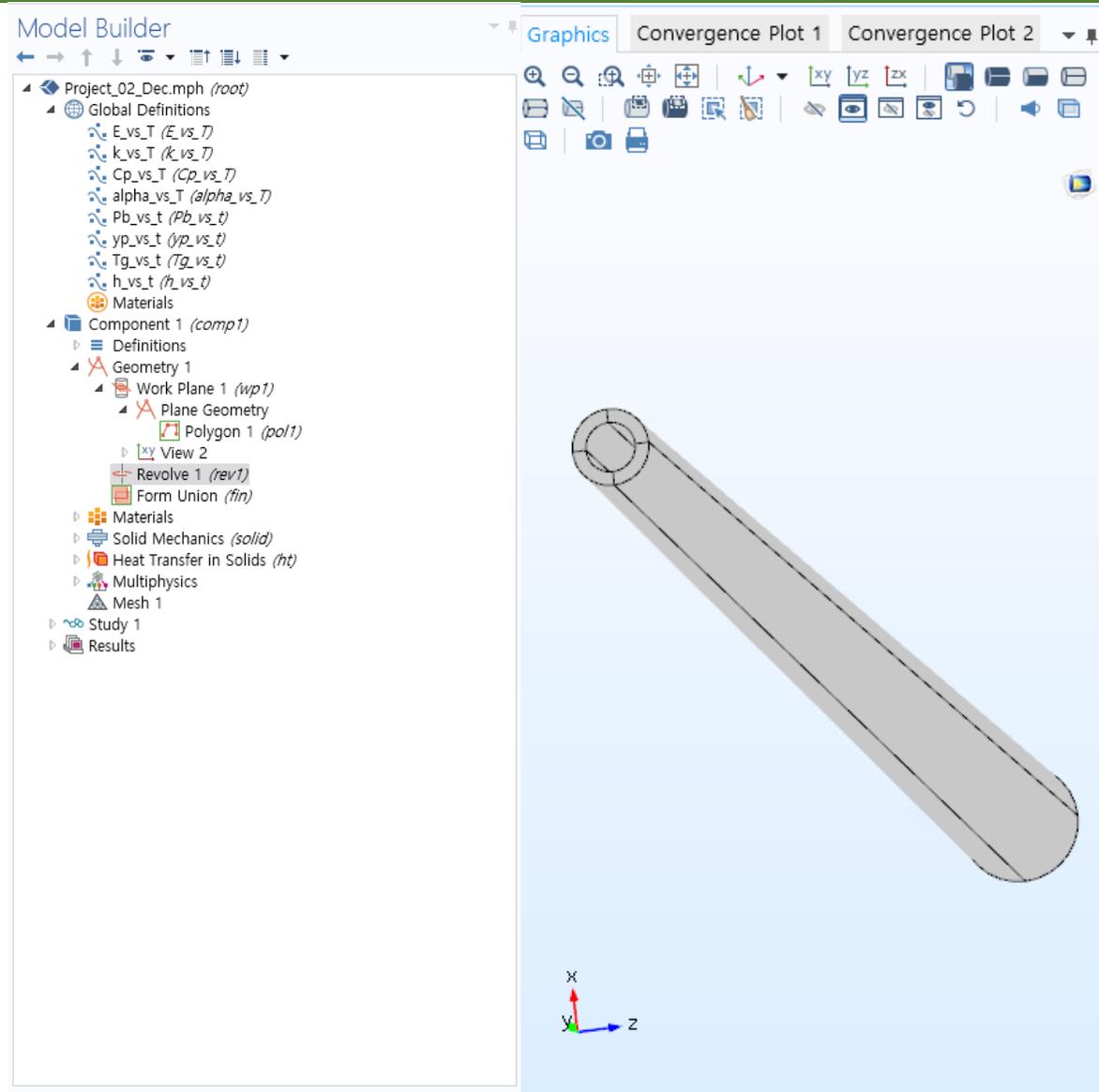
Simulink

변위 데이터 추출
목표 좌표 조준
제어기 설계

Multi-Physics Analysis (COMSOL)



COMSOL Multi-physics Analysis



Geometry

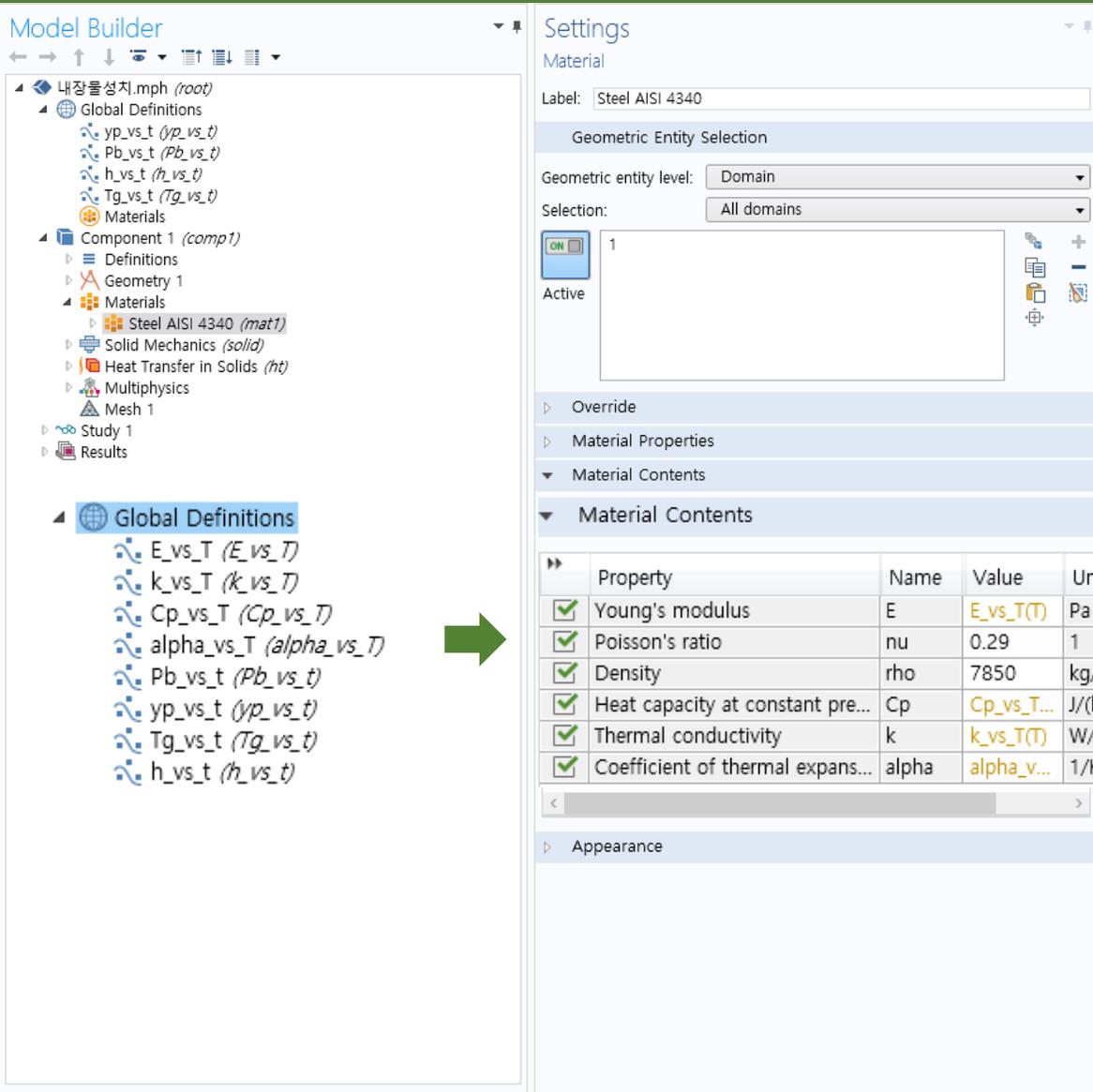
2D 축대칭 모델은 열과 압력에 의한 횡방향 진동 구현 불가

CAD모델링을 COMSOL로 Import -> 해석 시간 문제



직경이 갈수록 두꺼워지는 원통 형상으로 3D모델링

COMSOL Multi-physics Analysis



Materials

COMSOL의 Built-in Material 사용



열에 의한 물성의 변화 X



온도에 따른 물성 함수를 직접 지정

COMSOL Multi-physics Analysis

Model Builder

- Project_02_Dec.mph (root)
 - Global Definitions
 - E_vs_T (E_vs_T)
 - k_vs_T (k_vs_T)
 - Cp_vs_T (Cp_vs_T)
 - alpha_vs_T (alpha_vs_T)
 - Pb_vs_t (Pb_vs_t)
 - yp_vs_t (yp_vs_t)
 - Tg_vs_t (Tg_vs_t)
 - h_vs_t (h_vs_t)
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Linear Elastic Material 1
 - Free 1
 - Initial Values 1
 - Boundary Load 1
 - Boundary Load 2
 - Spring Foundation 1
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Results

Settings

Solid Mechanics

Label: Solid Mechanics

Name: solid

Domain Selection

Selection: All domains

Active

Equation

Structural Transient Behavior

Include inertial terms

Reference Point for Moment Computation

0	x	m
0	y	
0	z	

Typical Wave Speed for Perfectly Matched Layers

C_{ref} solid.cp m/s

Dependent Variables

Boundary Condition



어떤 수학적 모델을 사용해야할까?

COMSOL Multi-physics Analysis



Contents lists available at [ScienceDirect](#)

Defence Technology

journal homepage: www.keaipublishing.com/en/journals/defence-technology



Modelling of internal ballistics of gun systems: A review

F. Ongaro*, C. Robbe, A. Papy, B. Stirbu, A. Chabotier

Royal Military Academy, Avenue de la Renaissance 30, Bruxelles 1000, Belgium



압력과 열이 매우 짧은 시간 동안
가해져 수학적 모델링이 매우 어려움

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Lumped-parameter model

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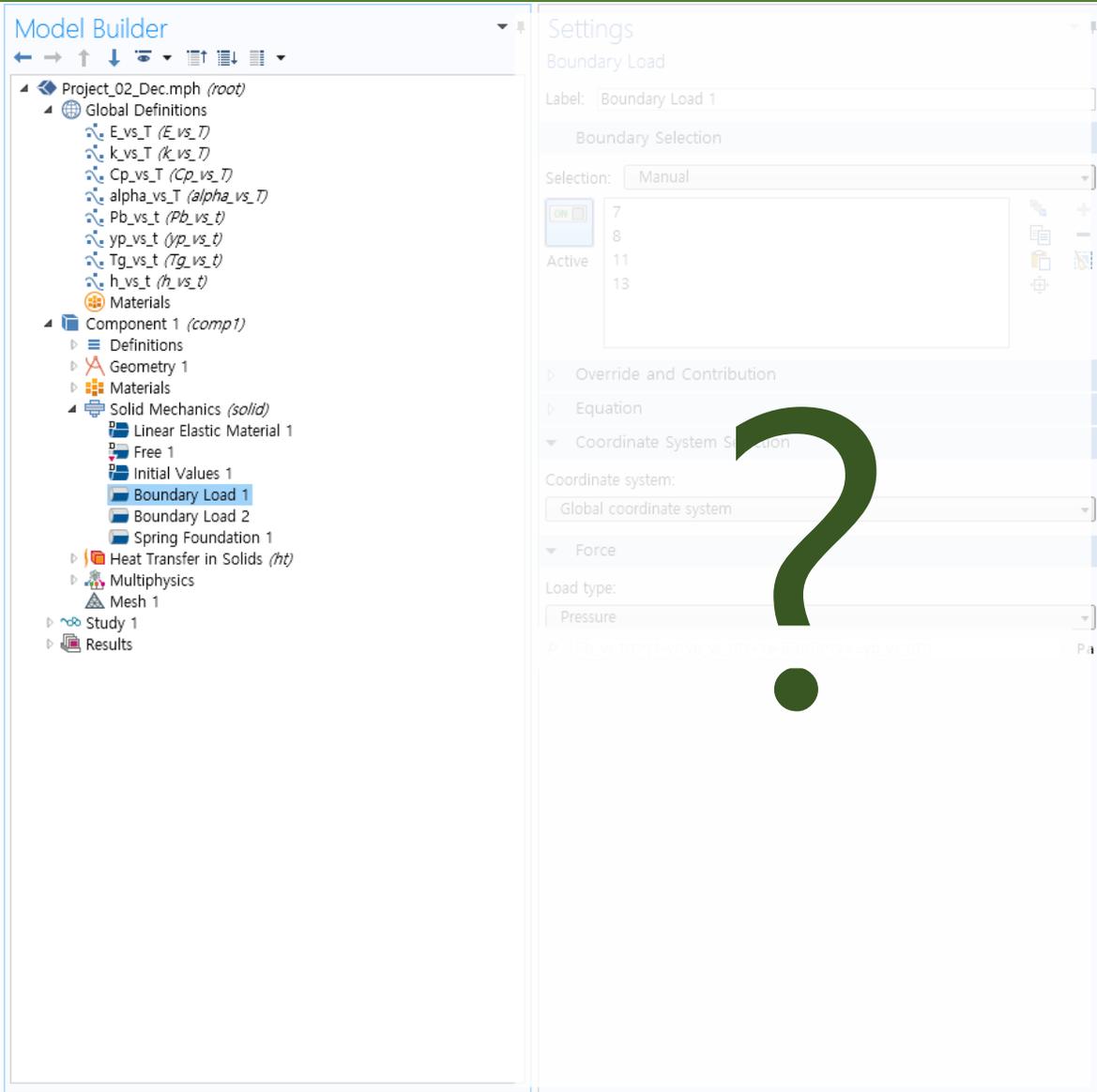
Gun systems

