USC University of Southern California

AME532a Group Presentation

ASW28 Model Controller Design and Simulation

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ASW-28 Aircraft

- Used Mass and Geometry properties from lecture notes and homework
- Key properties: $m = .48\ kg,$

$$J = \begin{bmatrix} .0494 & 0 & -.0017 \\ 0 & .0223 & 0 \\ -.0017 & 0 & .0708 \end{bmatrix}$$

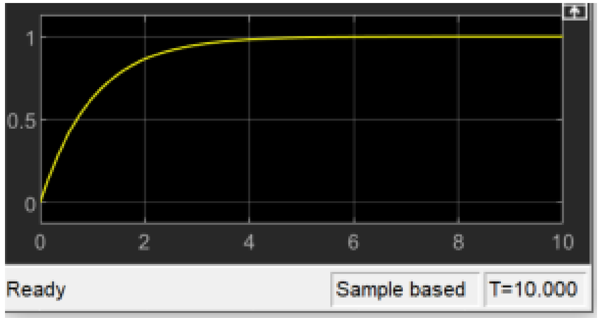
- FlightGear Visualization

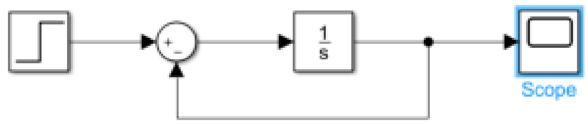
Nonlinear Dynamics Simulation

- Block Diagram:

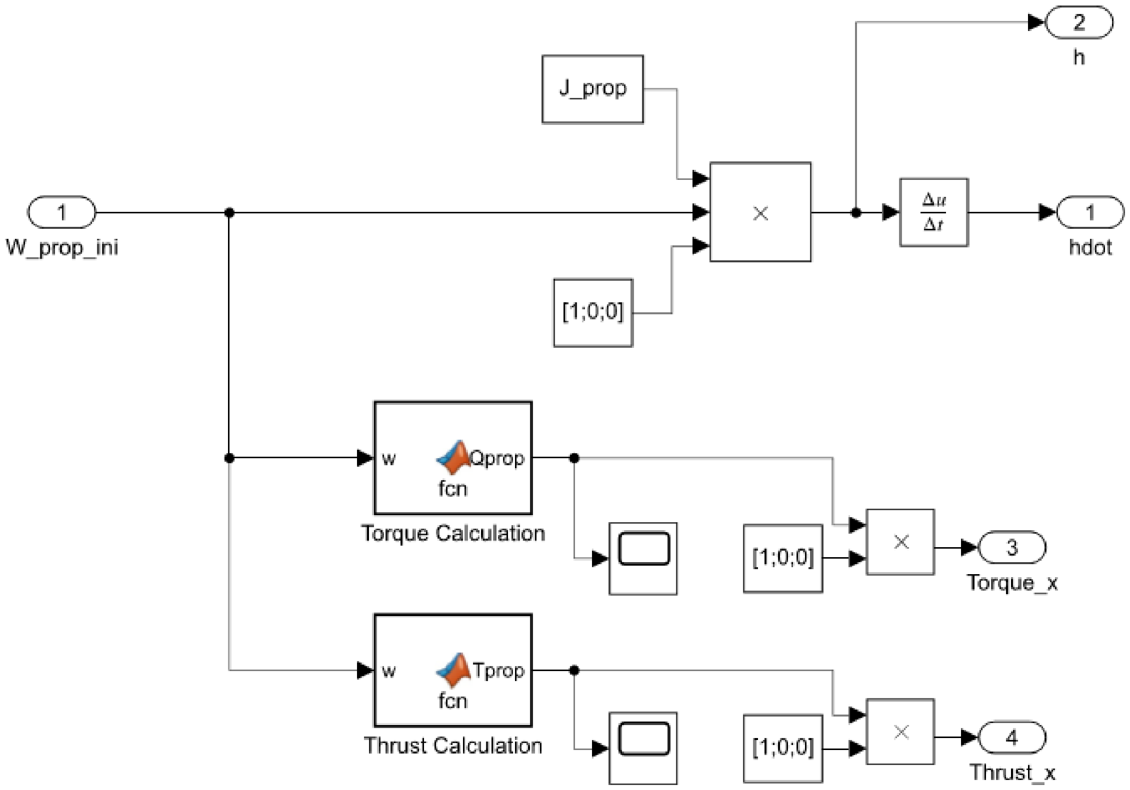
Non-linear Dynamics Simulation Top Level.pdf

- 1st order actuator model





- Simple Propeller Model:



Trim & Linearization

- Trim Results (Trans Kin, Propeller, 1st order actuators commented out):

State		Desired Value	Actual Value	Desired dx	Actual dx
Model_to_Trim/Rotational Dynamics/Integrator					
State - 1	P	[-Inf , Inf]	-1.4774e-13	0	5.2303e-12
State - 2	Q	[-Inf , Inf]	-8.0076e-18	0	-4.5985e-11
State - 3	R	[-Inf , Inf]	-8.1001e-13	0	9.3652e-13
Model_to_Trim/Rotational Kinematics/Integrator					
State - 1	phi	[-Inf , Inf]	-1.7683e-12	0	6.028e-18
State - 2	theta	[-Inf , Inf]	-0.18042	0	-8.0076e-18
State - 3	psi	[-Inf , Inf]	-5.135e-10	[-Inf , Inf]	-8.2337e-13
Model_to_Trim/Translational Dynamics/Integrator					
State - 1	U	[-Inf , Inf]	18.7783	0	-4.0394e-09
State - 2	V	[-Inf , Inf]	2.6454e-13	0	-2.012e-12
State - 3	W	[-Inf , Inf]	-0.64048	0	-2.2141e-08

- Trim Condition (Glider) FlightGear Demonstration:

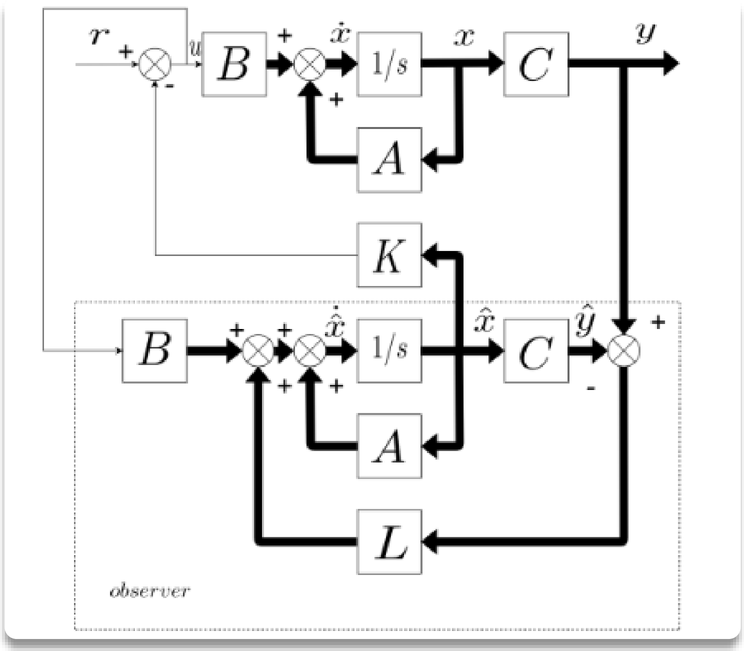
https://www.youtube.com/watch?v=aavscQ1y04M

Longitudinal Mode

- State: [Θ; U; W; Q; h]
- Control Surfaces: [δ_F; δ_E; δ_T]
- Sensors: [Q; V_∞; α; h; a_x; a_z] and GPS data (lat, long & alt)
- Phugoid mode Eigenvalues: -0.10 $\pm$ 0.63i
- Short Period mode Eigenvalues: -23.97 $\pm$ 31.29i
- Full State Observer: Estimate the states for full-state feedback
- Stability Augmentation System: Dampen Short Period mode
- Autopilot Design: Automatic Takeoff with LQR

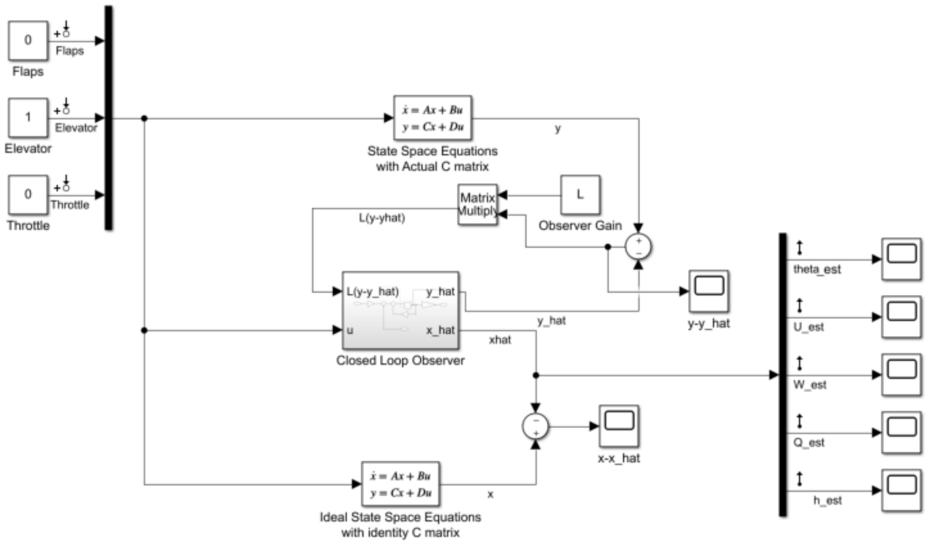
Full-State Observer

- Observer Equation $\dot{\hat{x}} = A\hat{x} + Bu + L(y - \hat{y})$
- State Error Equation $\dot{\tilde{x}} = \dot{x} - \dot{\hat{x}} = (A - LC)\tilde{x}$
- Closed loop feedback equation $\dot{x} = (A - BK)x$
- Observer gain “L” is determined with pole placement, similar to the feedback gain “K”
- K = place(A, B, P)
- L = place(A^T, C^T, P)

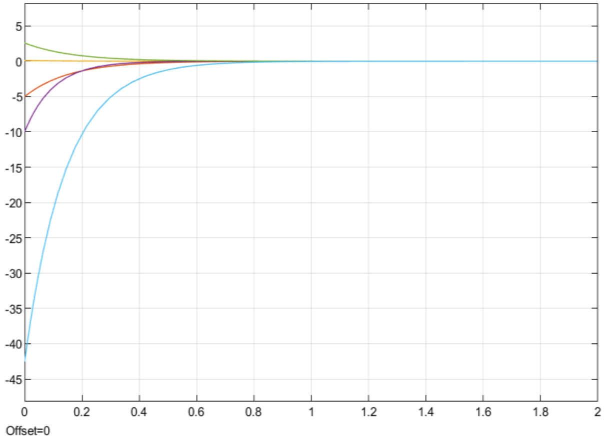


Full-State Observer

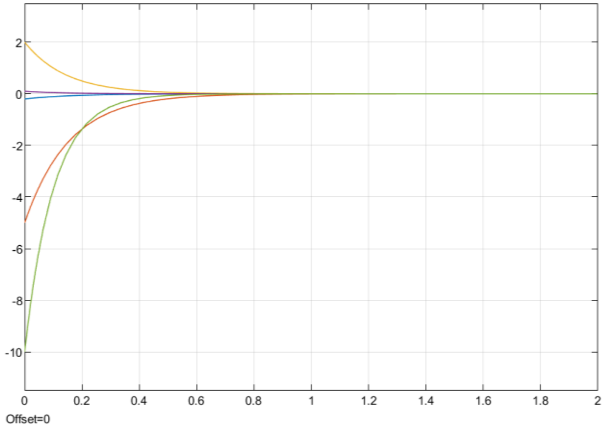
- Linearized State Space System with Full-State Observer:



- P=[-6 -6.5 -7 -7.5 -10]
- "Actual" States initial conditions: [0; 0; 0; 0; 0]
- "Observer" States initial conditions: [.2; 5; -2; -1; 10]
- Error converges to 0 in less than 1 second



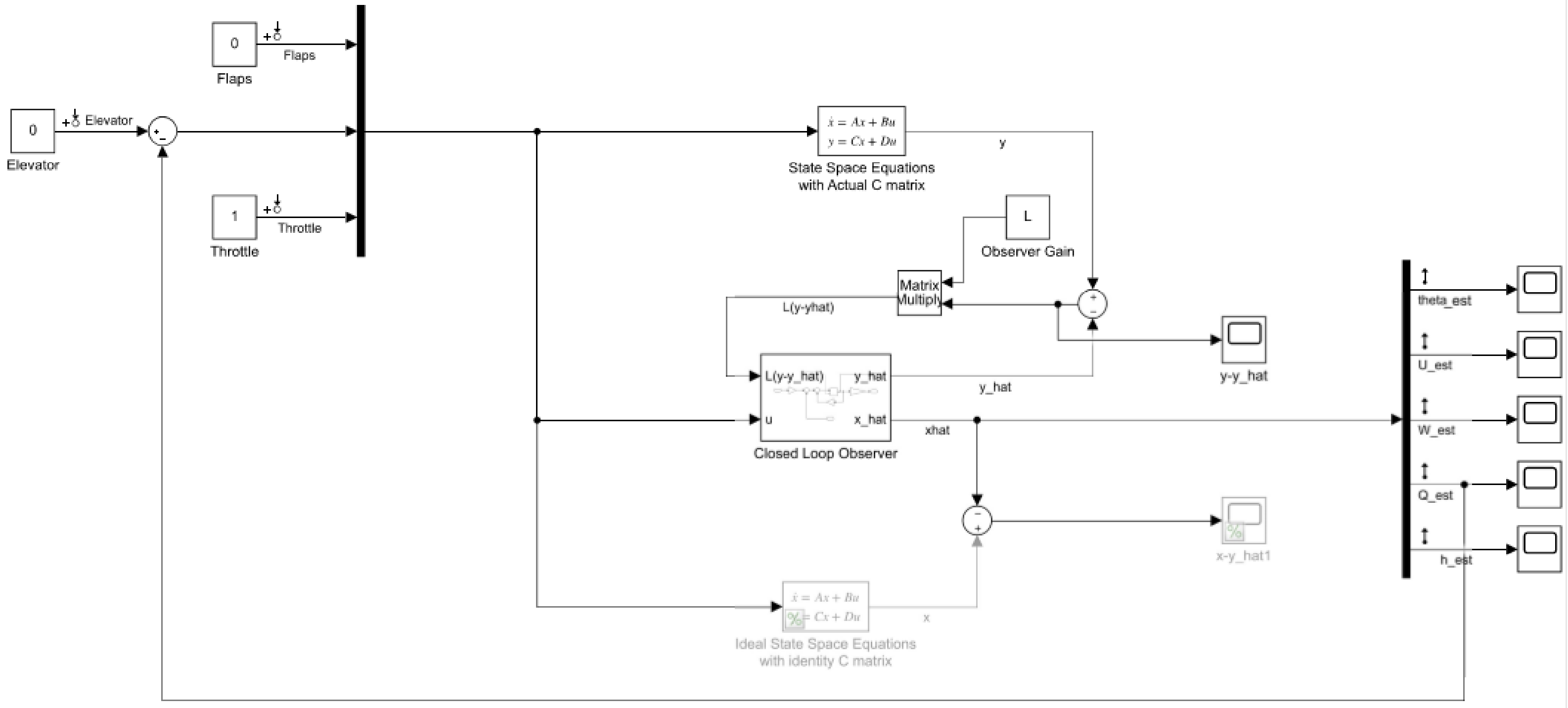
$y - \dot{y}$



$x - \dot{x}$

Pure Rate Feedback SAS

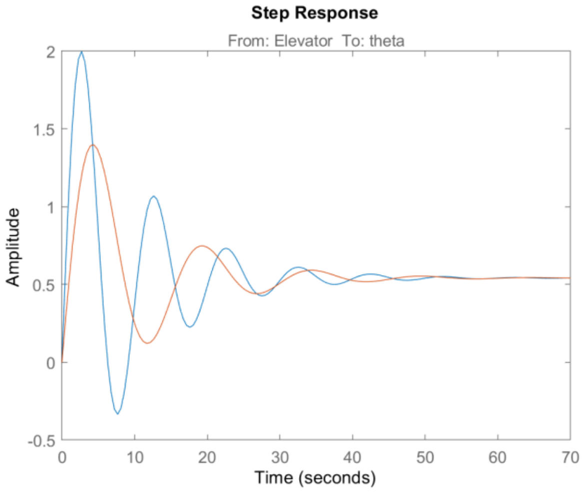
- Goal of the SAS system is to dampen short period, as the initial response is fast and oscillatory with poles at $-23.97 \pm 31.29i$
- Short Period Mode is most related with Pitch rate Q to Elevator input
- Pure Rate Feedback Block Diagram:

