Aeroelasticity and Flight Dynamics Simulation Program : Level Flight Performance Comparison

Jaehyun Jin* (Professor, Sunchon National University, Korea)

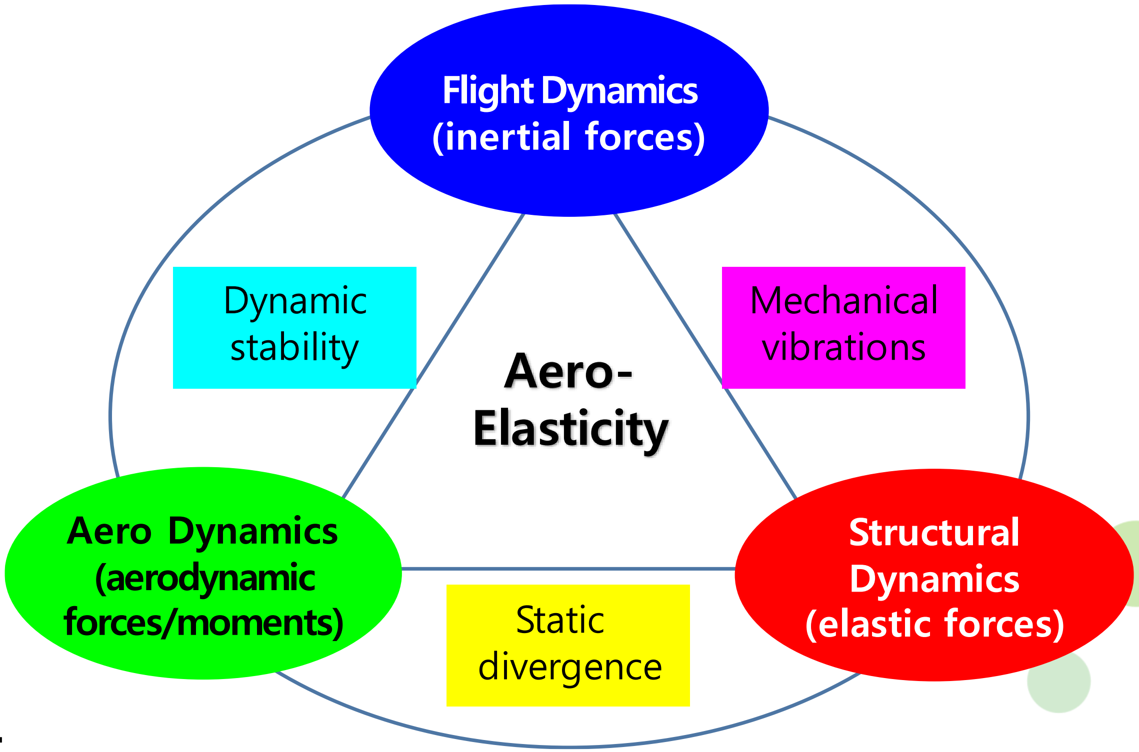
Seung-Kil Paek (Senior Researcher, Korea Aerospace Research Institute)

Joongyong Park (Senior Researcher, Korea Aerospace Research Institute)

Contents

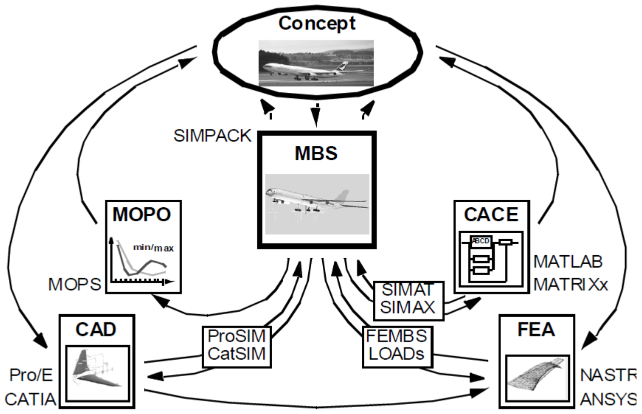
Introduction

- Aero-Elasticity …
  - the aircraft behaviors affected by forces from different sources.
- For high performance, lightweight aircraft
  - Aero-Elasticity can be one of dominant factors to determine or to limit flight performances.
- For the accurate analysis
  - An integrated simulation program is necessary: flight dynamics, aero dynamics, structural dynamics.

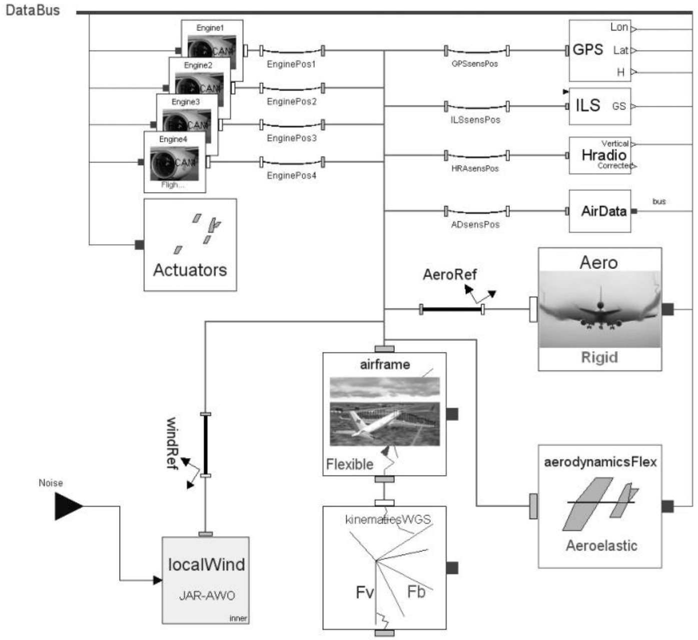


- Purposes of the study …
  - To develop the integrated simulation program
  - Multi-body dynamics simulation technique

- Previous Studies
  - Spieck (2005), Looye (2008)
  - Motivations of this research

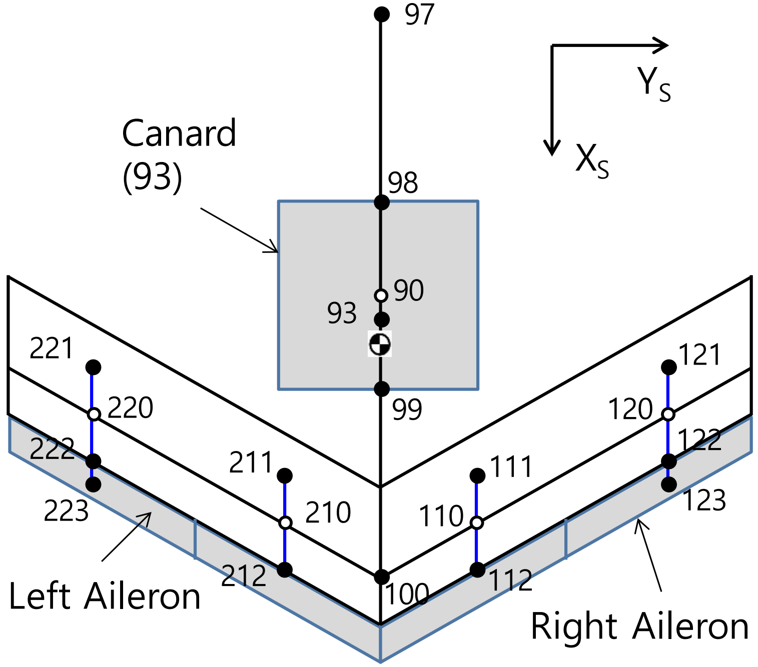


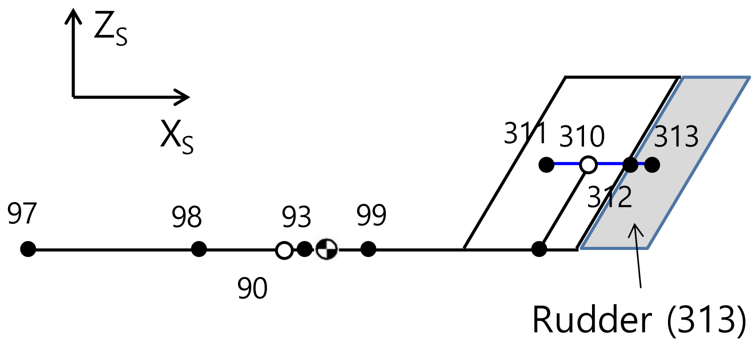
Spieck (2005)



Looye (2008)