ABSTRACT

A deep understanding of the internal ballistic process and the factors affecting it is of primary importance to efficiently design a gun system and ensure its safe management. One of the main goals of internal ballistics is to estimate the gas pressure into the combustion chamber and the projectile muzzle velocity in order to use the propellant to its higher efficiency while avoiding over-pressure phenomena. **Dealing with the internal ballistic problem is a complex undertaking since it requires handling the interaction between different constituents during a transient time lapse with very steep rise of pressure and temperature.** Several approaches have been proposed in the literature, based on different assumptions and techniques. Generally, depending on the used mathematical framework, they can be classified into two categories: computational fluid dynamics-based models and lumped-parameter ones. By focusing on gun systems, this paper offers a review of the main contributions in the field by mentioning their advantages and drawbacks. An insight into the limitations of the currently available modelling strategies is provided, as well as some considerations on the choice of one model over another. Lumped-parameter models, for example, are a good candidate for performing parametric analysis and optimisation processes of gun systems, given their minimum requirements of computer resources. Conversely, CFD-based models have a better capacity to address more sophisticated phenomena like pressure waves and turbulent flow effects. The performed review also reveals that too little attention has been given to small calibre guns since the majority of currently available models are conceived for medium and large calibre gun systems. Similarly, aspects like wear phenomena, bore deformations or projectile-barrel interactions still need to be adequately addressed and our suggestion is to dedicate more effort on it.

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COMSOL Multi-physics Analysis



Boundary Condition

1. 내부 압력

포신이 받는 압력은 시간과 공간에 따른 함수로 표현됨
->선형으로 근사

$P_b(t)$

$P = 0$



$$p(x, t) = P_b(t) \left(1 - \frac{x}{y_p(t) + \varepsilon} \right) \mathbf{1}_{x \leq y_p(t)}$$

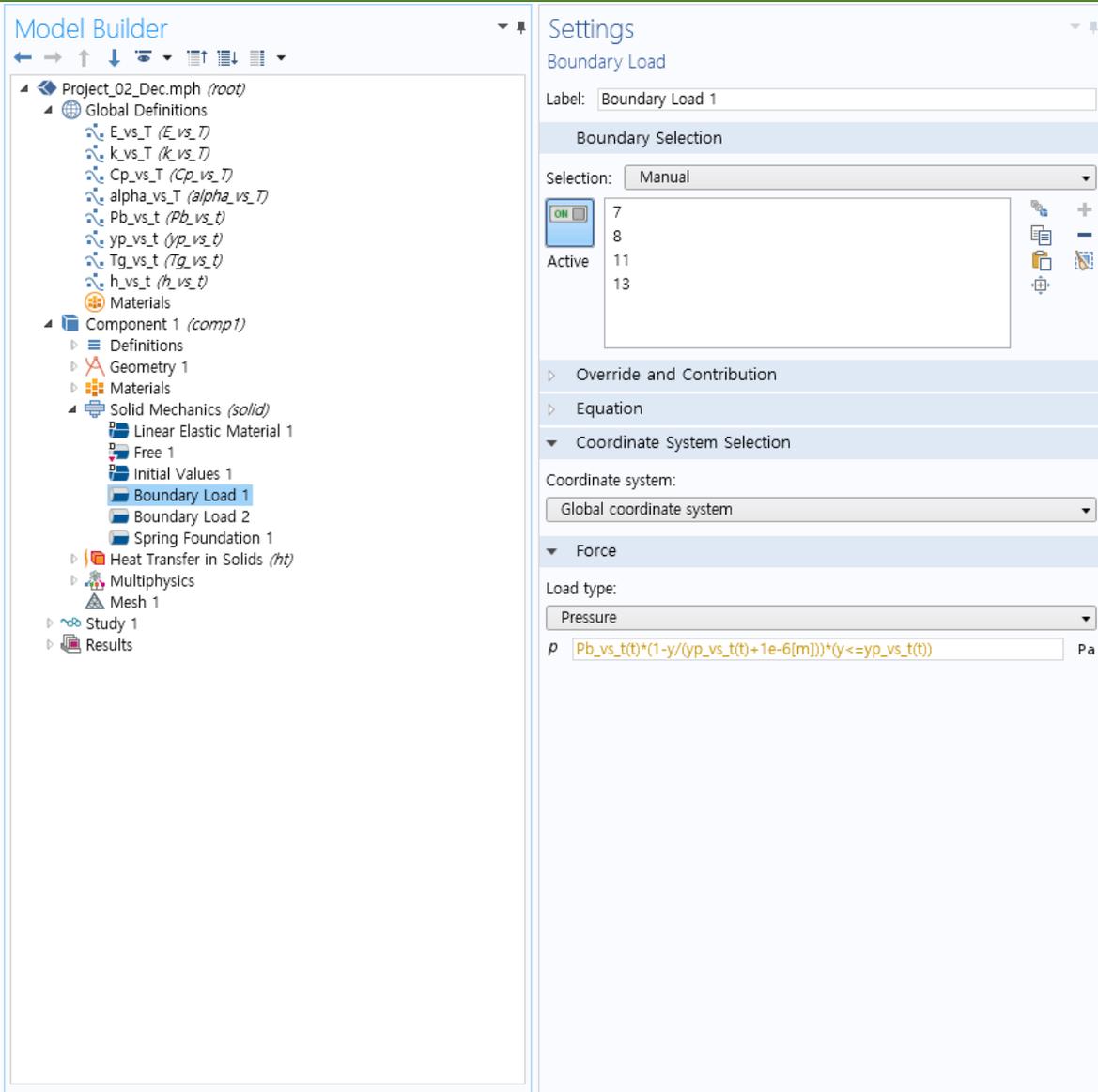
$P_b(t)$ 시간에 따른 최대 압력

$y_p(t)$ 시간 t에 따른 탄의 위치

$\mathbf{1}_{x \leq y_p(t)}$ 탄 앞의 압력은 0

ε 0으로 나누어 지지 않도록 하는 값

COMSOL Multi-physics Analysis



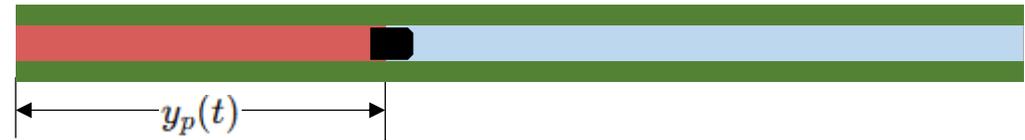
Boundary Condition

1. 내부 압력

포신이 받는 압력은 시간과 공간에 따른 함수로 표현됨
-> 선형으로 근사

$$P_b(t)$$

$$P_b = 0$$



$$p(x, t) = P_b(t) \left(1 - \frac{x}{y_p(t) + \epsilon} \right) \mathbf{1}_{x \leq y_p(t)}$$

$P_b(t)$ 시간에 따른 최대 압력은 어떻게 표현 할 것인가?

-> 수학적 모델링 사례 X

-> 공개된 데이터 이용

COMSOL Multi-physics Analysis

Boundary Condition

1. 내부 압력

공개된 데이터를 기반으로 Global Definition 설정

The screenshot shows the COMSOL Model Builder interface. On the left, the 'Global Definitions' tree is expanded, with 'Pb_vs_t (Pb_vs_t)' selected. The 'Settings' panel on the right shows the configuration for this interpolation function. The 'Label' is 'Pb_vs_t', the 'Data source' is 'Local table', and the 'Function name' is 'Pb_vs_t'. A table of data points is visible, showing time (t) and pressure (f(t)). The 'Interpolation and Extrapolation' section is set to 'Linear' interpolation and 'Constant' extrapolation.

t	f(t)
0	0
0.003	35e6
0.005	327e6
0.006	338e6
0.01	156e6
0.020	0

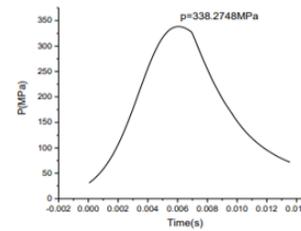


Fig. 1. Simulation Curve for Calculating the Maximum Bore Pressure of Artillery

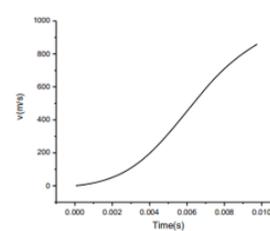


Fig. 2. Muzzle Velocity Calculating Simulation Curve

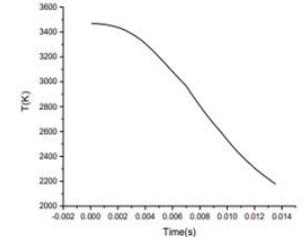


Fig. 3. Simulation Curve of Gun Gas Temperature Calculation

Table 3. Simulation Results of Interior Ballistic Performance of Artillery

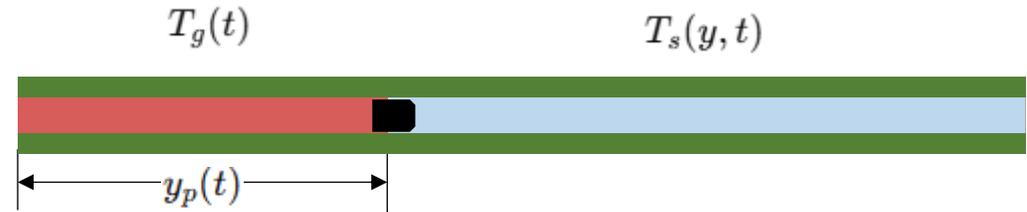
T [s]	p [MPa]	v [m·s ⁻¹]	T [K]
0.00005	31.07375	0.6244	3468.402
0.00025	35.61718	3.3476	3467.982
0.0053	327.5129	355.8887	3164.382
0.0605	338.2748	459.3889	3075.322
0.0097	165.3699	855.1019	2573.933