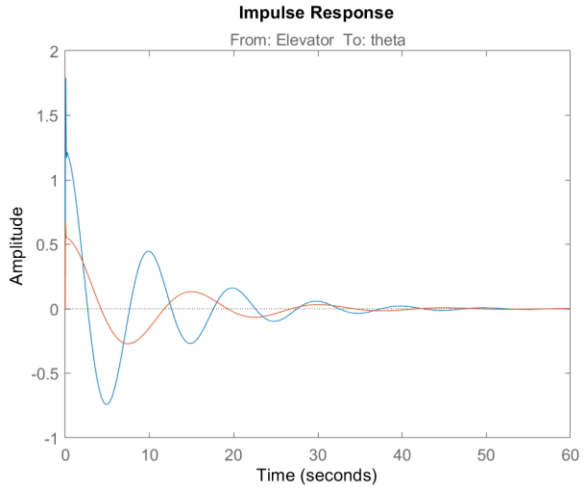


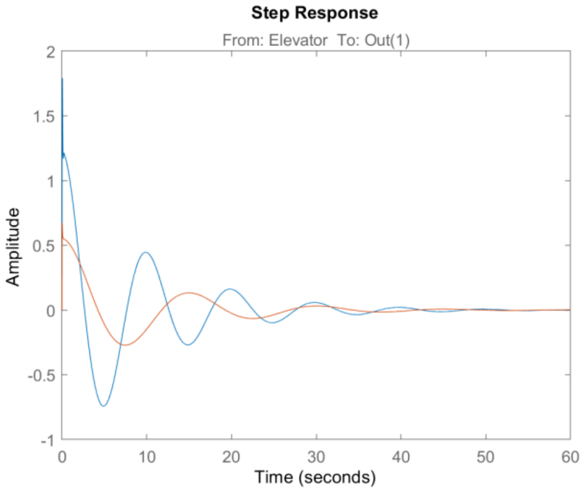
Pure Rate Feedback SAS

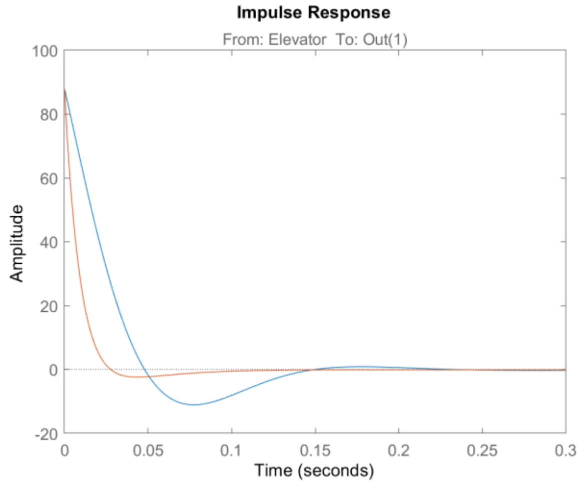
- Open loop eigenvalue:
  $-23.97 \pm 31.29i$
  ω_n = 39.42 rad/s
  ζ = .61
  τ = .0417 s

- Closed loop eigenvalue:
  $-34.00 \pm 0.00i$
  ω_n = 34.00 rad/s
  ζ = 1
  τ = .0294 s



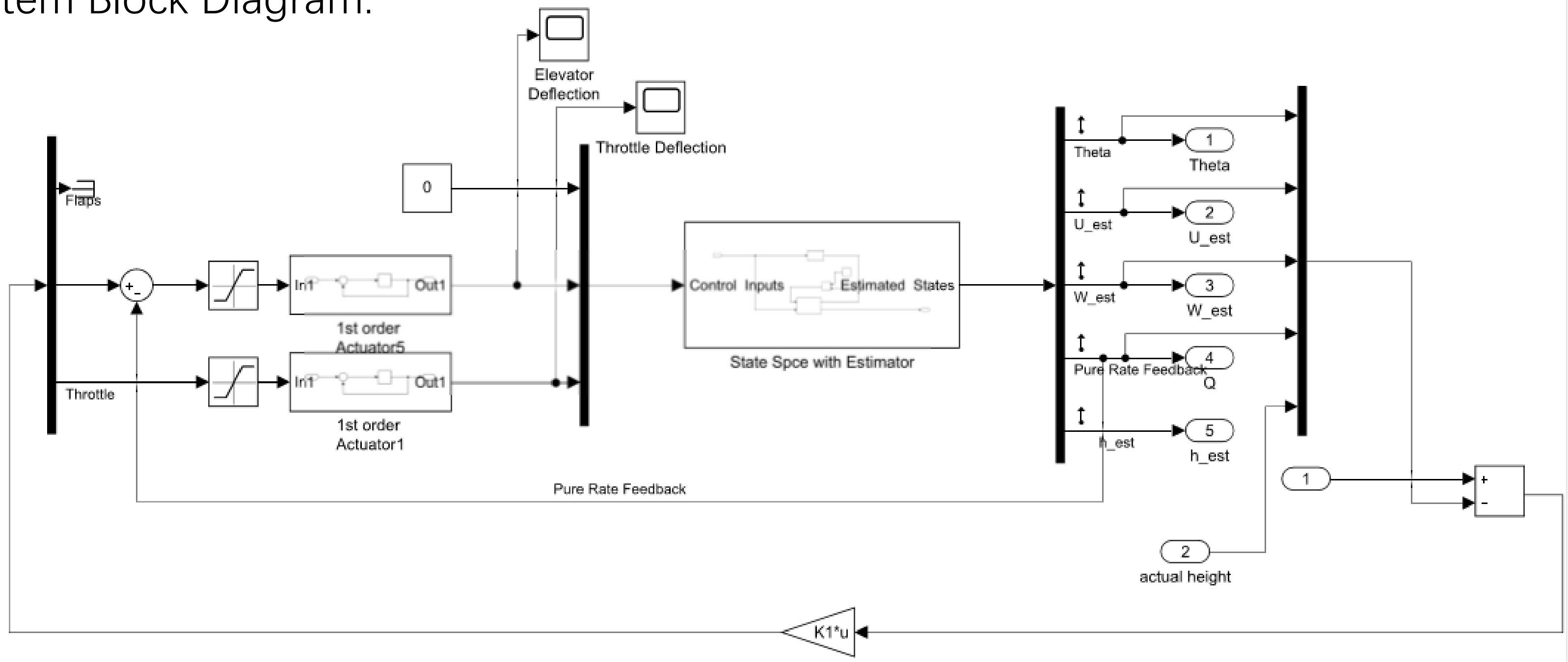






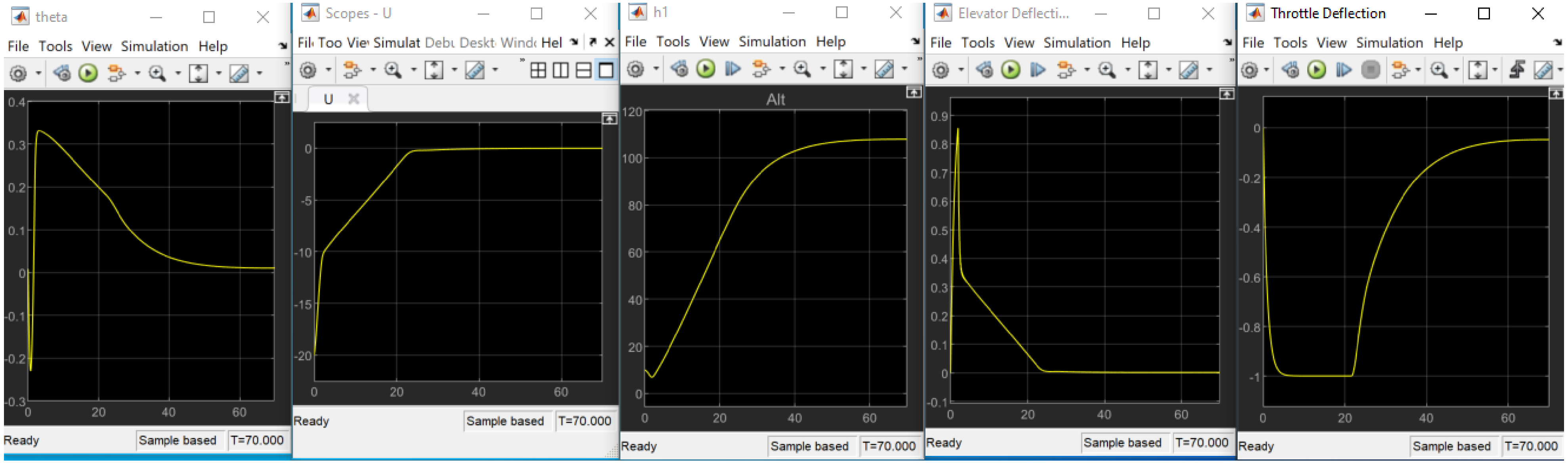
Automatic Takeoff with LQR

- Assume the aircraft already starts in air at 10 m altitude with zero velocity
- Initial State x_0 =[Θ; U; W; Q; h] = [0; -20; 0; 0; -90]
- Goal State: x_{ref} = [0; 0; 0; 0; 0] (trim condition, 20m/s at 0 degree Θ angle at 100 m altitude)
- Controller $u = K(x_{ref} - x)$
- Closed loop Equation: $\dot{x} = Ax + B[K(x_{ref} - x)] = (A - BK)x + BKx_{ref}$
- Control System Block Diagram:



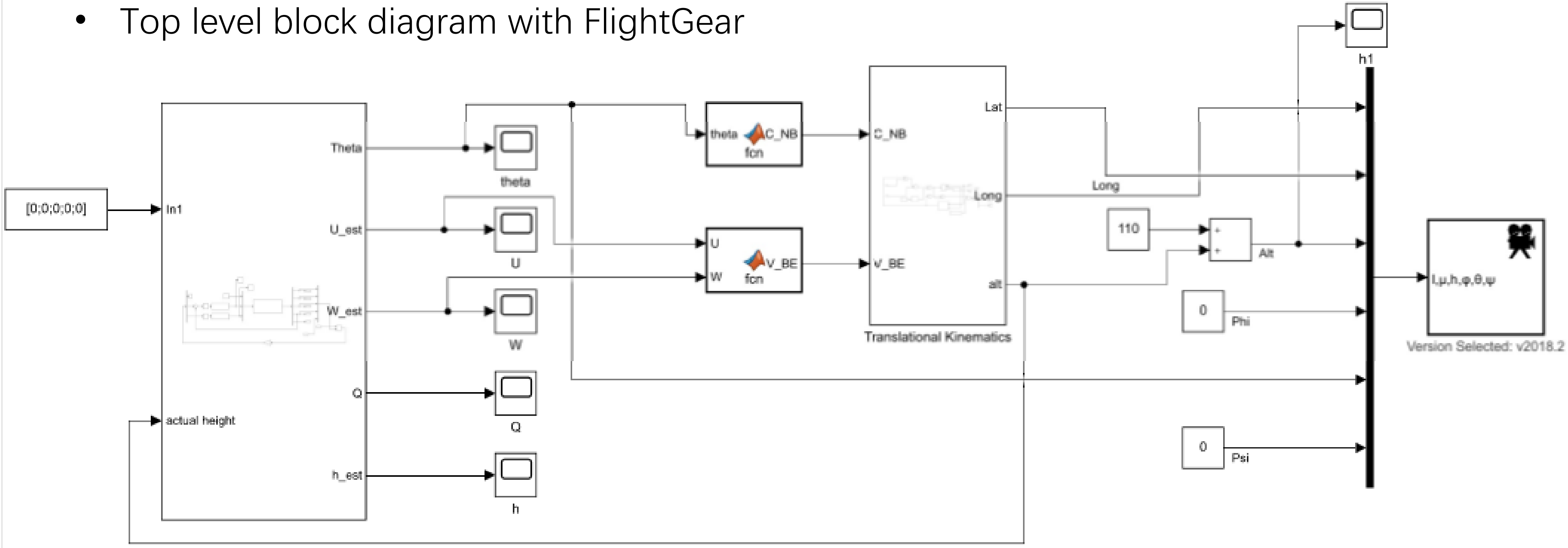
Automatic Takeoff with LQR

- LQR Equation: $$J = \int_0^T \left(x(\tau)^T Q x(\tau) + u(\tau)^T R u(\tau)\right)\, d\tau + x(T)^T Q_f x(T)$$
- Large Q matrix penalizes changes in state
- Large R matrix penalizes changes in actuator
- Q=diag([35000,.1,30000,1,1]) for [Θ; U; W; Q; h], prioritizes slow, small changes in Θ
- R=diag([1,1,1]) for [δ_F; δ_E; δ_T]
- Good strategy to prioritize performance over actuation cost which is low already



Automatic Takeoff with LQR

- Top level block diagram with FlightGear

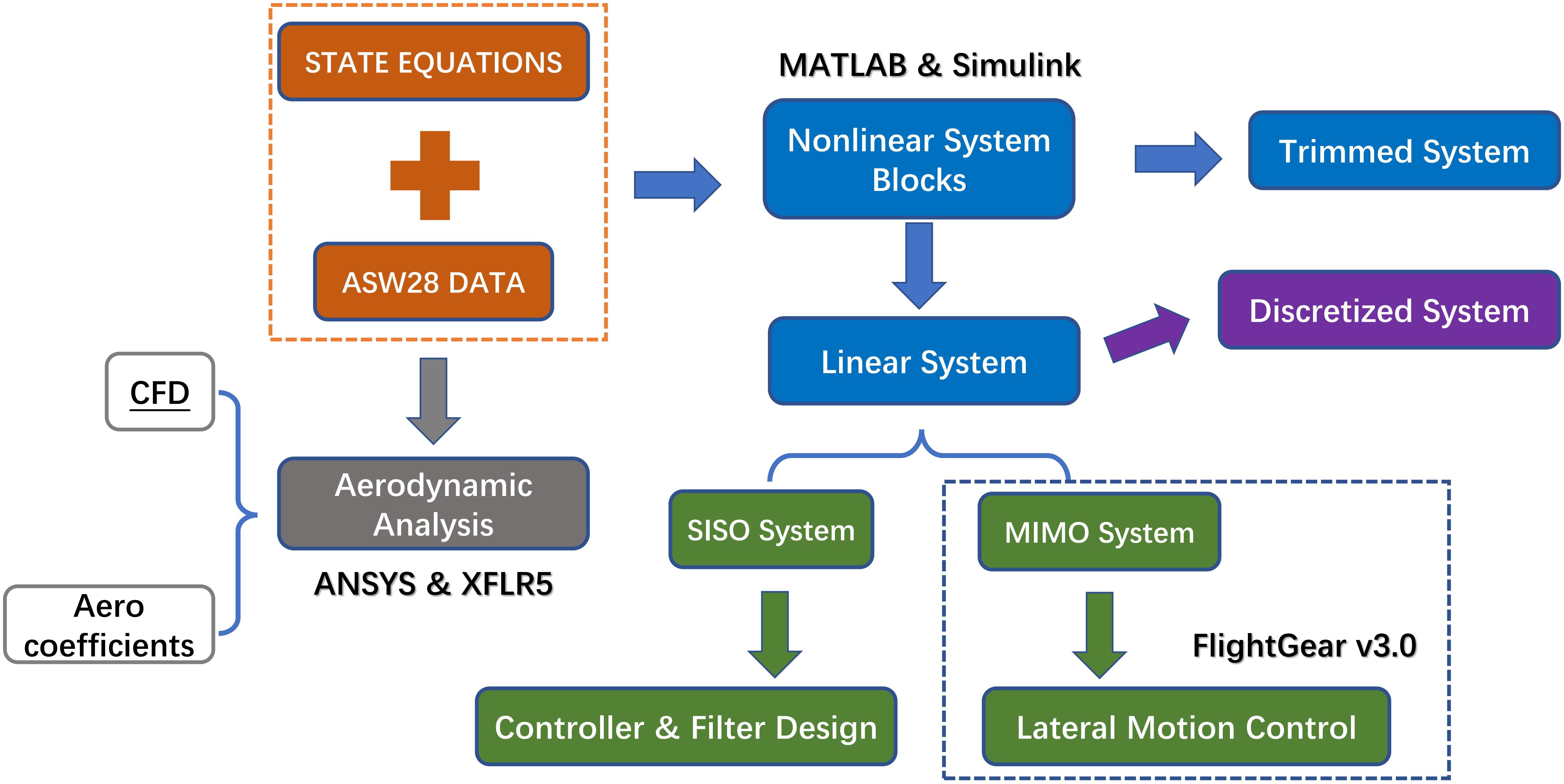


- FlightGear Demonstration: https://www.youtube.com/watch?v=ZxiTEh3dW9o

Contents

- **System Overall Block Diagram**
  --Basic Blocks & Attached Blocks
- **Non-linear System Analysis.**
- **System Linearization.**
  --Steady State Analysis.
  --Lateral Motion Control (Wash out Filter).
  --System Discretization
- **Aerodynamic Analysis for *Sonic Flight***
  --Model Aero-coefficient Analysis in **XFLR5**
  --The CFD & FEA in **ANSYS**
- **Simulation**
  --Skidded to Turn in **FlightGear**.

