



초전도 리니어 모터카의 작용력 분석

2014012524 변무경

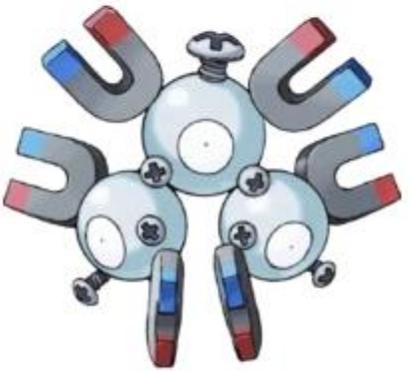
2014012706 조준형

2014012715 조힘찬

팀명

코일 コイル 코이루 Magnemite		No.081
		
타입	분류	
전기 강철 (2세대부터) 전기 (1세대)	자석포켓몬	

× 3 =

레어코일 レアコイル 레아코이루 Magneton		No.082
		
타입	분류	
전기 강철 (2세대부터) 전기 (1세대)	자석포켓몬	

Magnetic Levitation

Electromagnetic levitation (EMS)



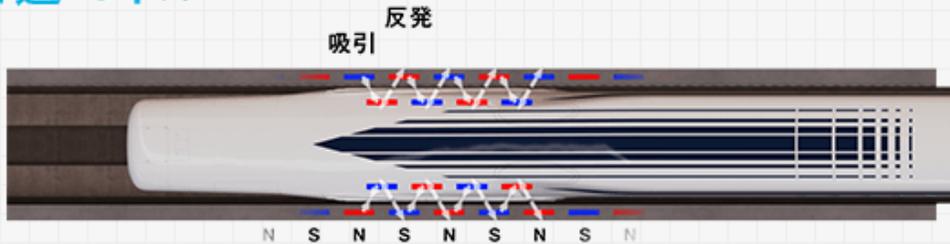
Electrodynamic levitation (EDS)



Electrodynamic suspension

추진 코일

推進コイル

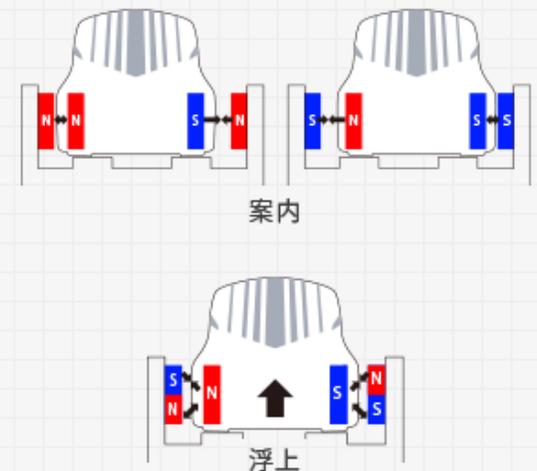


推進コイルに変電所から電流を流し、N極⇄S極と切り替えることによって超電導磁石を搭載した車両を吸引・反発させ、加減速させます。

부상·안내 코일

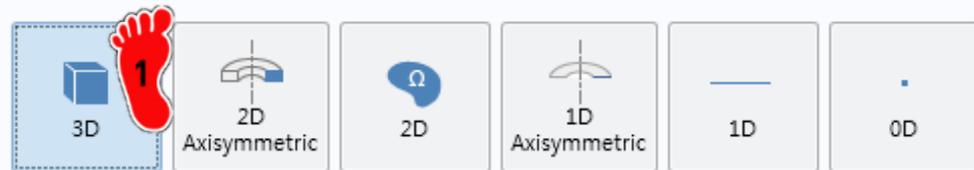
浮上・案内コイル

車両の超電導磁石が高速で通過することで、浮上・案内コイルに電流が流れて電磁石となり、車両を押し上げる力と引き上げる力が発生します。また車両がガイドウェイの中心からずれると、車両が遠ざかった側には吸引力、近づいた側には反発力が働くため、車両には常にガイドウェイの中心に戻ろうとする力が働きます。



모델링 - 부상력, 안내력, 저항력

Select Space Dimension



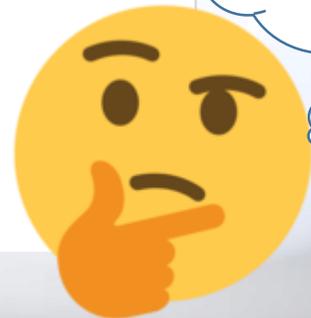
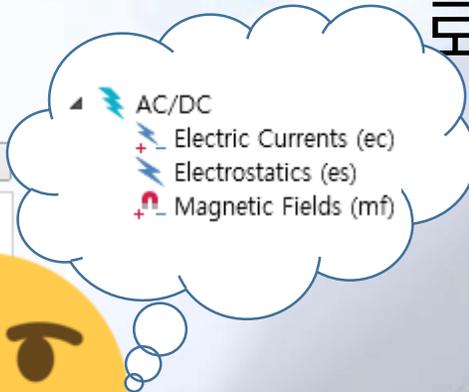
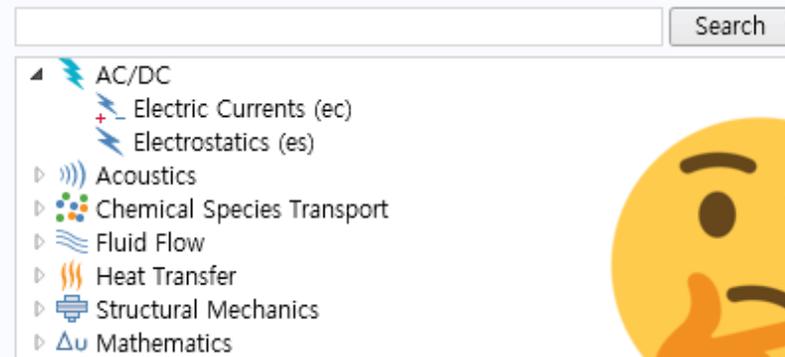
자기장 계산(COMSOL)

→ 유도기전력 계산(Excel+MATLAB)

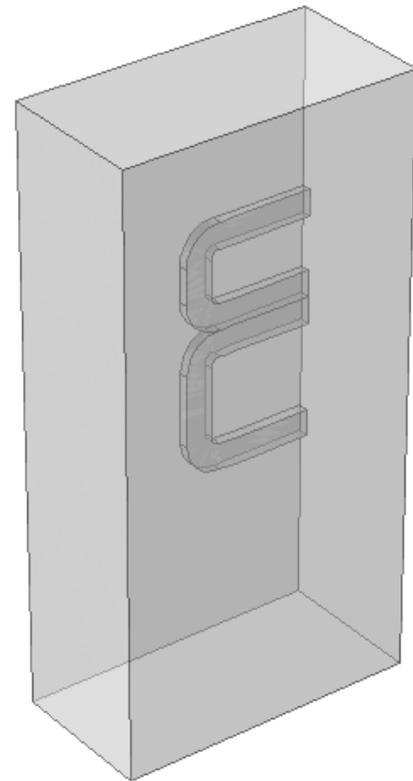
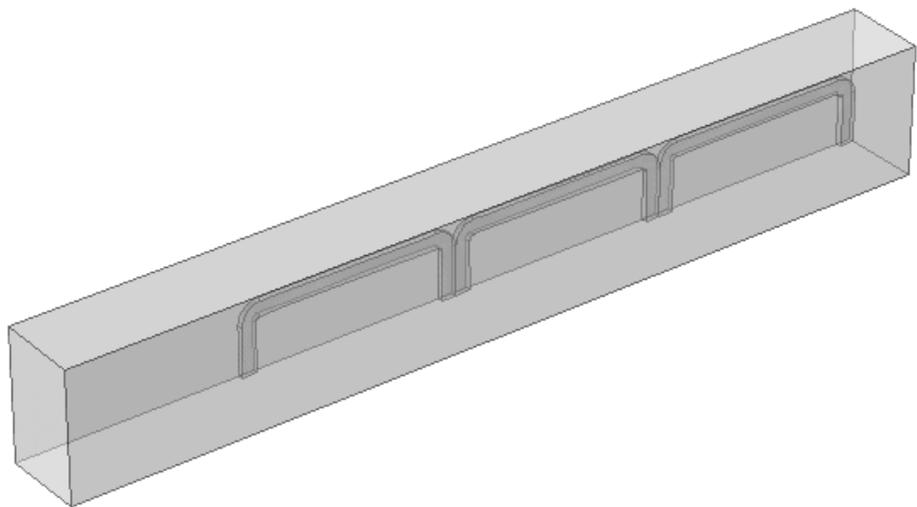
→ 유도전류 계산(MATLAB)

로렌츠 힘 계산(MATLAB)

Select Physics

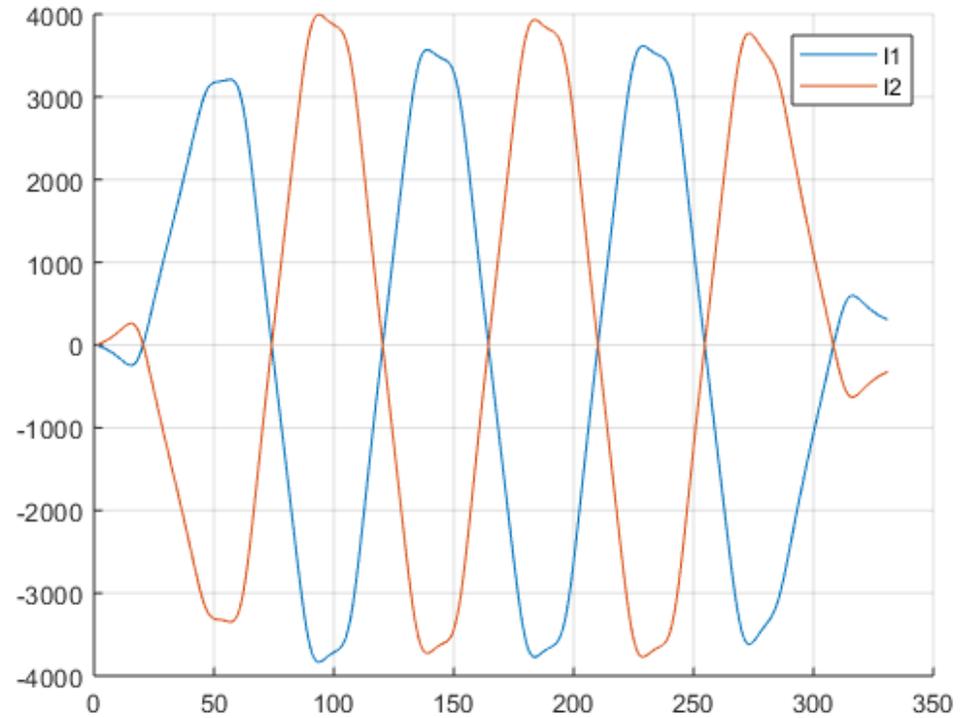
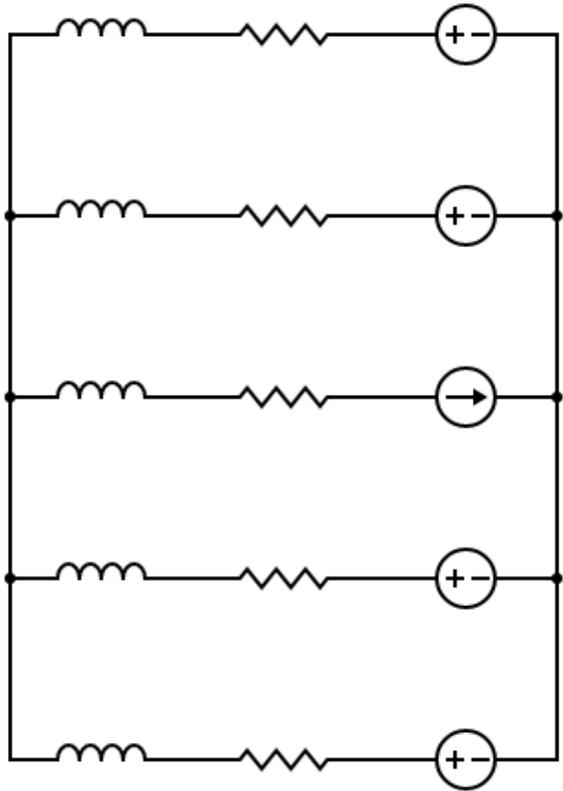


모델링 - 부상력, 안내력, 저항력



모델링 - 부상력, 안내력, 저항력

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모델링 - 부상력, 안내력, 저항력

COMSOL

- Parametric sweep
- Force computation
- 한 조건 계산에 30분 소요
- 속도 조건 10개
- 변위 조건 25개
- 최소 소요시간 5일 이상

MATLAB

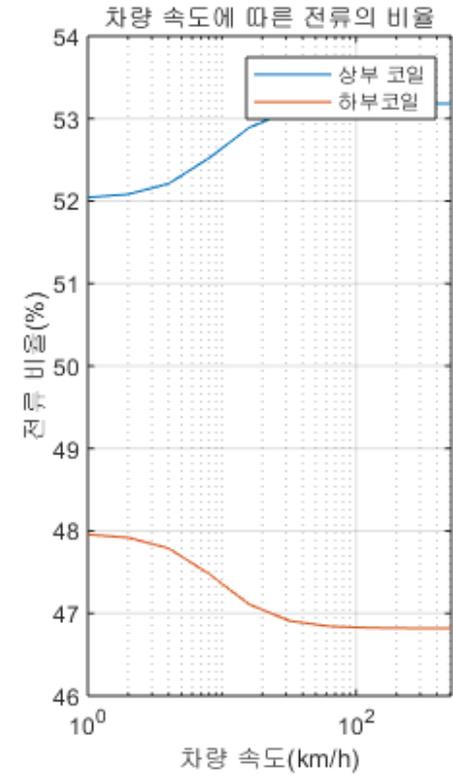
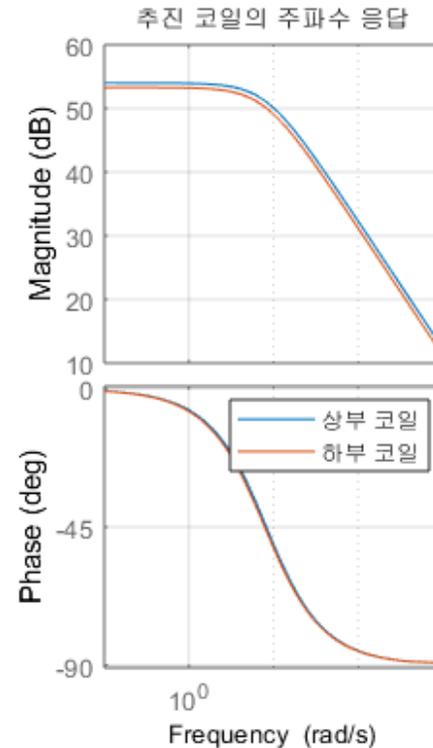
- $\vec{F} = \int i(d\vec{L} \times \vec{B}) \approx \sum i(\Delta\vec{L} \times \vec{B})$
- 소요시간 10분 내외