COMSOL Multi-physics Analysis

Boundary Condition

2. 내부 열

포신 내부에 가해지는 열 -> 대류 열유속 식 사용



$$q(y, t) = h(t) (T_g(t) - T_s(y, t)) \mathbf{1}_{y \leq y_p(t)}$$

$h(t)$ 시간 의존 열전달 계수

$T_g(t)$ 시간 t에 따른 가스 온도

$T_s(y, t)$ 벽면 온도 T

$y_p(t)$ 시간 t에 따른 탄의 위치

$\mathbf{1}_{x \leq y_p(t)}$ 탄 앞의 온도는 T

Model Builder

Settings

Heat Flux

Label: Heat Flux 2

Boundary Selection

Selection: Manual

Active: 7, 8, 11, 13

Override and Contribution

Equation

Frame Selection

Heat Flux

General inward heat flux

$q_0 = h_{vs,t}(t) * (Tg_{vs,t}(t) - T) * (y \leq yp_{vs,t}(t))$ W/m²

Convective heat flux

$q_0 = h \cdot (T_{ext} - T)$

Overall heat transfer rate

$q_0 = \frac{P_0}{A}$

COMSOL Multi-physics Analysis

Model Builder

- Project_02_Dec.mph (root)
 - Global Definitions
 - E_vs_T (E_vs_T)
 - k_vs_T (k_vs_T)
 - Cp_vs_T (Cp_vs_T)
 - alpha_vs_T (alpha_vs_T)
 - Pb_vs_t (Pb_vs_t)
 - yp_vs_t (yp_vs_t)
 - Tg_vs_t (Tg_vs_t)
 - h_vs_t (h_vs_t)
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Results

Settings

Mesh

Build All

Label: Mesh 1

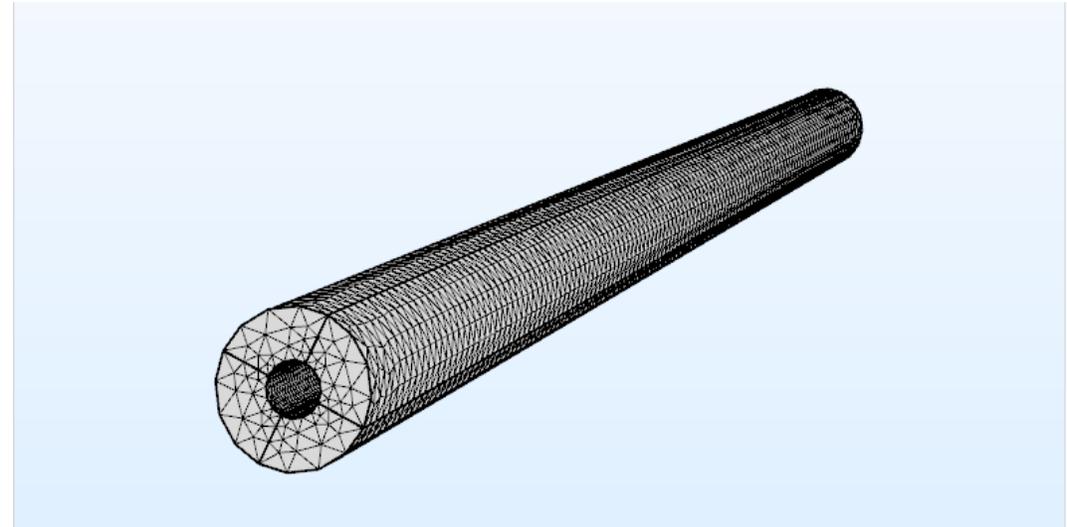
Mesh Settings

Sequence type: Physics-controlled mesh

Element size: Finer

Mesh

요소 크기 Fine으로 Mesh생성



COMSOL Multi-physics Analysis

Study

자주포 발포 시 열과 압력이 매우 빠른 시간동안 변화함
-> Time Step을 매우 촘촘하게 설정 후 Compute

Model Builder

- Project_02_Dec.mph (root)
 - Global Definitions
 - E_vs_T (E_vs_T)
 - k_vs_T (k_vs_T)
 - Cp_vs_T (Cp_vs_T)
 - alpha_vs_T (alpha_vs_T)
 - Pb_vs_t (Pb_vs_t)
 - yp_vs_t (yp_vs_t)
 - Tg_vs_t (Tg_vs_t)
 - h_vs_t (h_vs_t)
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Step 1: Time Dependent
 - Solver Configurations
 - Results

Settings

Time Dependent

Compute Update Solution

Label: Time Dependent

Study Settings

Time unit: s

Times: range(0,0.001,1.5) s

Relative tolerance: 0.01

Include geometric nonlinearity

Results While Solving

Physics and Variables Selection

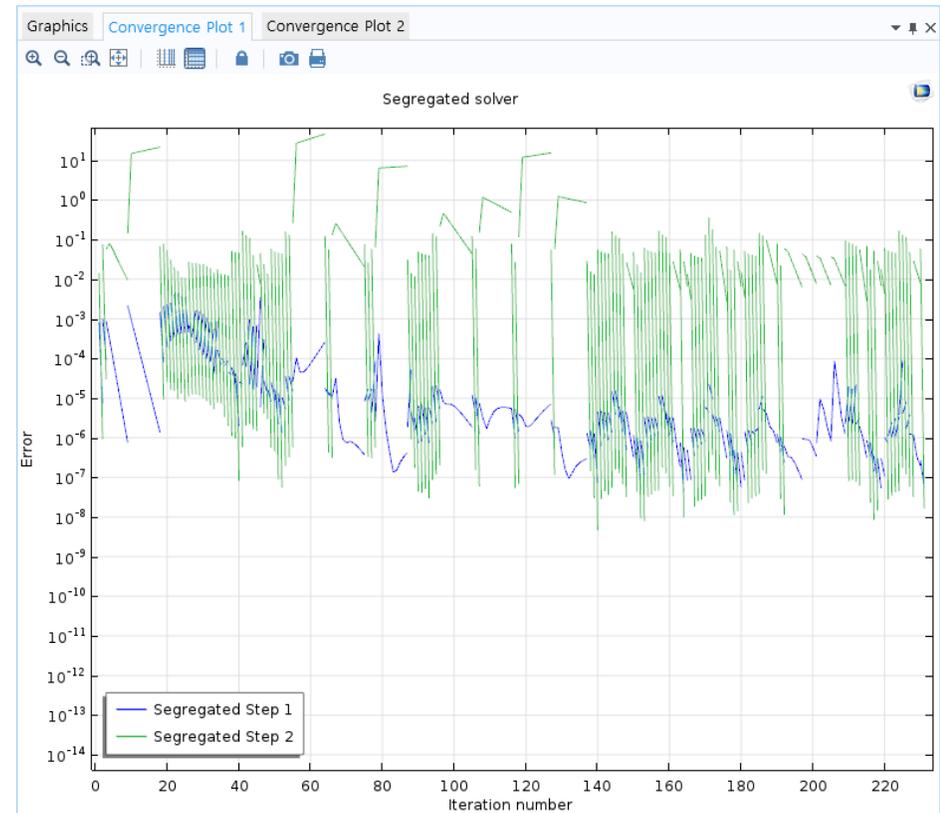
Modify physics tree and variables for study step

Physics interface	Solve for	Discretization
Solid Mechanics (solid)	<input checked="" type="checkbox"/>	Physics settings
Heat Transfer in Solids (ht)	<input checked="" type="checkbox"/>	Physics settings

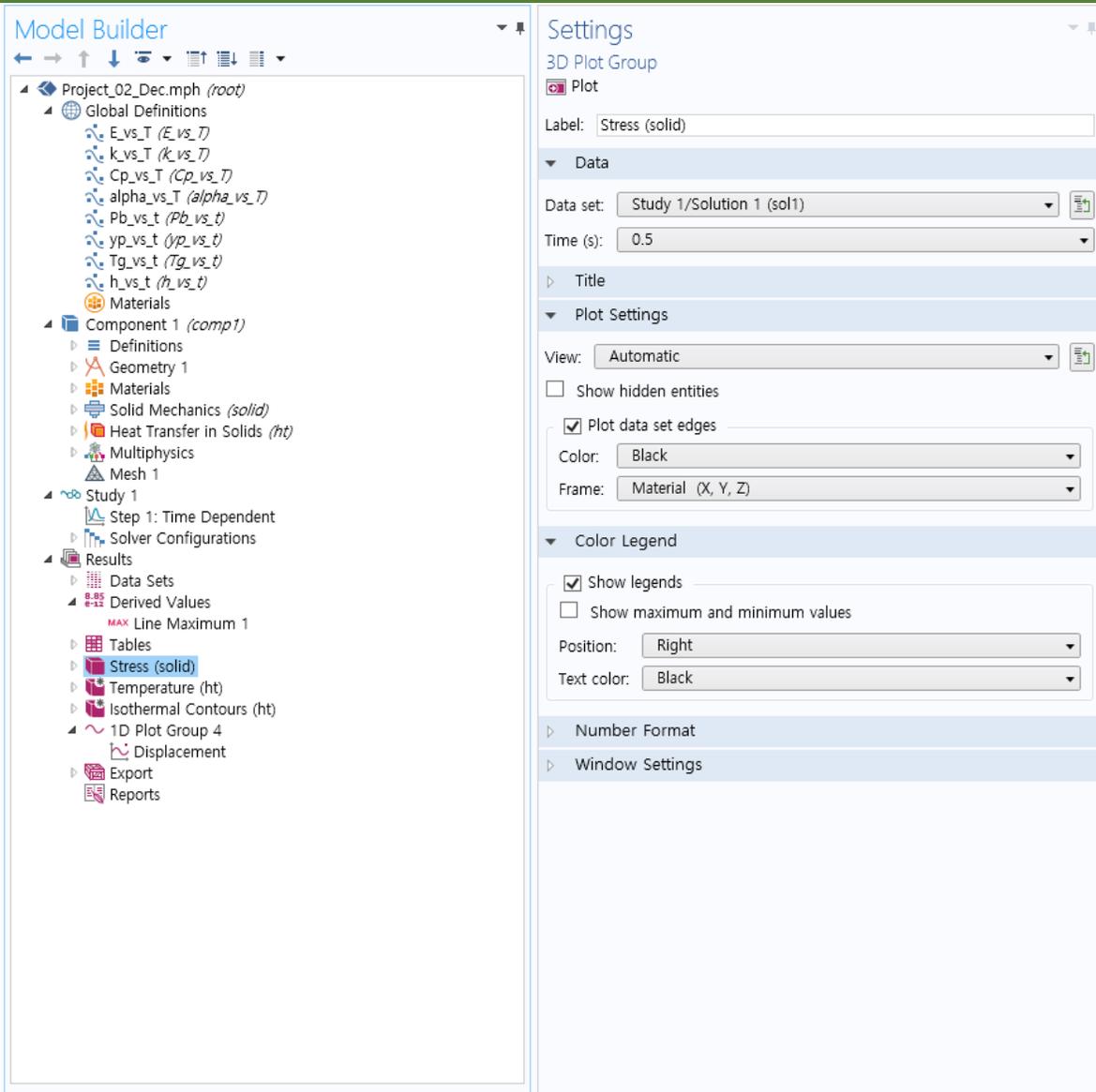
Values of Dependent Variables

Mesh Selection

Study Extensions

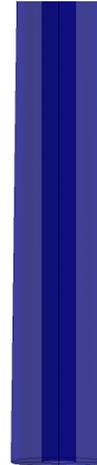


COMSOL Multi-physics Analysis



Case with Fixed Plain

축방향 진동이 없도록 포신의 끝을 고정한다면?



