Autopilot 2022
Group 3

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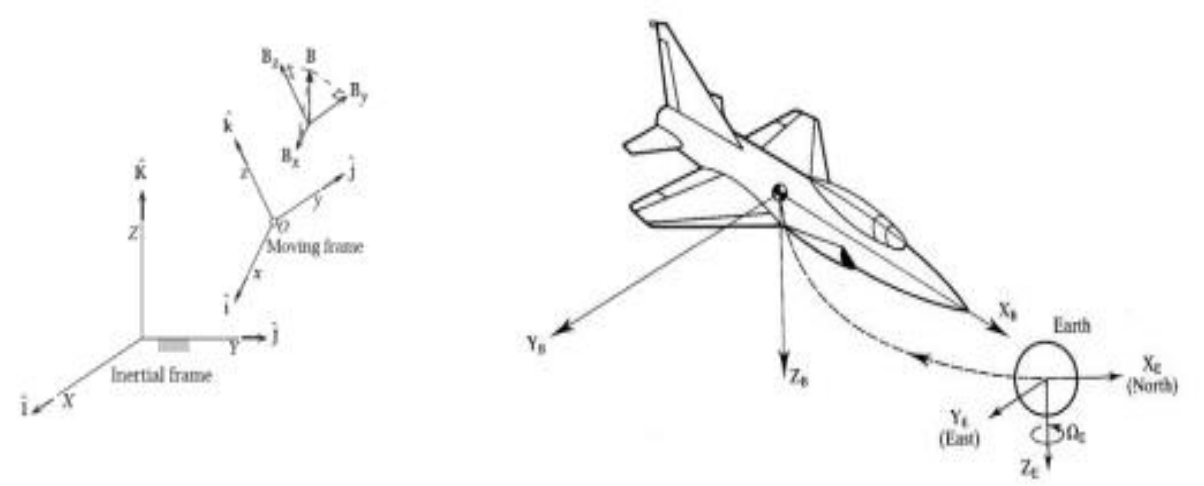
➢ TASK 1