- Example Aircraft – ZAERO Example
  - Forward swept wing configuration





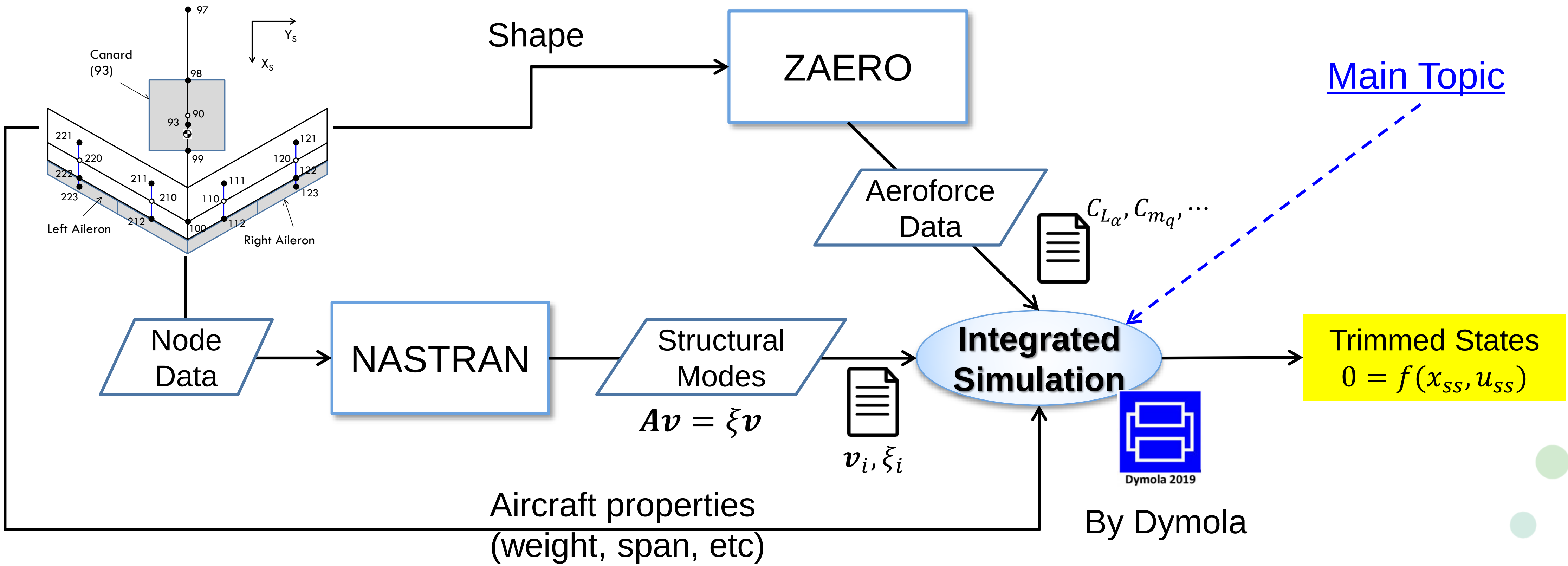
Node information

Node	Wi (lbf)	Xs (ft)	Ys (ft)	Zs (ft)	Node	Wi (lbf)	Xs (ft)	Ys (ft)	Zs (ft)
CG	-	17.380	0	0.046	**211**	600	24.61	-5	0
90	-	15	0	0	**212**	400	29.61	-5	0
93	50	16.25	0	0	**220**	-	21.34	-15	0
97	3000	0	0	0	**221**	600	18.84	-15	0
98	3000	10	0	0	**222**	400	23.84	-15	0
99	3000	20	0	0	**223**	50	25.084	-15	0
100	3000	30	0	0	**310**	-	32.89	0	5
110	-	27.11	5	0	**311**	60	30.39	0	5
111	600	24.61	5	0	**312**	40	35.39	0	5
112	400	29.61	5	0	**313**	50	36.64	0	5
120	-	21.34	15	0	**Sum**	16300			
121	600	18.84	15	0					
122	400	23.84	15	0					
123	50	25.084	15	0					
210	-	27.11	-5	0					

Moment of Inertia

$$I = \begin{bmatrix} 526216 & 0 & 12317 \\ 0 & 1837794 & 0 \\ 12317 & 0 & 2356578 \end{bmatrix} \quad (lb_f \times ft^2)$$

Overall Process



Basic Equations (1)

- Modes
  - Rigid body modes + Flexible modes

Modes components

$$\xi = \begin{bmatrix} \xi_{Rigid} \\ \cdots \\ \xi_{Flex} \end{bmatrix} = \begin{bmatrix} \begin{bmatrix} \xi_{translational} \\ \xi_{rotational} \end{bmatrix} \\ \xi_{Flex} \end{bmatrix}$$

$$\xi_{translational} \rightarrow \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}, \quad \xi_{rotational} \rightarrow \begin{bmatrix} \phi \\ \theta \\ \psi \end{bmatrix}, \quad \xi_{Flex} \rightarrow \begin{bmatrix} \xi_{F,1} \\ \xi_{F,2} \\ \vdots \\ \xi_{F,5} \end{bmatrix}$$

Interactions between modes

$$\begin{bmatrix} \ddot{\xi}_{Rigid} \\ \cdots \\ \ddot{\xi}_{Flex} \end{bmatrix} \leftarrow \begin{bmatrix} \tilde{Q}(s)_{RR} & \vdots & \tilde{Q}(s)_{RF} \\ \cdots & & \cdots \\ \tilde{Q}(s)_{FR} & \vdots & \tilde{Q}(s)_{FF} \end{bmatrix} \begin{bmatrix} \xi_{Rigid} \\ \cdots \\ \xi_{Flex} \end{bmatrix}$$

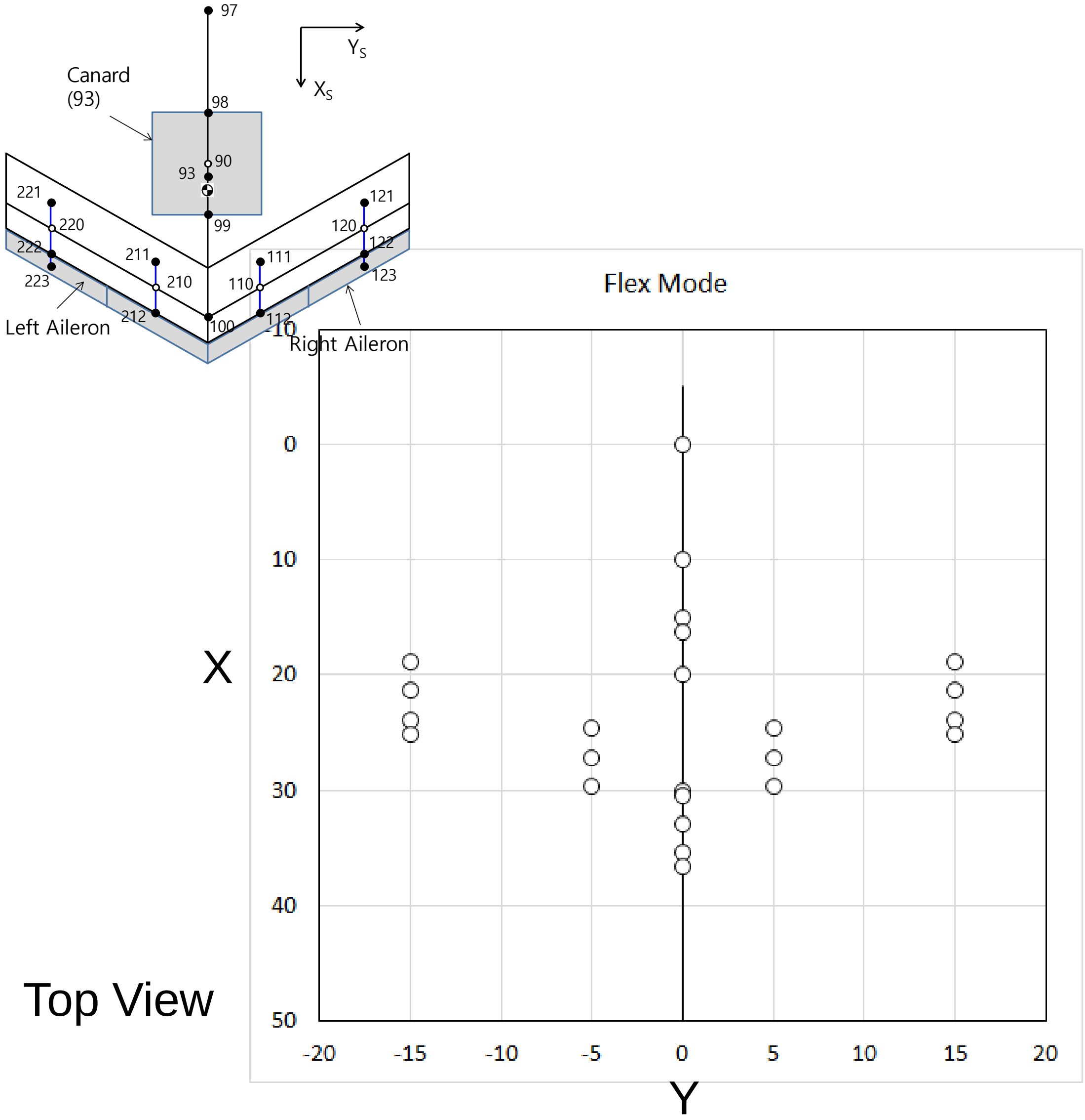
- Structural Mechanics
  - NASTRAN calculates flexible modes($\xi_{F,i}$)