고강도 특수강 ASTM A723 가정

항복강도 약 1,100MPa

$$S = \frac{\text{재료의 기준 강도 (Strength)}}{\text{허용 응력 (Allowable Stress)}}$$

$S \gg 1$: 안전함

$S < 1$: 구조물이 하중을 견디지 못함

$S \sim 1$: 피로파괴의 위험이 있음

자주포 포신의 경우 1.5-2.0

$$S = 1100 / 1019 = 1.08$$

Time (s)	von Mises stress (N/m ²)
0.0040000	3.5368E8
0.0050000	6.8685E8
0.0060000	1.0194E9
0.0070000	9.8107E8
0.0080000	7.8477E8

-> 피로 파괴의 위험 매우 높음

-> 잘못된 설계

-> 댐핑 시스템 필요

COMSOL Multi-physics Analysis

Model Builder

- Project_02_Dec.mph (root)
 - Global Definitions
 - E_vs_T (E_vs_T)
 - k_vs_T (k_vs_T)
 - Cp_vs_T (Cp_vs_T)
 - alpha_vs_T (alpha_vs_T)
 - Pb_vs_t (Pb_vs_t)
 - yp_vs_t (yp_vs_t)
 - Tg_vs_t (Tg_vs_t)
 - h_vs_t (h_vs_t)
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Linear Elastic Material 1
 - Free 1
 - Initial Values 1
 - Boundary Load 1
 - Boundary Load 2
 - Spring Foundation 1
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Results

Settings

Boundary Load

Label: Boundary Load 2

Boundary Selection

Selection: Manual

Active: 3, 4, 9, 12

Override and Contribution

Equation

Coordinate System Selection

Coordinate system: Global coordinate system

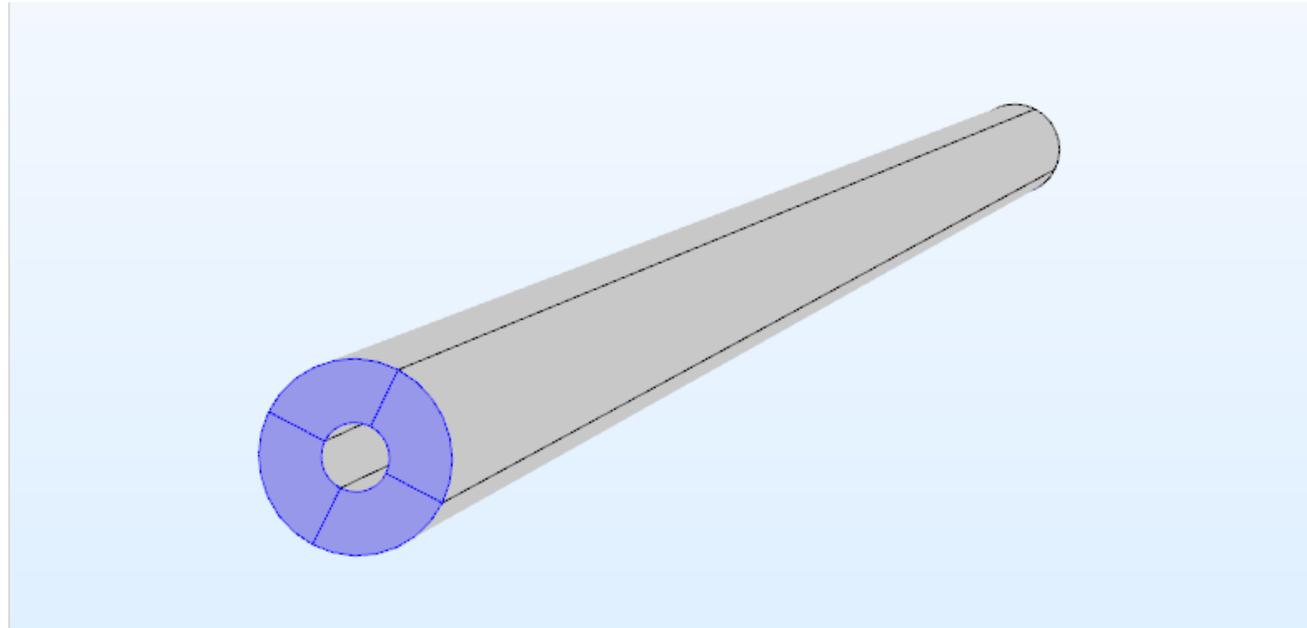
Force

Load type: Total force

F _{tot}	x	y	z
0			
$-Pb_vs_t(t) \cdot (0.0775^2) \cdot \pi$			
0			

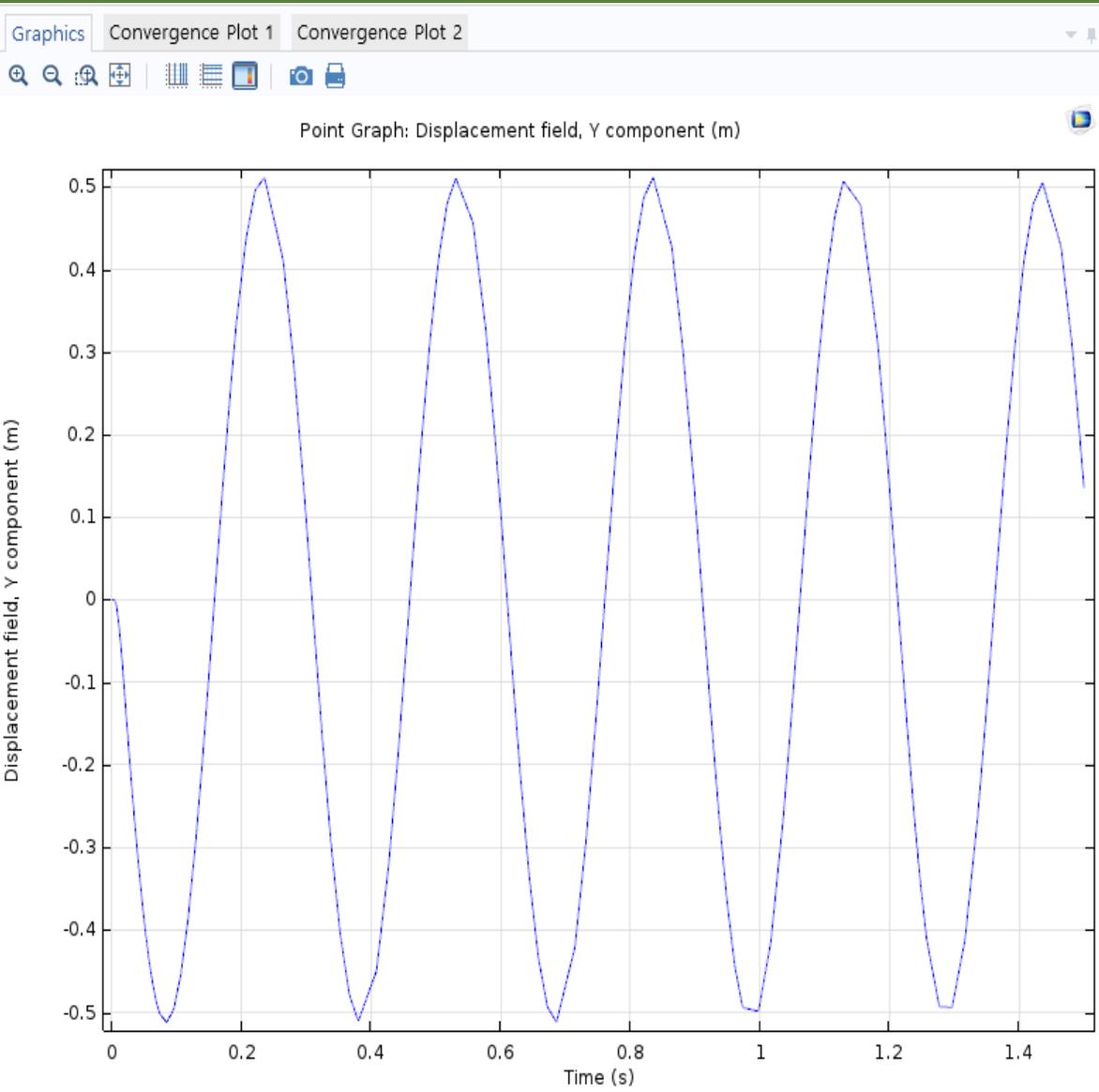
Boundary Condition

Fixed plain -> 반발력 작용 + Spring Foundation 추가



Recoil system Spring coefficient = 2100kN

COMSOL Multi-physics Analysis



Damping System Design

댐퍼가 없을 때 포신의 축방향 변위

-> 해석 결과 최대 변위가 **0.5m** 수준.



-> 포신의 축방향 진동은 탄속에 영향을 줌.

사거리(고저각) 오차: $R \propto v_0^2$

-> 보정하지 않을 시 40km 표적 기준 **수십m 차이** 발생

내부 탄도 불안정 유발

-> **발사 일관성 저하** 등의 문제 발생

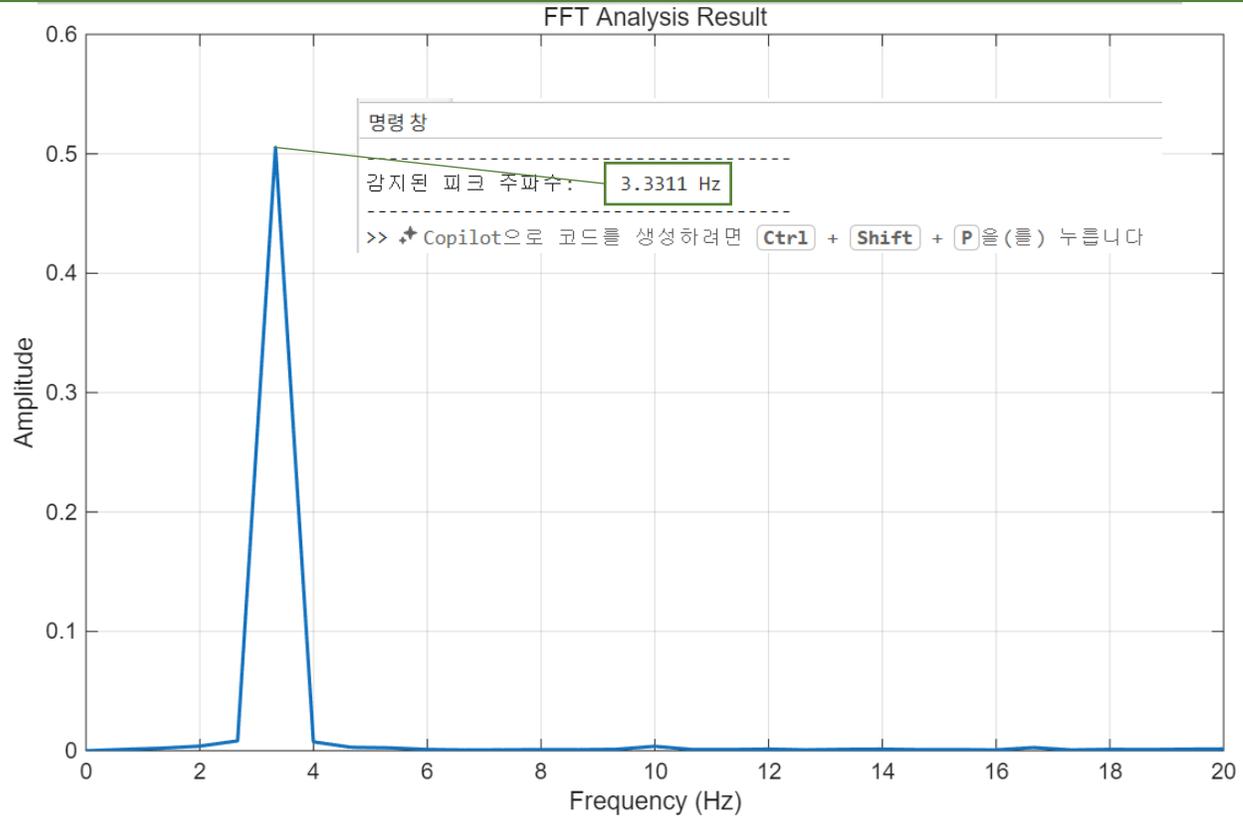
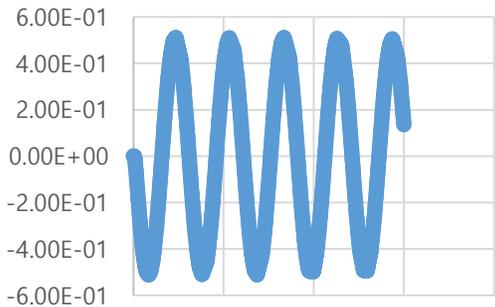
-> 횡방향 진동을 빠르게 제어하여 **분당 발포 수**를 늘리는 것이 중요함