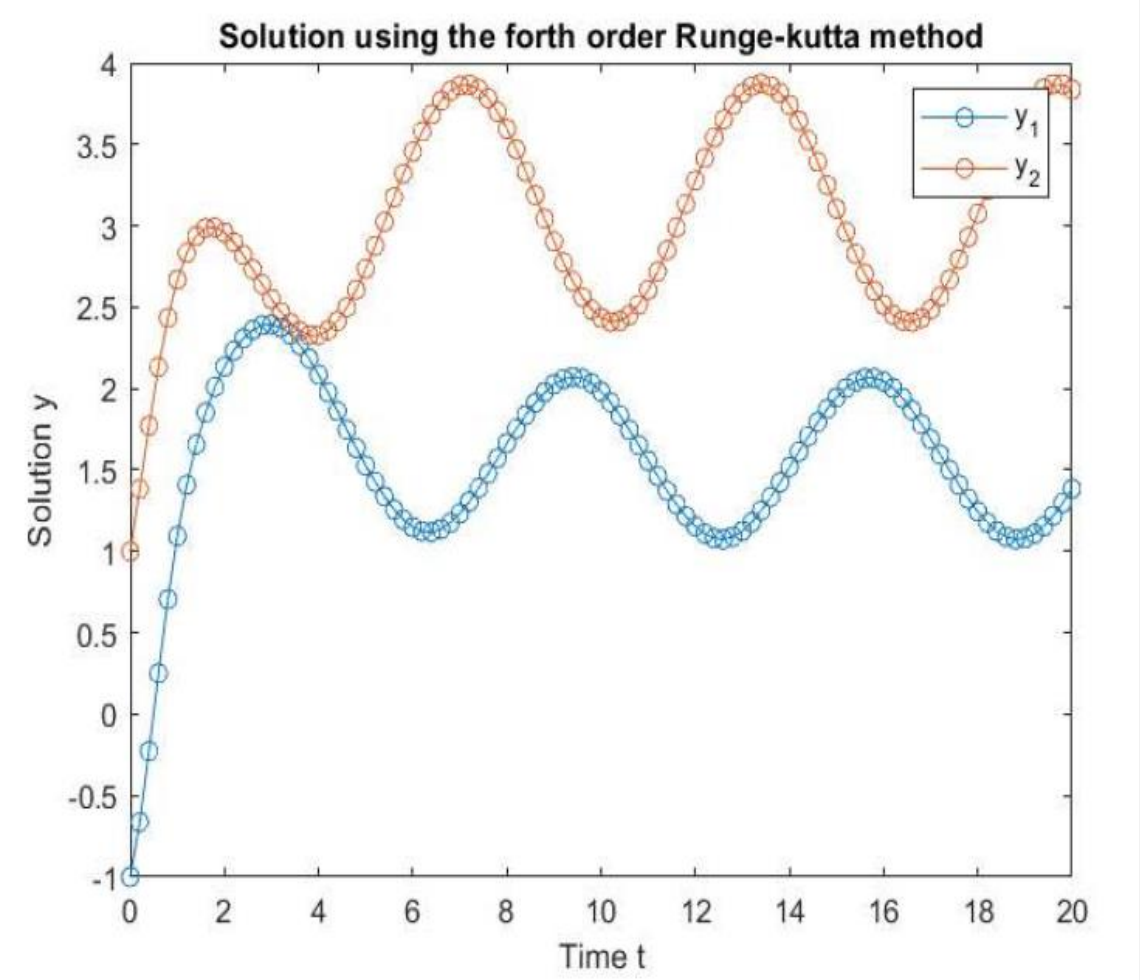
Overview

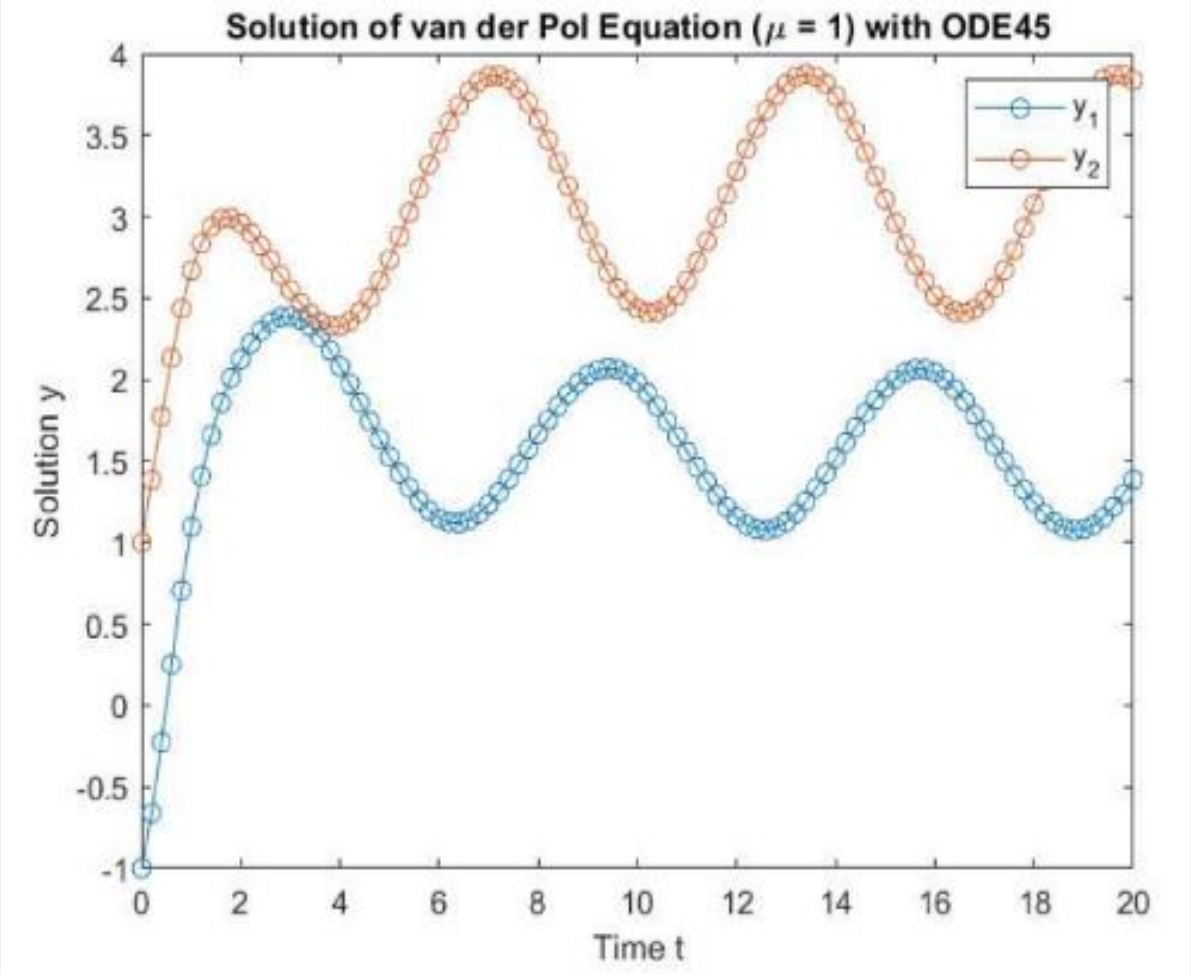
- What is the Autopilot ?
  - Autopilot objectives.
  - Autopilot Roles.
  - Input and Output to Autopilot.
  - Differences between SAS & Autopilot.
  - Onboard Computer sensors.