모델링 - 추진력

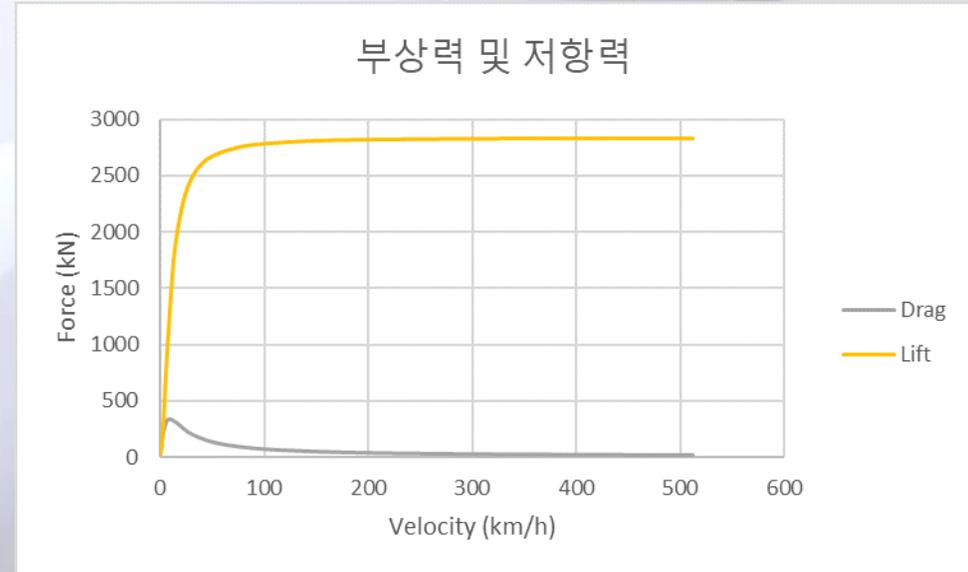
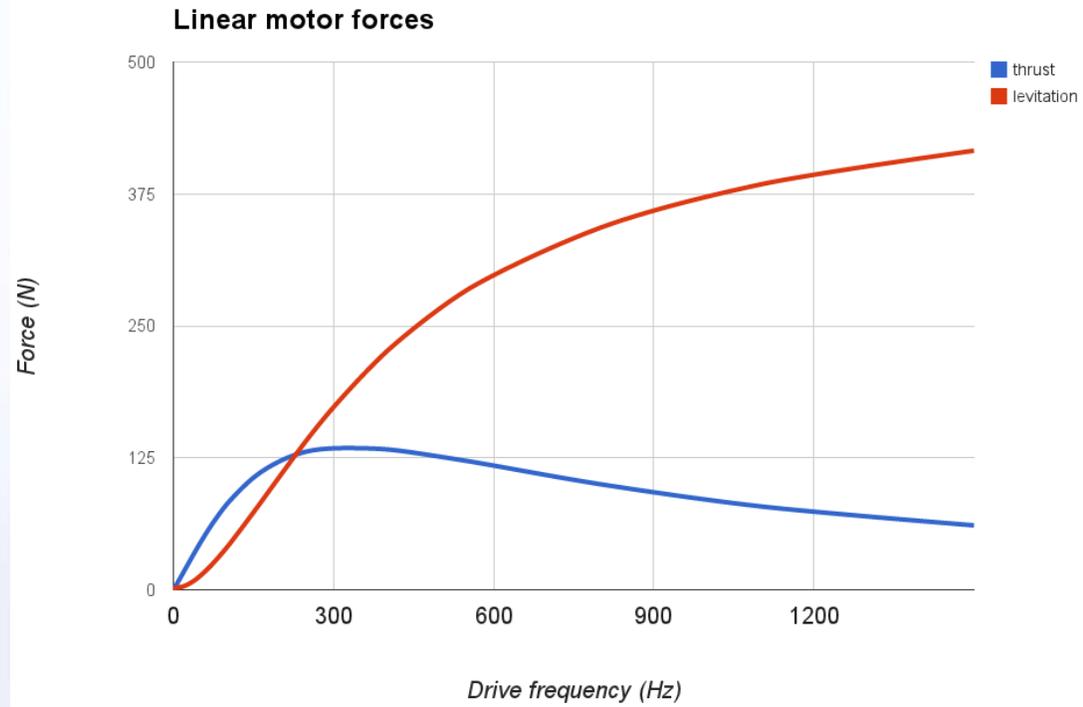
- 속도마다 다른 전류 응답

- $\vec{F} = \int i(d\vec{L} \times \vec{B}) \approx \sum i(\Delta\vec{L} \times \vec{B})$

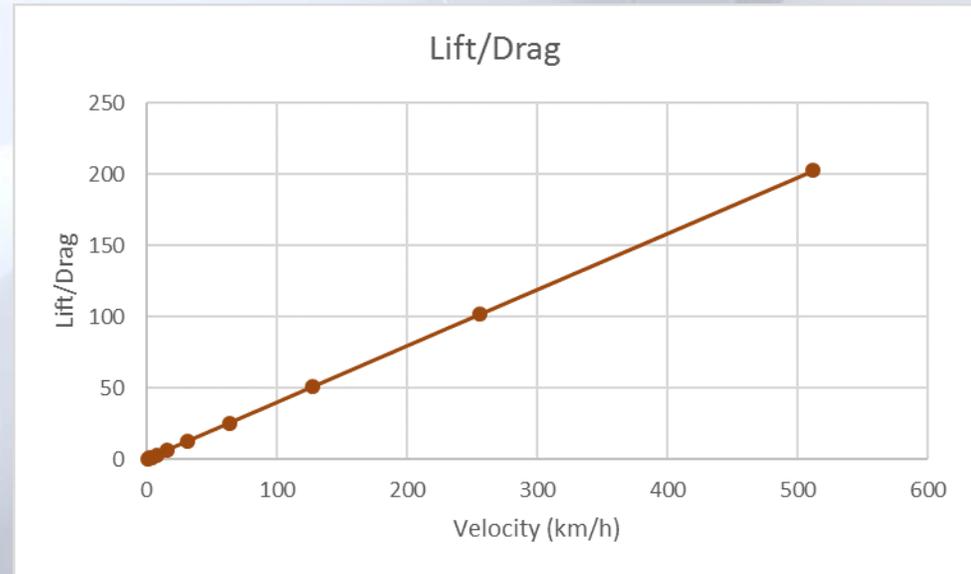
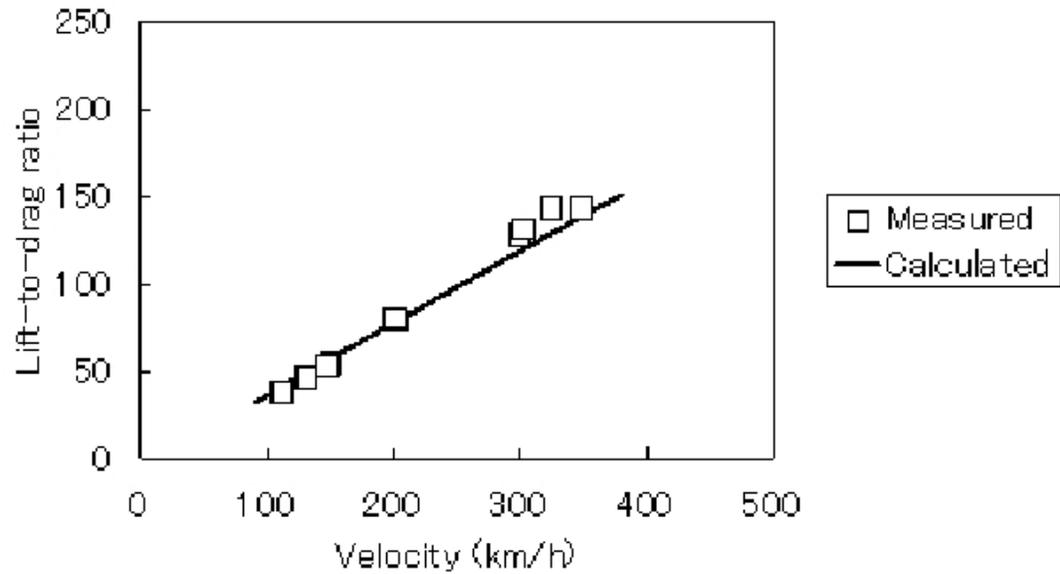
- MATLAB으로 효율이 가장 좋은 3상 전류 위상 구함(1°단위)



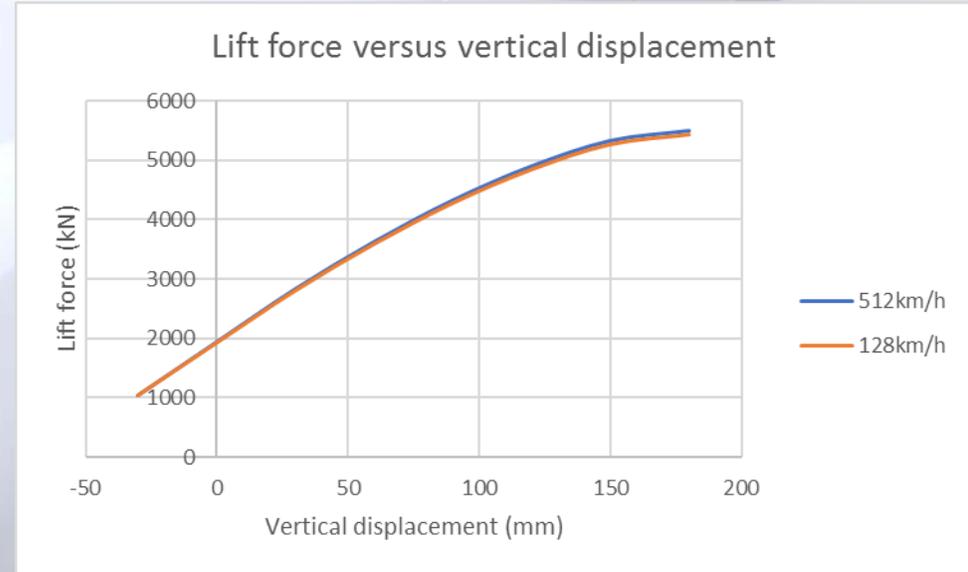
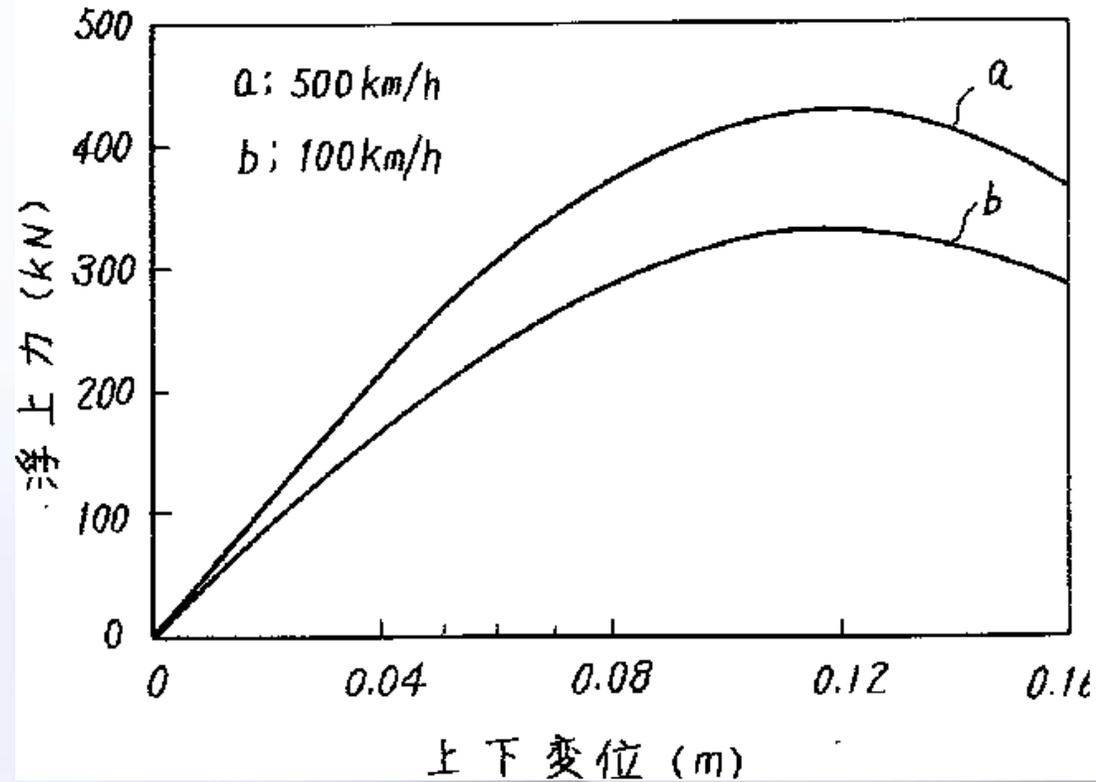
모델링 - 결과