COMSOL Multi-physics Analysis

Damping System Design

1	% Model	Project_02_Dec.mph
2	% Version	COMSOL 5.2.0.220
3	% Date	Dec 2 2025, 18:02
4	% Dimensi	1
5	% Nodes	1501
6	% Expressi	1
7	% Descript	Point graph
8	% X	Height
9	0	7.05E-21
10	0.001	-1.51E-05
11	0.002	-7.50E-05
12	0.003	-1.80E-04
13	0.004	-5.60E-04
14	0.005	-0.00152
15	0.006	-0.00372

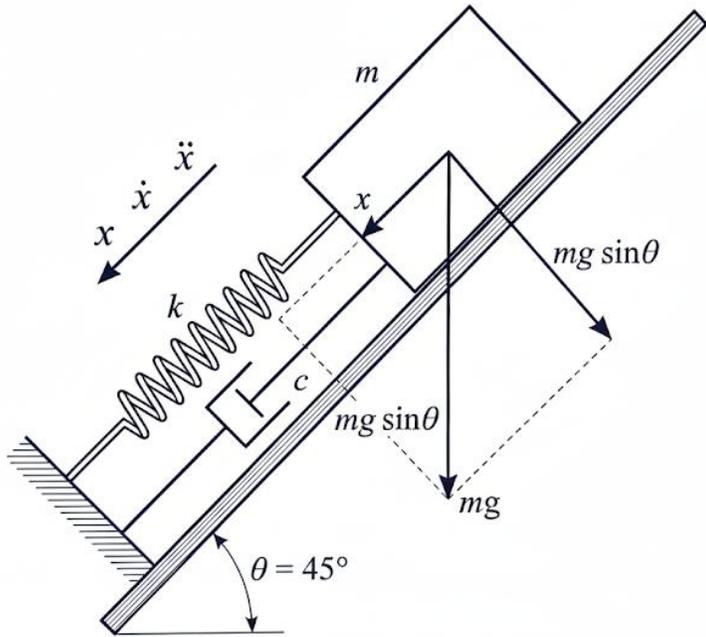
Displacement-Y



Point graph를 이용해 Y축 방향 변위->.csv
Fourier Transform을 이용하여 고유진동수를 측정

COMSOL Multi-physics Analysis

Damping System Design



$$m\ddot{x} + c\dot{x} + kx = F$$

$$(ms^2 + cs + k)X(s) = F(s)$$

$$\frac{X(s)}{F(s)} = \frac{1}{ms^2 + cs + k}$$

$$G(s) = \frac{X(s)}{F(s)} = \frac{\frac{1}{m}}{s^2 + \frac{c}{m}s + \frac{k}{m}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

$$\omega_n = 3.3311\text{Hz} = 20.9299[\text{rad/s}]$$

$$\frac{k}{m} = \frac{2.1 * 10^6}{m} = 20.9299^2 \therefore m = 4793.8\text{kg}$$

$$2\omega_n = \frac{c}{m} \quad \text{Critical Damping 특성을 갖도록 설계 } \zeta = 1$$

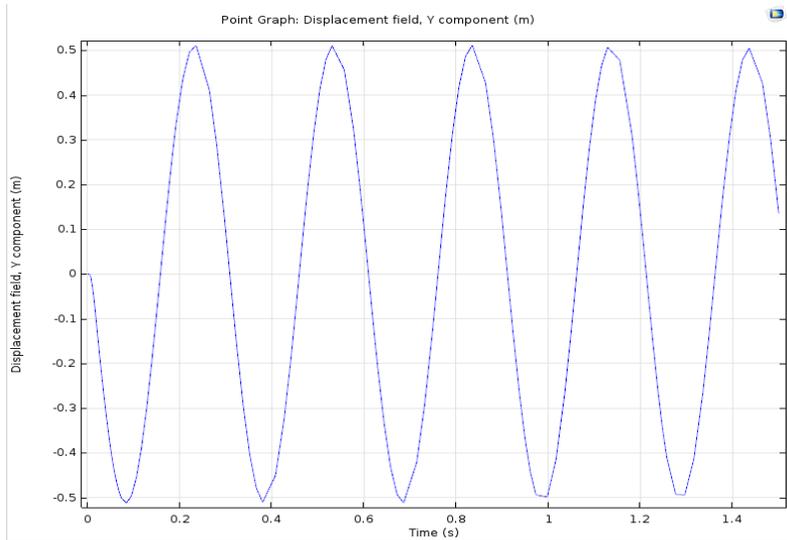
$$c_{\text{critical}} = 2 * 20.9299 * 4793.8 = 200,667[\text{N} * \text{s/m}]$$

COMSOL Multi-physics Analysis

Damping System Design



$C_{critical}$ 적용

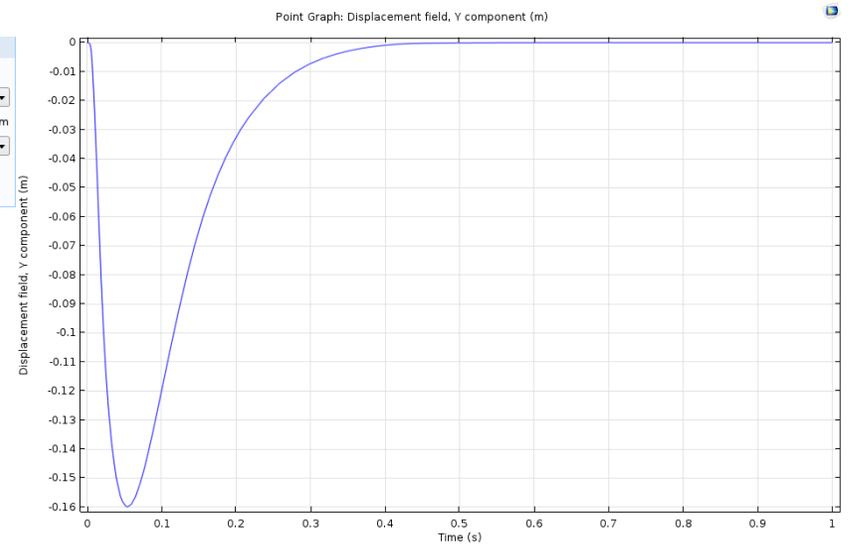


Viscous Damping

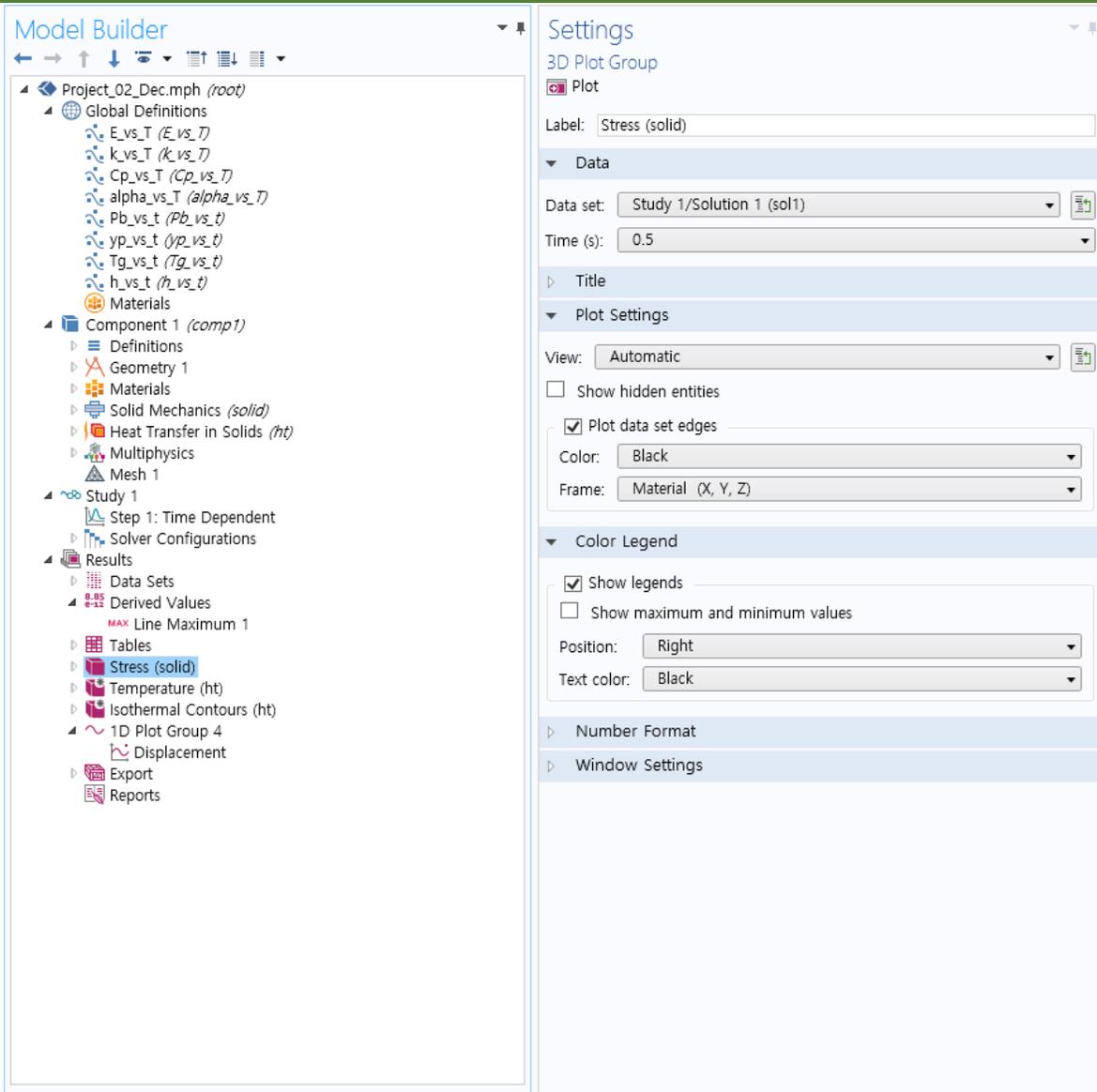
Damping type: Total damping constant

d_{tot} 200667 N·s/m

Isotropic

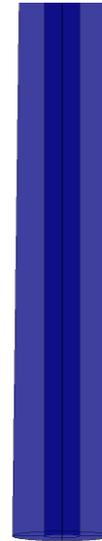


COMSOL Multi-physics Analysis



Results

1. 포신의 내벽이 받는 응력 및 변형



고강도 특수강 ASTM A723 가정

항복강도 약 1,100MPa

Safety Factor $S = 1100/658 = 1.67$

Time (s)	von Mises stress (N/m ²)
0.0030000	5.6906E7
0.0040000	3.0485E8
0.0050000	6.5795E8
0.0060000	6.4259E8
0.0070000	5.9724E8

-> 피로수명 보장
-> 안정적인 설계

COMSOL Multi-physics Analysis

Model Builder

- Project_02_Dec.mph (root)
 - Global Definitions
 - E_vs_T (E_{vs_T})
 - k_vs_T (k_{vs_T})
 - Cp_vs_T (Cp_{vs_T})
 - alpha_vs_T ($alpha_{vs_T}$)
 - Pb_vs_t (Pb_{vs_t})
 - yp_vs_t (yp_{vs_t})
 - Tg_vs_t (Tg_{vs_t})
 - h_vs_t (h_{vs_t})
 - Materials
 - Component 1 (comp1)
 - Definitions
 - Geometry 1
 - Materials
 - Solid Mechanics (solid)
 - Heat Transfer in Solids (ht)
 - Multiphysics
 - Mesh 1
 - Study 1
 - Step 1: Time Dependent
 - Solver Configurations
 - Results
 - Data Sets
 - Derived Values
 - MAX Line Maximum 1
 - Tables
 - Stress (solid)
 - Temperature (ht)
 - Isothermal Contours (ht)
 - 1D Plot Group 4
 - Displacement
 - Export
 - Reports