- Flight Mechanics overview
  - Difference between body axes & inertial(fixed) axes.
  - Kinetics & kinematics EOM of an A/C.
- Numerical solution of ODEs
  - Runge Kutta method : $y_{n+1} = y_{n+1} + \frac{1}{6}(k_1 + 2k_2 + 2k_3 + k_4)$
  - RK4 & validate it with ODE45 on Matlab.

The following figures shows the results obtained from solving using Runge Kutta method and validation with ODE45 MATLAB function:





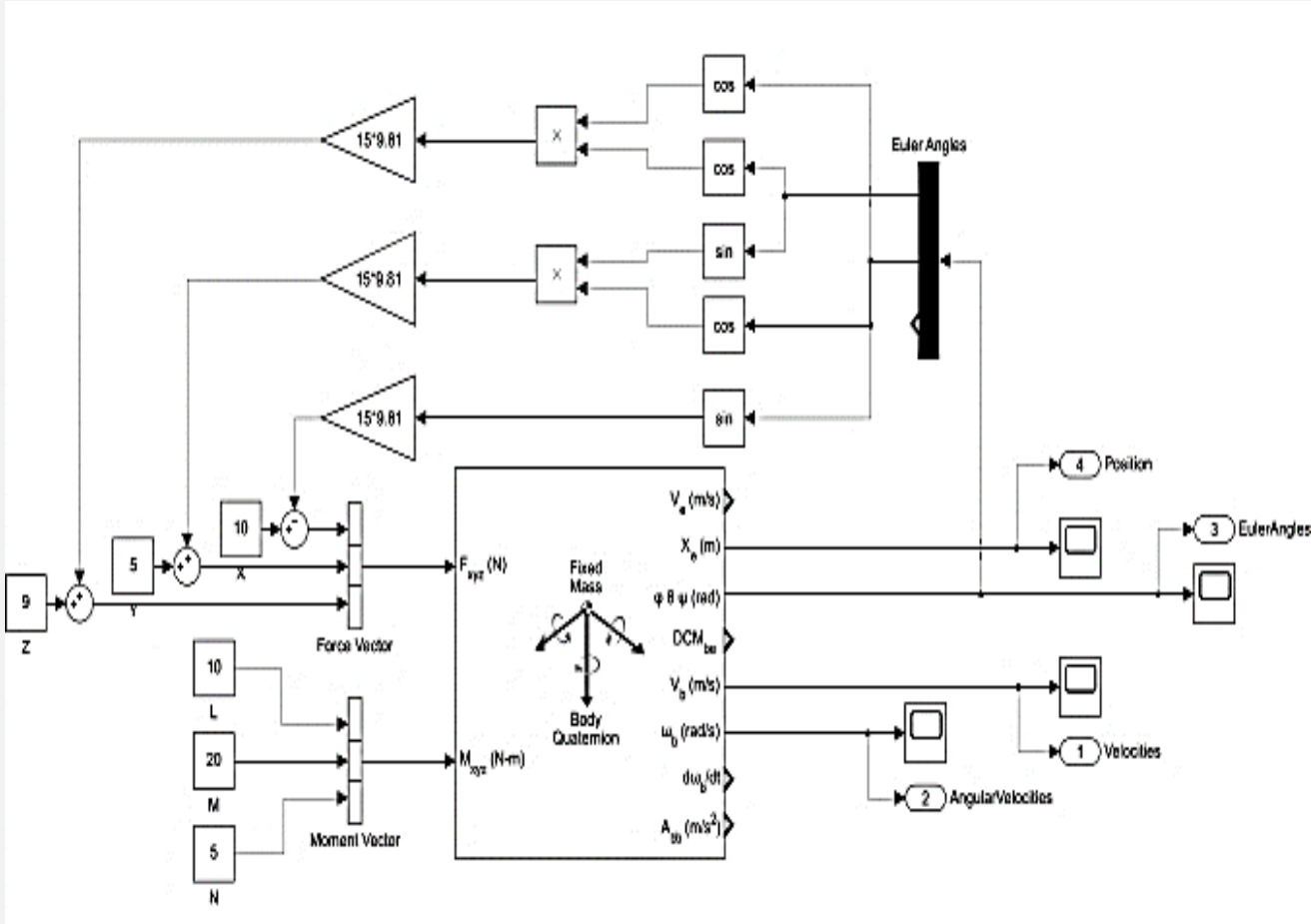
➢ TASK 2

Overview

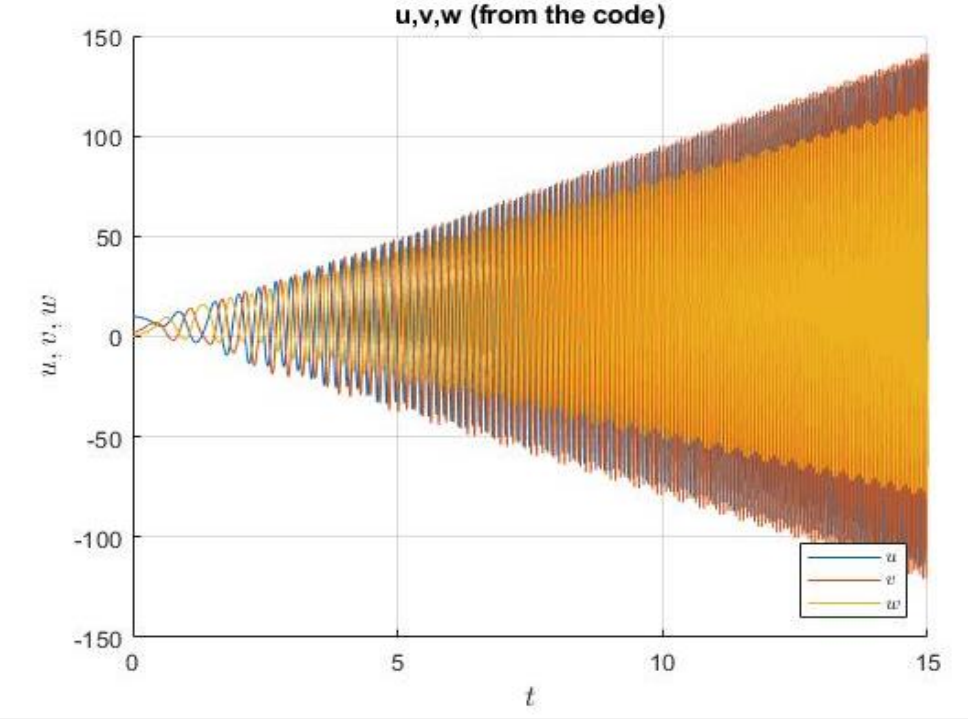
- Assumptions that EOM of A/C based on :
  1. The A/C is a point of mass(constant mass)
  2. XZ plane is the plane of symmetry

$$(I_{xy} = I_{zy} = 0)$$

- Solving the 12 EOM of A/C by using RK4
  - Inputs are IC's, A/C Mass, Forces(constant), Moments(constant) & Body inertia
  - Validation for our code results using Simulink