$$m_i\ddot{\xi}_{F,i} + k_i\xi_{F,i} = F_{F,i}$$

A factor to adjust frequency just for simulation

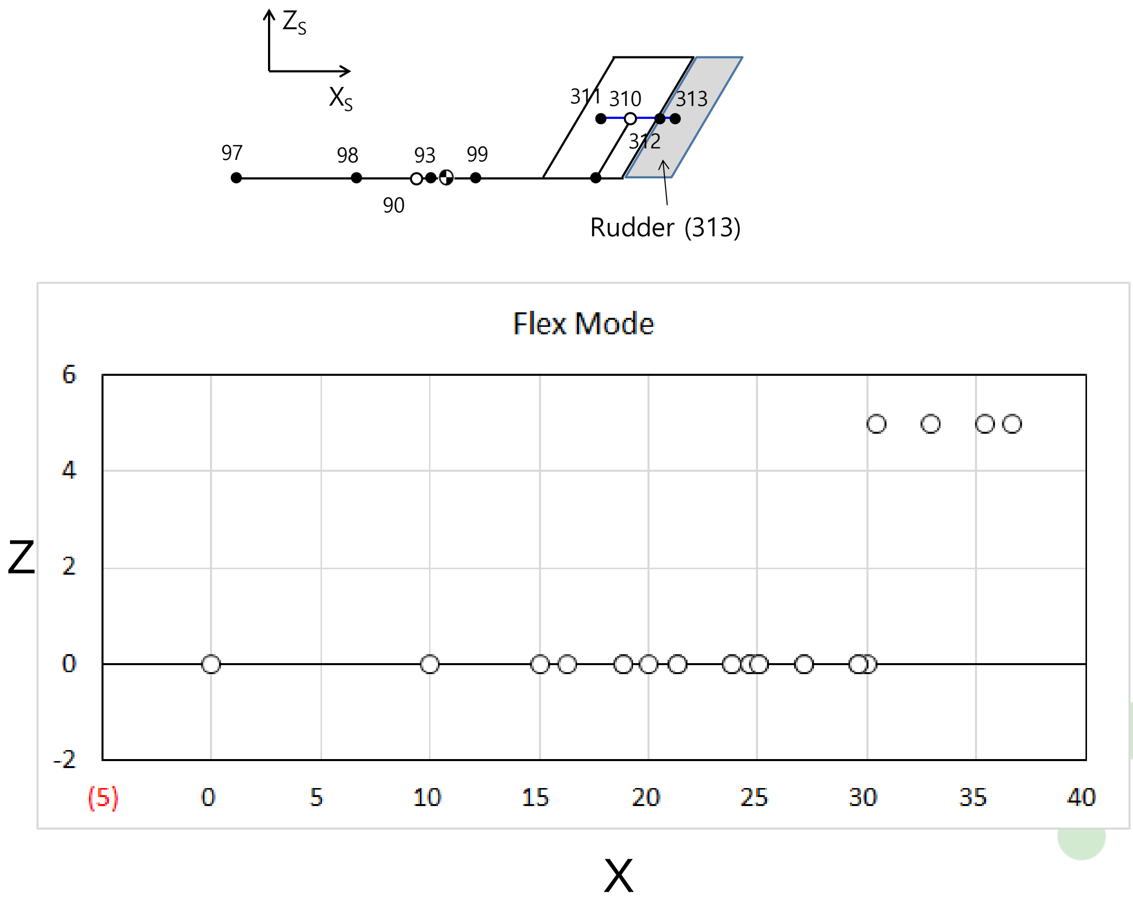
No.	Gen. Mass (slug), m_i	Gen. Stiffness (lbf/ft), βk_i	Frequency (Hz)
1	132.6447	291459.5	$7.46\sqrt{\beta}$
2	94.13681	350988.6	$9.72\sqrt{\beta}$
3	318.1353	4010646	$17.87\sqrt{\beta}$
4	212.1501	4395465	$22.91\sqrt{\beta}$
5	123.4828	6270494	$35.86\sqrt{\beta}$

1st Flexible Mode (7.46 hz) (Asymmetric Directional Mode)



Top View

2nd Flexible Mode (9.72 hz) (Symmetric Longitudinal Mode)



Side View

Basic Equations (2)

- Aerodynamics
  - Aerodynamics Forces in the frequency domain:

$$\tilde{Q}(s) = q_\infty [Q_{hh}(s), Q_{hc}(s)] \begin{bmatrix} \boldsymbol{\xi}(s) \\ \delta(s) \end{bmatrix}$$

$$= q_\infty \left\{ A_0 + \frac{L}{V} A_1 s + \frac{L^2}{V^2} A_2 s^2 + \underbrace{D \left[sI - \frac{V}{L} R \right]^{-1}}_{} E s \right\} \begin{bmatrix} \boldsymbol{\xi}(s) \\ \delta(s) \end{bmatrix} \qquad A_i = [A_{h,i}, A_{c,i}], i = 0,1,2, \qquad E = [E_h, E_c]$$

Time Lag Effect modelled by RFA : $\xrightarrow{\mathcal{L}^{-1}}$

$$\begin{cases} \dot{x}_a = \frac{V}{L} R x_a + E [\dot{\boldsymbol{\xi}}, \dot{\delta}]^T \\ Z_a = D x_a \end{cases}$$

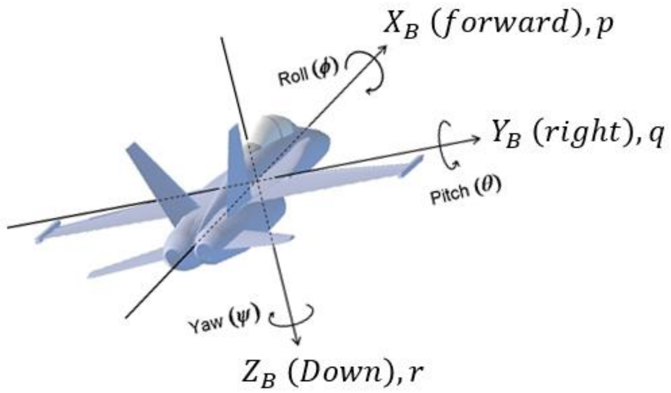
  - Forces in the time domain:

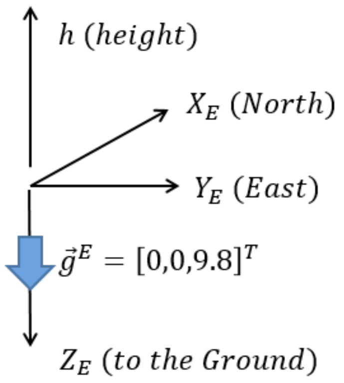
$$Q(t) = q_\infty \left[A_{h,0} \boldsymbol{\xi} + \frac{L}{V} A_{h,1} \dot{\boldsymbol{\xi}} + \frac{L^2}{V^2} A_{h,2} \ddot{\boldsymbol{\xi}} \right] + q_\infty \left[A_{c,0} \delta + \frac{L}{V} A_{c,1} \dot{\delta} + \frac{L^2}{V^2} A_{c,2} \ddot{\delta} \right] + q_\infty Z_a$$

  - ZAERO calculates the coefficient matrices: $A_i = [A_{h,i}, A_{c,i}], i = 0,1,2,\ E = [E_h, E_c], D$

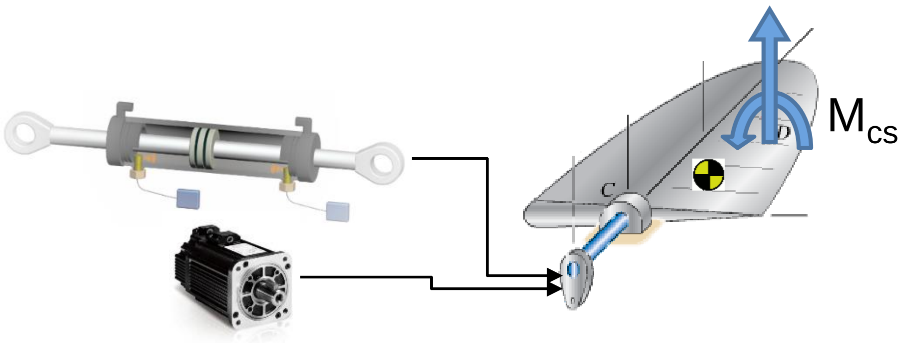
Basic Equations (3)

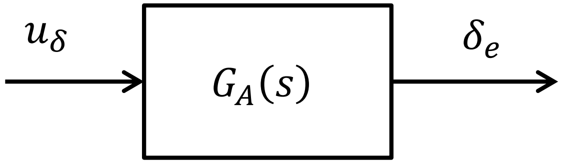
- Flight dynamics (Rigid-body, Nonlinear 6 DOF Eqs.)
  - Translational motions:
  $$m\frac{d\vec{v}^E}{dt} = \vec{F}^E + m\vec{g}^E$$
  - Rotational motions:
  $$I\frac{d\vec{\omega}^B}{dt} + \vec{\omega}^B \times I\vec{\omega}^B = \vec{M}^B$$
  - Attitude Kinematics:
  $$\begin{bmatrix}\dot{\phi}\\ \dot{\theta}\\ \dot{\psi}\end{bmatrix} = \begin{bmatrix}1 & \sin\phi\tan\theta & \cos\phi\tan\theta\\ 0 & \cos\phi & -\sin\phi\\ 0 & \sin\phi\sec\theta & \cos\phi\sec\theta\end{bmatrix}\begin{bmatrix}p\\ q\\ r\end{bmatrix}, \qquad \vec{\omega}^B = \begin{bmatrix}p\\ q\\ r\end{bmatrix}$$
  - Variables: $\vec{v}^E = R_B^E\vec{v}^B, \quad \vec{F}^E = R_B^E\vec{F}^B, \quad \vec{g}^E = [0, 0, 9.8]^T$