Settings

3D Plot Group

Plot

Label: Temperature (ht)

Data

Data set: Study 1/Solution 1 (sol1)

Time (s): 0.5

Title

Plot Settings

View: Automatic

Show hidden entities

Plot data set edges

Color: Black

Frame: Material (X, Y, Z)

Color Legend

Show legends

Show maximum and minimum values

Position: Right

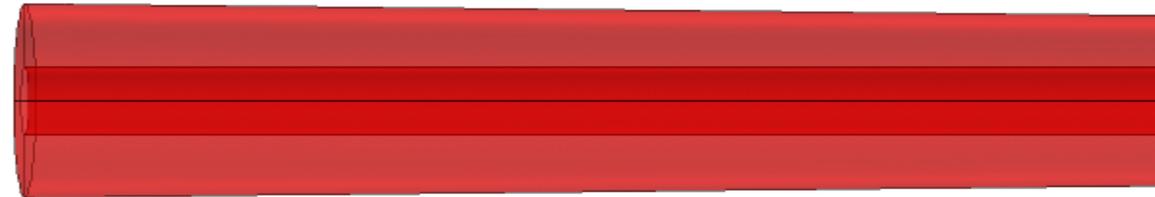
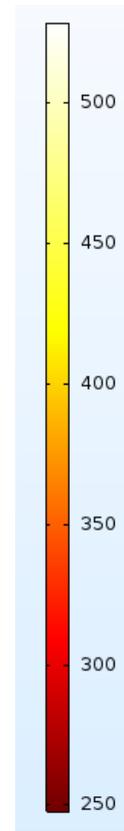
Text color: Black

Number Format

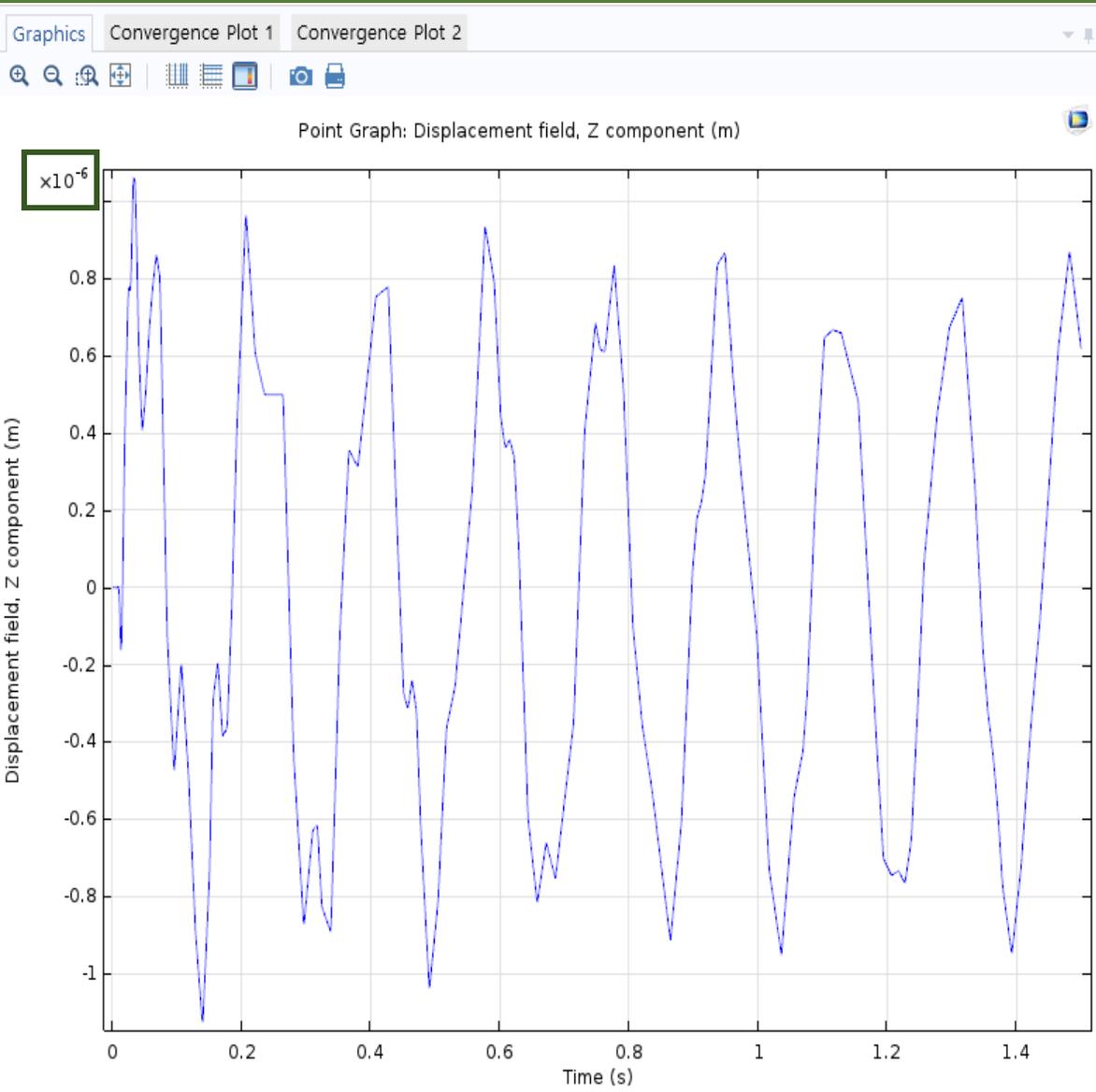
Window Settings

Results

2. 포신의 내부가 받는 열



COMSOL Multi-physics Analysis



Results

3. 포신의 횡방향 변위

-> 해석 결과 최대 변위가 **1e-6(m)** 수준.

1) 조준 각 오차 :

$$\theta \approx \frac{\delta}{L} = \frac{1 \times 10^{-6}}{8.060} = 1.24 \times 10^{-7} \text{ rad}$$

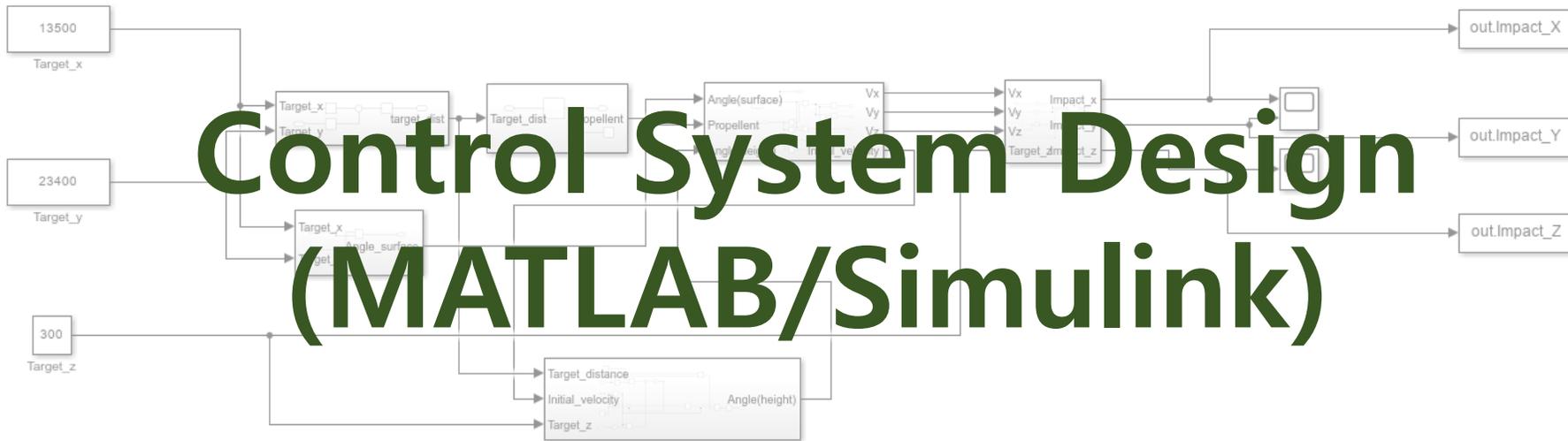
2) 40km 밖 표적에서의 횡방향 오차

$$\Delta x = \theta \cdot R = (1.24 \times 10^{-7}) \times 40,000 \approx 4.96 \text{ mm}$$

-> 무시할 수 있는 수준의 오차

-> 계산 과정에서의 수치적 오류일 가능성 높음

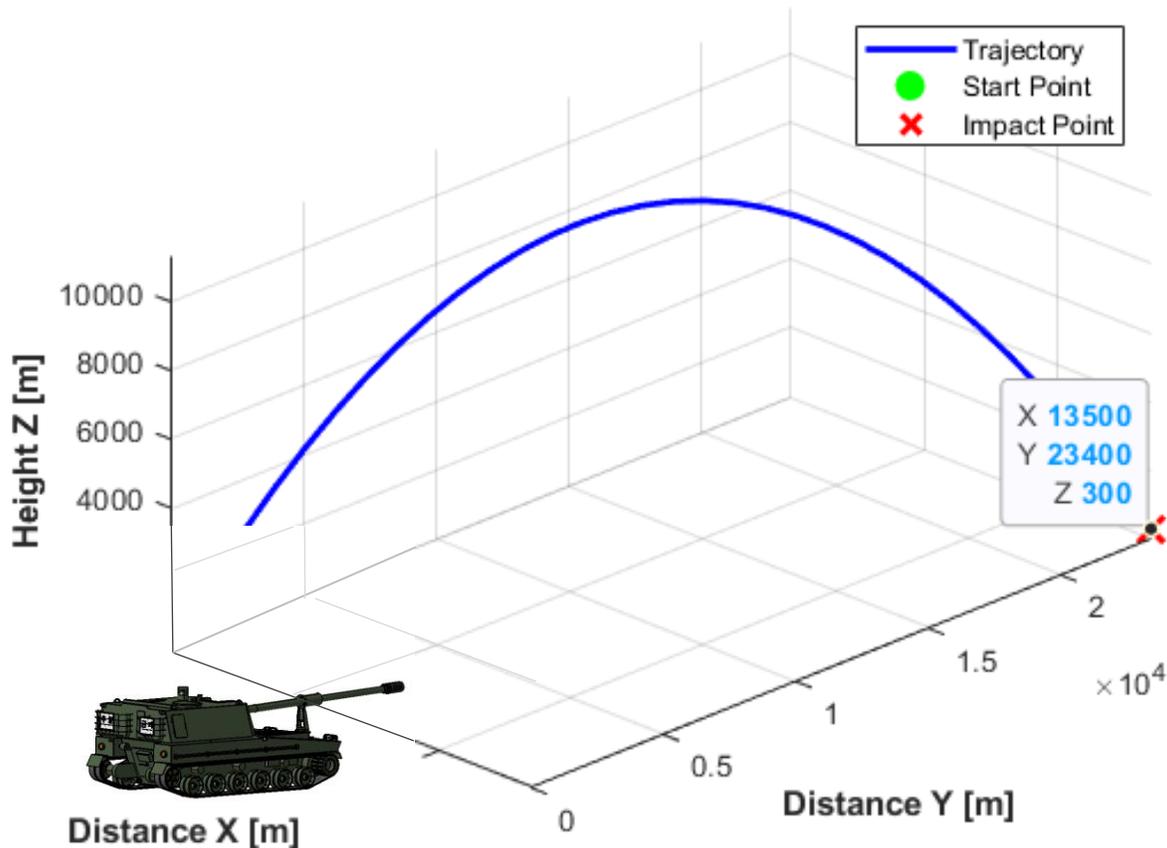
Control System Design (MATLAB/Simulink)