Results


u,v,w (from the code)
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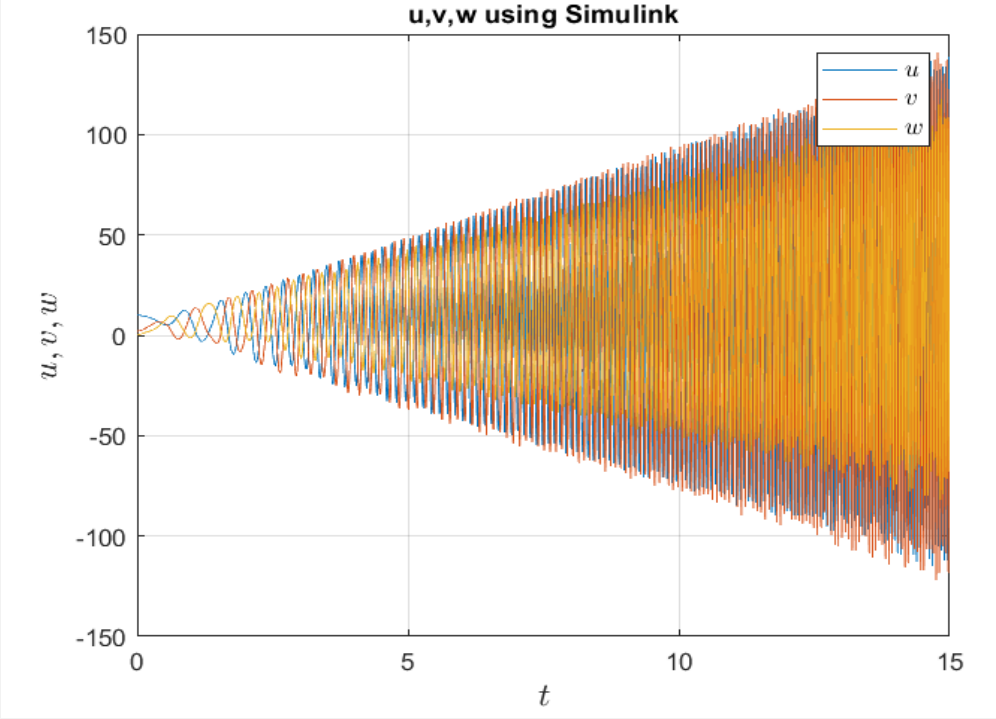
100
50
0
-50
-100
-150
u, v, w
0
5
10
15
t
u
v
w


u,v,w using Simulink
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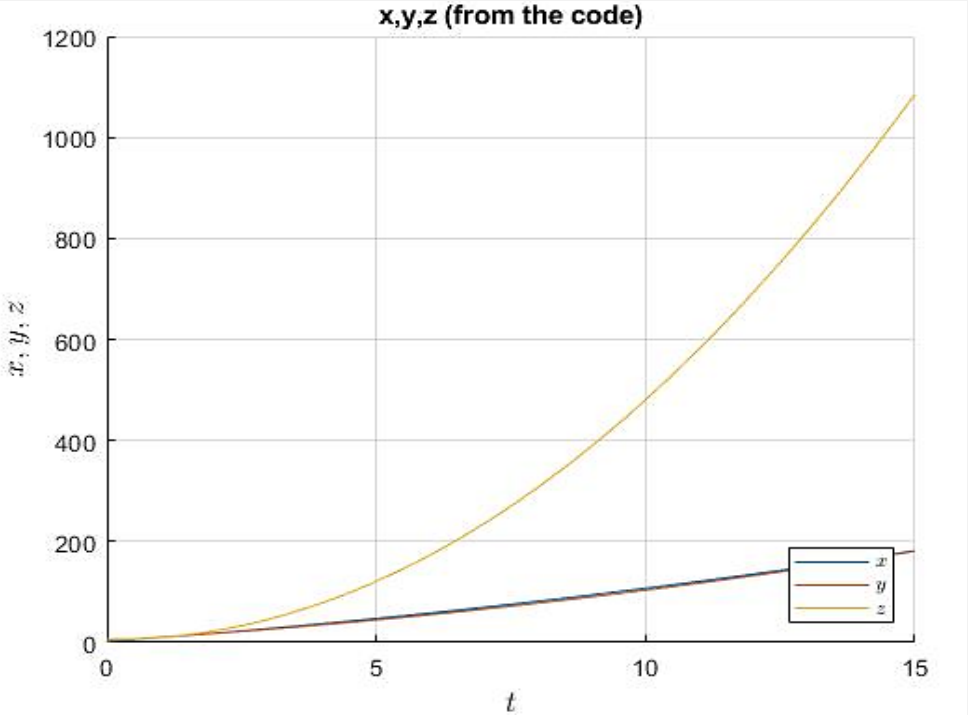
100
50
0
-50
-100
-150
u, v, w
0
5
10
15
t
u
v
w