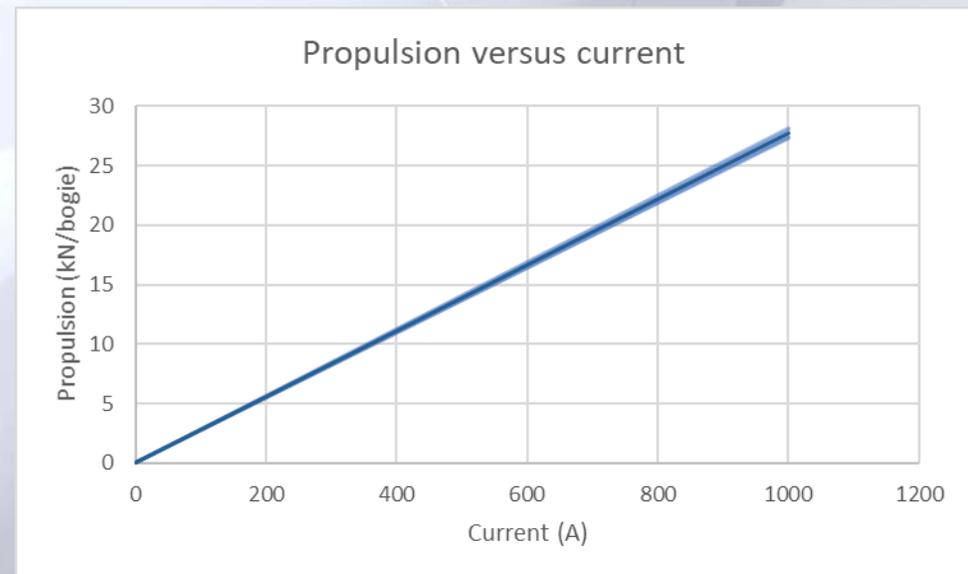
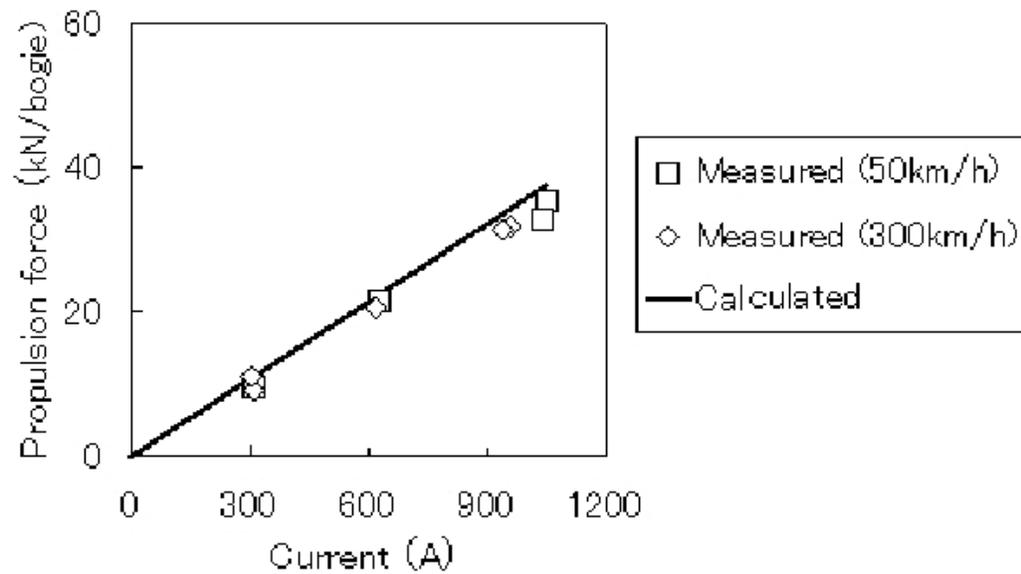
모델링 - 결과



모델링 - 결과



모델링 - 결과

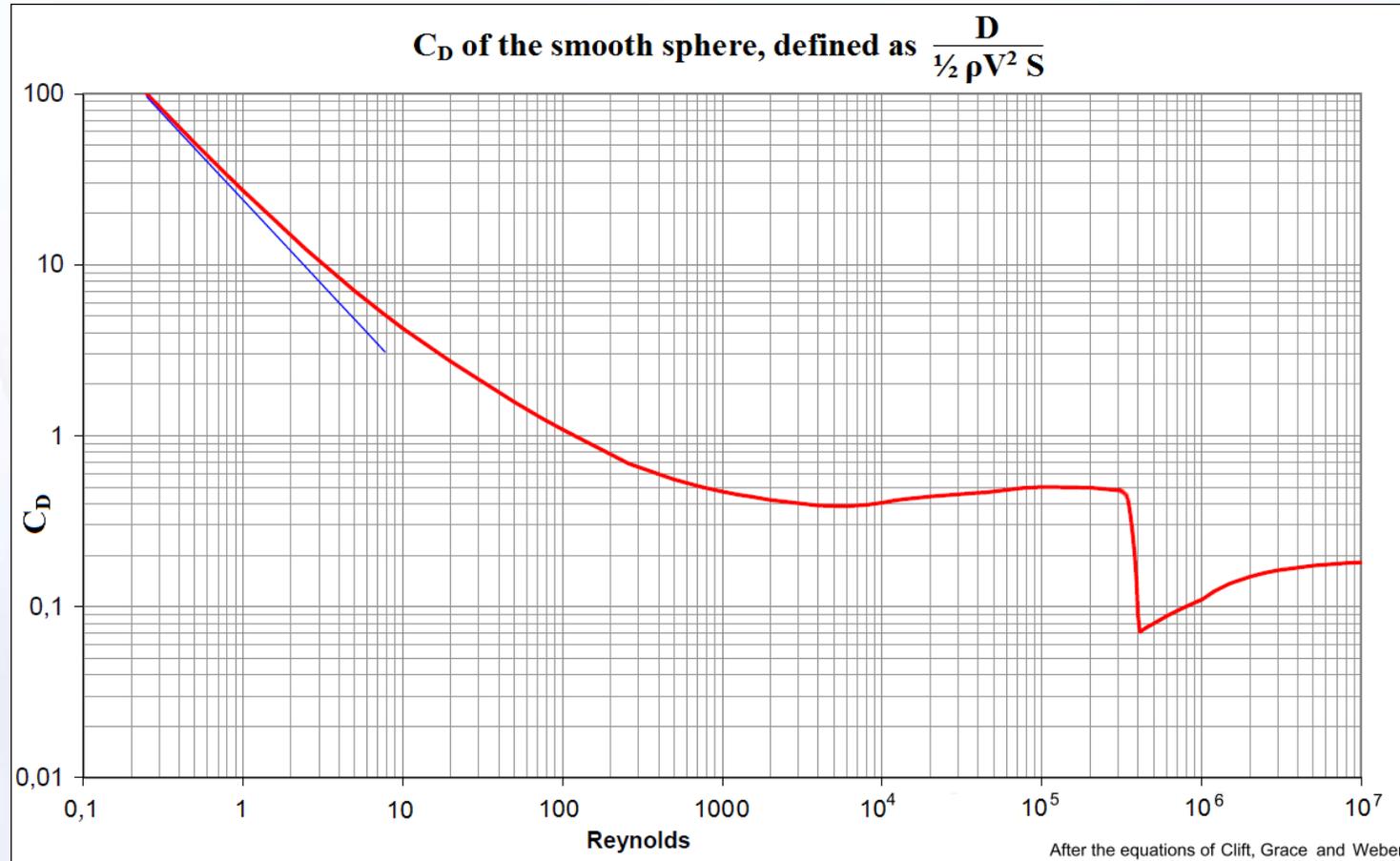


모델링 - 결과

SC current: 500kA	128 km/h	256 km/h	512 km/h
저항력 (kN)	55	28	14
부상력 (kN)	2805	2829	2836
부상력 리플	8.4%	8.3%	8.3%
추진력 (kN/kA)	366	355	366
수직 유효 스프링 상수 (MN/m)	27.1	27.4	27.5
수직 유효 감쇠비	25	25	25
수평 유효 스프링 상수 (MN/m)	143	144	144
수평 유효 감쇠비	84	84	84

※조건: 선로 중앙, 수직변위 3cm, 12량 편성

모델링 - 공기저항

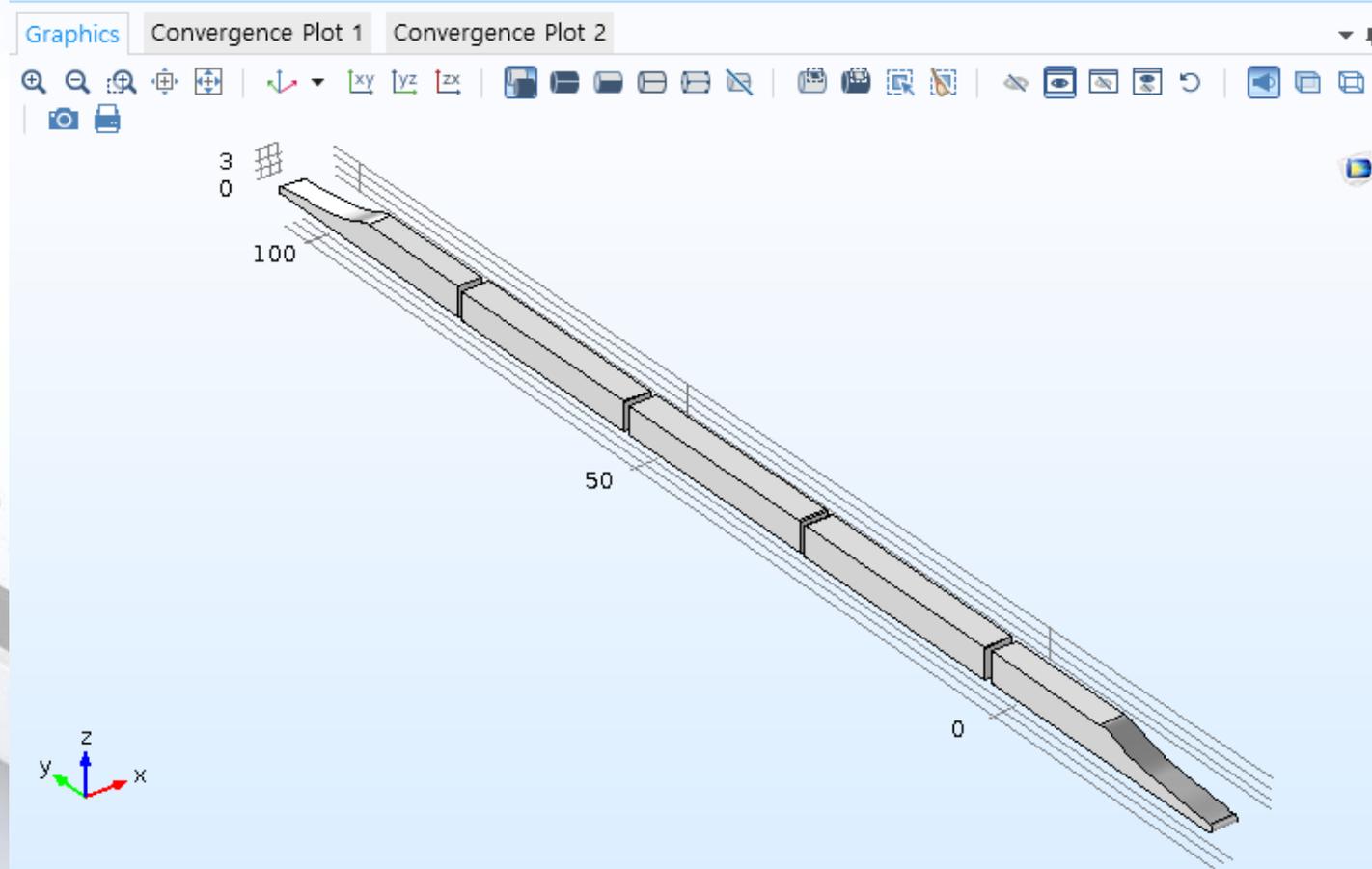


$$Re = \frac{\rho V D}{\mu}$$

$$= \frac{1.2044 * 30 * 3}{1.814 * 10^{-5}}$$

$$\approx 6 * 10^5$$

모델링 - 공기저항



모델링 - 공기저항

The image displays the ANSYS Model Builder interface for a simulation. The main window shows a 3D model of an airfoil with a mesh. The 'Settings' panel is open, showing the 'Rotate' tool configuration. The 'Input' section lists 'sca1', 'mov1', 'copy1', 'copy2', and 'rot2'. The 'Rotation Angle' is set to 270 degrees. The 'Point on Axis of Rotation' is set to (0, 0, 0). The 'Graphics' panel shows two convergence plots. The 'Messages' panel at the bottom displays simulation progress and error messages.

Model Builder

- Materials
- Component 1 (*comp1*)
- Definitions
- Geometry 1
 - Import 1 (*imp1*)
 - Scale 1 (*sca1*)
 - Import 2 (*imp2*)
 - Scale 2 (*sca2*)
 - Move 1 (*mov1*)
 - Copy 1 (*copy1*)
 - Copy 2 (*copy2*)
 - Copy 3 (*copy3*)
 - Rotate 2 (*rot2*)
 - Rotate 1 (*rot1*)
 - Block 1 (*blk1*)
 - Block 2 (*blk2*)
 - Form Union (*fin*)
- Materials
- Turbulent Flow, $k-\epsilon$ (*spf*)
 - Fluid Properties 1
 - Initial Values 1
 - Wall 1
 - Inlet 1
 - Outlet 1
 - Symmetry 1
- Mesh 1

Settings

Rotate

Build Selected Build All Objects

Label: Rotate 1

Input

Input objects:

OFF sca1
mov1

Active
copy1
copy2
rot2

Keep input objects

Rotation Angle

Rotation: 270 deg

Point on Axis of Rotation

x: 0 m
y: 0 m
z: 0 m

Graphics Convergence Plot 1 Convergence Plot 2

Messages Log Progress Table 16

8.85 e-12 AUTO 8.5 e-1 850 e-3 0.85

모델링 - 공기저항

The image shows a CAD software interface with three main panels:

- Model Builder:** A tree view on the left showing the model's structure. It includes a 'Materials' section, 'Component 1 (comp1)' with 'Definitions' and 'Geometry 1'. Under 'Geometry 1', there are several 'Import' and 'Scale' objects, followed by 'Move 1 (mov1)', 'Copy 1 (copy1)', 'Copy 2 (copy2)', 'Copy 3 (copy3)', 'Rotate 2 (rot2)', 'Rotate 1 (rot1)', and 'Block 1 (blk1)'. Below this are 'Materials', 'Turbulent Flow, k-ε (spf)' with 'Fluid Properties 1', 'Initial Values 1', 'Wall 1', 'Inlet 1', 'Outlet 1', and 'Symmetry 1', and finally 'Mesh 1'.
- Settings:** A central panel for configuring the selected 'Block 1'. It shows 'Object Type' as 'Solid' and 'Size and Shape' parameters: Width: 10 m, Depth: 250 m, Height: 20 m. The 'Position' section shows 'Base' as 'Center' and coordinates: x: 5 m, y: 60 m, z: 9.5 m. The 'Axis' section shows 'Axis type' as 'Z-axis'.
- Graphics:** A 3D view on the right showing a rectangular block. The block is oriented along the Z-axis. Dimensions are labeled: width is 10, depth is 100, and height is 15. A coordinate system with X, Y, and Z axes is visible at the bottom left of the graphics area.