Design Diagram

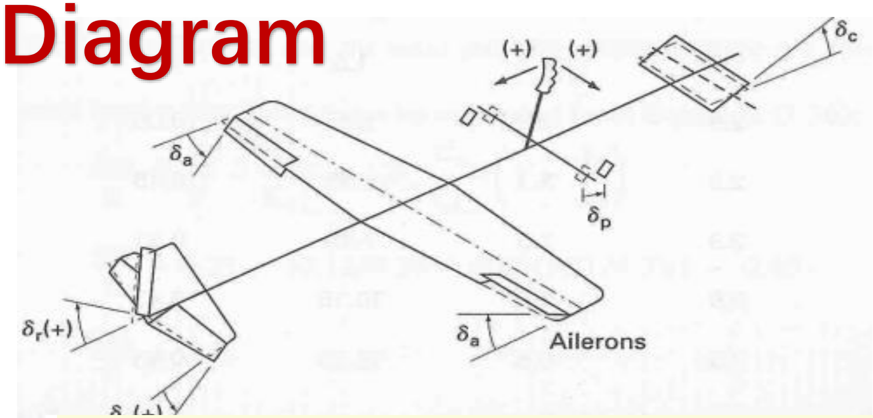


System Overall Block Diagram

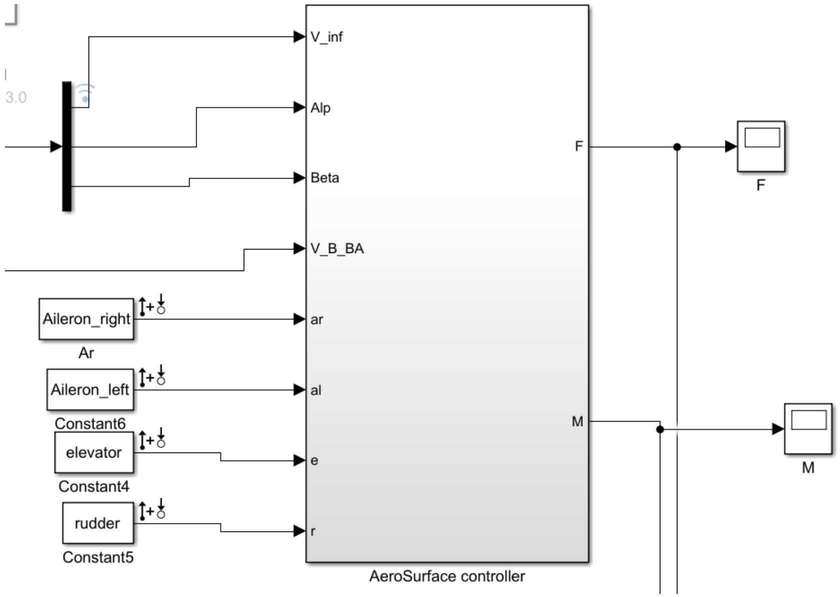
① Basic Control Blocks

② Attached Control Blocks(AeroSurf & Propeller)

System Block Diagram



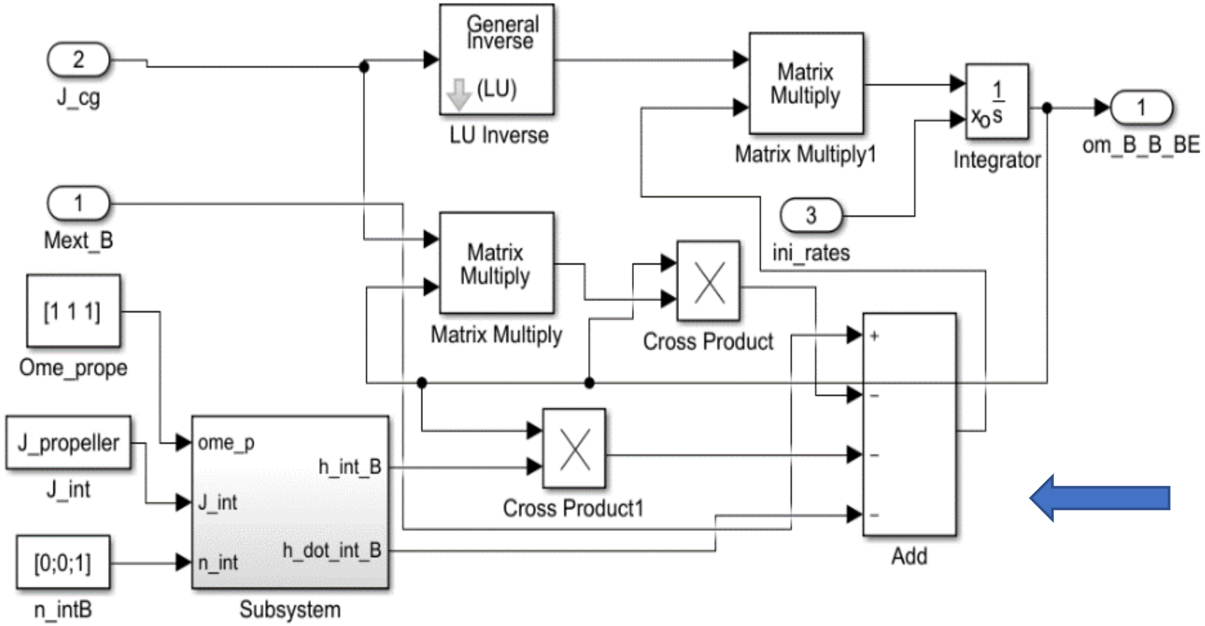

```
CL1=CL0_2345(1)+CLa(1).*a_ss1+3*elevator*0.5;
CL2=CL0_2345(2)+CLa(2).*a_ss2+3*rudder*0.5;
CL3=CL0_2345(3)+CLa(3).*a_ss3+3*aileron_r*0.5;
CL4=CL0_2345(4)+CLa(4).*a_ss4+3*aileron_l*0.5;
```

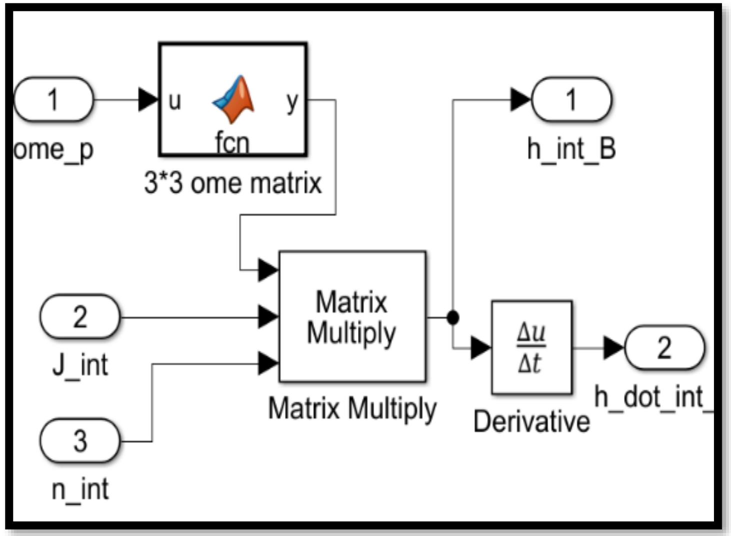


Basic Control Blocks

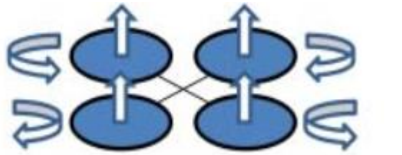
- Translational Kinematics
- Translational Dynamics
- Rotational Kinematics
- Rotational Dynamics

Propeller Control Diagram

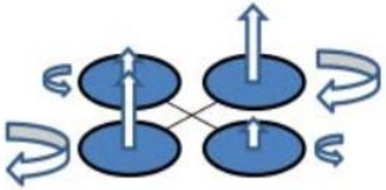




Aero-Surface Control



Increase Thrust by
Adding Power to All Motors Evenly
All Torques Cancel



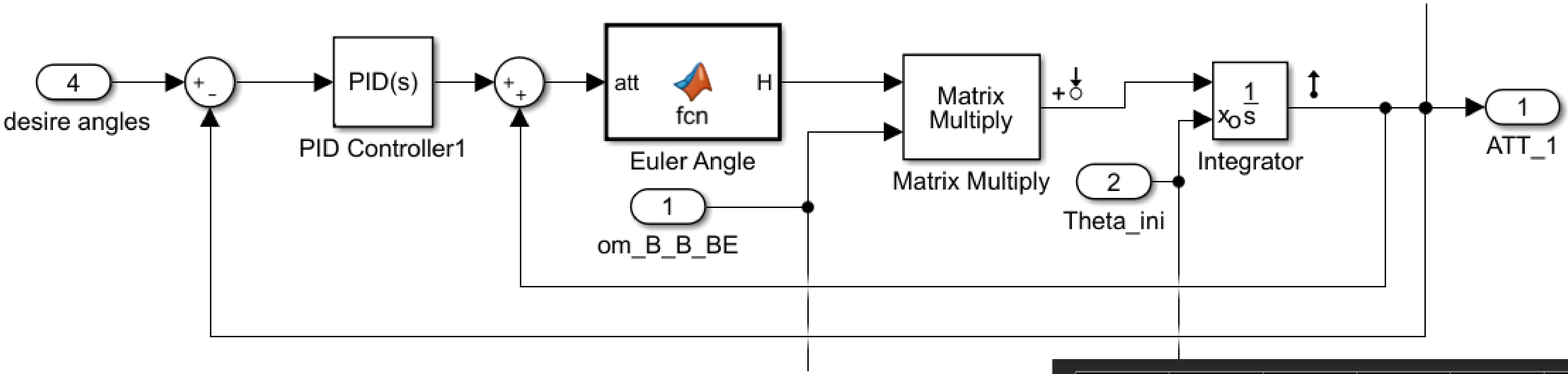
Yaw Right by
Adding Power to FR/BL Motors,
Reducing Power to FL/BR Motors

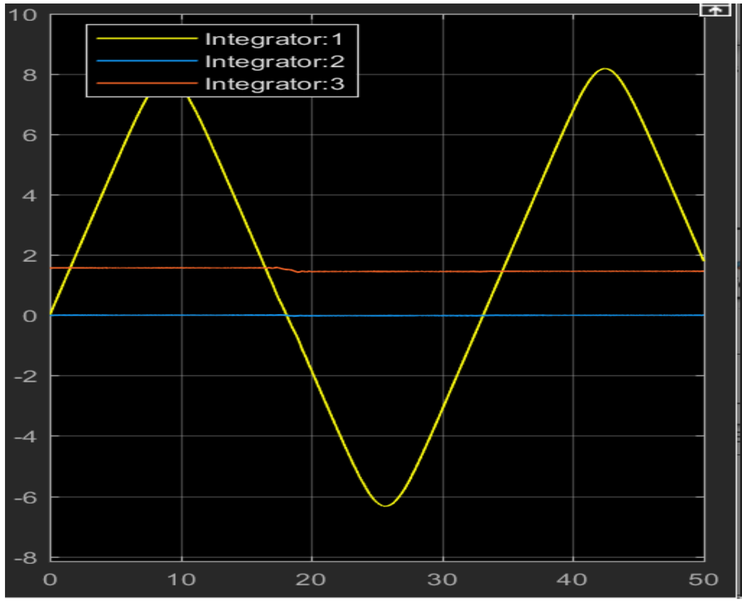
Non-linear System

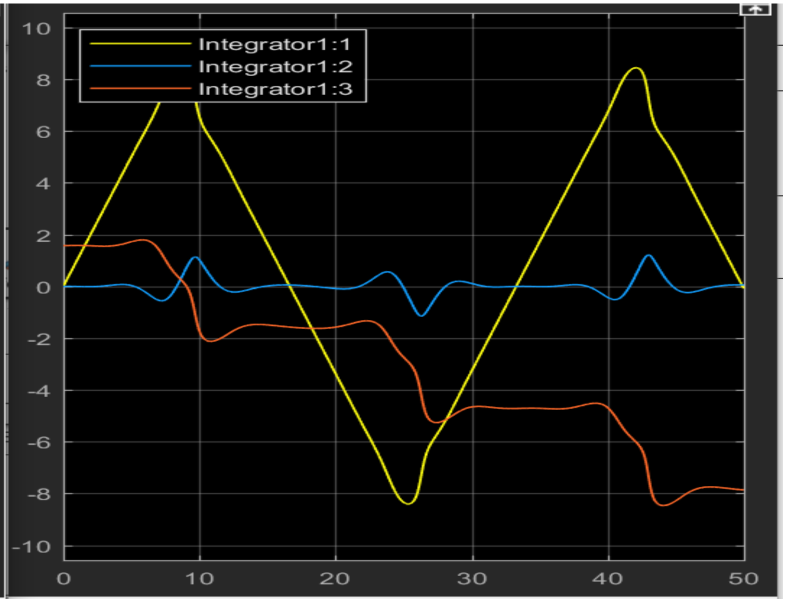
① Trimmed Model

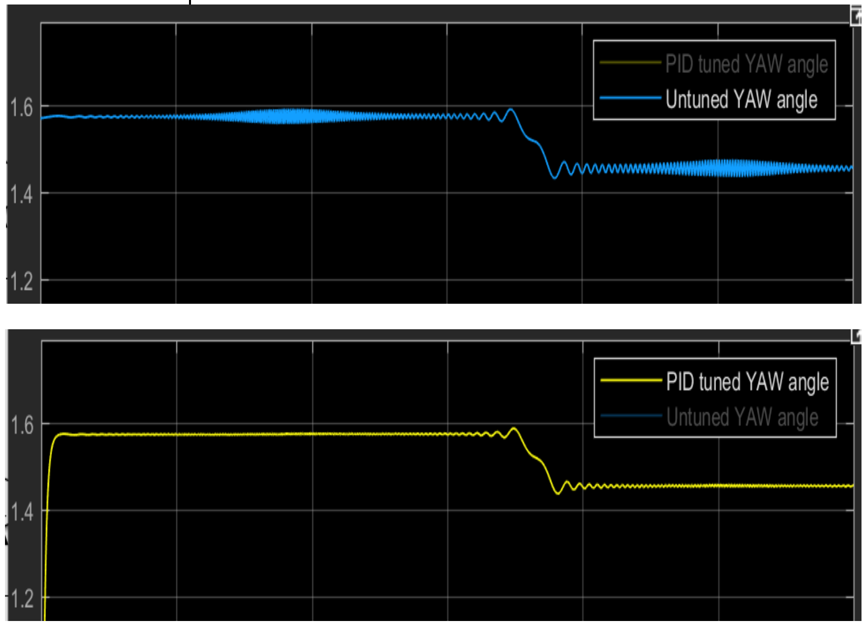
② PID Controller Design for System Damping