MATLAB/Simulink Control System Design

Aiming System Design

3D Projectile Trajectory

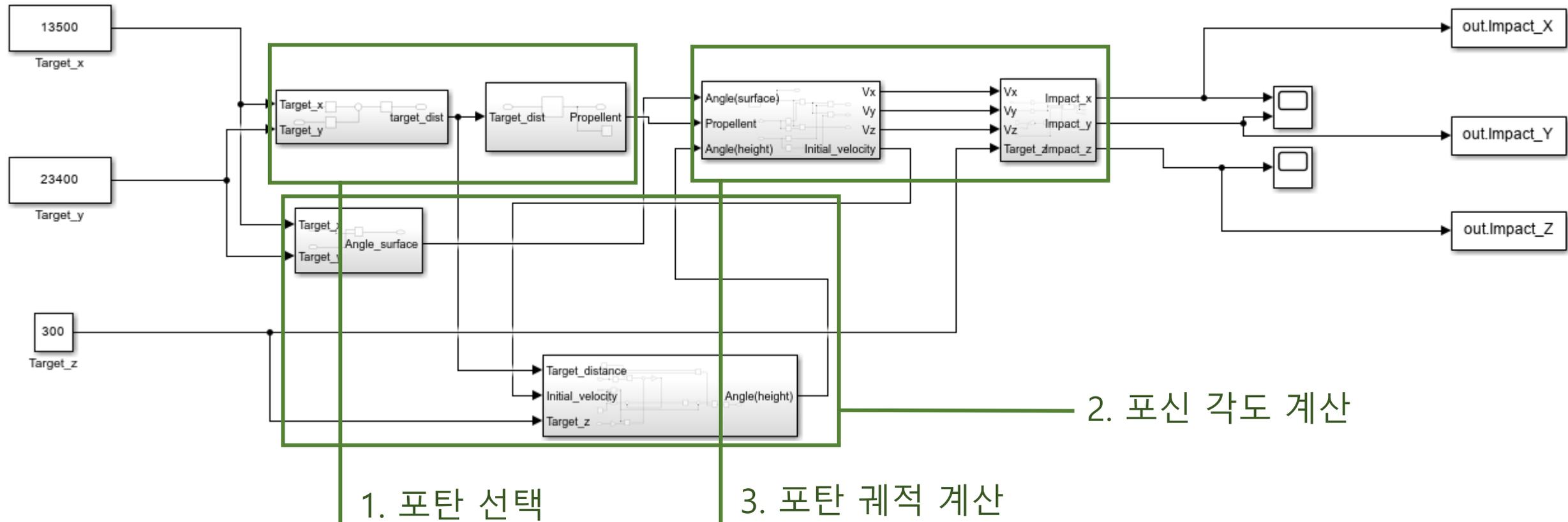


조준 거리에 따라 다른 포탄을 사용

1. 사거리에 따른 포탄 선택
2. 해당 포탄 속도를 고려한 조준 시스템 설계

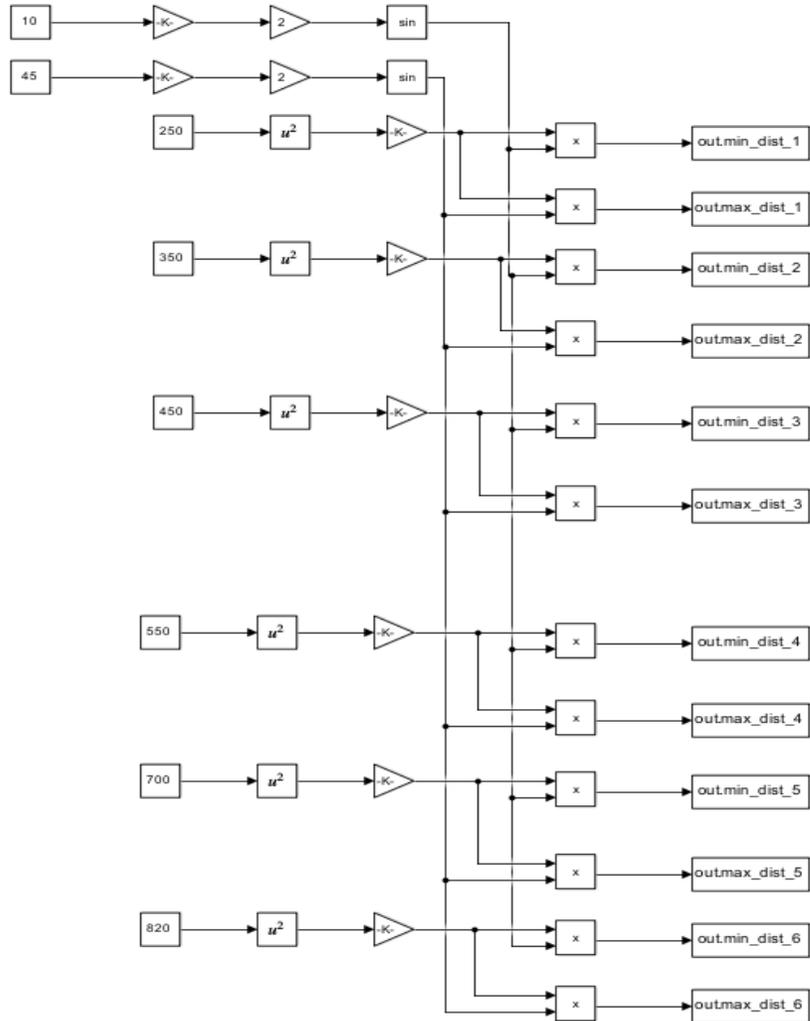
MATLAB/Simulink Control System Design

Aiming System Design



MATLAB/Simulink Control System Design

1. 포탄 모드 선택



```
1 clc; clear all;
2 max_dist_1 = out.max_dist_1;
3 max_dist_2 = out.max_dist_2;
4 max_dist_3 = out.max_dist_3;
5 max_dist_4 = out.max_dist_4;
6 max_dist_5 = out.max_dist_5;
7 max_dist_6 = out.max_dist_6;
8
9 breakpoints = [0, max_dist_1, max_dist_2, max_dist_3, max_dist_4, max_dist_5, max_dist_6];
```

max_dist_1	6.3710e+03
max_dist_2	1.2487e+04
max_dist_3	2.0642e+04
max_dist_4	3.0836e+04
max_dist_5	4.9949e+04
max_dist_6	6.8542e+04

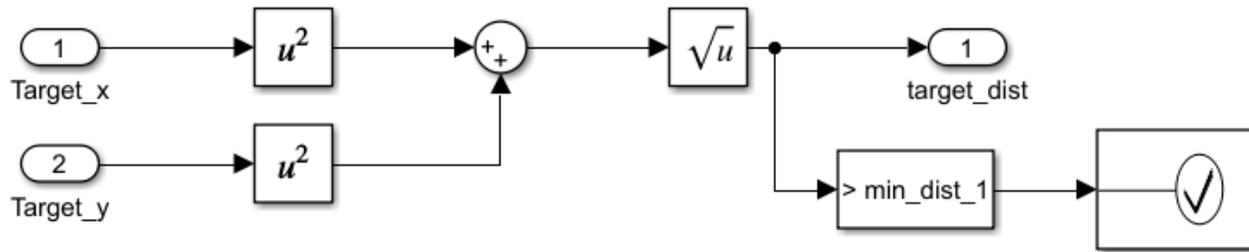
포탄 종류별 다른 초기속도

공개된 데이터가 없어 임의로 설정

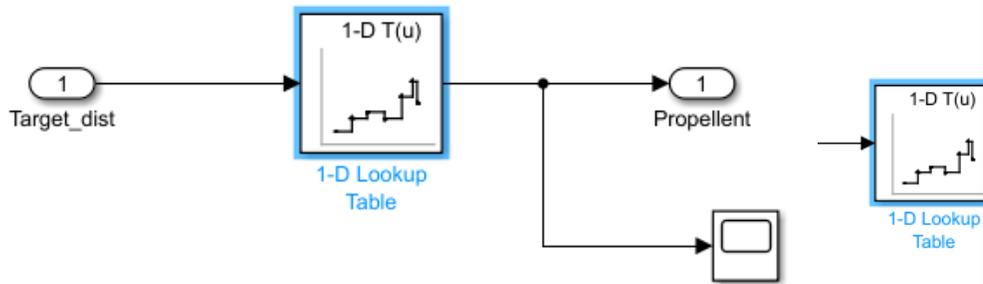
-> Angle Range(10-45)에 따른 최대/최소 사거리 계산

MATLAB/Simulink Control System Design

1. 포탄 모드 선택



1. 목표 지점과의 거리 계산



Block Parameters: 1-D Lookup Table

Lookup Table (n-D)
Perform n-dimensional interpolated table lookup including index searches. The table is a sampled representation of a function in N variables. Breakpoint sets relate the input values to positions in the table. The first dimension corresponds to the top (or left) input port.

Table and Breakpoints Algorithm Data Types

Number of table dimensions: 1

Data specification: Table and breakpoints

Breakpoints specification: Explicit values

Support tunable size

Source	Value
Dialog	[1,2,3,4,5,6,6]
Dialog	breakpoints: <1x7 double>

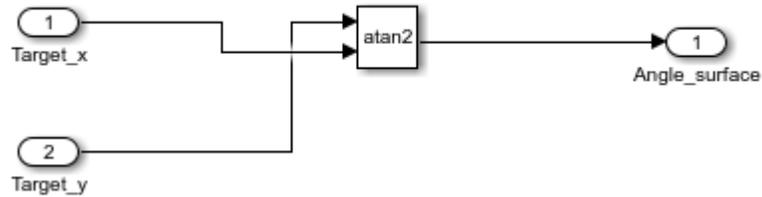
Edit table and breakpoints...

OK Cancel Help Apply

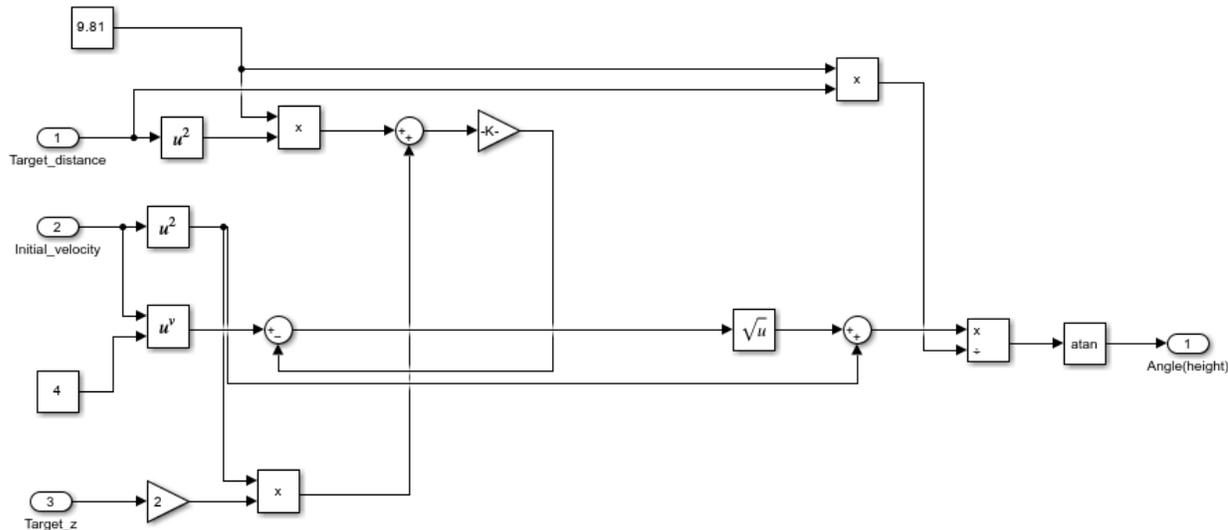
2. 포탄 별 최대 거리를 Look-Up Table 작성 -> 상황에 맞는 포탄 선정