x,y,z (from the code)
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1000
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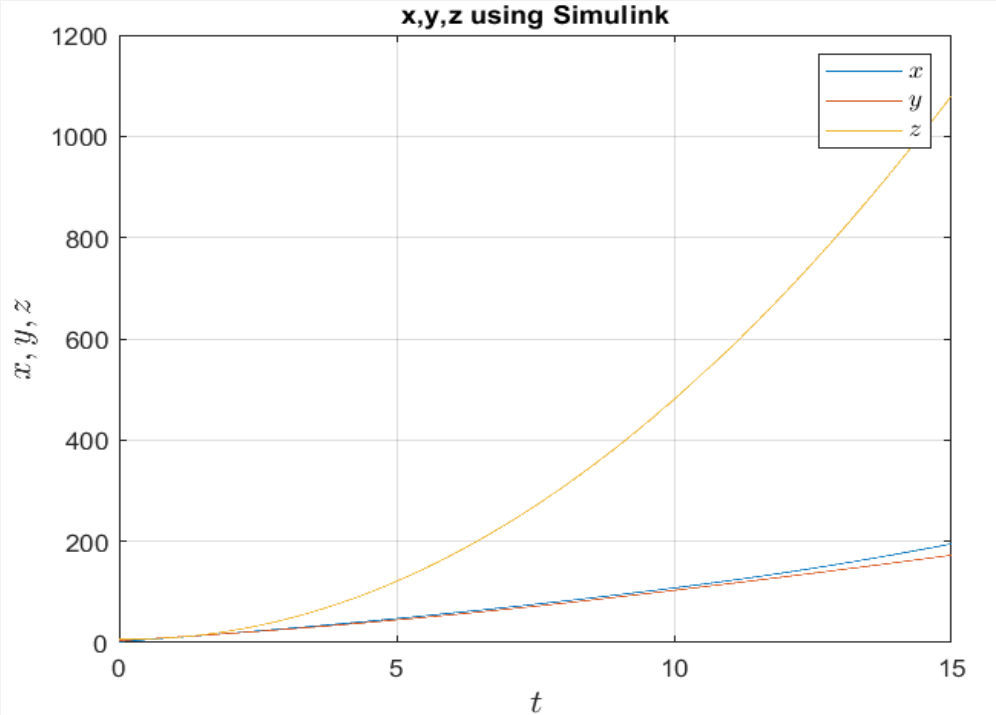
200
0
x, y, z
0
5
10
15
t
x
y
z