PID Controller Design for System Damping









◆ **With PID**

◆ **Without PID**

◆ **Yaw Angle Tuned**

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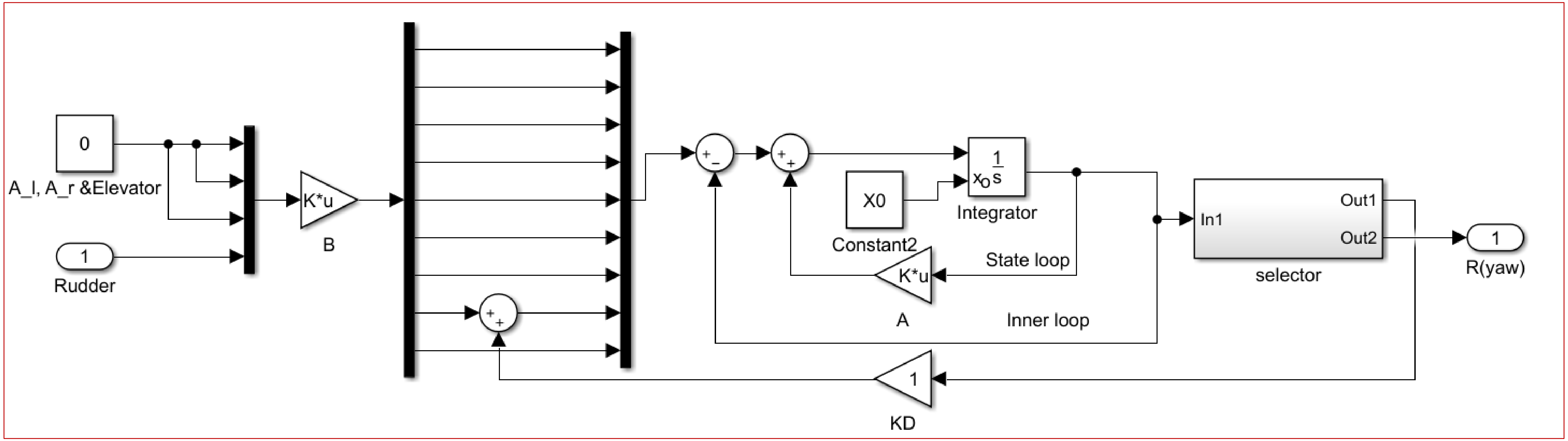
System Linearization

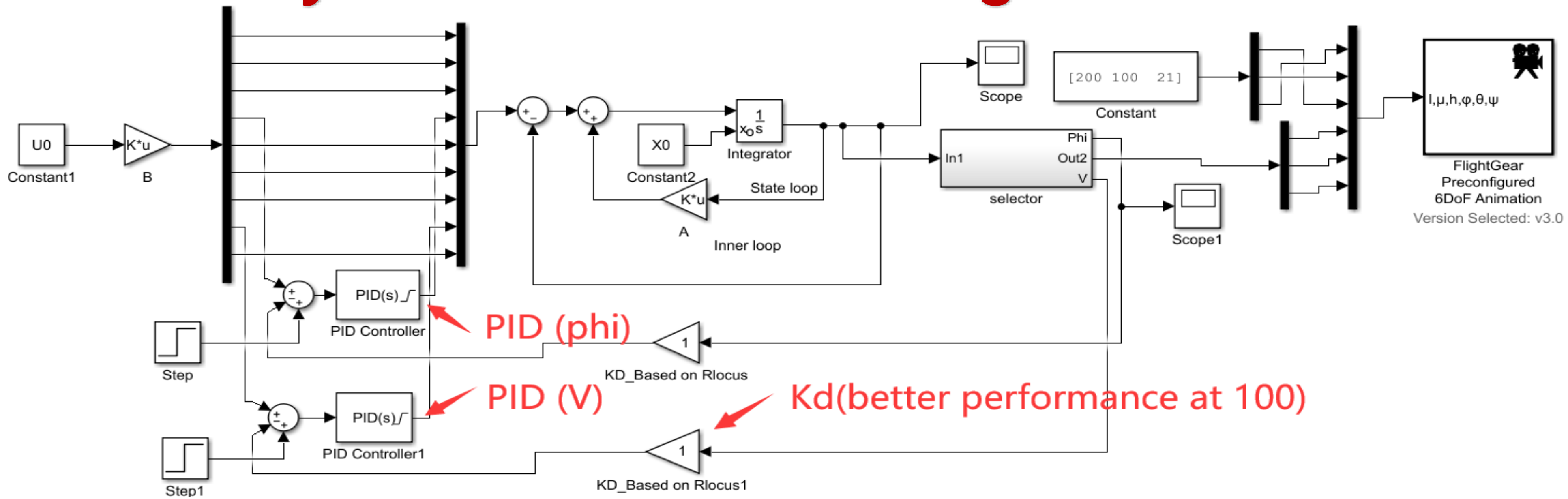
① Linearized System Behaviors & PID design
② Steady State Analysis.
③ Lateral Motion Control (Wash out Filter).
④ System Discretization

Model Linearization

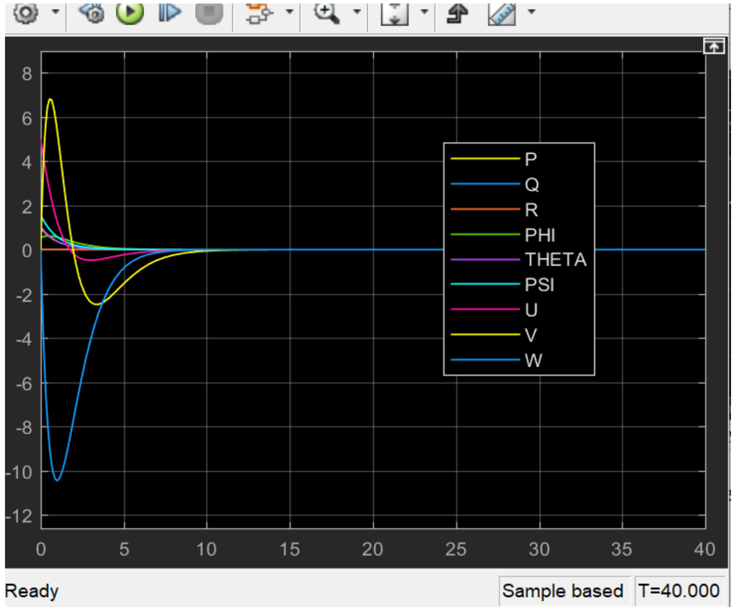
A	P	Q	R	PHI	THETA	PSI	U	V	W	Wash out
P_dot	-1	0.00017	-0.000284	0	0	0	-2.56E-06	-7.97E-06	3.61E-06	6.88E-09
Q_dot	9.76E-07	-1	0.004509	0	0	0	-0.00094	0.0007193	-0.001111	1.18E-07
R_dot	0.00011	0.00178	-1	0	0	0	-4.48E-05	-0.000135	6.26E-05	-3.80E-08
PHI_dot	1	0.3858	-0.8841	-1	0.000664	0	0	0	0	0
THETA_dot	0	-0.9165	-0.3999	-0.000344	-1	0	0	0	0	0
PSI_dot	0	0.5557	-1.273	-0.000229	0.000461	-1	0	0	0	0
U_dot	0	-0.00335	0.002001	-3.476	-2.786	3.102	-0.9998	-0.000298	-0.0001301	-8.55E-09
V_dot	0.003349	0	0.002582	-30.67	-2.13	30.73	0.0002746	7.64E-05	0.00463	7.35E-09
W_dot	-0.002	-0.00258	-1.24E-09	-1.42E-10	-22.26	-3.329	0.0001314	-0.004547	-1	6.18E-09
Wash out	0	0	1	0	0	0	0	0	0	-5.00E+00



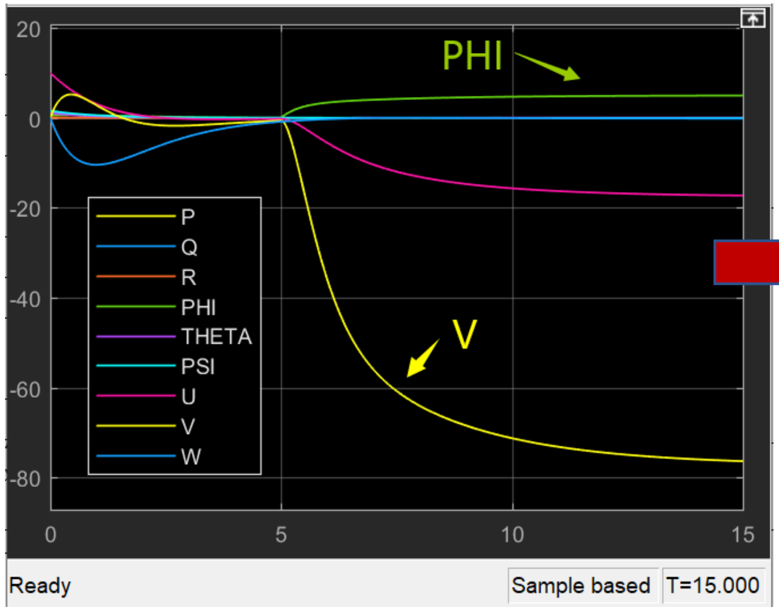
Linearized System Controller Design



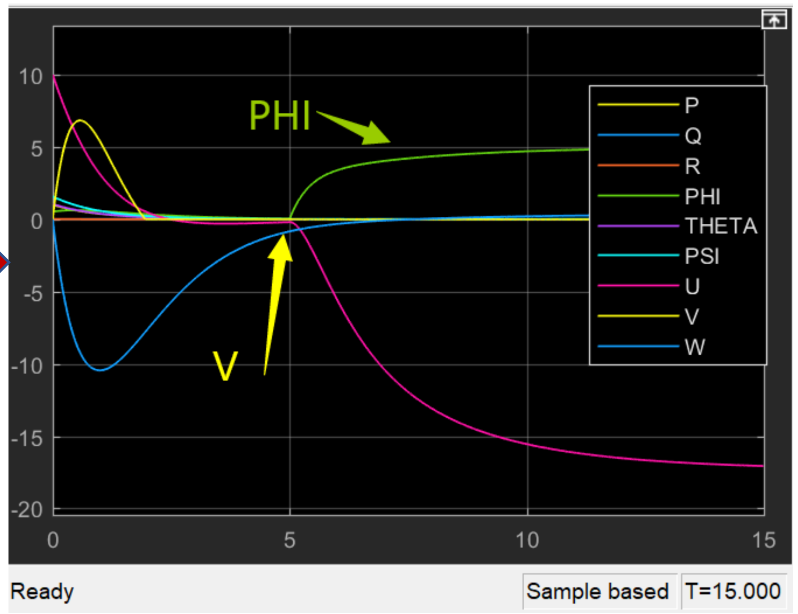
◆ No PID Applied



◆ PID only applied to 'phi'



◆ PID applied to 'phi' &'V'



Steady State Analysis.

Oscillatory Mode

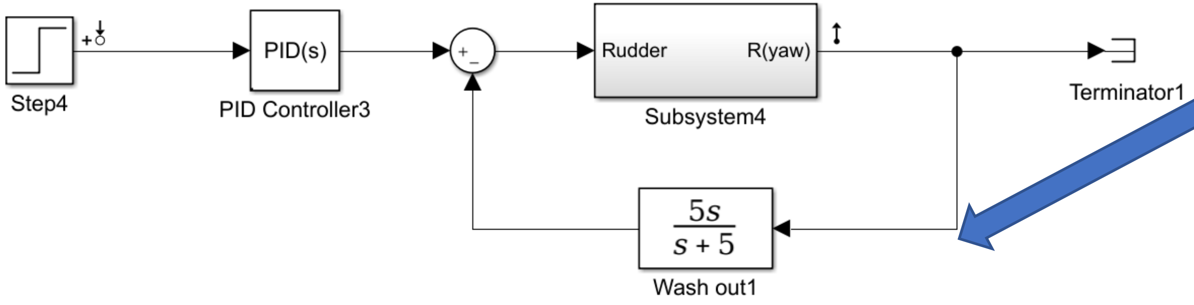
$$\lambda = \begin{cases} -\zeta\omega_n \pm \omega_n\sqrt{\zeta^2 - 1} & \text{for } \zeta > 1 \\ -\zeta\omega_n & \text{for } \zeta = 1 \\ -\zeta\omega_n \pm i\omega_n\sqrt{1 - \zeta^2} & \text{for } \zeta < 1 \end{cases}$$

Short-period			Dutch Roll Mode		
-0.86282	+	0.25016i	-1.0241	+	0.058674i
-0.86282	-	0.25016i	-1.0241	-	0.058674i
Damping Ratio		0.96045	Damping Ratio		0.99836
Natural Freq (rad/s)		0.89835	Natural Freq (rad/s)		1.0258
Time Period (s)		6.9906	Time Period (s)		6.1221

Stable Exponential Mode

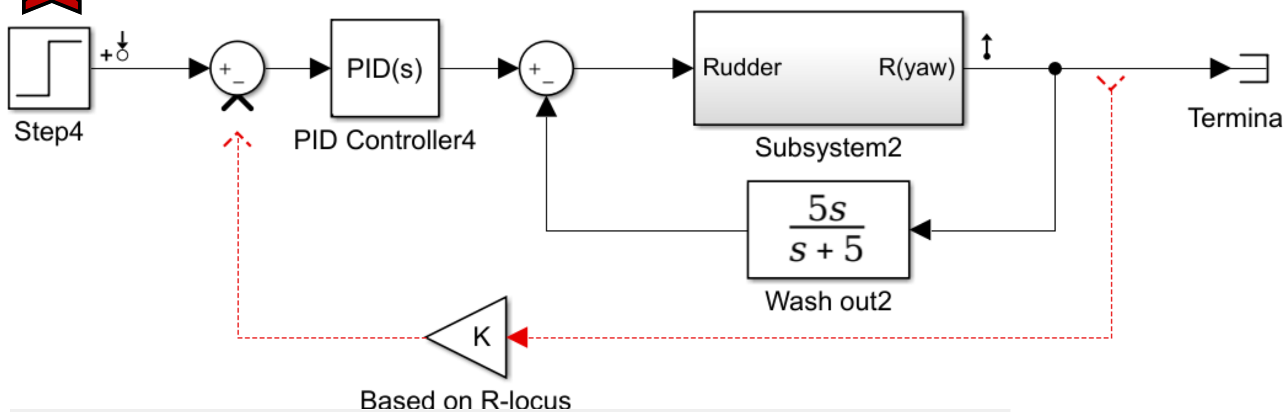
$$\lambda_{roll} = -\frac{1}{\tau} = L_p$$

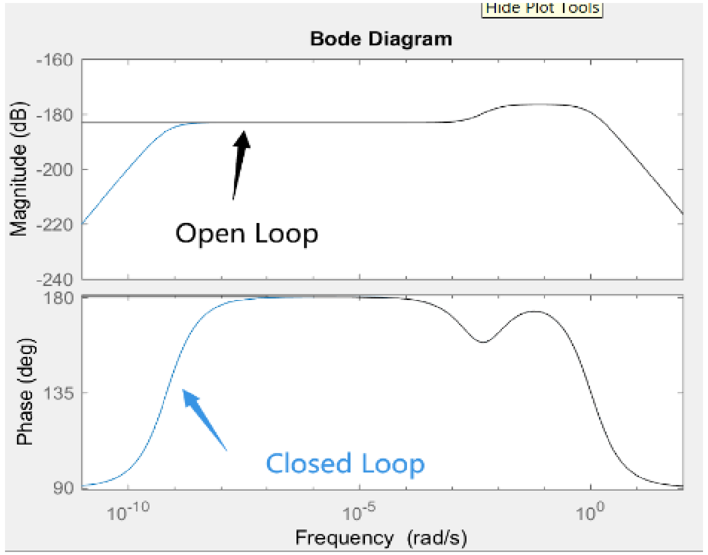
Roll Mode			Time Constant(s)	
-1.0002	+	0i	0.99980004	
-0.99896	+	0i	1.00104108	
-0.9549	+	0i	1.04723008	
-1.2786	+	0i	0.78210543	
Roll Mode (unstable)			Time Constant(s)	
0.0068486	+	0i	146.015244	(Long)
Roll Mode (From Washout)			Time Constant(s)	
-5	+	0i	0.2	