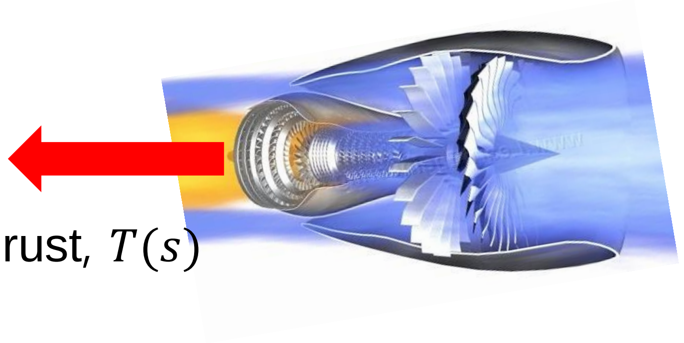
Actuators

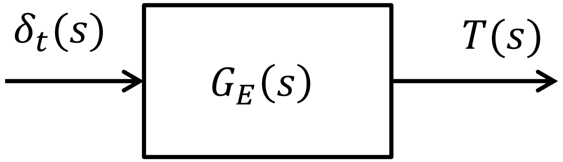




$$G_A(s) = \frac{\delta_e(s)}{u_\delta(s)} = \frac{a_0}{s^3 + b_2 s^2 + b_1 s + b_0}$$

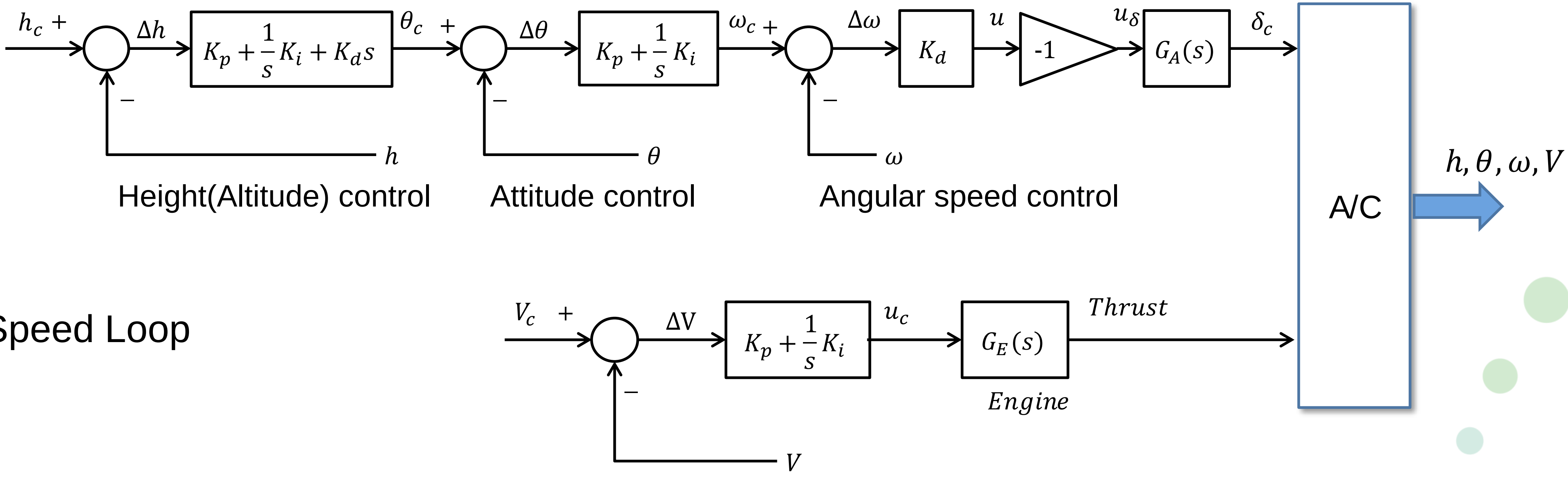
Thrust(Engine)





$$G_E(s) = \frac{T(s)}{\delta_t(s)} = \frac{T_{max}}{\tau s + 1}$$

- Controller
  - PID based
  - Height / Attitude / Angular speed control

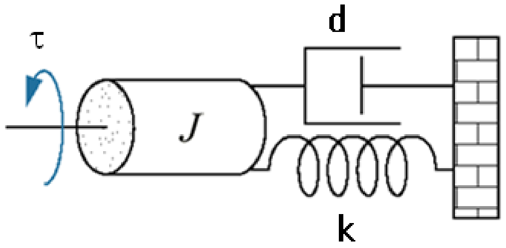


  - Speed Loop

Simulation Program

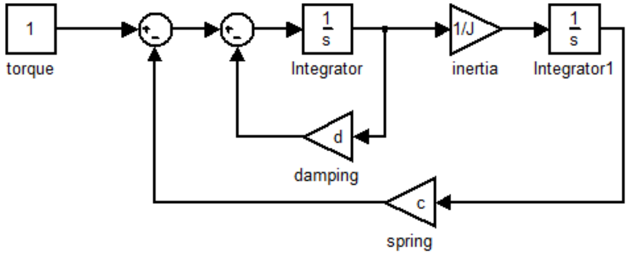
- Dymola
  - Software provided by Dassault Systems
  - Based on **Modelica Language**, specialized in coding simulation programs

Physical system



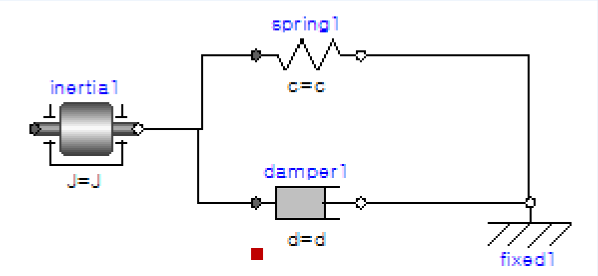
$$\dot{\phi} = \omega$$
$$J\dot{\omega} + c\omega + k\phi = \tau$$

Simulink

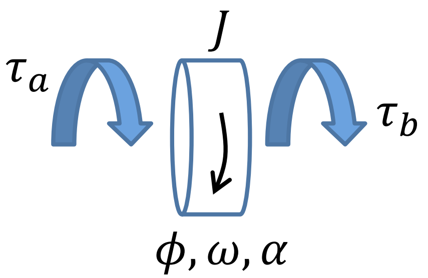


Dymola (Modelica)

Dymola 2019



1) Make modules by Modelica Language



$$\omega = \dot{\phi}$$
$$\alpha = \dot{\omega}$$
$$J\alpha = \tau_a + \tau_b$$

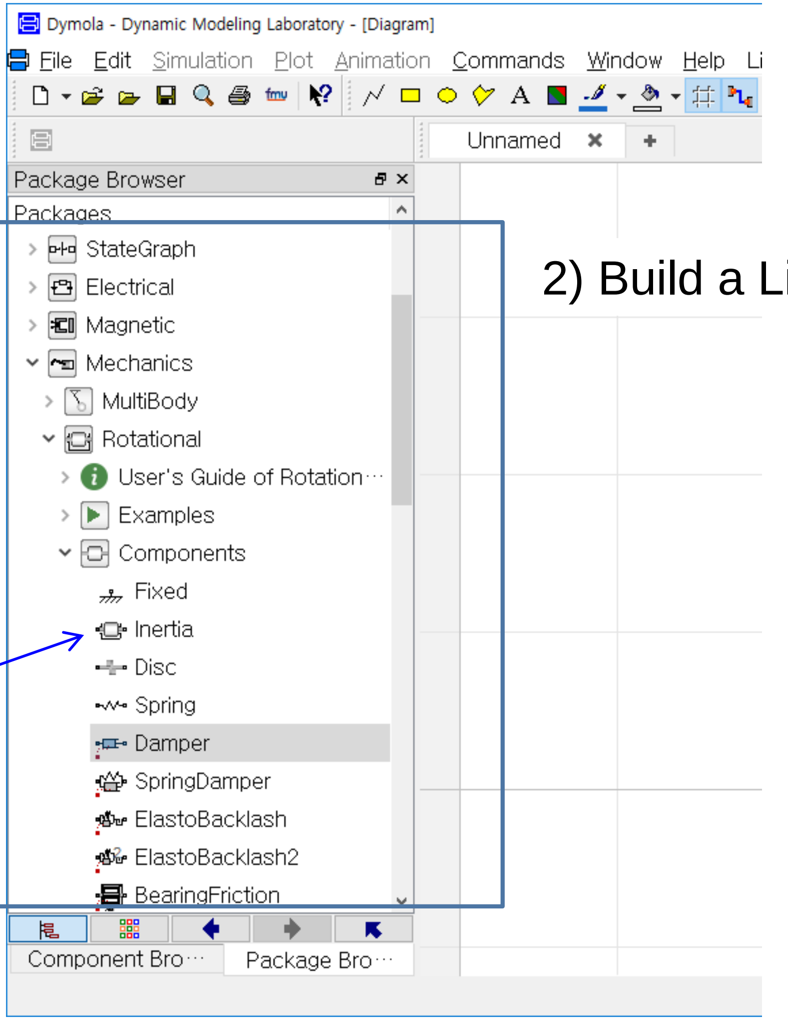
interface: flange_a, flange_b declarations