MATLAB/Simulink Control System Design

2. 포신의 각도 계산



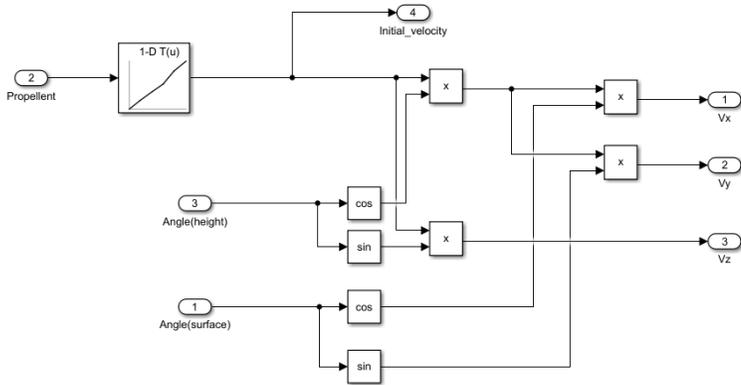
1. xy 지면 좌표계 상에서의 포신의 각도를 목표 지점의 좌표를 이용하여 atan 함수로 계산



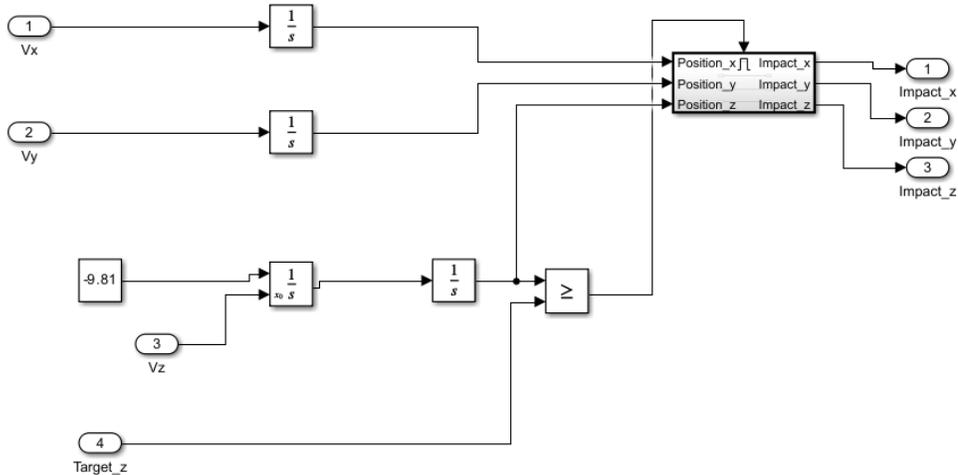
2. 선정된 포탄의 초기속도, 중력을 고려하여 목표한 지점에 도달하기 위한 지면에 대한 포신의 각도 계산

MATLAB/Simulink Control System Design

3. 포탄의 궤적 계산



1. 선정된 각도에 따른 포탄의 x,y,z 좌표 별 속도 계산

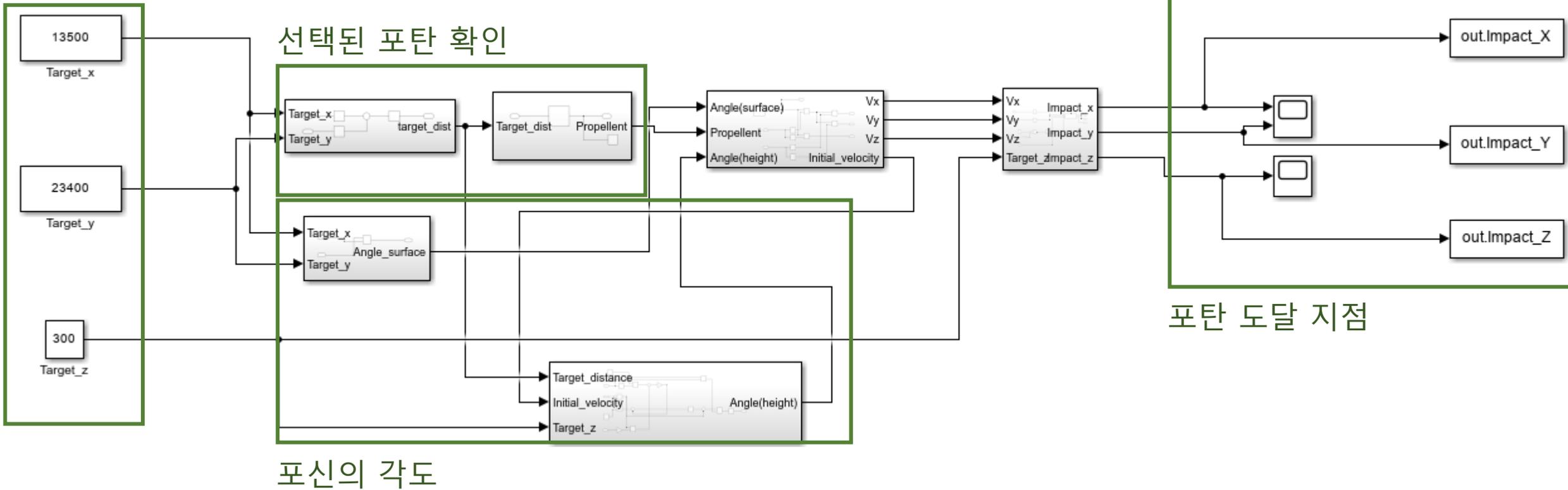


2. 포탄의 z축 좌표가 목표 값에 도달할 때까지의 x,y,z 좌표가 출력되도록 설계->발포된 포탄의 궤적 도출

MATLAB/Simulink Control System Design

System Test

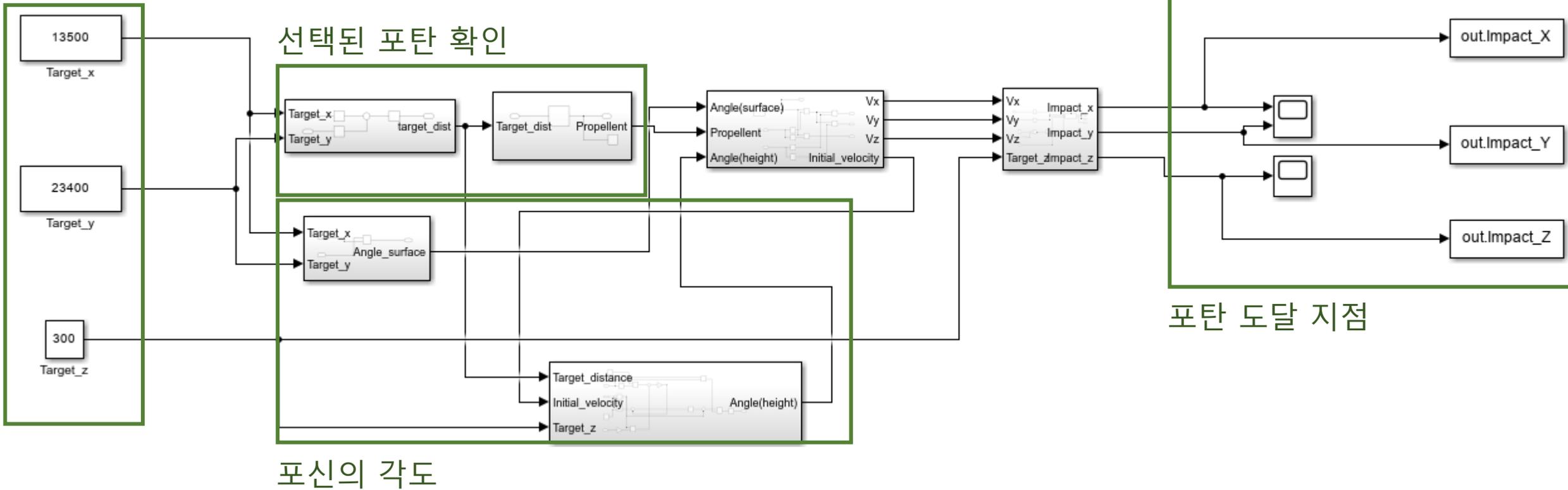
임의의 목표 지점 좌표 입력



MATLAB/Simulink Control System Design

System Test

임의의 목표 지점 좌표 입력

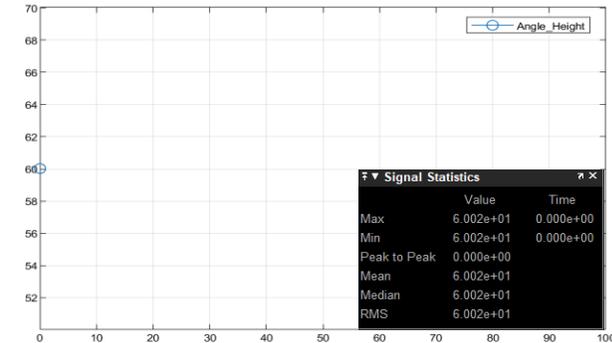


Results

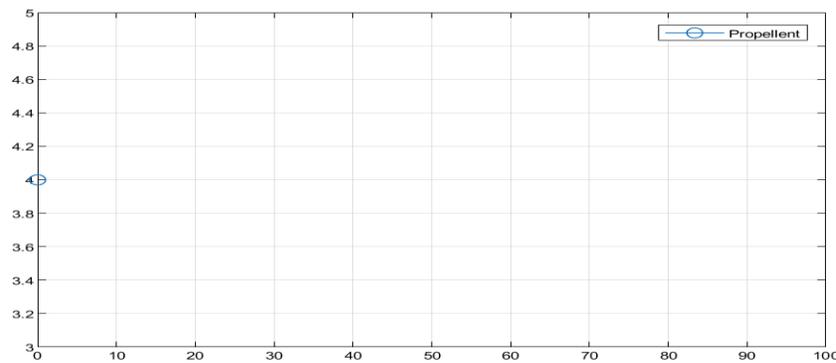
System Test



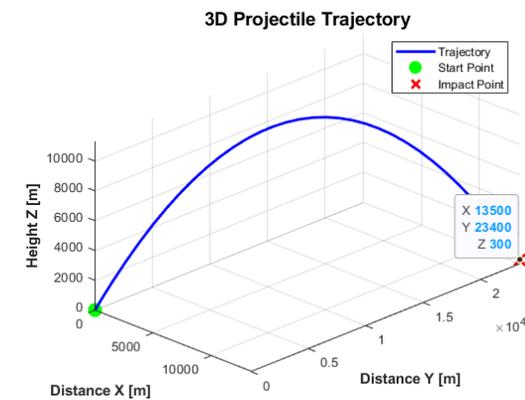
목표지점 좌표 (13500, 23400, 300)[m]



포신의 각도 확인



포탄 선택 확인 (4)



목표지점에 정확히 도달 확인(13500, 23400, 300)

Results

Results

Summary

1. 열이 물성에 미치는 영향을 고려하여 시스템 모델링
2. 발포 시 포신에 가해지는 열과 압력 수학적 모델링
3. 이를 바탕으로 포신의 내벽에 가해지는 응력을 해석하고 **Damping system**이 필요한 이유를 찾고, **Safety Factor**를 고려한 **Damping System** 설계
4. 목표 지점의 좌표를 바탕으로 필요한 탄환을 선택하고 **조준하는 시스템** 설계

MATLAB/Simulink Control System Design

고찰

1. K-9이나 비슷한 사양의 자주포에 대한 **공개된 자료가 거의 없어** 수학적 모델링의 단순화
2. **비대칭 요소 X -> 횡방향 진동 X** , 실제 가동 환경에서 발생할 수 있는 여러 **외란에 대한 제어 X**
3. 컴퓨터 및 프로그램의 **성능 제한**으로 인한 **포신 모델링의 단순화**

Q&A