At the bottom of the interface, there is a 'Messages' panel with tabs for 'Log', 'Progress', and 'Table 16'. The 'Progress' tab is active, showing a progress bar and numerical values: 8.89, 8.5, 850, 850, 0.85.

모델링 - 공기저항

The image displays a CAD software interface with three main panels:

- Model Builder:** Shows a hierarchical tree of the model. Under "Component 1 (comp1)", "Geometry 1" includes "Import 1 (imp1)", "Scale 1 (sca1)", "Import 2 (imp2)", "Scale 2 (sca2)", "Move 1 (mov1)", "Copy 1 (copy1)", "Copy 2 (copy2)", "Copy 3 (copy3)", "Rotate 2 (rot2)", "Rotate 1 (rot1)", "Block 1 (blk1)", "Block 2 (blk2)", and "Form Union (fin)". Under "Materials", "Turbulent Flow, k-ε (spf)" includes "Fluid Properties 1", "Initial Values 1", "Wall 1", "Inlet 1", "Outlet 1", and "Symmetry 1".
- Settings:** Shows the configuration for the "Inlet" boundary. The "Boundary Selection" is set to "Manual" with a value of "35". The "Boundary Condition" is set to "Velocity". Under "Velocity", "Normal inflow velocity" is selected. The velocity value is U_n vel m/s.
- Graphics:** Shows a 3D model of a duct with an airfoil inside. The duct has a length of 100 and a height of 15. A coordinate system (x, y, z) is shown at the bottom left. The "Convergence Plot 1" and "Convergence Plot 2" tabs are visible at the top.

모델링 - 공기저항

The image displays the Ansys Model Builder software interface for a computational fluid dynamics (CFD) simulation. The main window shows a 3D model of an airfoil with a rectangular computational domain around it. The domain is defined by a top surface at $z=15$, a bottom surface at $z=0$, and a length of $x=100$. The airfoil is positioned at the bottom of the domain, with its leading edge at $x=0$ and its trailing edge at $x=10$. The y -axis is perpendicular to the xz -plane.

The left-hand pane shows the project tree with the following structure:

- Materials
 - Component 1 (*comp1*)
 - Definitions
 - Geometry 1
 - Import 1 (*imp1*)
 - Scale 1 (*sca1*)
 - Import 2 (*imp2*)
 - Scale 2 (*sca2*)
 - Move 1 (*mov1*)
 - Copy 1 (*copy1*)
 - Copy 2 (*copy2*)
 - Copy 3 (*copy3*)
 - Rotate 2 (*rot2*)
 - Rotate 1 (*rot1*)
 - Block 1 (*blk1*)
 - Block 2 (*blk2*)
 - Form Union (*fin*)
- Materials
 - Turbulent Flow, $k-\epsilon$ (*spt*)
 - Fluid Properties 1
 - Initial Values 1
 - Wall 1
 - Inlet 1
 - Outlet 1
 - Symmetry 1

The central Settings panel is for the 'Outlet' boundary condition. It shows the following configuration:

- Label: Outlet 1
- Boundary Selection: Manual
- Selection: 71
- Active:
- Override and Contribution:
- Equation:
- Boundary Condition: Pressure
- Pressure Conditions:
 - Pressure: p_0 0 Pa

The right-hand Graphics window shows the 3D model and two convergence plots. The bottom status bar displays the following information:

- Messages
- Log
- Progress
- Table 16
- 8.85 e-12
- AUTO
- 8.5 e-1
- 850 e-3
- 0.85

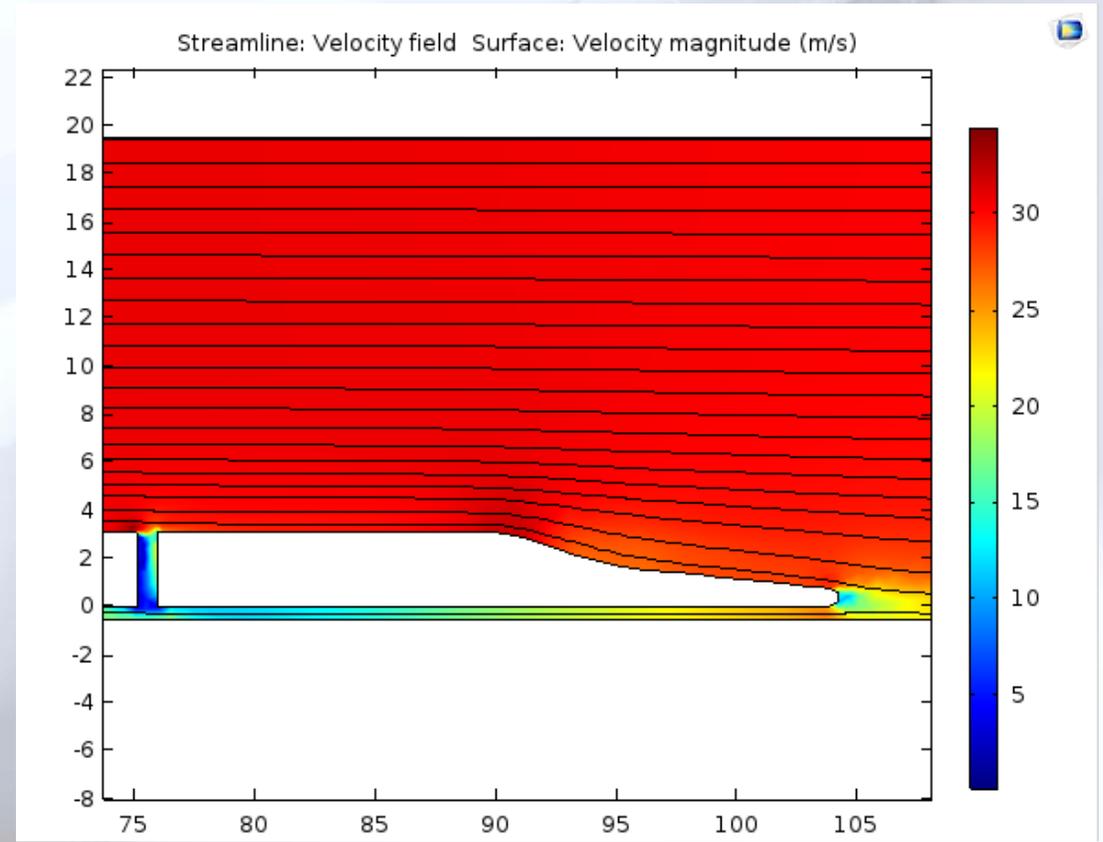
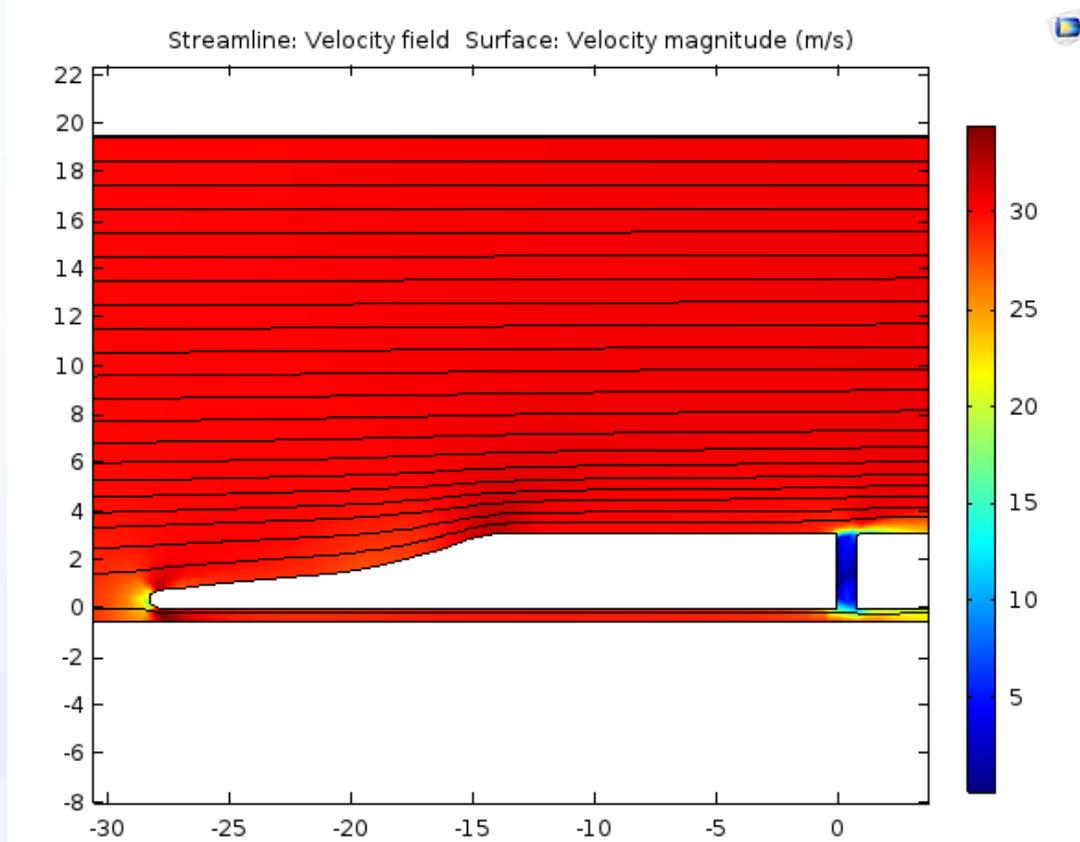
모델링 - 공기저항

The image displays a CAD software interface for modeling an airfoil. The main window is divided into three primary sections:

- Model Builder (Left):** A tree view showing the model's structure. It includes a 'Materials' section, 'Component 1 (comp1)' with 'Definitions' and 'Geometry 1' (containing various import, scale, move, copy, and rotate operations), and another 'Materials' section with 'Turbulent Flow, k-ε (spf)' containing 'Fluid Properties 1', 'Initial Values 1', 'Wall 1', 'Inlet 1', 'Outlet 1', and 'Symmetry 1'.
- Settings (Middle):** A panel for the 'Symmetry' boundary condition. It shows 'Label: Symmetry 1', 'Boundary Selection' with 'Selection: Manual', and a list of selected faces: 34, 37, and 77. There are also sections for 'Override and Contribution' and 'Equation'.
- Graphics (Right):** A 3D view of the airfoil model. The model is shown in a blue color. A coordinate system (x, y, z) is visible at the bottom left. The airfoil is oriented along the x-axis, with a length of 100 units. The y-axis ranges from 0 to 15, and the z-axis ranges from 0 to 10. The model is shown with a symmetry plane at the top and bottom.

At the bottom of the interface, there is a 'Messages' and 'Log' section, and a 'Progress' section showing 'Table 16' with various numerical values and a progress bar.

모델링 - 공기저항



모델링 - 공기저항

Surface Integration
= Evaluate ▾

Label: shinkansen_stress_y

▼ Data

Data set: Study 1/Solution 1 (st) [icon]

Selection

Selection: Manual ▾

39
 40
Active 41
 42
 43
 66

▼ Expression + ▾ ▶ ▾

Expression:
$$-spf.T_stressy^4/(spf.rho*(8.40875[m^2])^4*vi$$

Unit:
1 ▾

Description:
drag_coeff(head&tail)

Messages Log Progress **Table 16**

drag_coeff(head&tail) (1)
0.17838636215449405

모델링 - 공기저항

Surface Integration

▬ Evaluate ▾

Label: shinkansen_stress_y_mid

Data

Data set: Study 1/Solution 1 (sc)

Selection

Selection: Manual



45

46

Active

47

48

49

50

Expression

Expression:

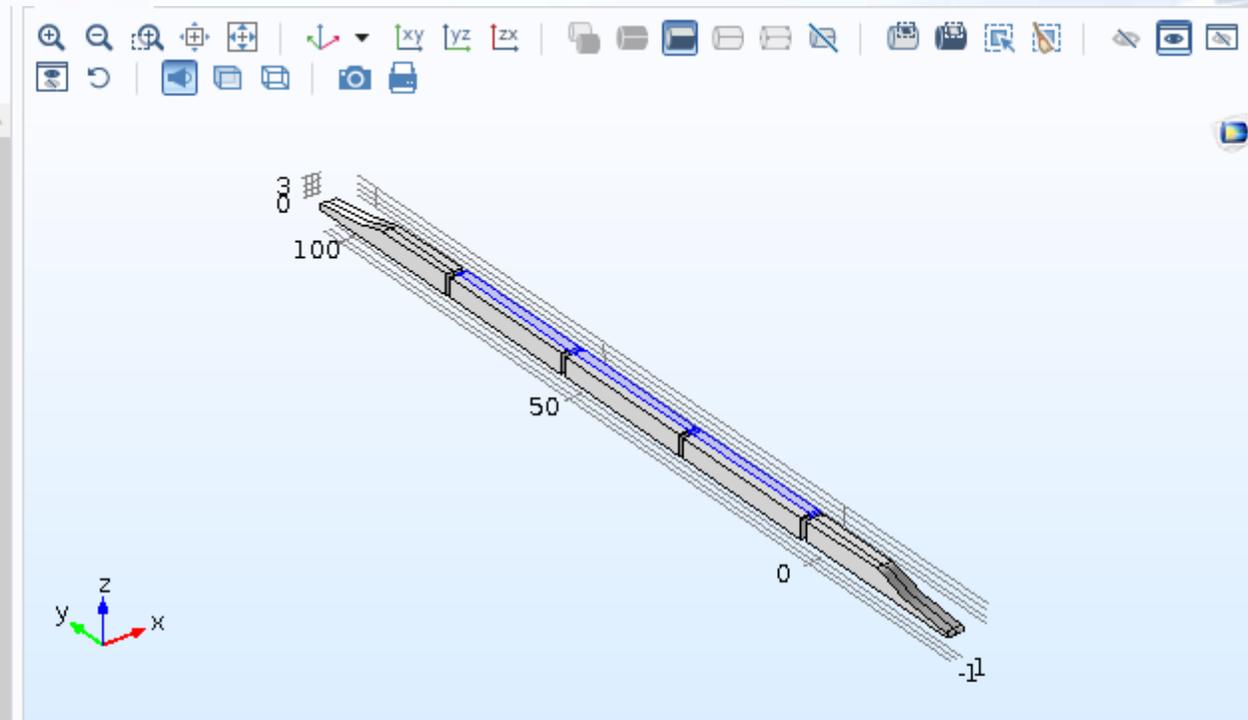
$$-\text{spf.T_stressy}^4/(\text{spf.rho}*(8.40875[\text{m}^2])^*v)$$