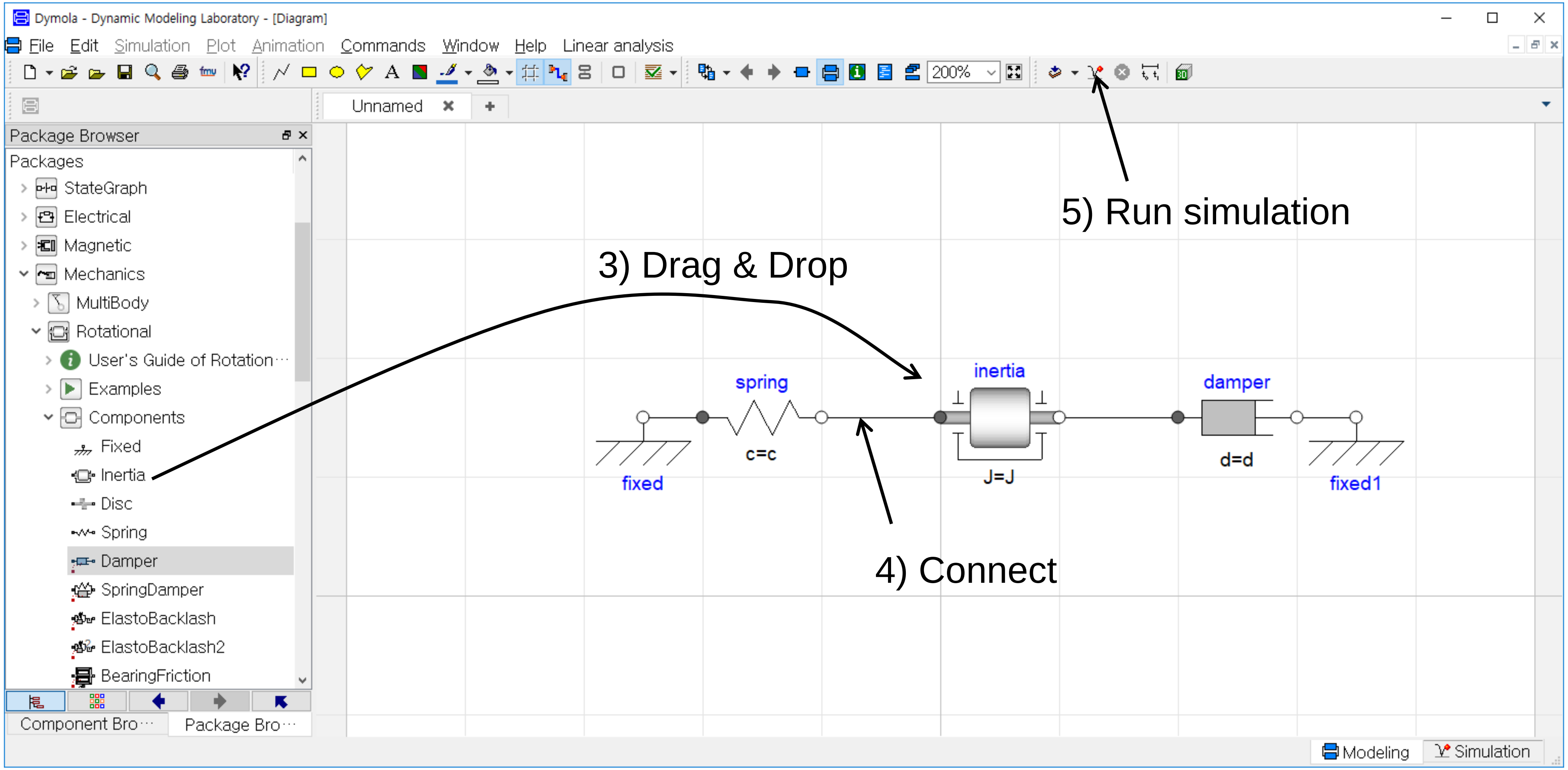
variables: J, phi, w, a declarations

dynamic equations: equation section

```
model Inertia
  Rotational.Interfaces.Flange_a flange_a;
  Rotational.Interfaces.Flange_b flange_b;
  parameter SI.Inertia J;
  SI.Angle phi;
  SI.AngularVelocity w;
  SI.AngularAcceleration a;
equation
  phi = flange_a.phi;
  phi = flange_b.phi;
  w = der(phi);
  a = der(w);
  J*a = flange_a.tau + flange_b.tau;
end Inertia;
```

2) Build a Library




Dymola - Dynamic Modeling Laboratory - [Diagram]
File Edit Simulation Plot Animation Commands Window Help Linear analysis
Package Browser
Packages
StateGraph
Electrical
Magnetic
Mechanics
MultiBody
Rotational
User's Guide of Rotation…
Examples
Components
Fixed
Inertia
Disc
Spring
Damper
SpringDamper
ElastoBacklash
ElastoBacklash2
BearingFriction
Component Bro…
Package Bro…
Unnamed
5) Run simulation
3) Drag & Drop
inertia
spring
damper
c=c
J=J
d=d
fixed
fixed1
4) Connect
Modeling
Simulation