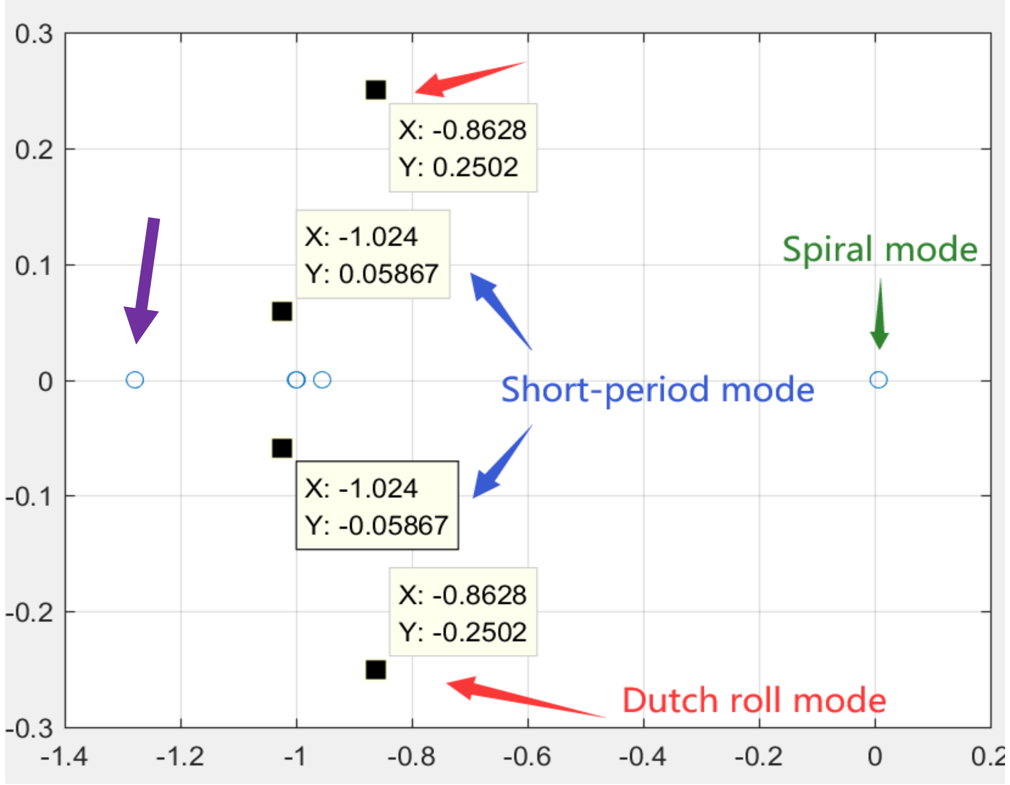
HOW can I change these Dynamic Behaviors?

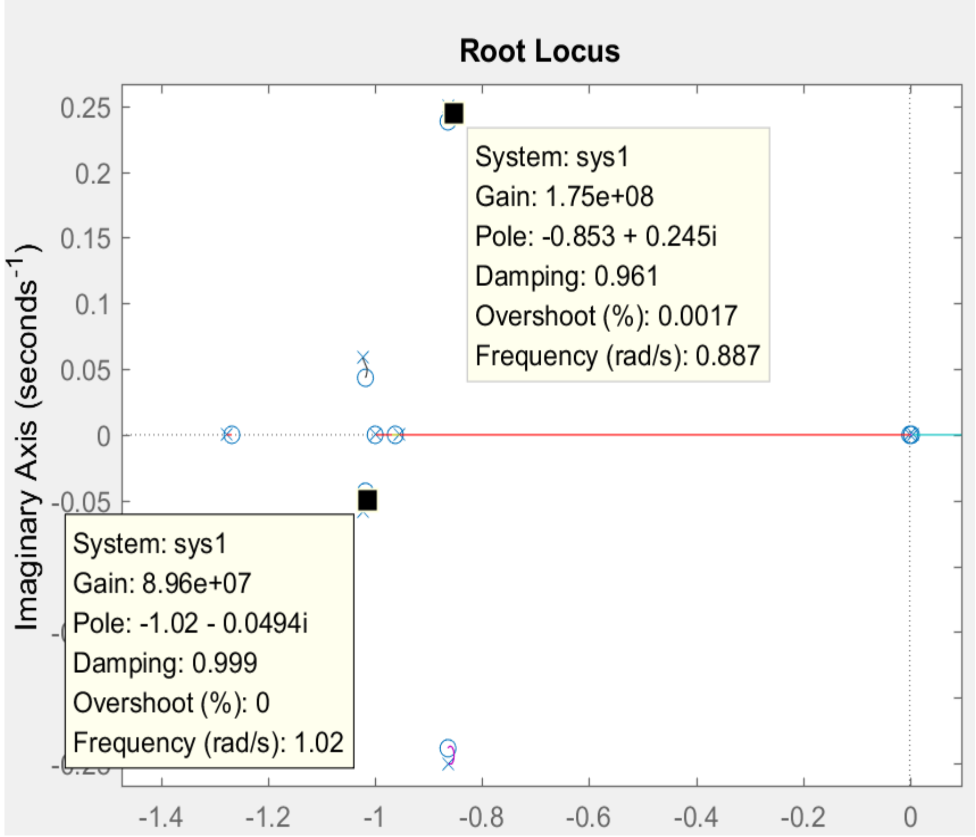
‘K’ Design Using R-locus





◆ Bode in Freq Domain

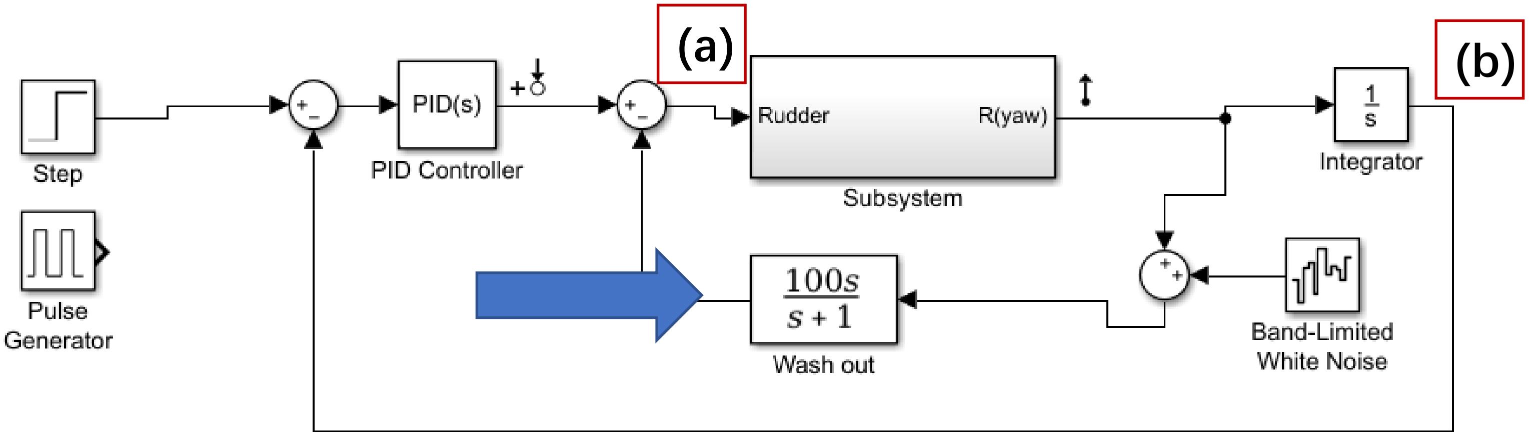




◆ Rlocus in Time Domain

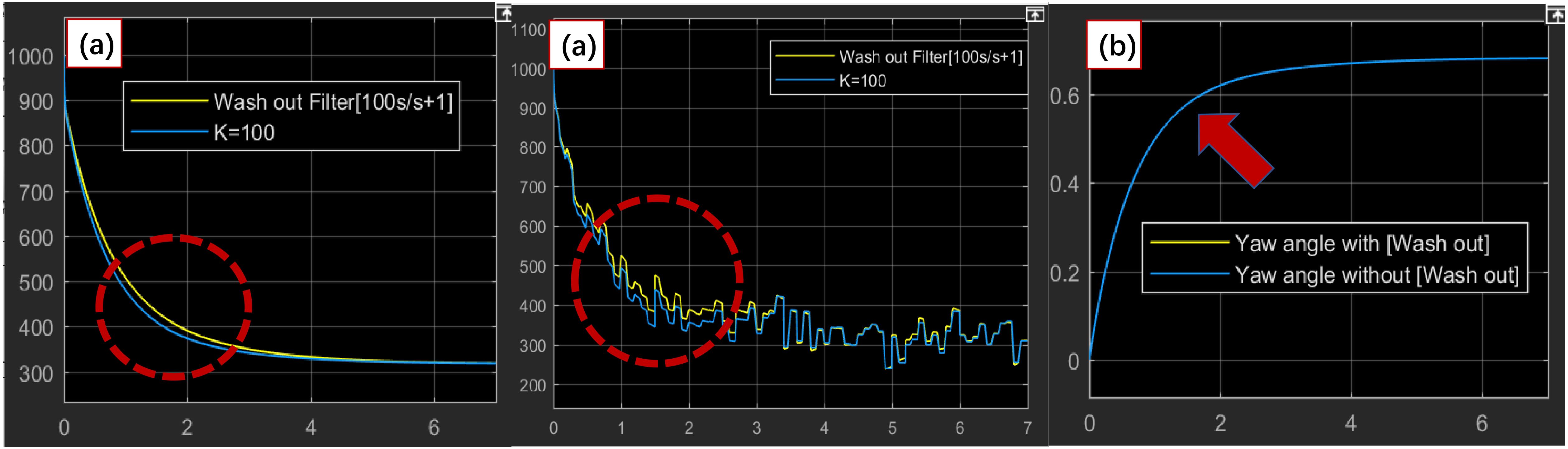
◆ Eigenvalue(A) Distribution

Wash Out Filter



① **Washout Filter** removes slowly-changing component and preserves the fast-changing component in **INPUT**

② **OUTPUT** remains unchanged



Discretized System (Digital Control)