Unit:

1

Description:

drag_coeff(mid3)



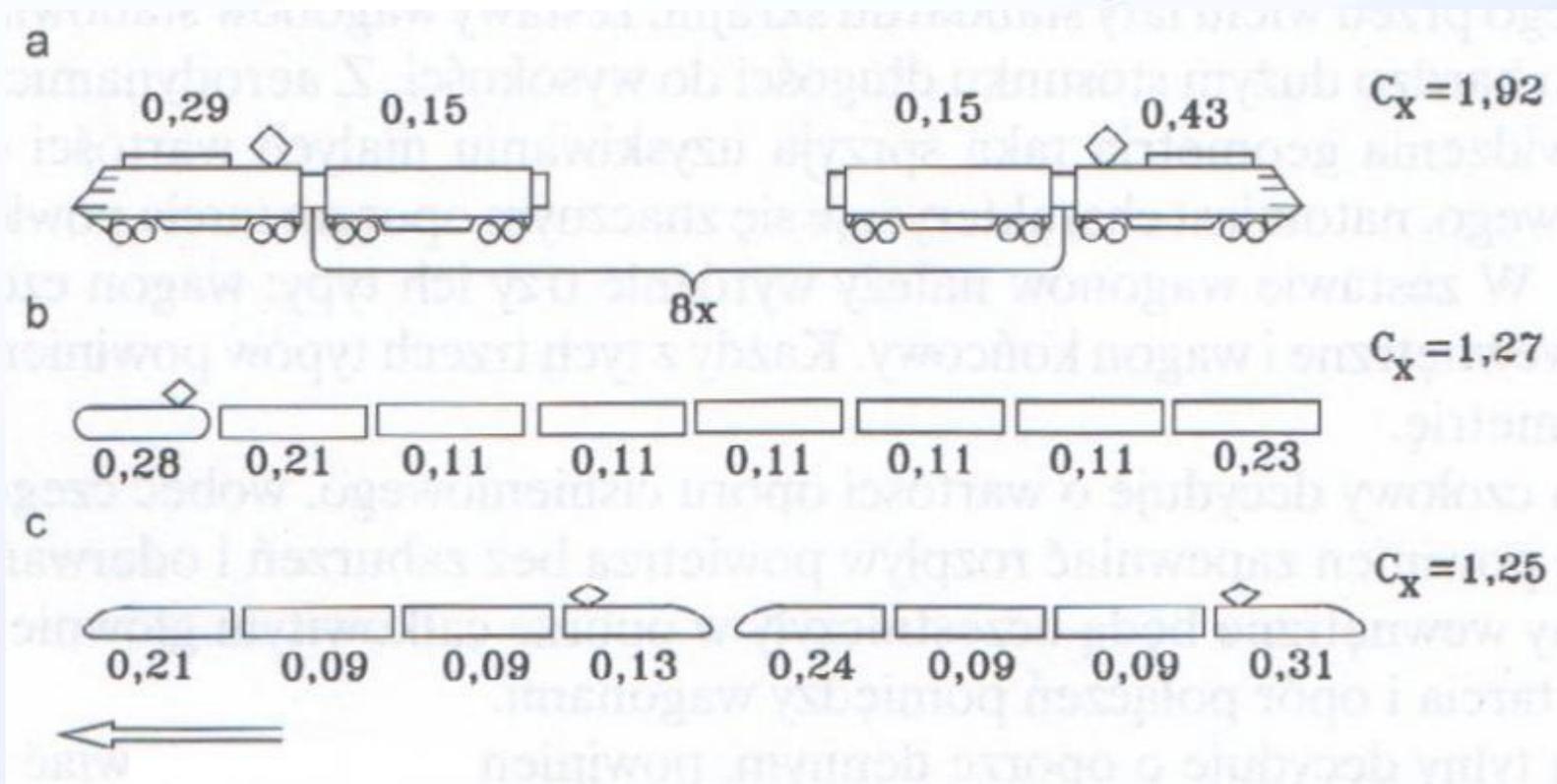
Messages Log Progress Table 16

8.85 e-12 AUTO 8.5 e-1 850 e-3 0.85

drag_coeff(head&tail) (1)

0.17838636215449405

모델링 - 공기저항



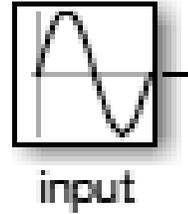
drag_coeff(head&tail) (1)
0.17838636215449405

drag_coeff(mid3) (1)
0.38037568450711035

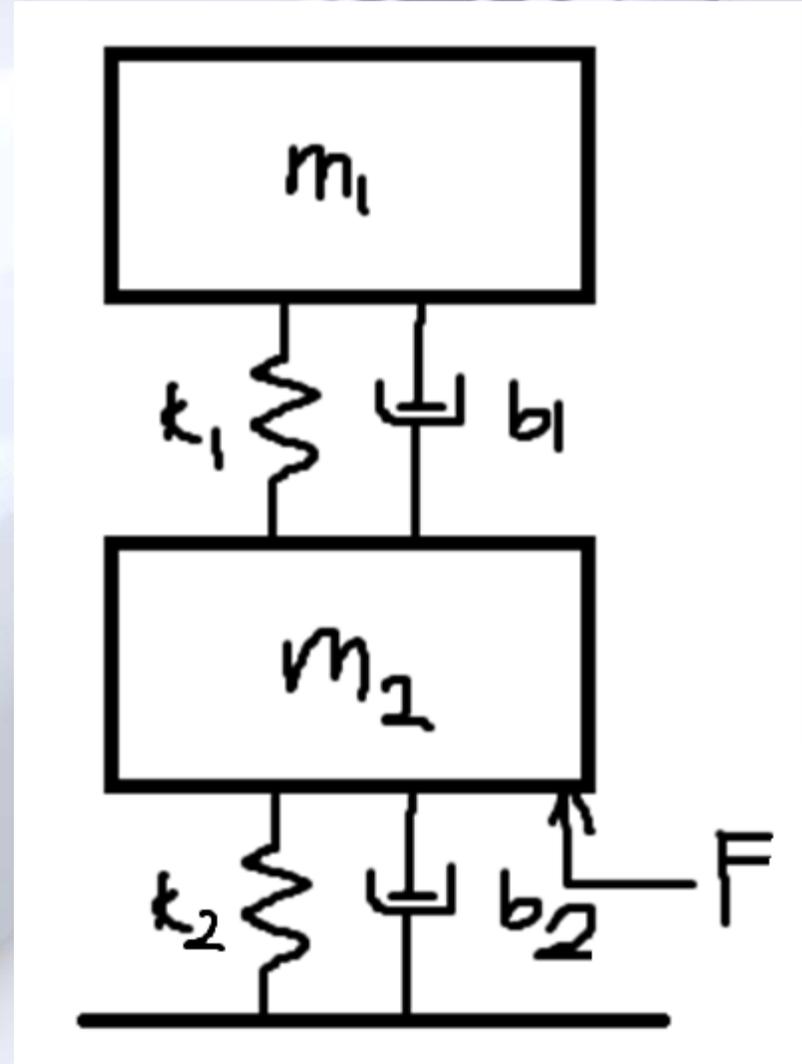
$$C_d \approx 1.572$$

1/52 모델

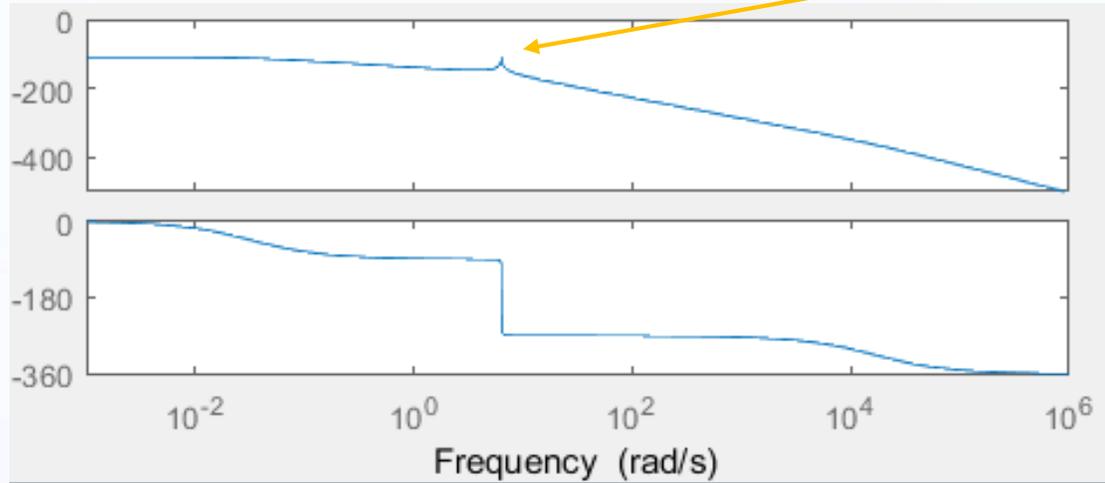
- 입력 = 부상력 ripple
- $F = 330000/52 * \cos(\omega * t)$
- $\omega = 2\pi * f = v * \frac{1000}{3600} / 0.45(\text{rad/sec})$



- 차량의 무게(m_1) = 270ton/52
- 대차의 무게(m_2) = 30ton/52
- $k_2 = 27000k/52$
- $b_2 = 500000k/52$



Bode plot



System: sys
I/O: In(1) to Out(2)
Frequency (rad/s): 6.32
Magnitude (dB): -106

$$k1 = m1 * 40 / 52$$

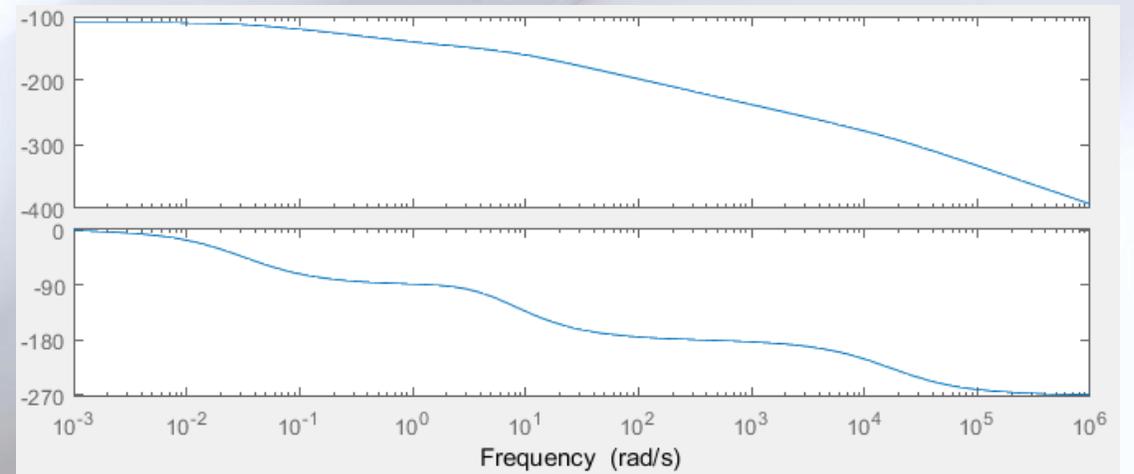
$$b1 = 2 * m1 * \sqrt{k1 / m1} * 0 / 52$$