Integrated Simulation Program

Library

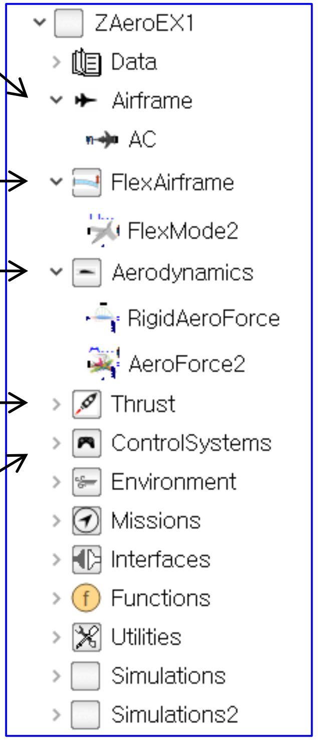
Rigid body dynamics

Structural dynamics

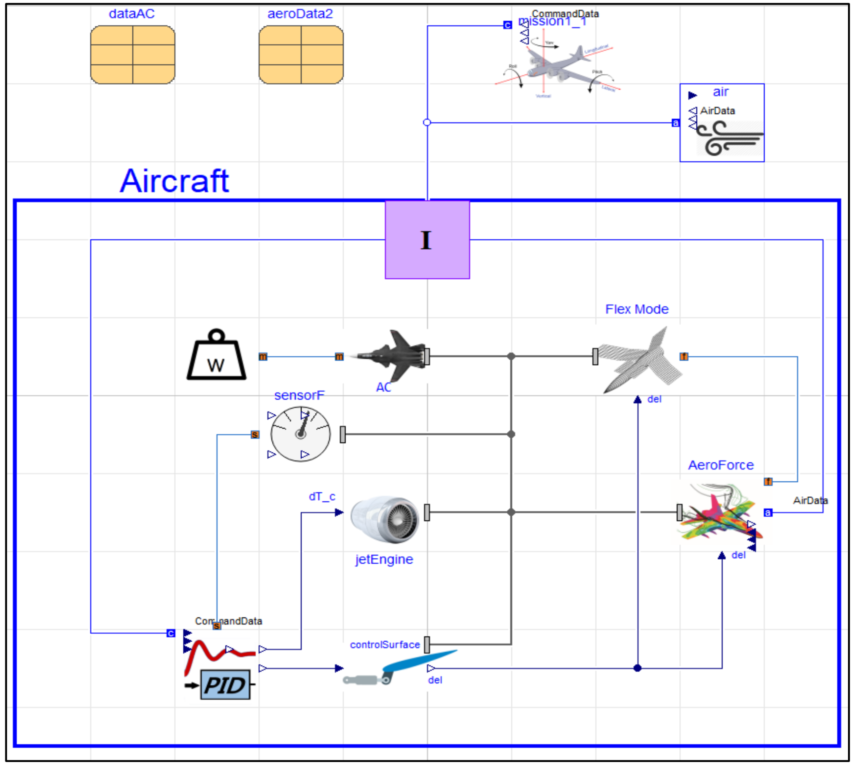
Aerodynamics

Thrust

Control



Simulation Program



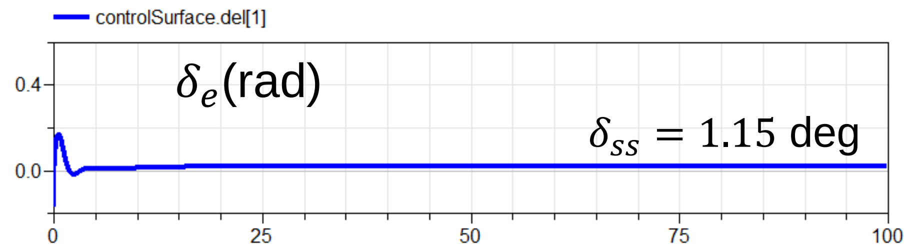
Simulation Results

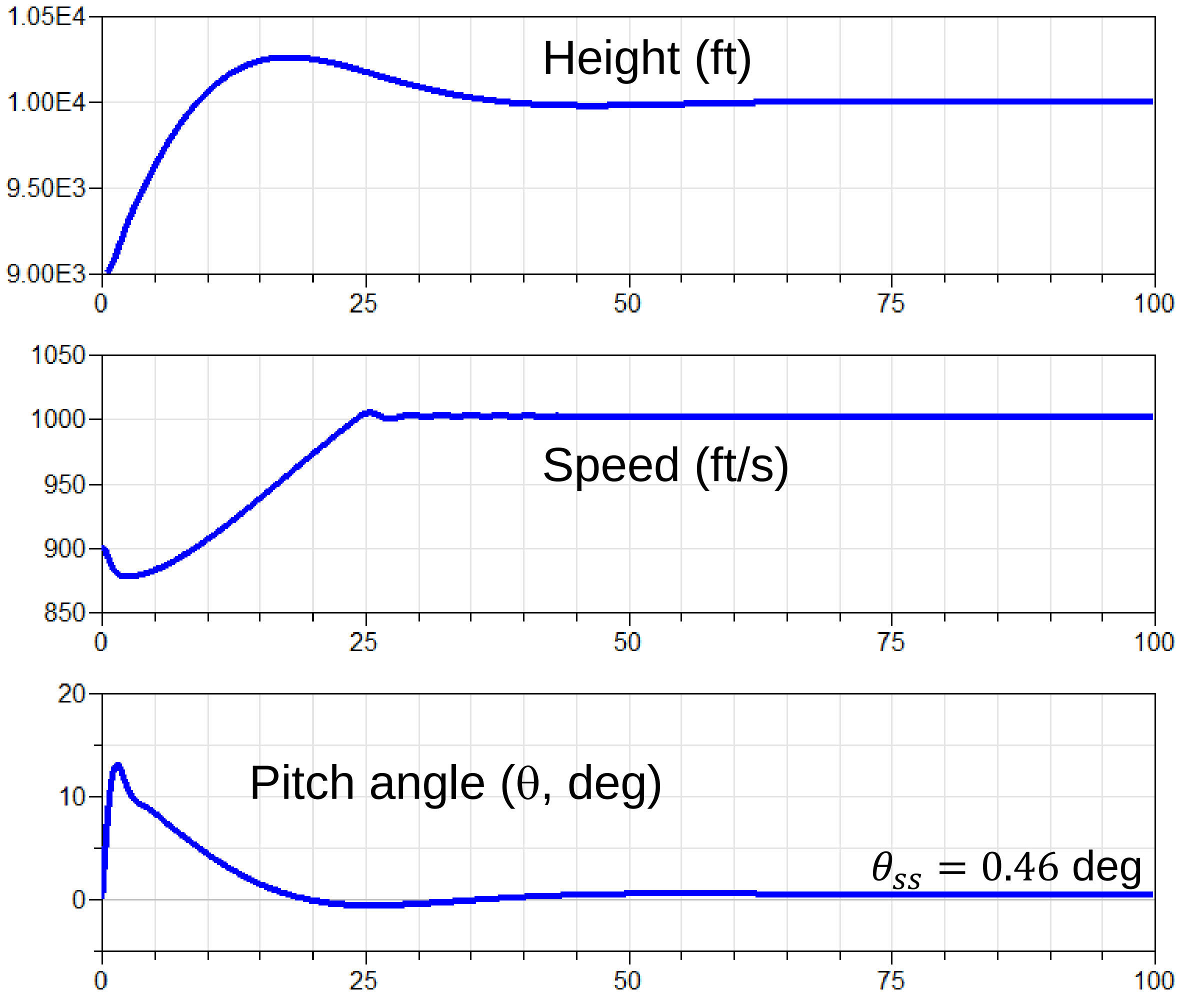
- Level flight : (height, speed):

  (9,000 ft, 900 ft/s)

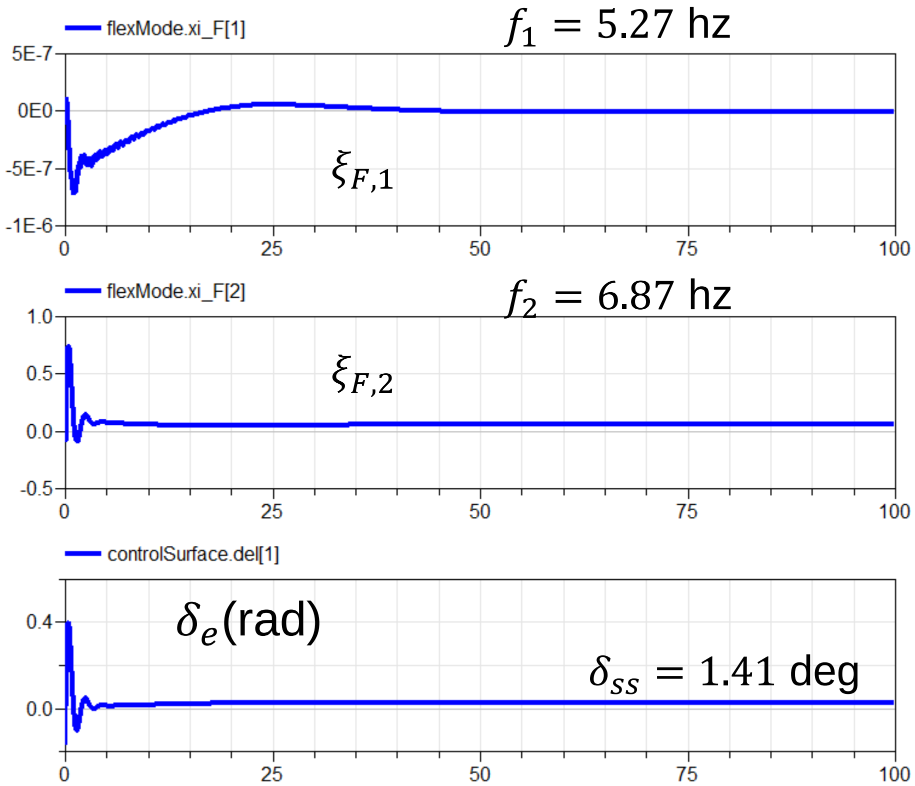
  → (10,000 ft, 1000 ft/s)