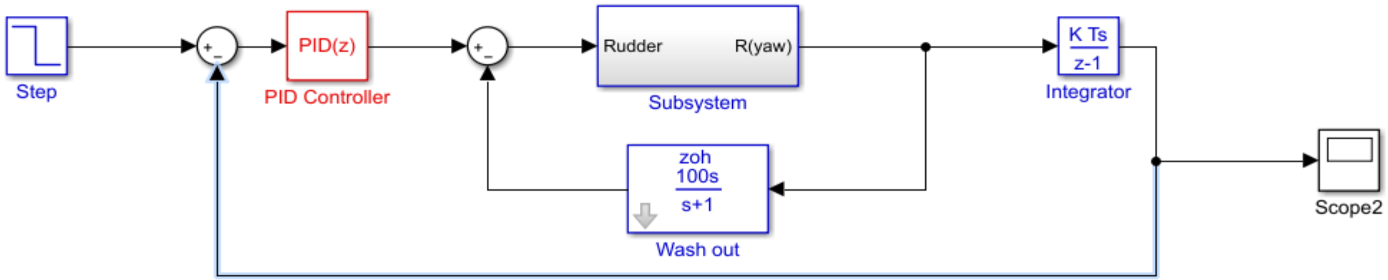


Figure-1 Discrete System

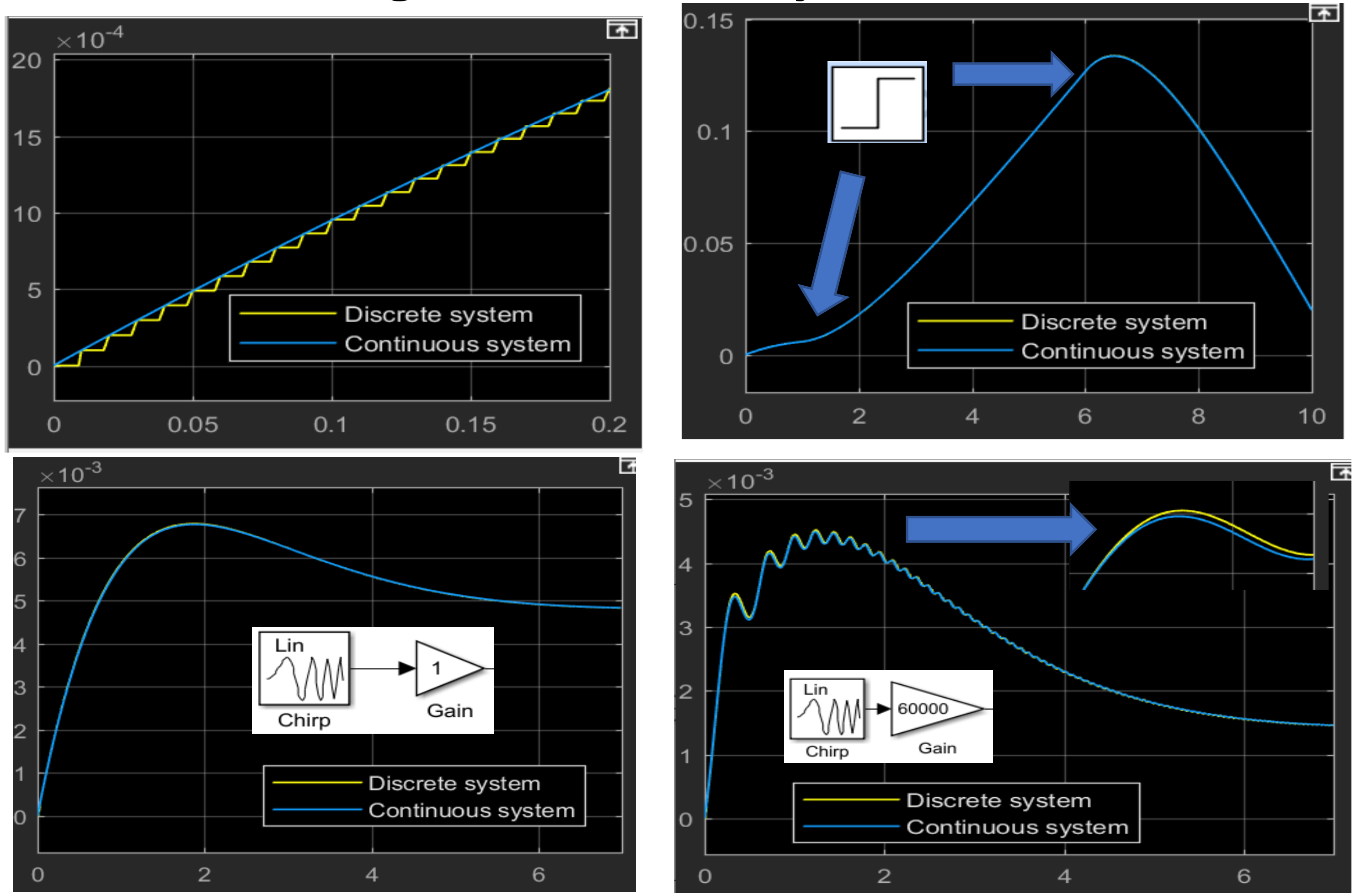


Figure-2 Discrete VS Continuous

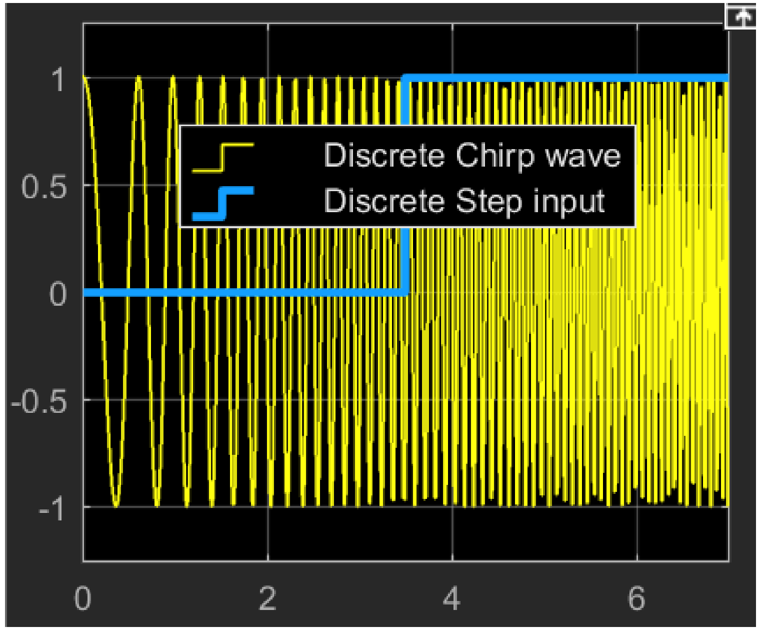


Figure-3 Signals

Signal: STEP & CHIRP

Sample time: 0.01s

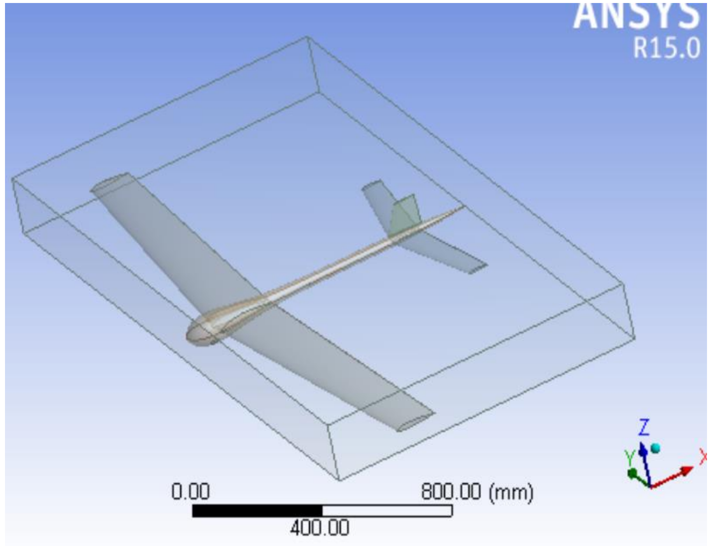
Discrete Method: ZOH

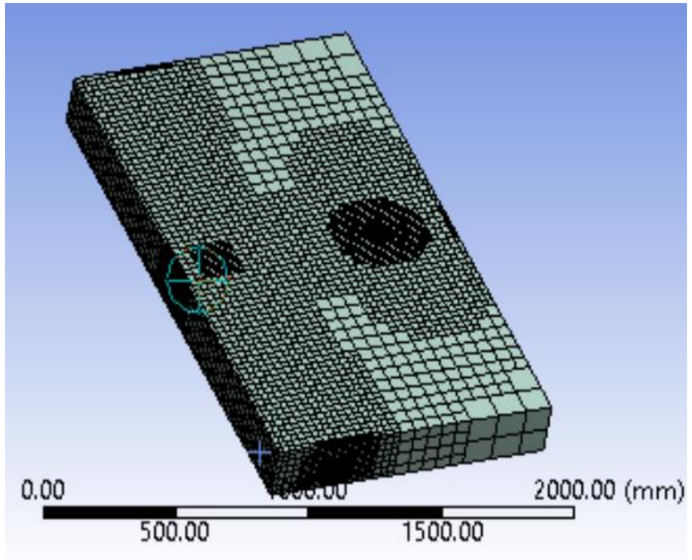
Aerodynamic Analysis for *Sonic Flight*

① FEA in ANSYS
② CFD & Wind Tunnel Analysis in ANSYS
③ Aero-coefficient Comparison (Alpha=Beta=0[deg])

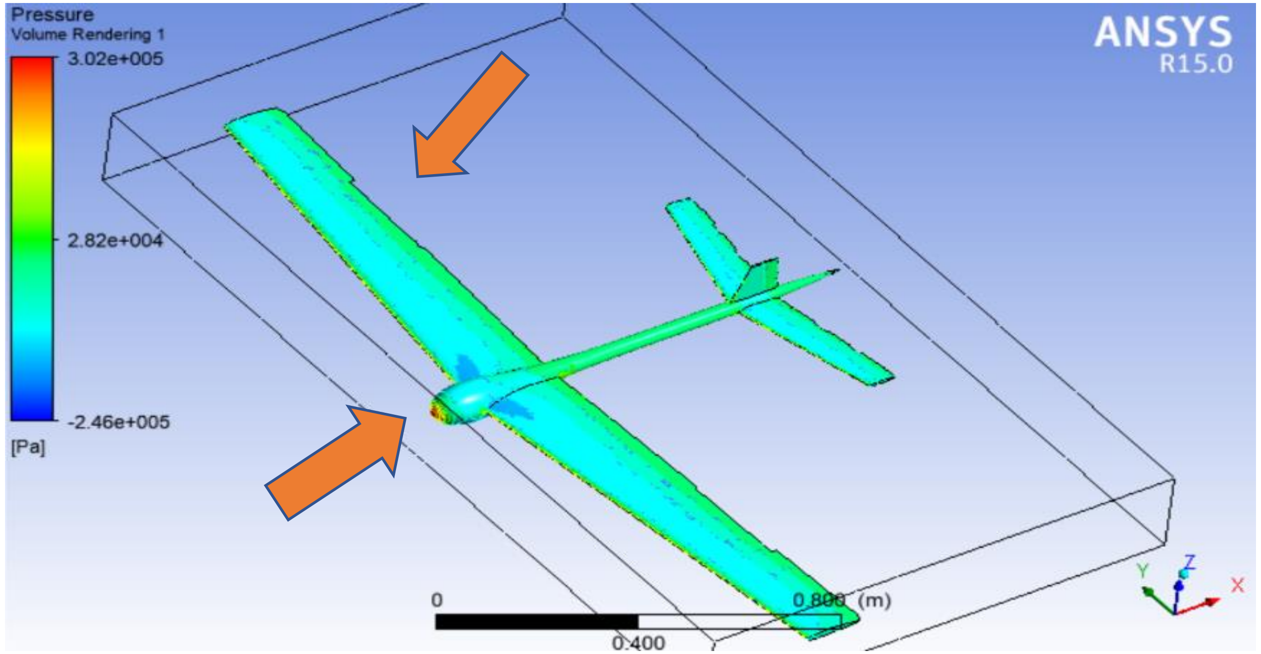
The Aerodynamic Analysis in ANSYS

Model Name	ASW28
Velocity(m/s)	400
Temperature(ºF)	77
Altitude(m)	1000
Air Density(kg/m^3)	1.074



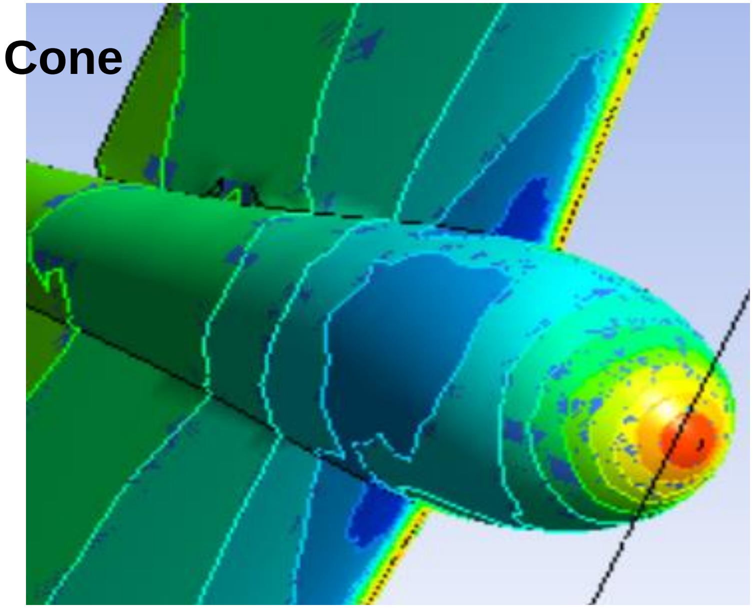


◆ Pressure Distribution



◆ Finite Element Analysis(FEA)

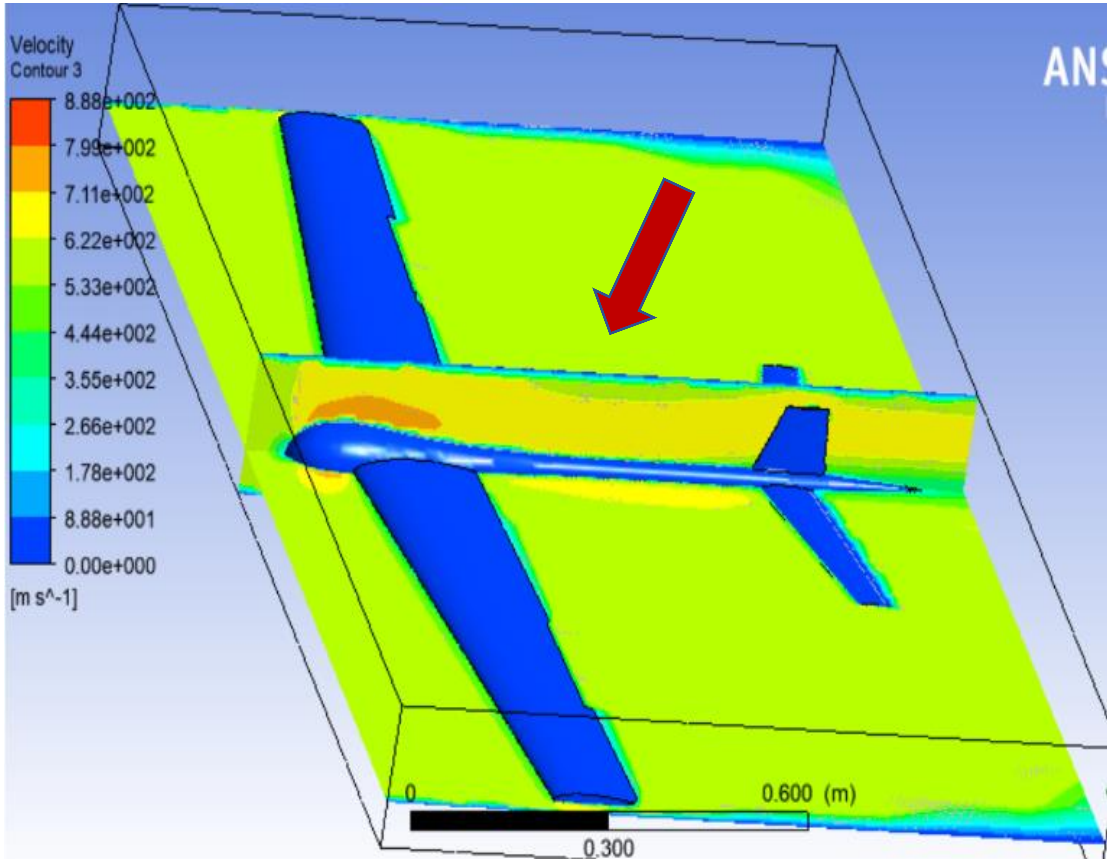
Cephalic Cone



Wind Tunnel & CFD Analysis in ANSYS

◆ Velocity Distribution

(Alpha=Beta=0[deg])



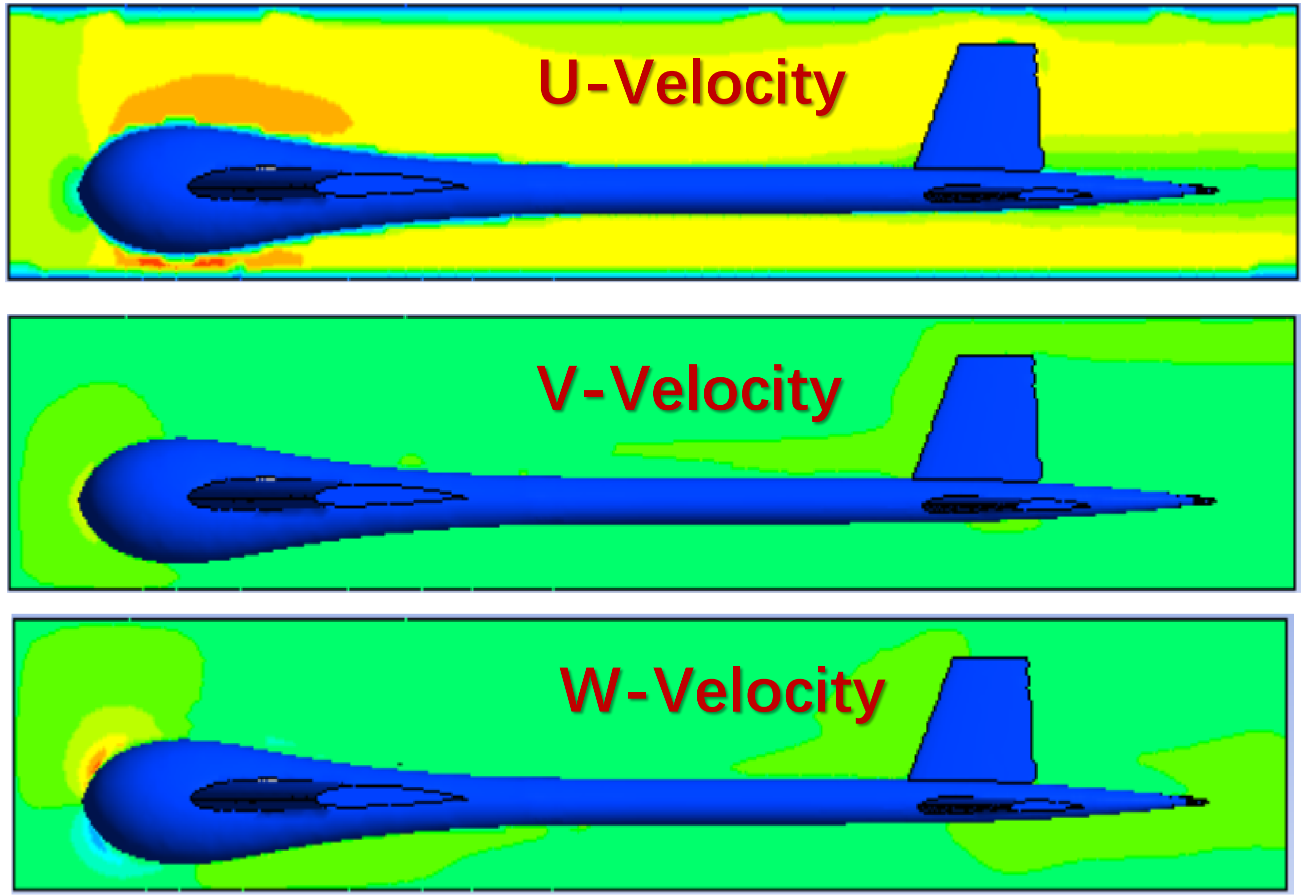
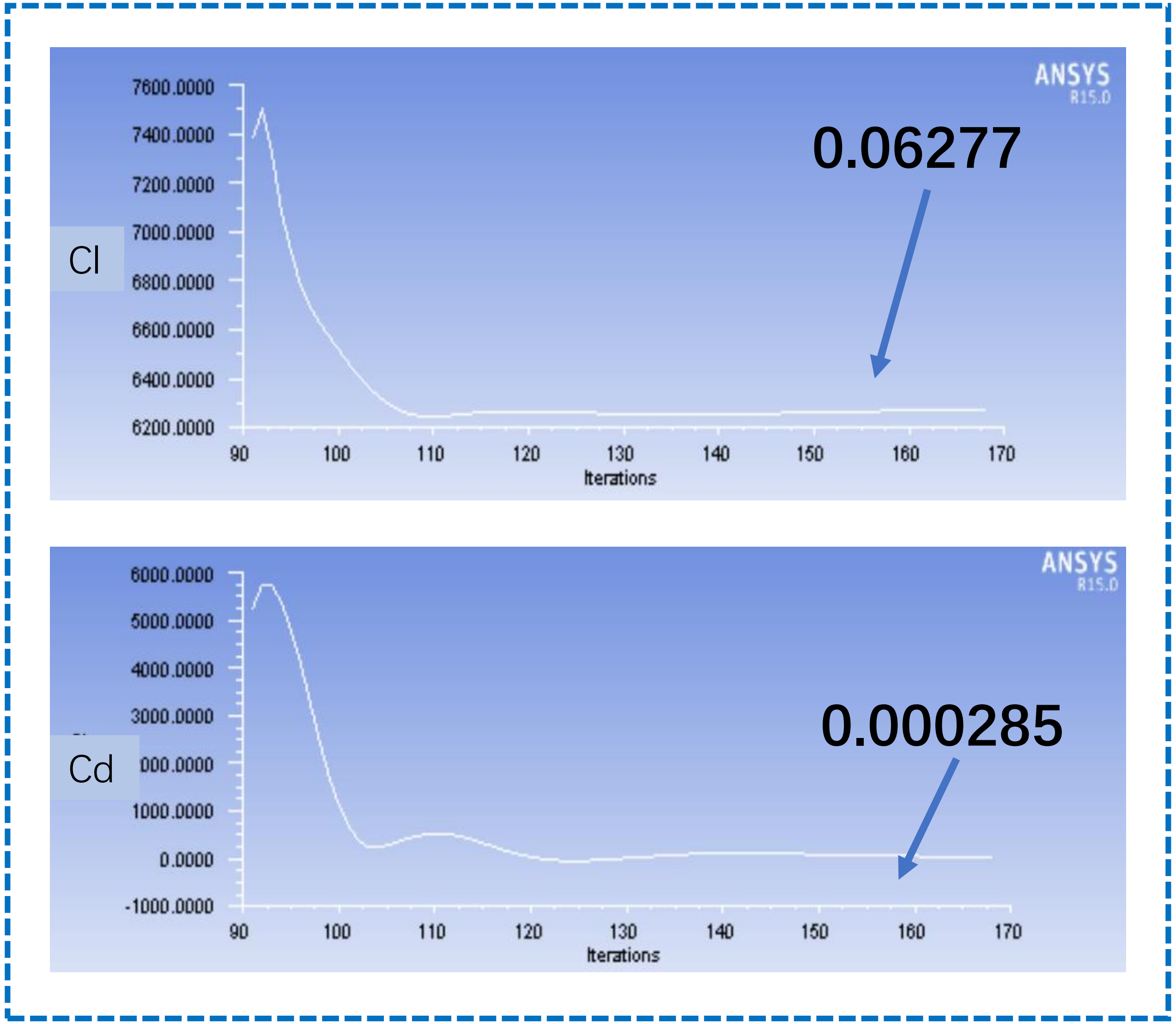
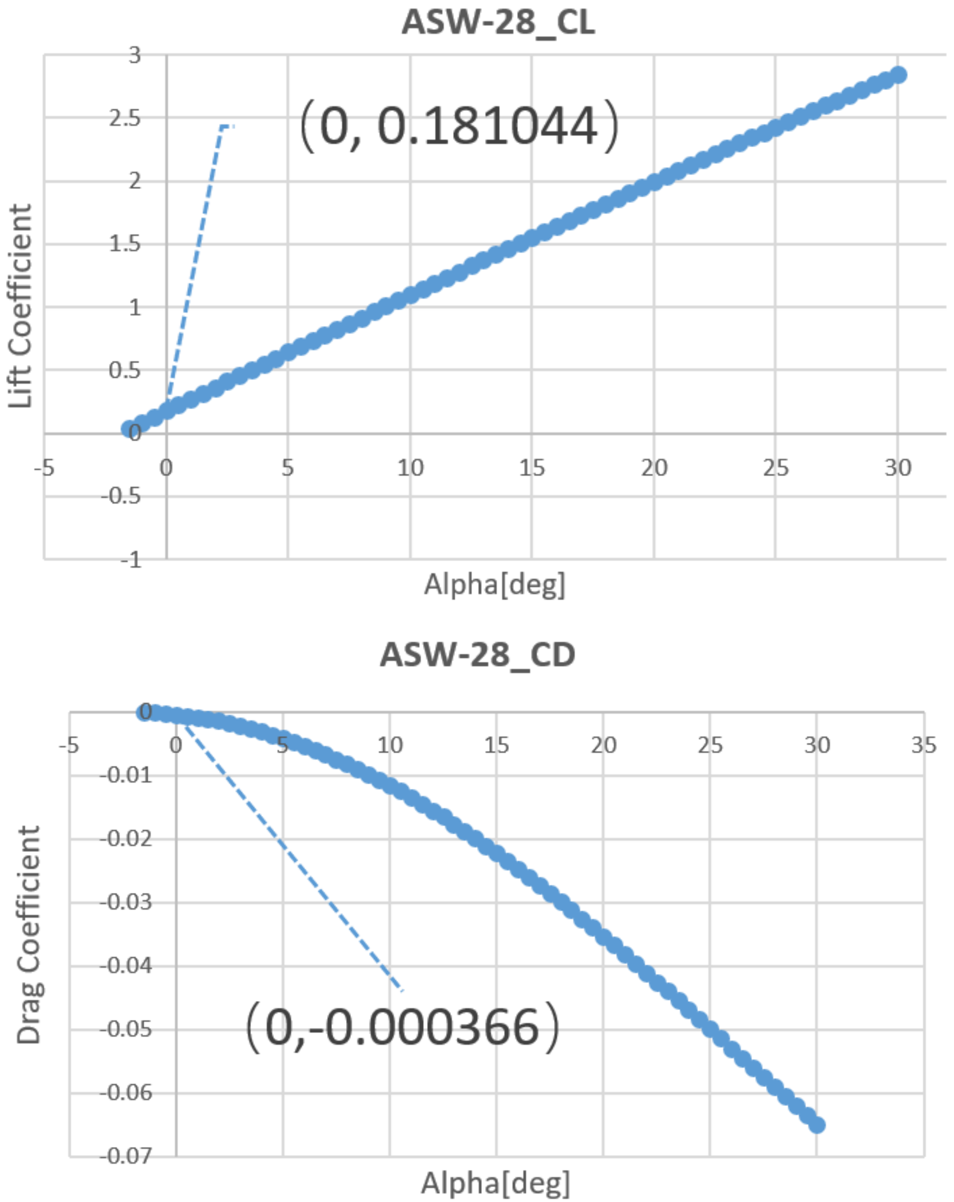