$$k1 = m1 * 40 / 52$$

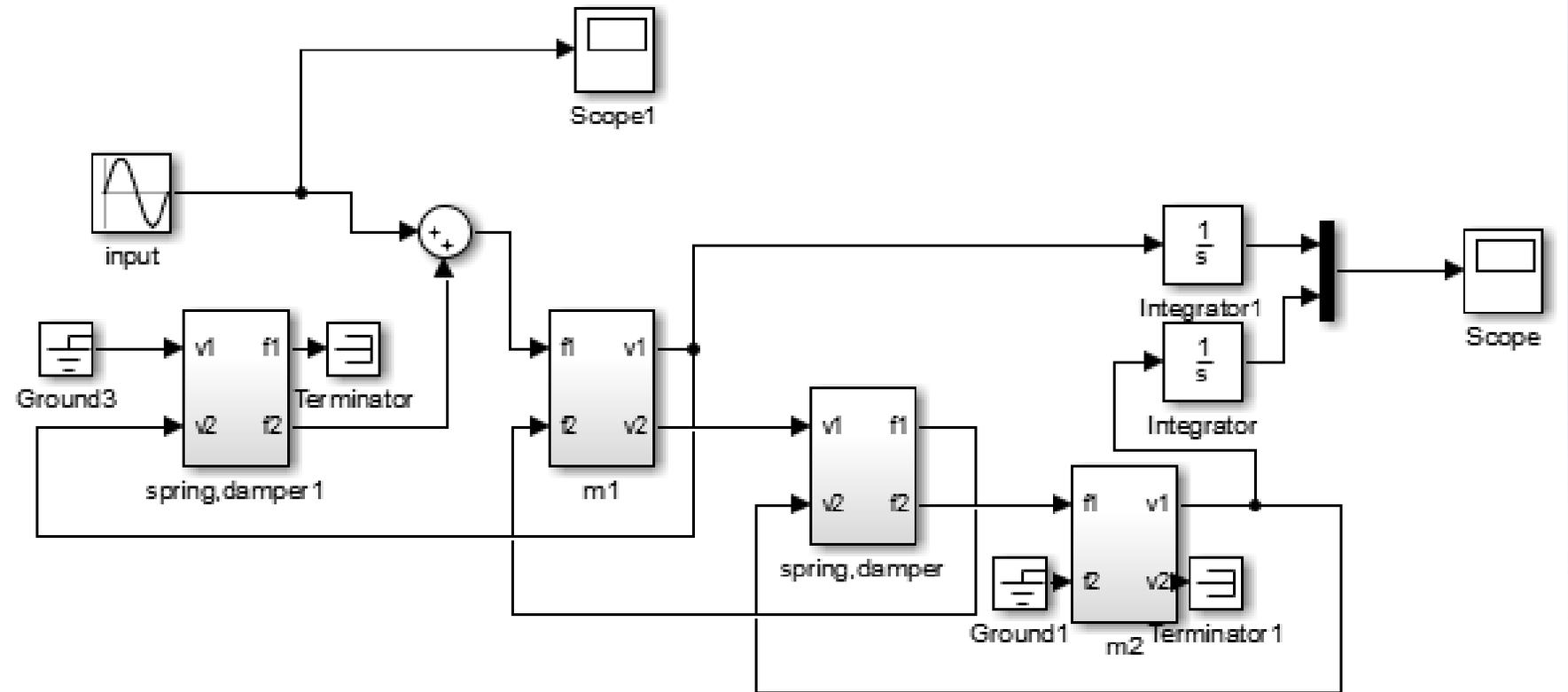
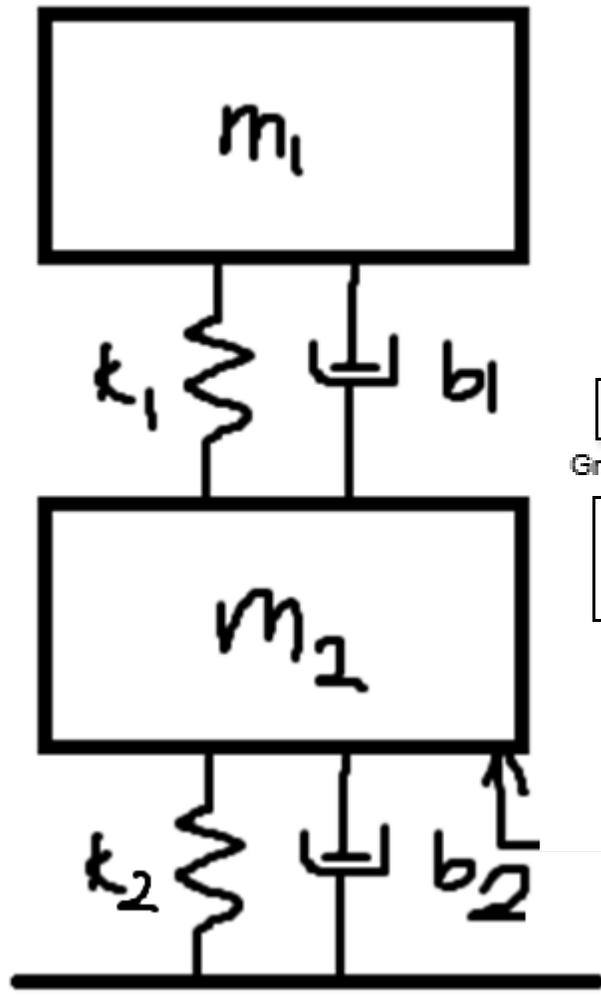
$$b1 = 2 * m1 * \sqrt{k1 / m1} * 1 / 52$$

$$\zeta = \text{damping ratio} = \frac{\text{actual damping value}}{\text{critical damping value}} = \frac{b}{2\sqrt{km}}$$

Critically damped ($\zeta = 1$)

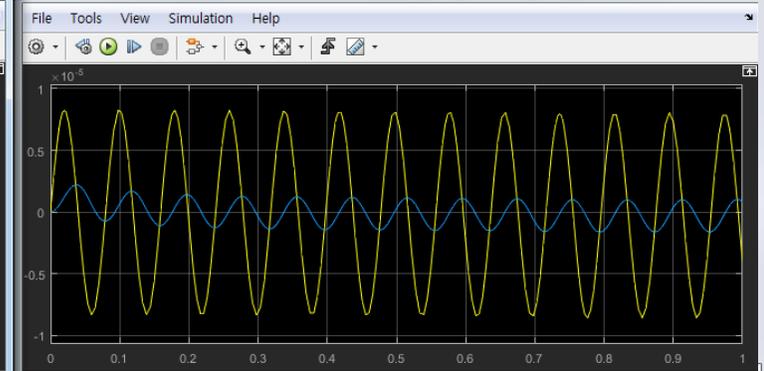
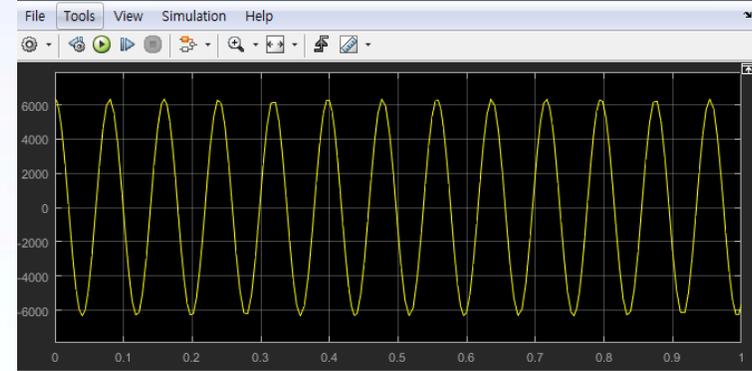


Simulink



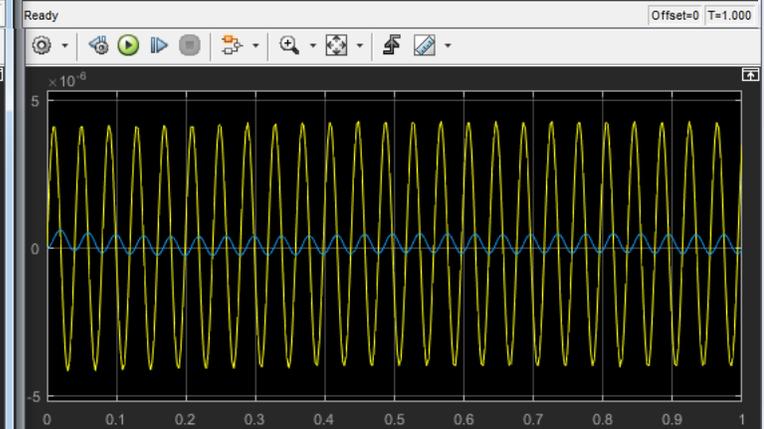
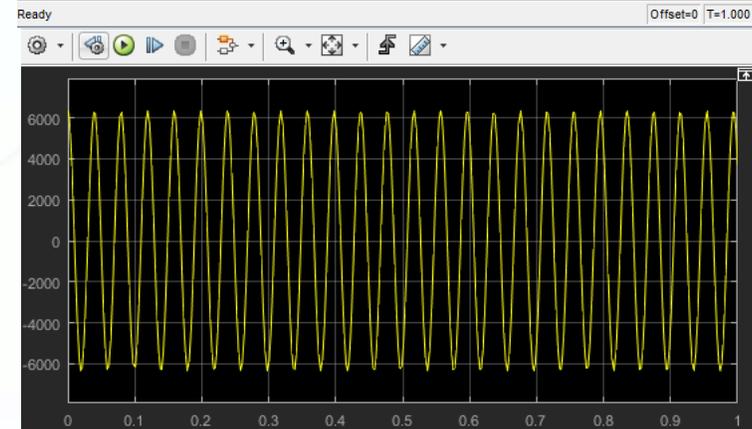
• $V = 128$

대차: $7.5 \times 10^{-6} \text{m}$
차체: $2.5 \times 10^{-6} \text{m}$



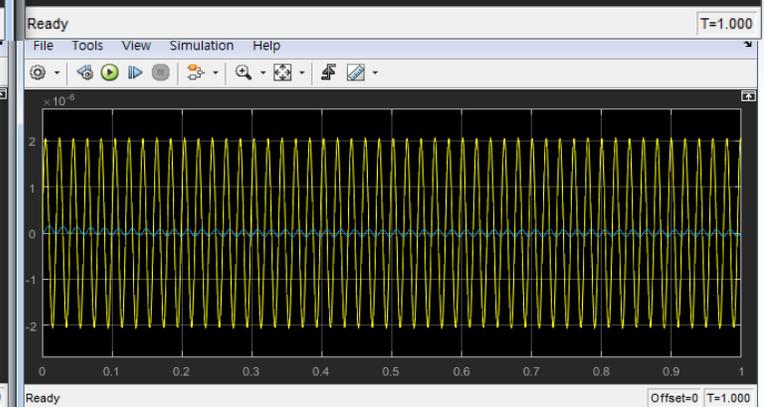
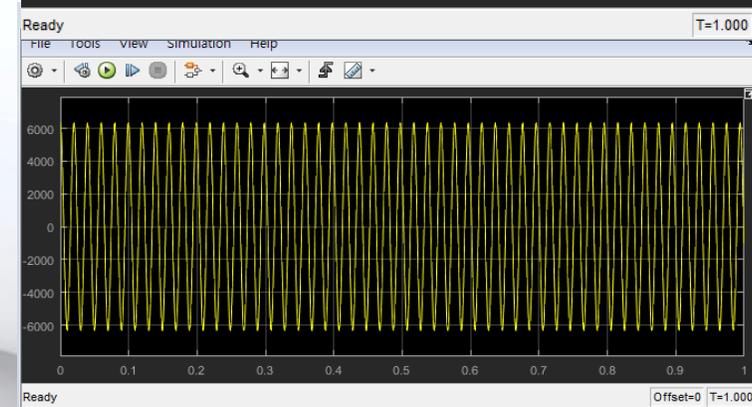
• $V = 256$

대차: $4 \times 10^{-6} \text{m}$
차체: $0.5 \times 10^{-6} \text{m}$

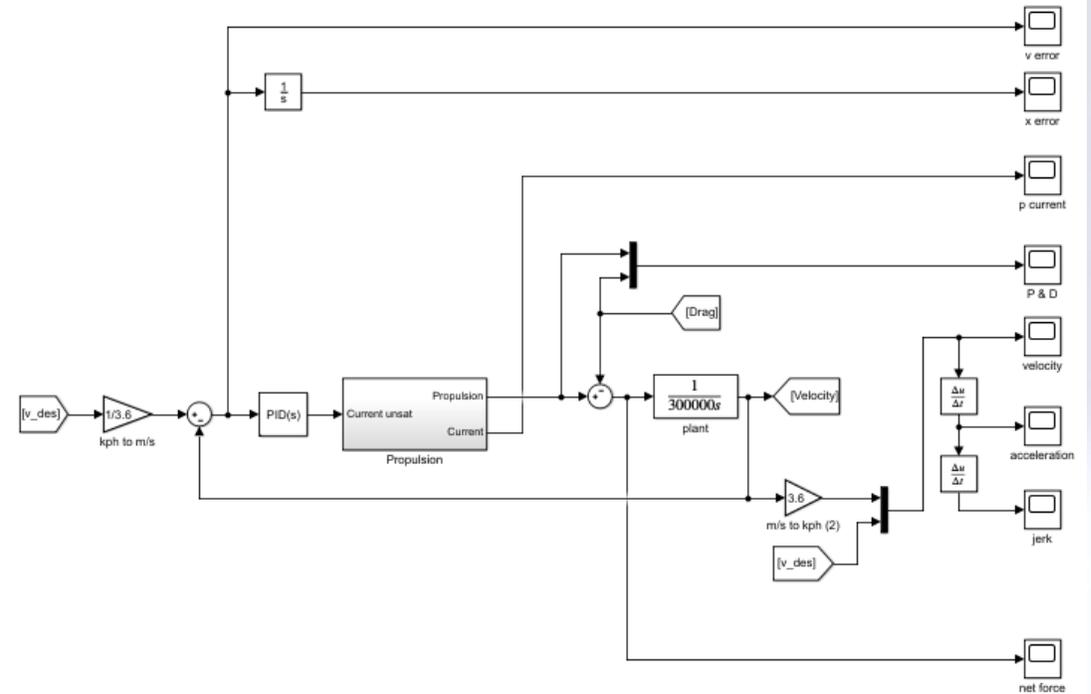
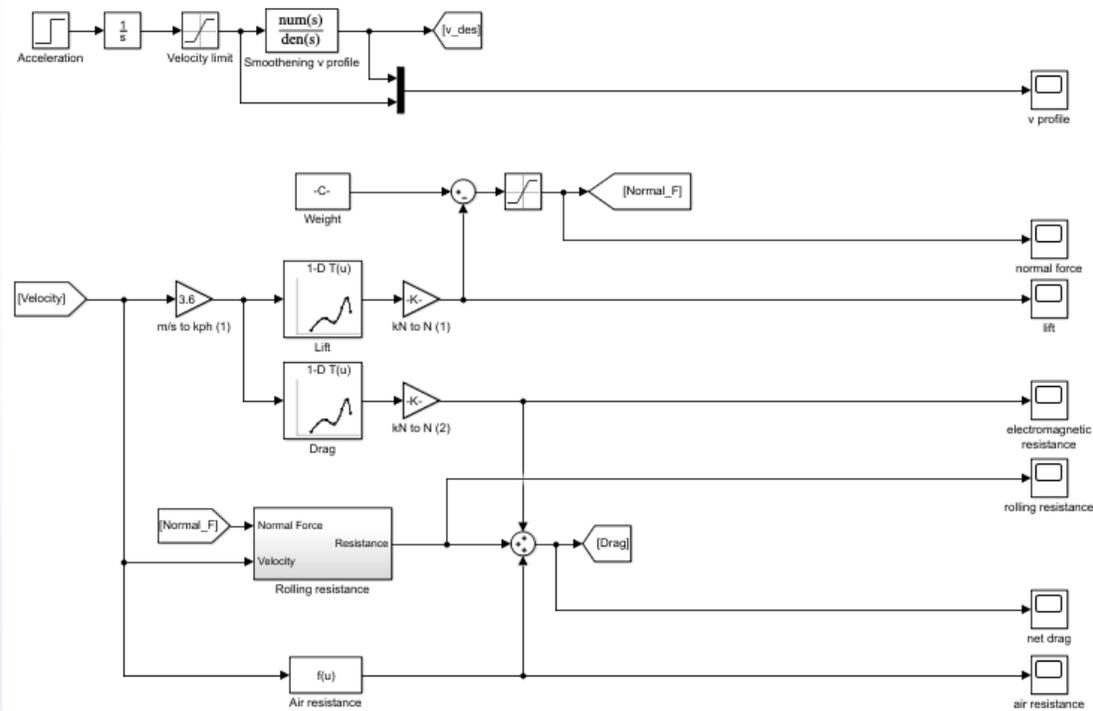