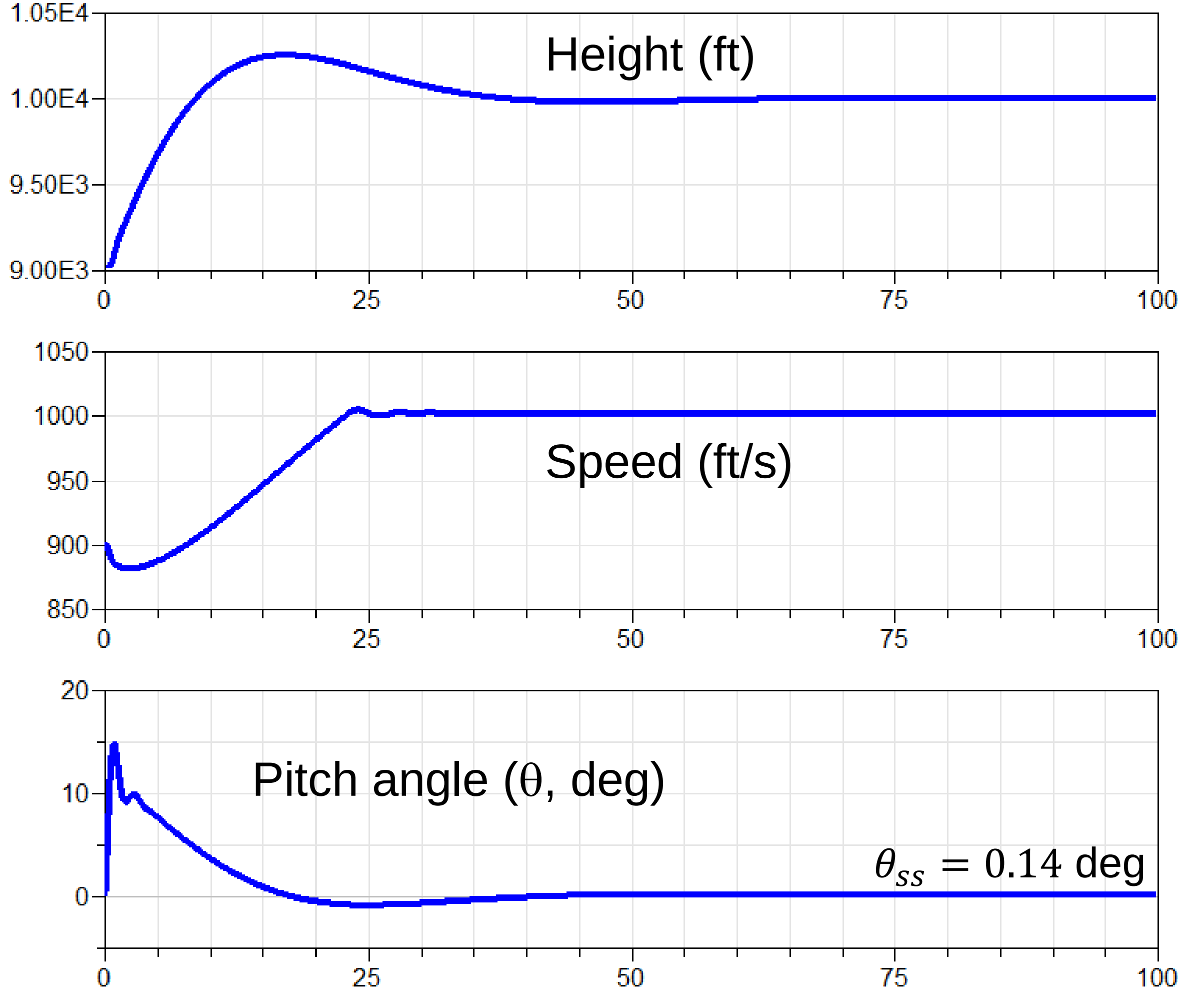
- Without flexible modes



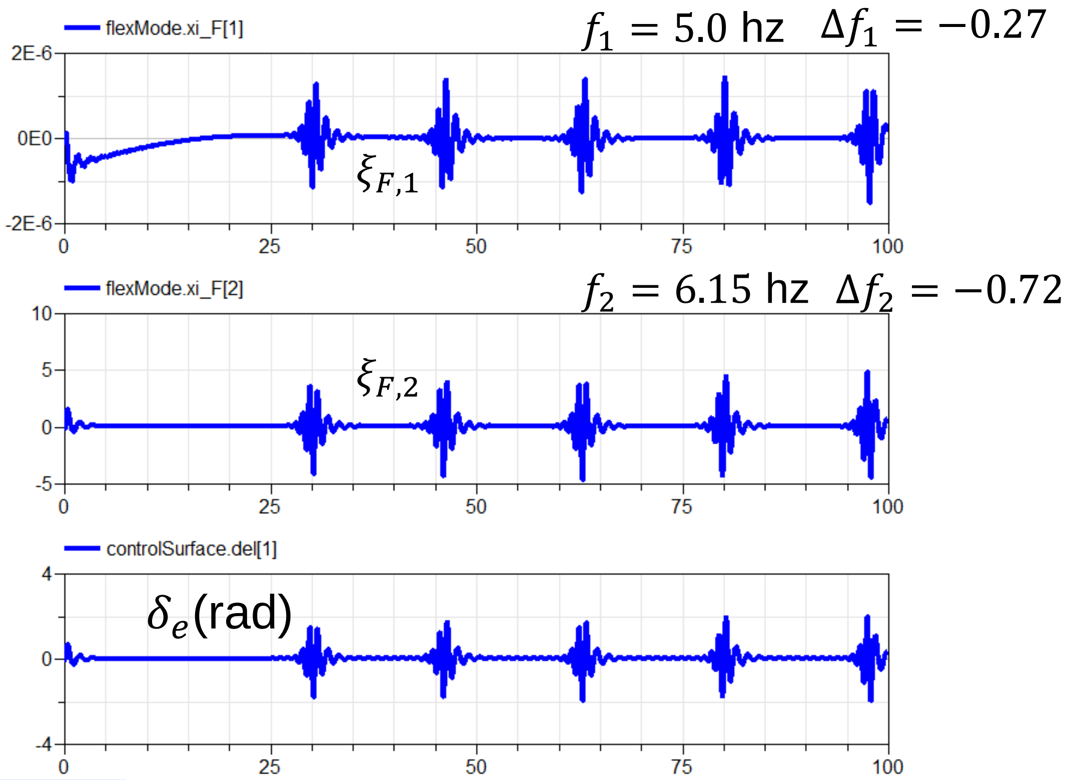


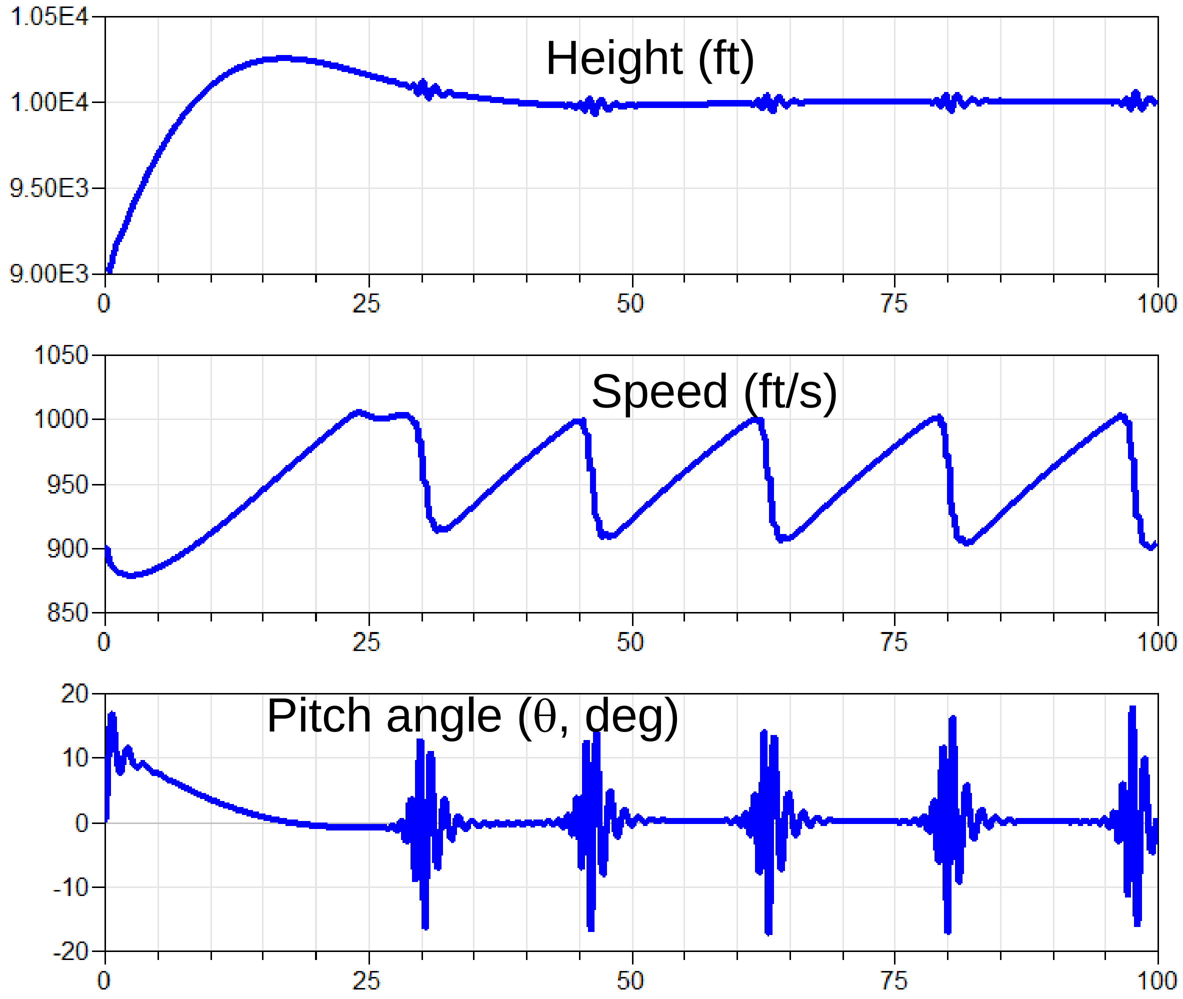
- With flexible modes
  - Flexible mode's frequency adjusting factor: $\beta = 0.5$





- With Flexible Modes
  - Flexible mode's frequency adjusting factor: $\beta = 0.4$