Figure. Velocity Contour (left); [u; v; w] in Longitudinal Symmetry Plane

Aero-coefficient Comparison (Alpha=Beta=0[deg])



ANSYS (x-time, y-coefficient)



XFLR5

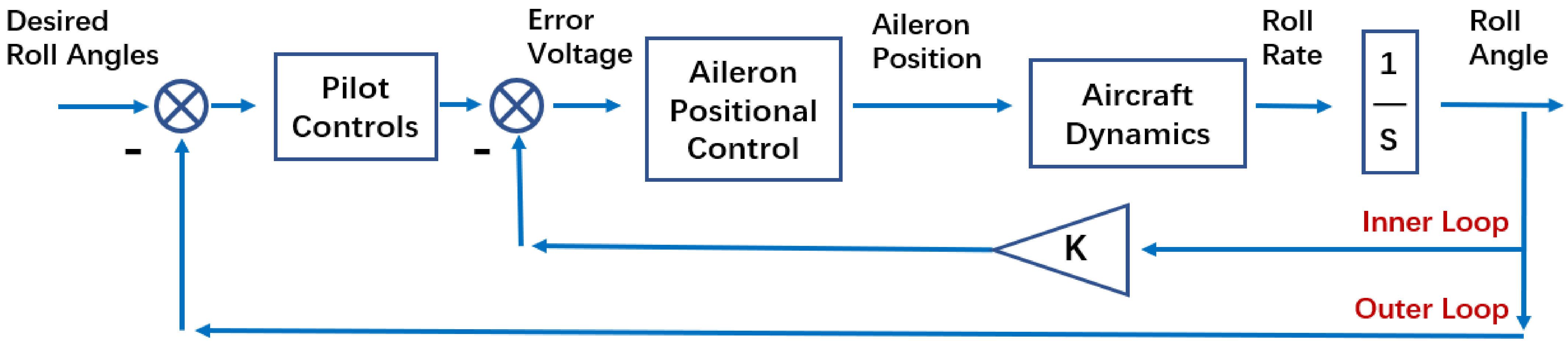
Simulation

① Pilot Control System

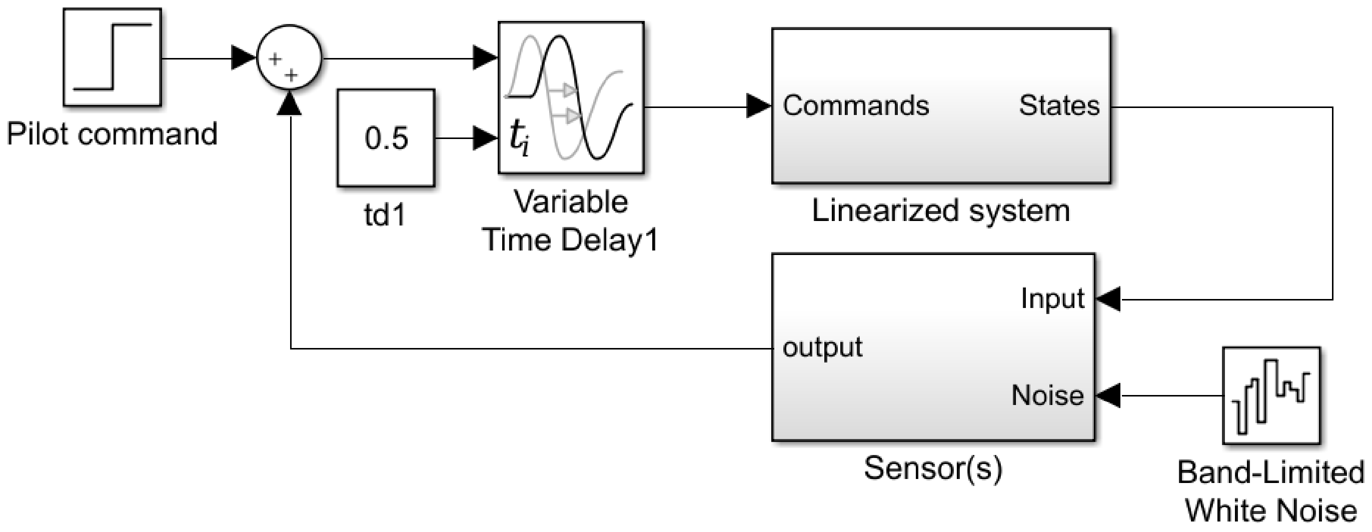
② Skidded to Turn Simulation

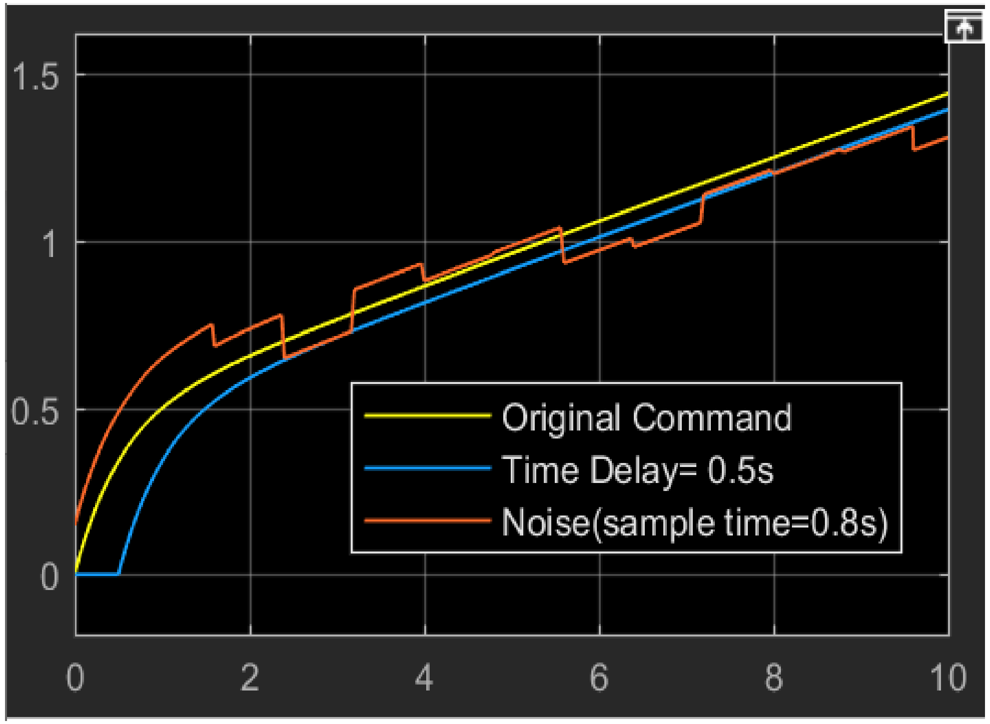
Pilot Control Simulation

➢ Autopilot Roll Angle Control Theorem

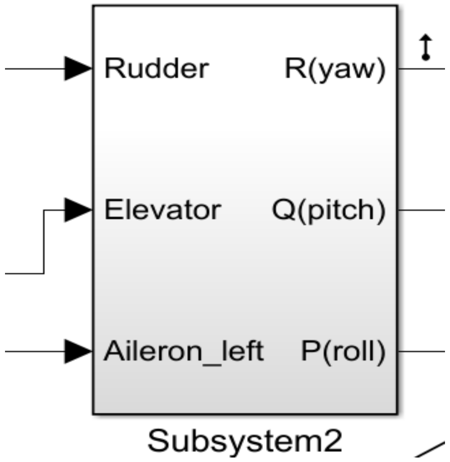


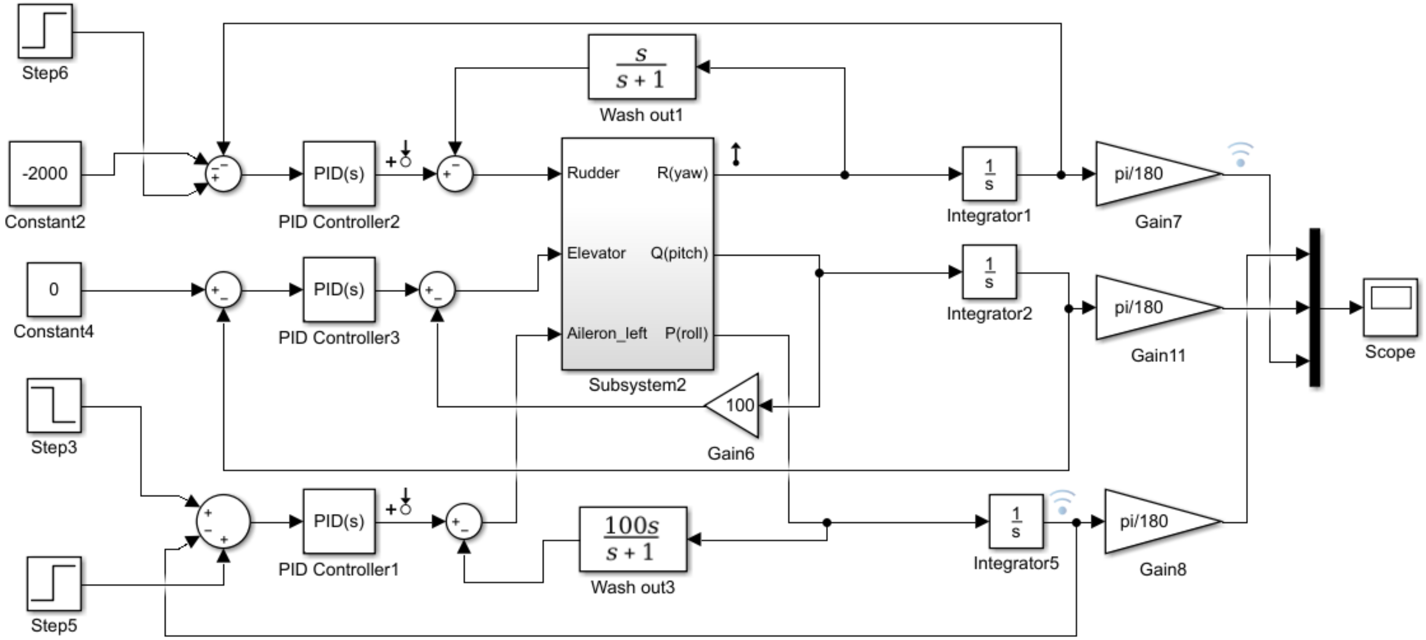
➢ Pilot Control (with Time-delay & Disturbance)