• $V = 512$

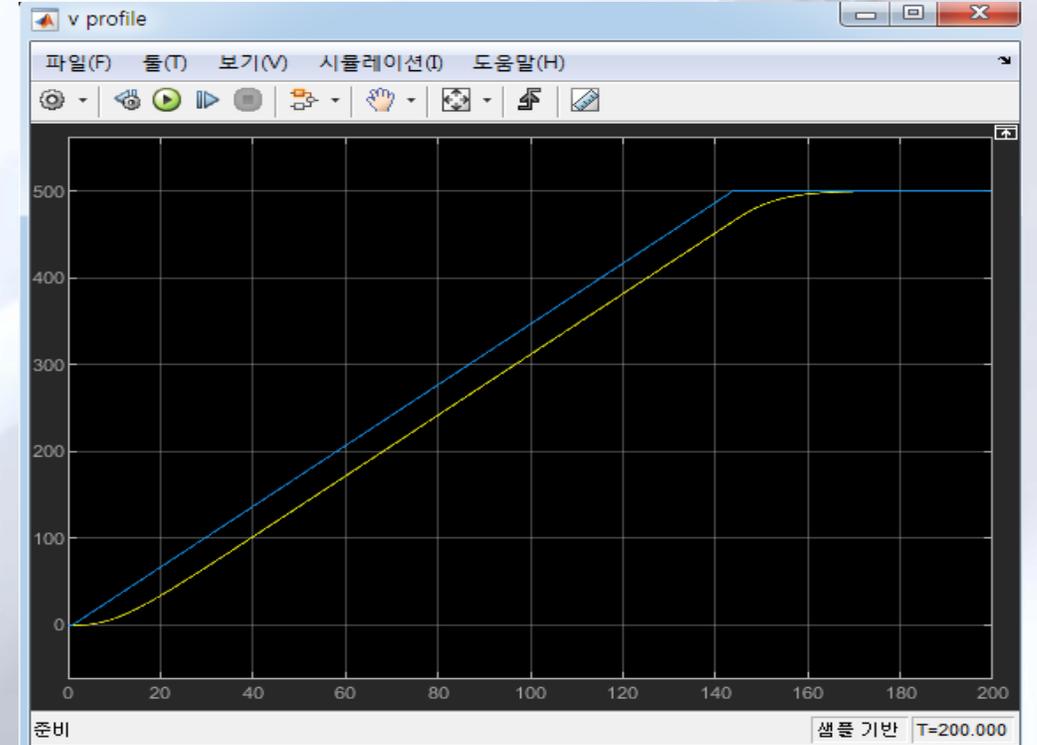
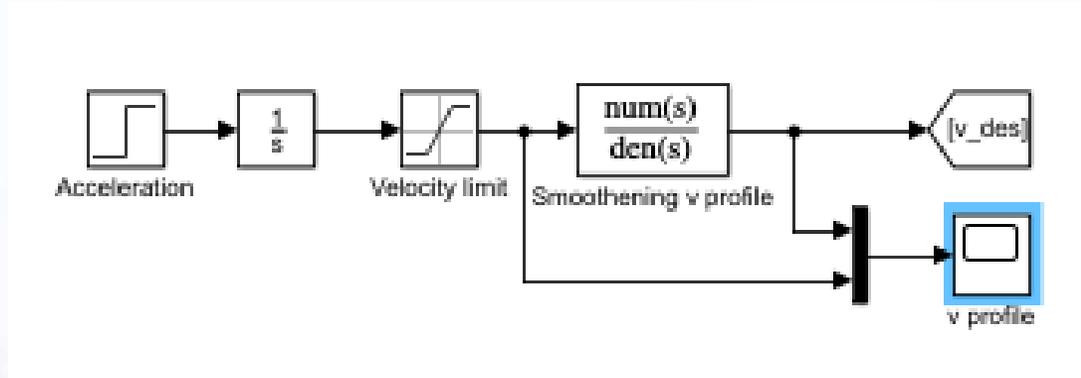
대차: $2 \times 10^{-6} \text{m}$
차체: $0.1 \times 10^{-6} \text{m}$



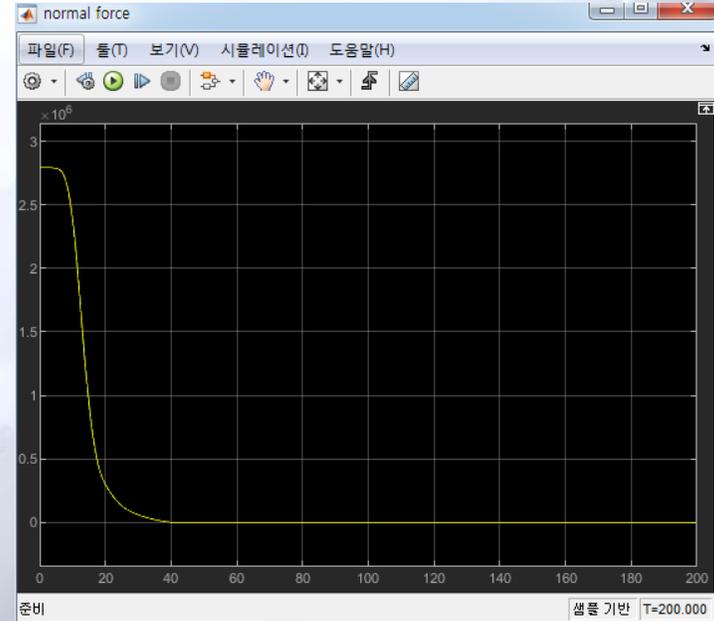
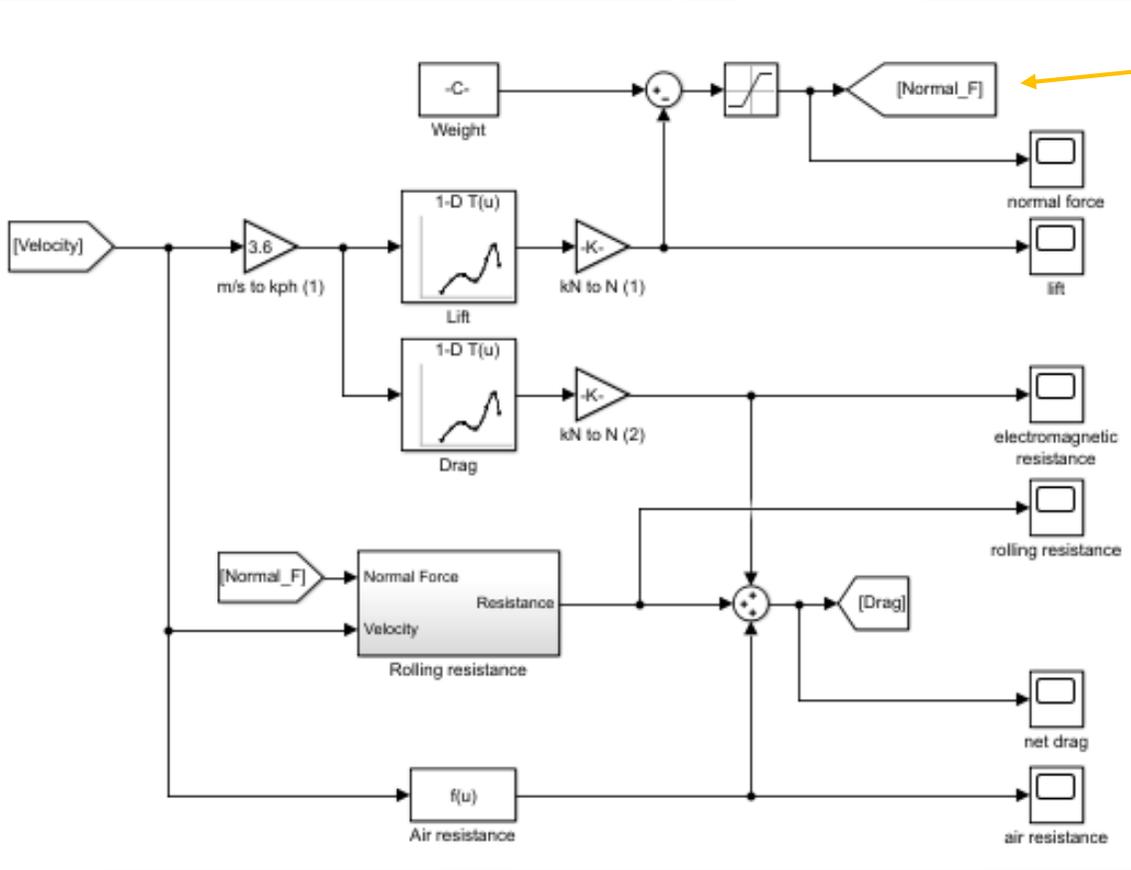
Complete Design



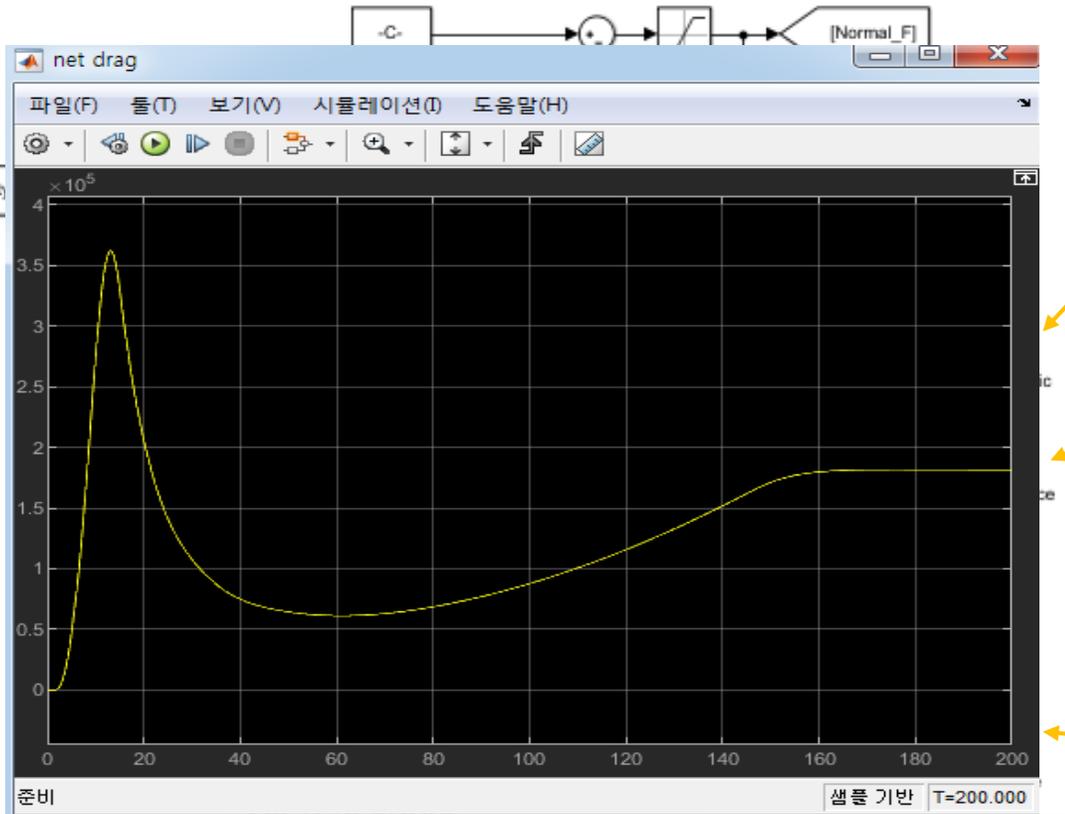
Desired velocity



수직항력



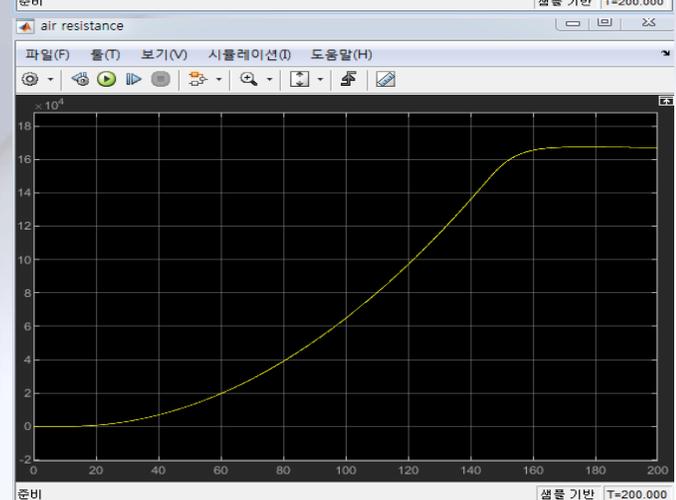
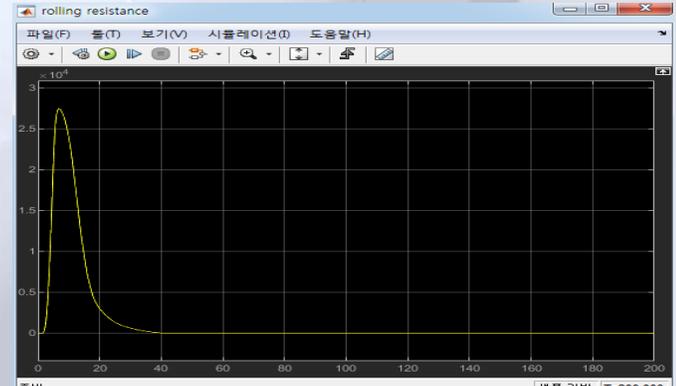
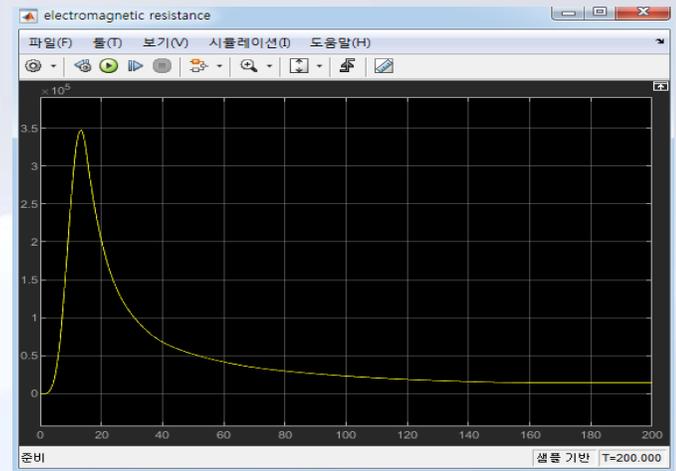
저항력