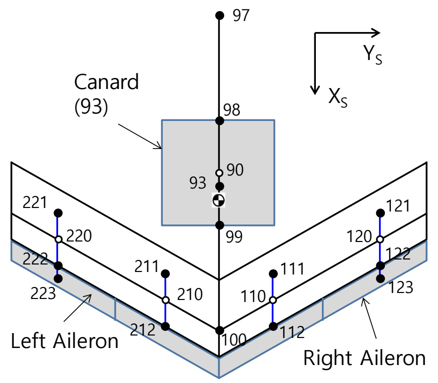


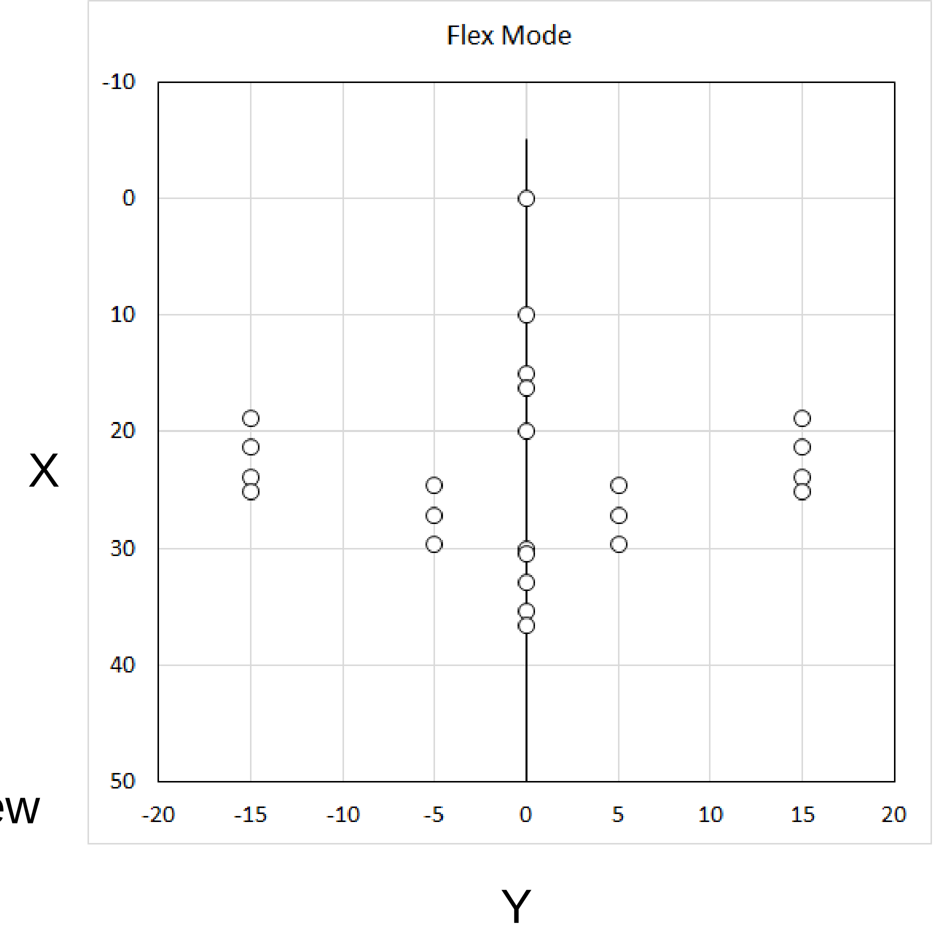
Conclusions

- Integrated Simulation Program
  - Modules of structural dynamics, aerodynamics, flight dynamics, and control
  - Some simulation results show the interactions among the three mechanics.

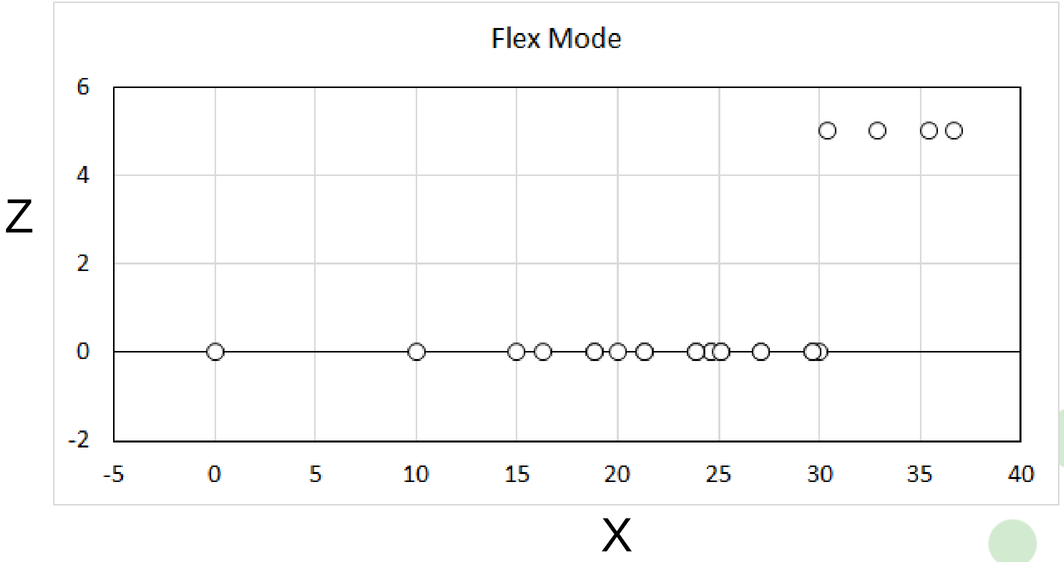
- Further Studies
  - The program will be certified by more reliable results.
  - To include the interactions between sensors' measurements and flexible modes

Thank You!

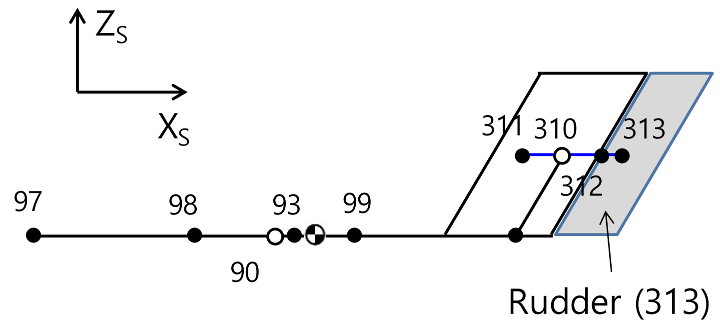




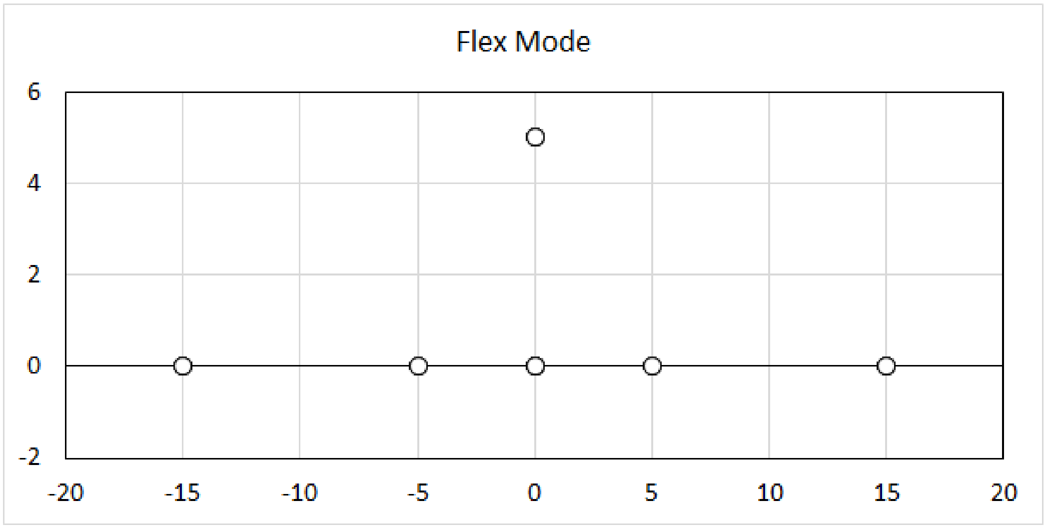
Top View



Side View



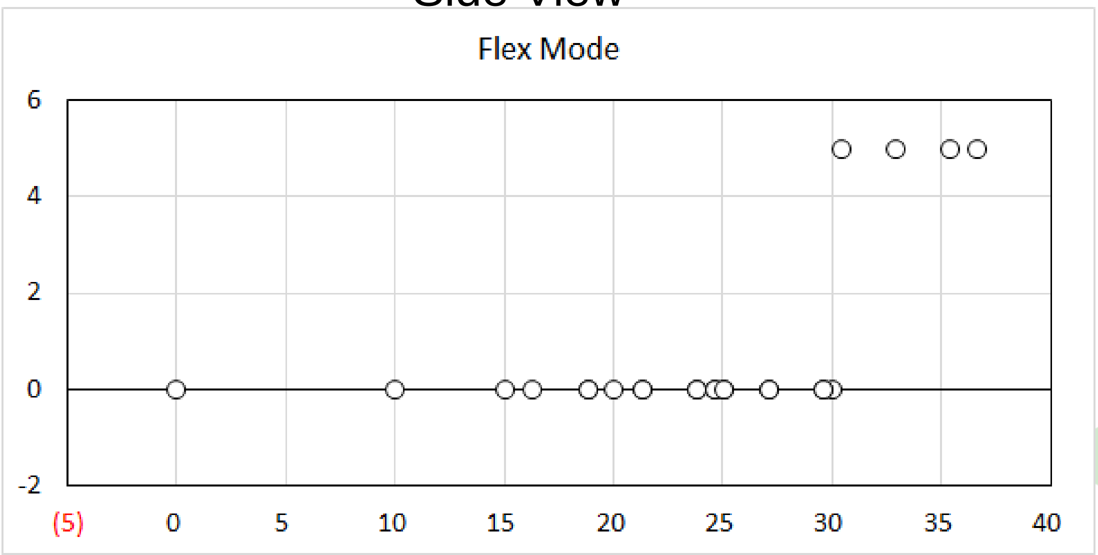
Front View



Z

Y

Side View



X