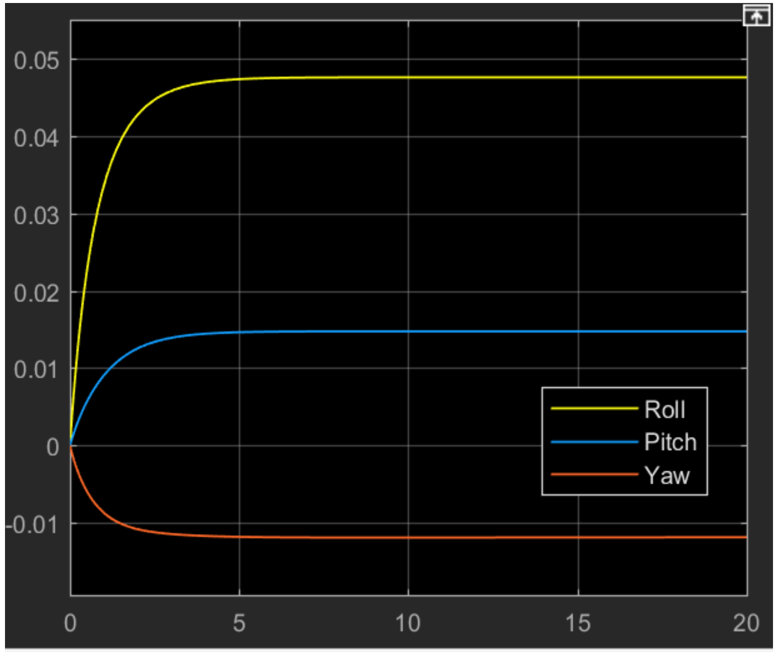


MIMO System Control

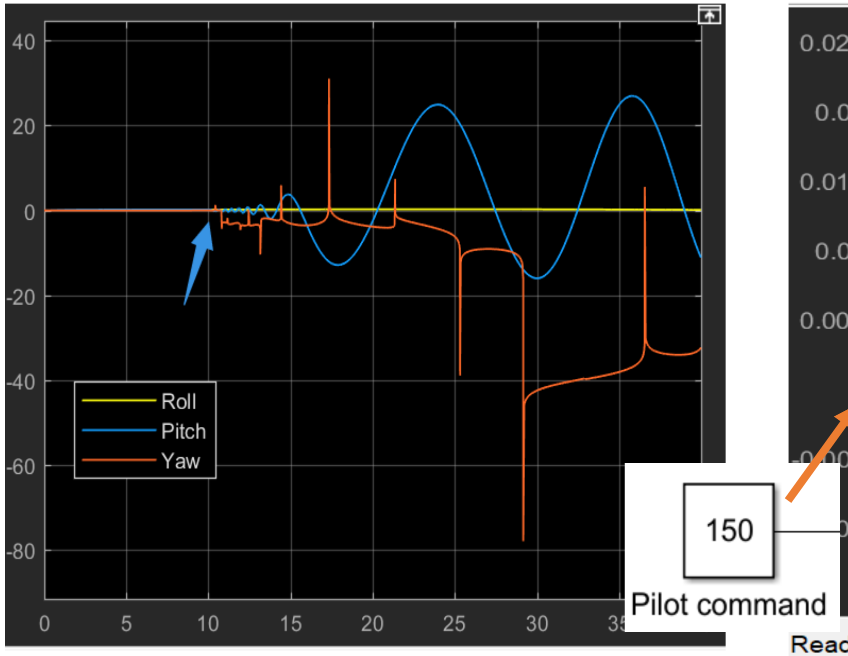




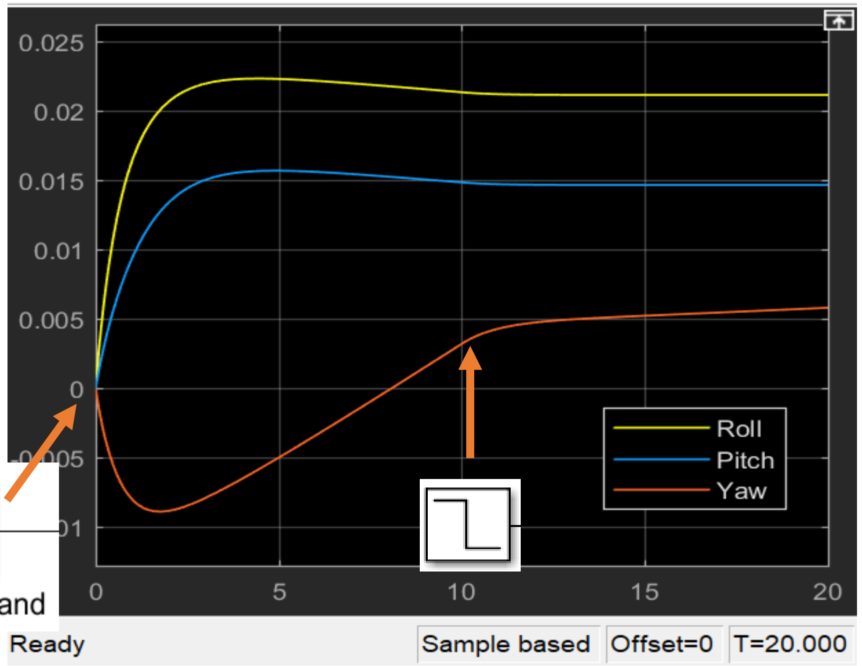
➢ No Signal Input



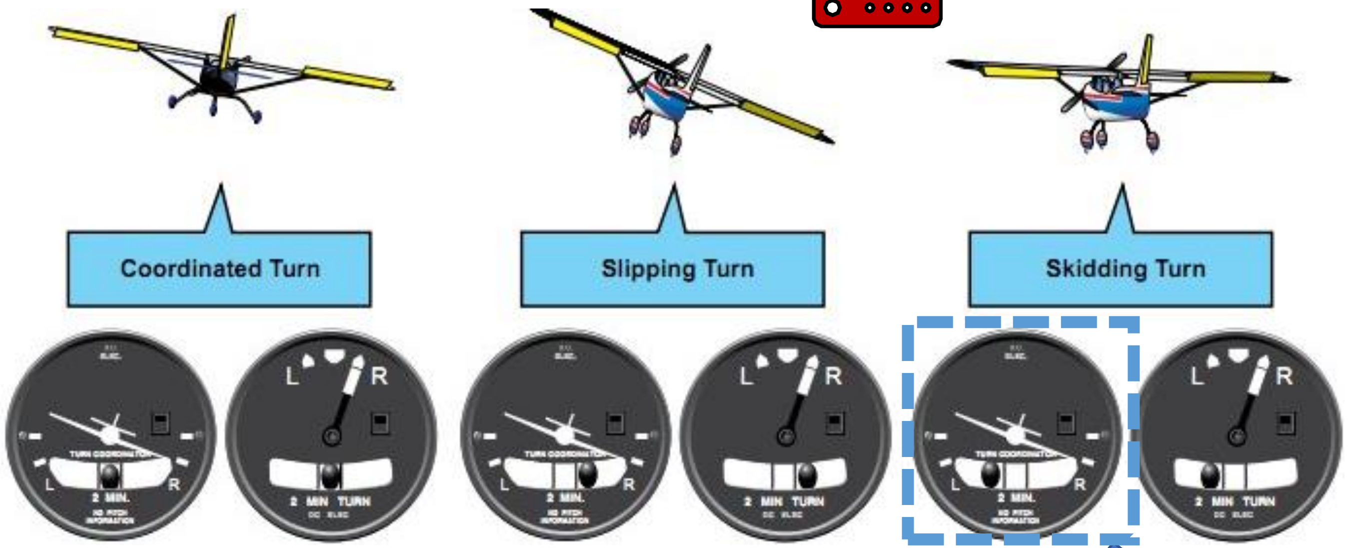
➢ Large Signal Input

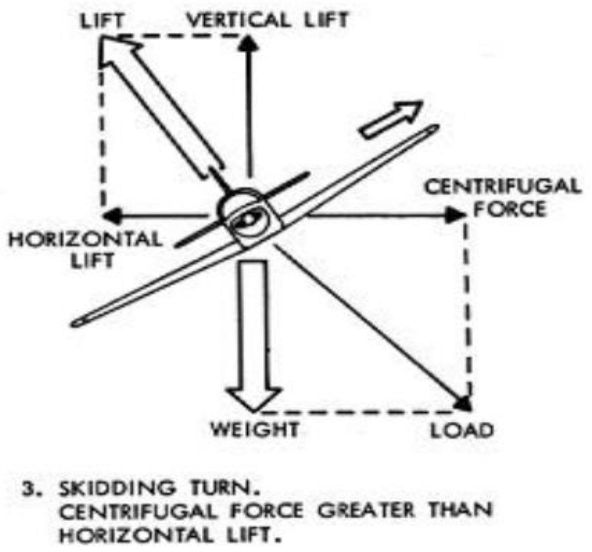


➢ Lateral Motion Control

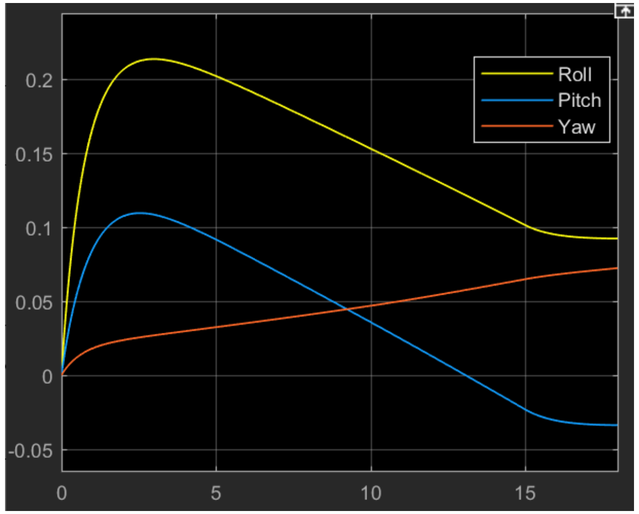


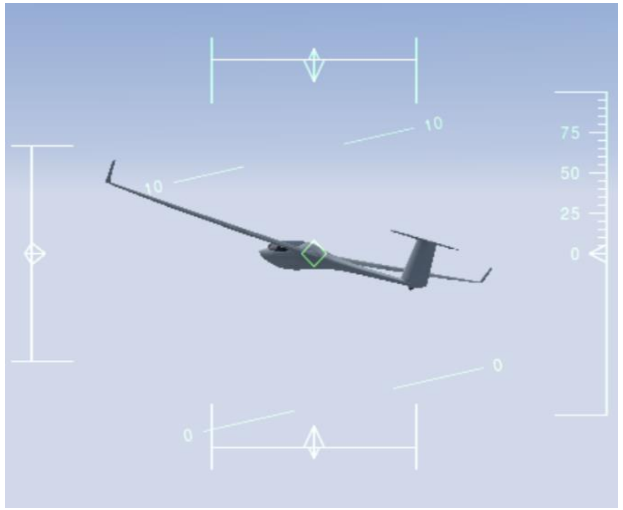
Lateral Motion Control-Skid to Turn

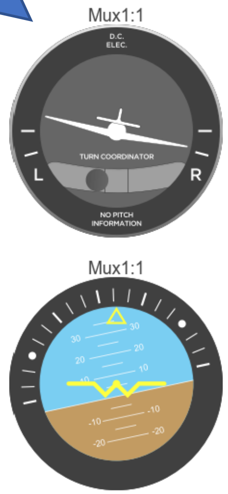


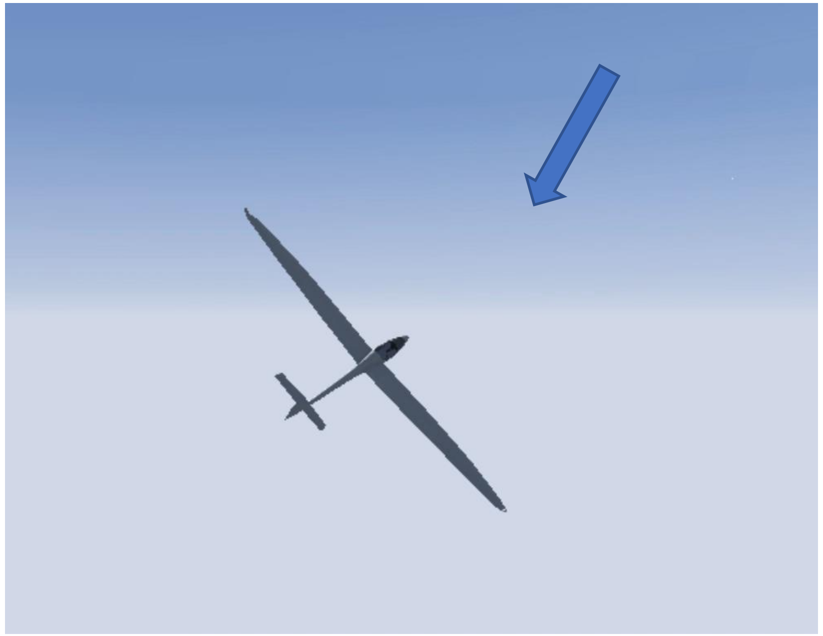


➢ Skid to Turn angles

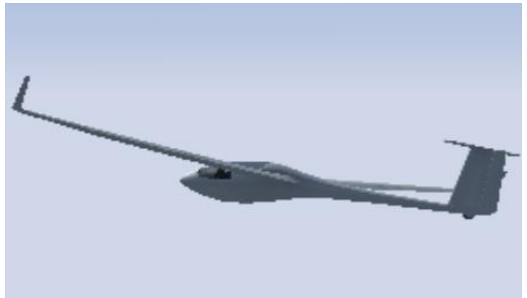


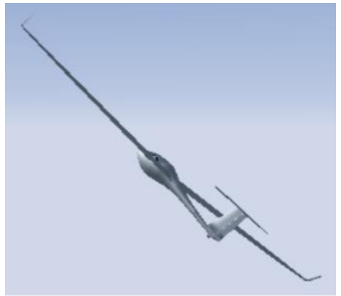




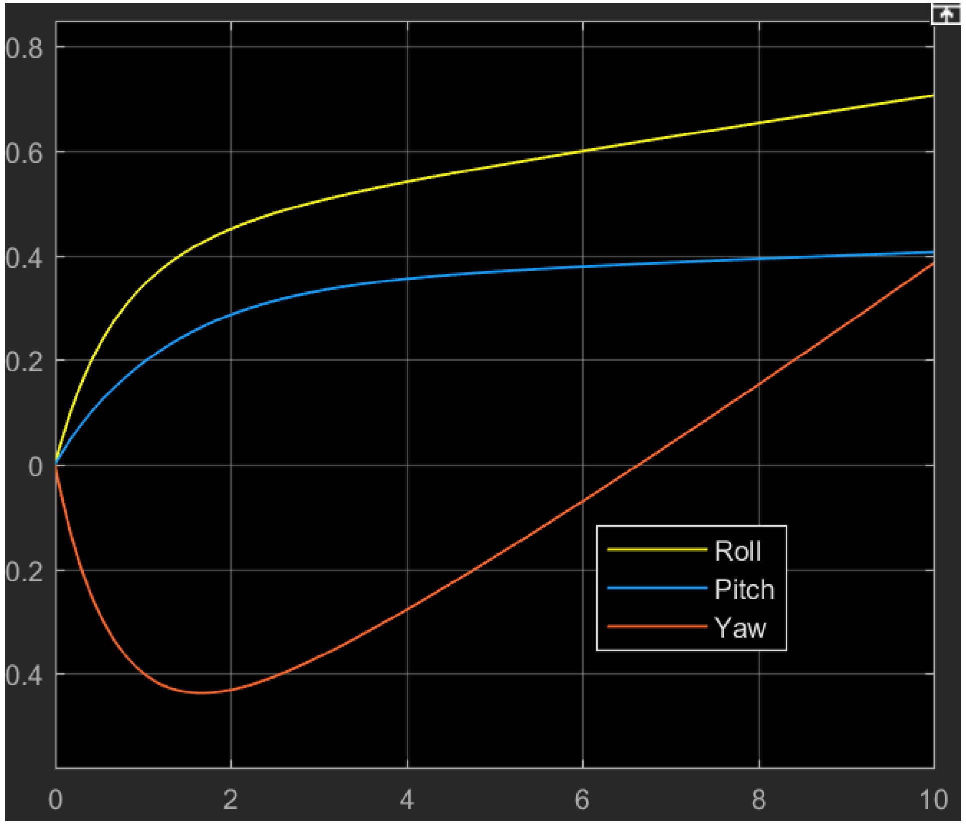


➢ Skid to Turn Simulation





Skid to Turn-Simulation



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Thanks for Watching!!

Questions ?