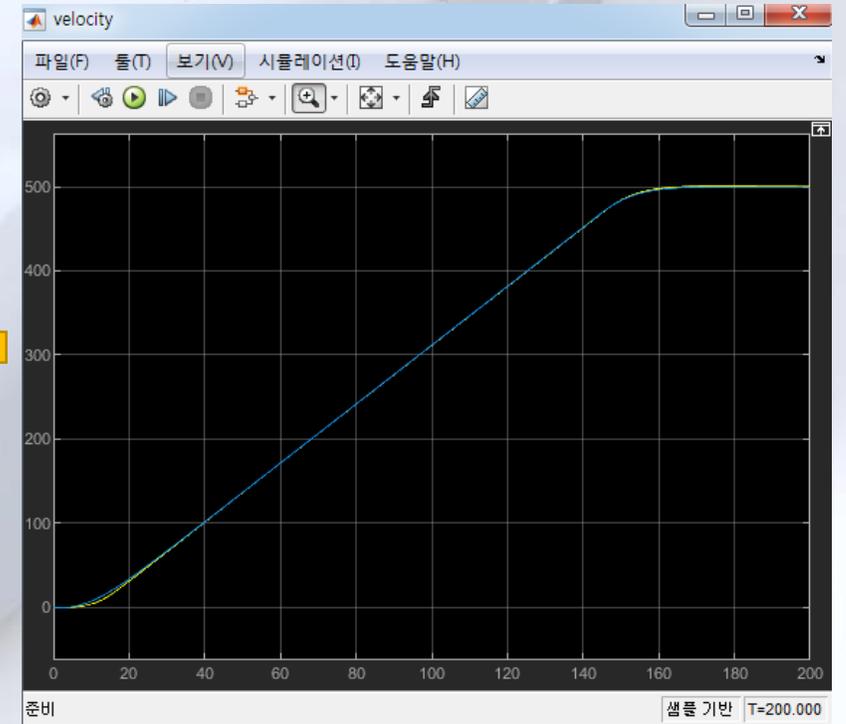
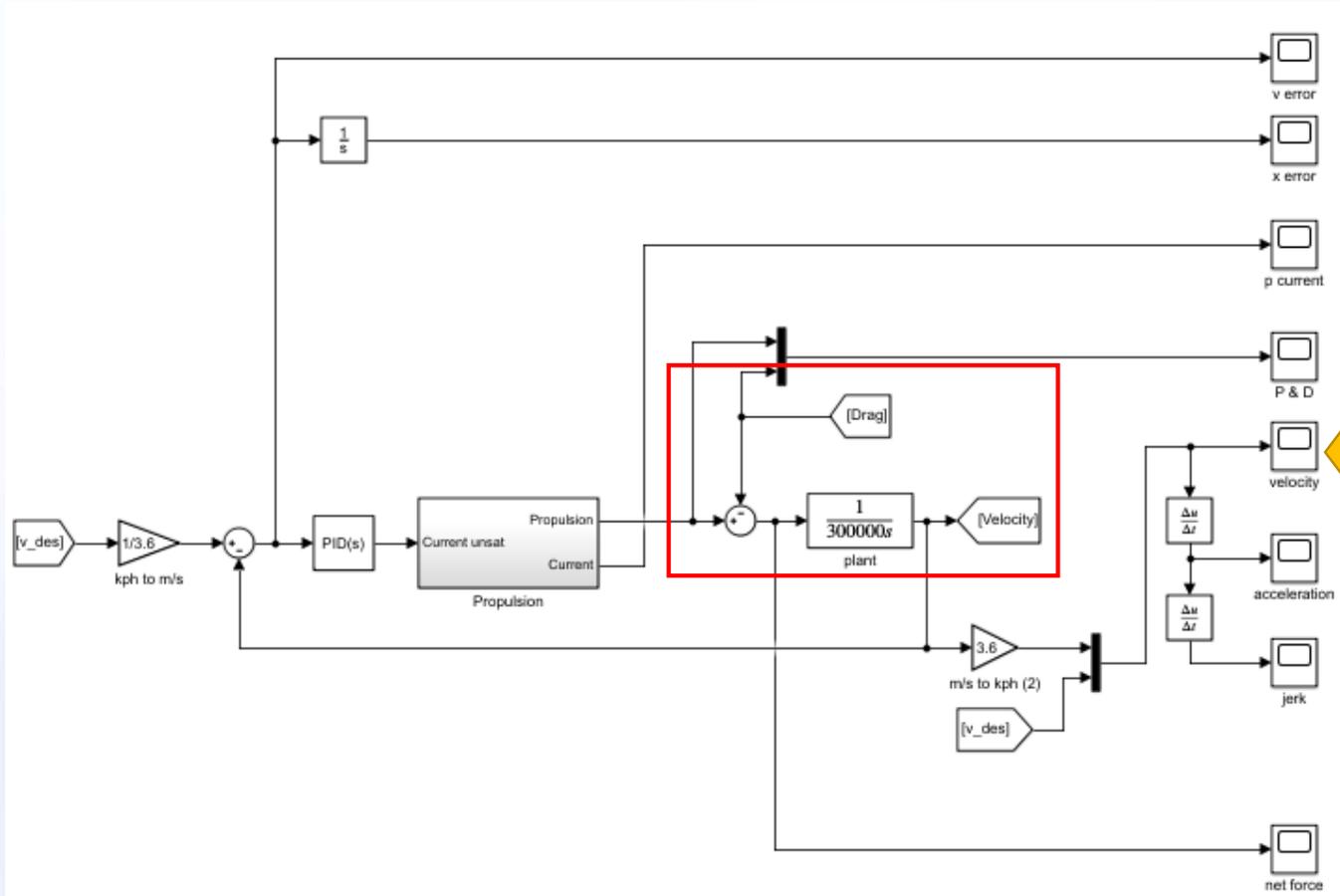
$$F_{air} = \frac{1}{2} C_d A_{fr} \rho_{air} V_{veh}^2$$

Rolling resistance

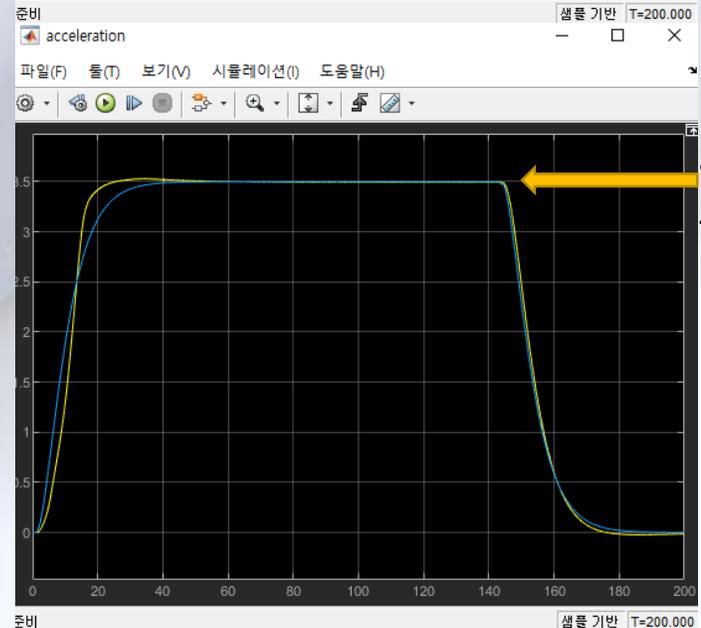
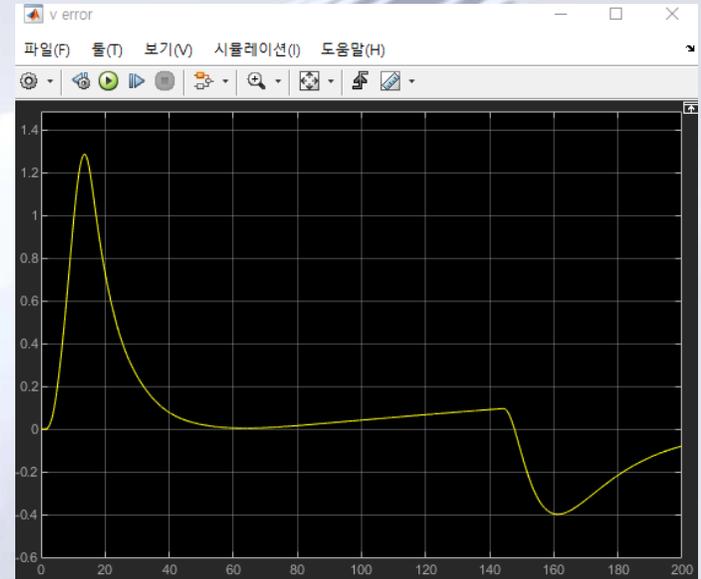
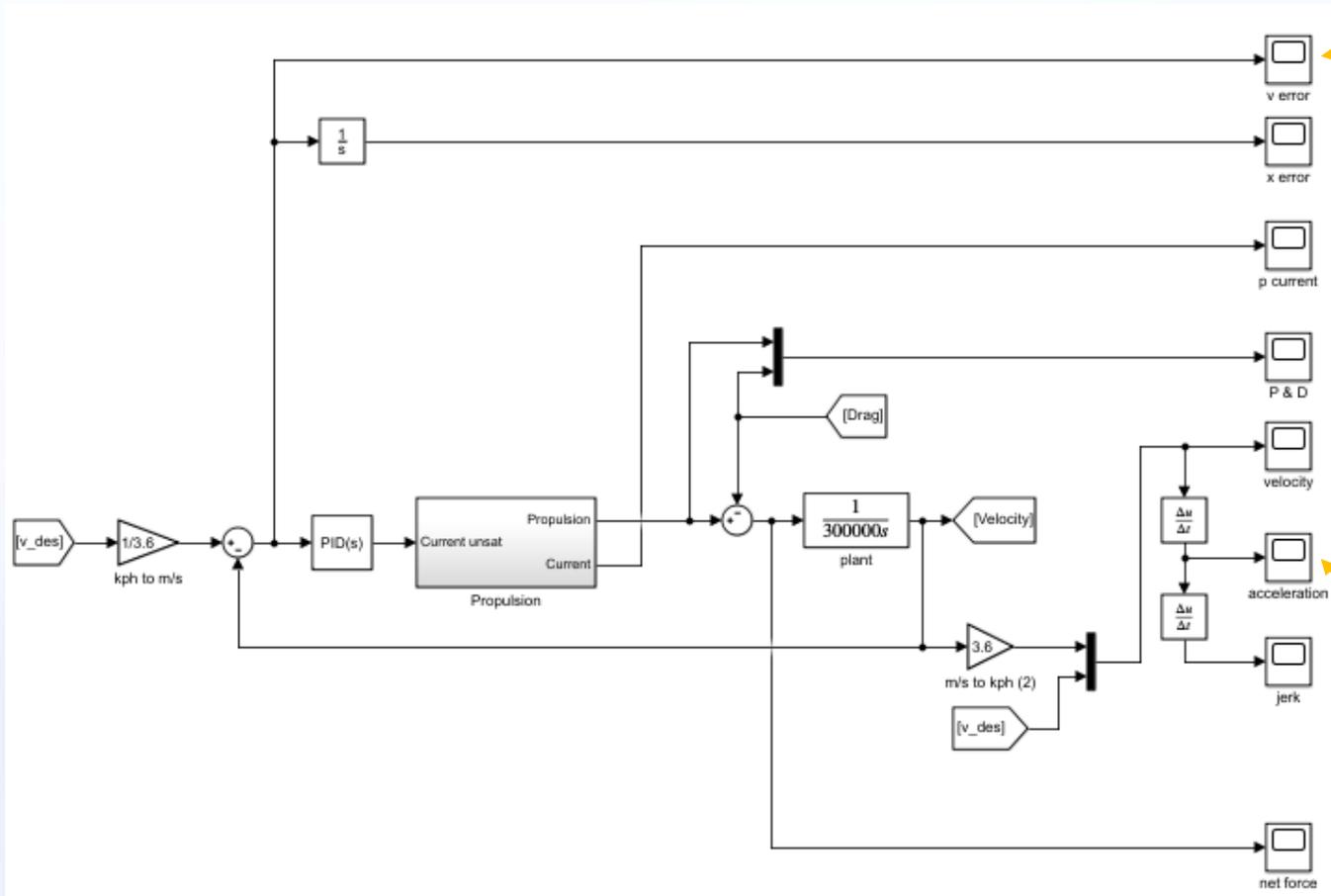
$$F_{roll} = \mu_r m_{body} g$$



Velocity



Error



500km/h
도달



Q&A

참고자료

- 超電導リニアの原理
 - <http://linear-chuo-shinkansen.jr-central.co.jp/about/>
- 超電導磁気浮上式鉄道の地上コイル及びその給電方式
 - <https://astamuse.com/ja/published/JP/No/1995211545>
- リニアモーターカーのコイル装置
 - <https://astamuse.com/ja/published/JP/No/2000134721>
- 推進浮上案内兼用地上コイル及びその配線方法
 - <https://astamuse.com/ja/published/JP/No/2008236936>
- PLG方式地上コイルのケーブル配線施工性検証
 - <https://bunken.rtri.or.jp/PDF/cdroms1/0001/2012/0001003568.pdf>

참고자료

- Development of the Ground Coil for Practical Use by the Combined Propulsion , Levitation and Guidance System
 - <https://pdfs.semanticscholar.org/f316/3148e34e5a15d0f3340a021f1a8298a12af2.pdf>
- Electrodynamic suspension
 - https://en.wikipedia.org/wiki/Electrodynamic_suspension
- Gackenholtz L., *Ergebnisse neuerer Untersuchungen zum Luftwiderstand von Fahrzeugen in Zugverband*, Elektrische Bahnen, Heft 12/42, 1971.