x,y,z using Simulink
1200
1000
800
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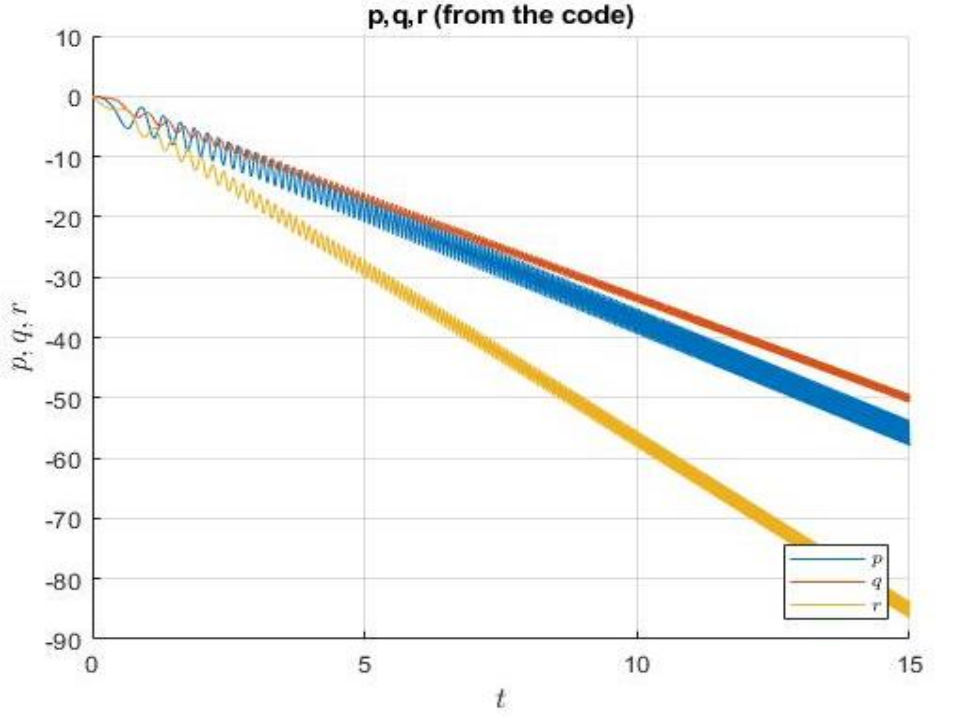
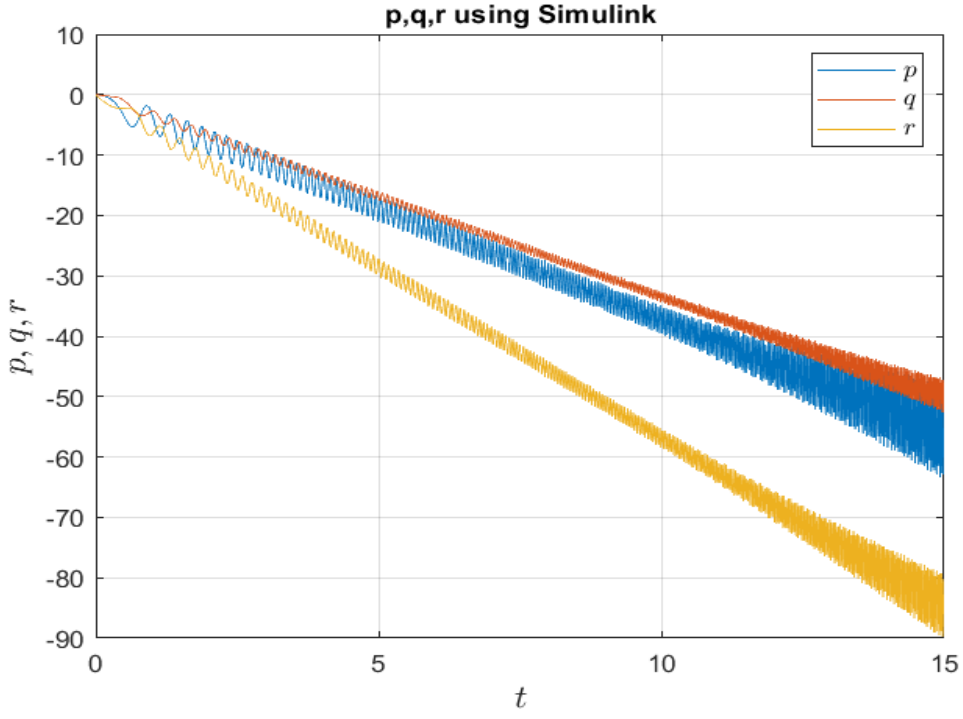
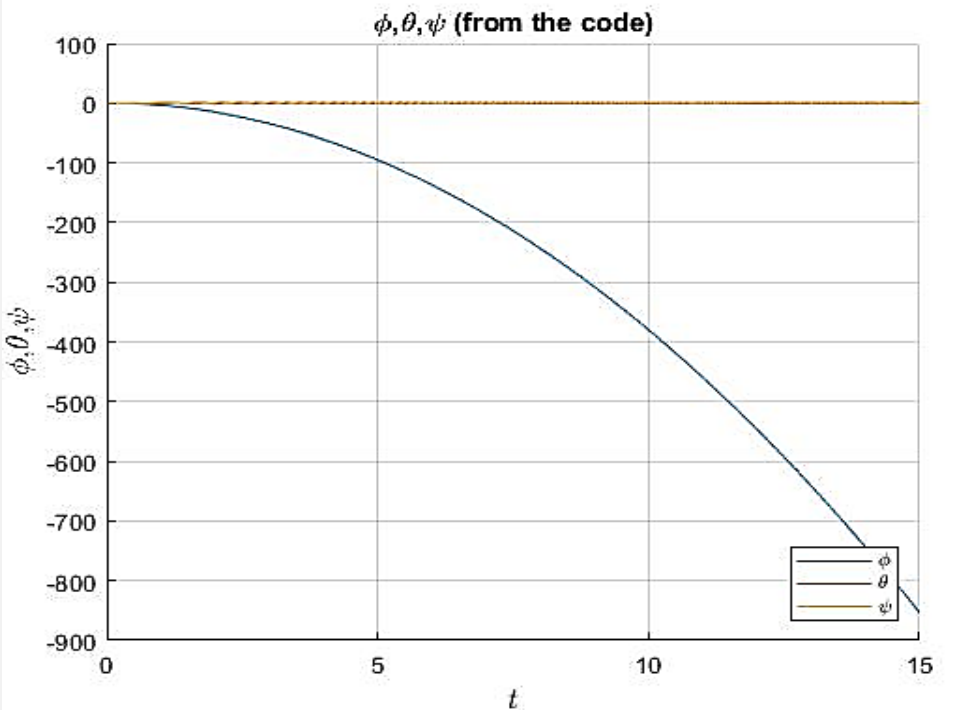
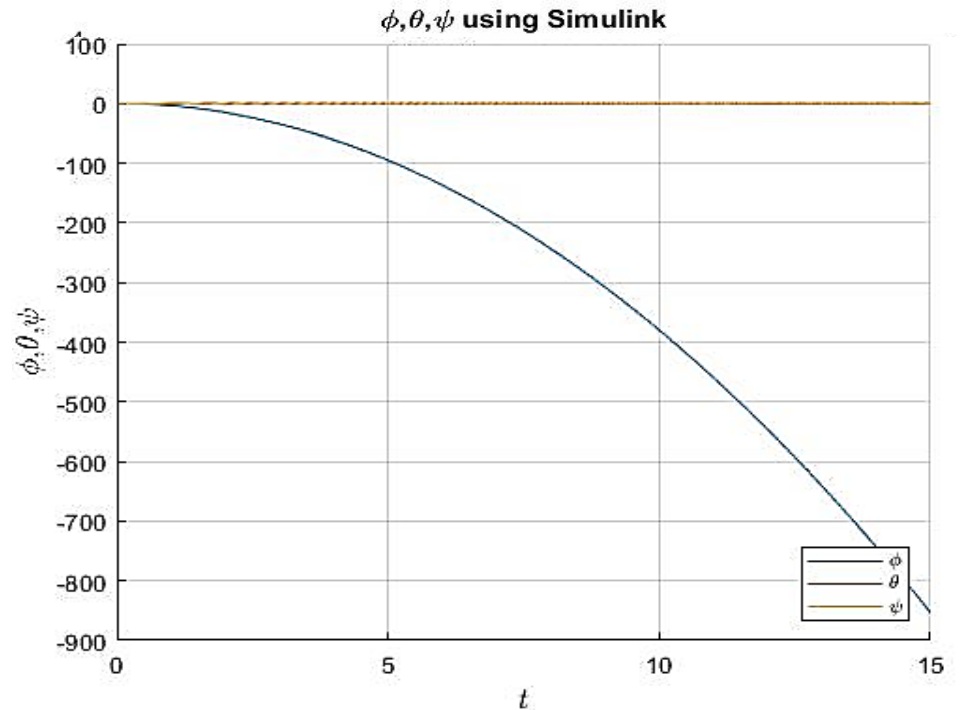
200
0
x, y, z
0
5
10
15
t
x
y
z

Results


p,q,r (from the code)
p, q, r
t
p
q
r


p,q,r using Simulink
p, q, r
t
p
q
r


ϕ,θ,ψ (from the code)
ϕ,θ,ψ
t
ϕ
θ
ψ


ϕ,θ,ψ using Simulink
ϕ,θ,ψ
t
ϕ
θ
ψ

➢ TASK 3

NT_33A
Flight Condition 3

Overview

- The Forces & Moments aren't constant any more, for example:

The X-Force will be : $X = \Delta X + X_o$

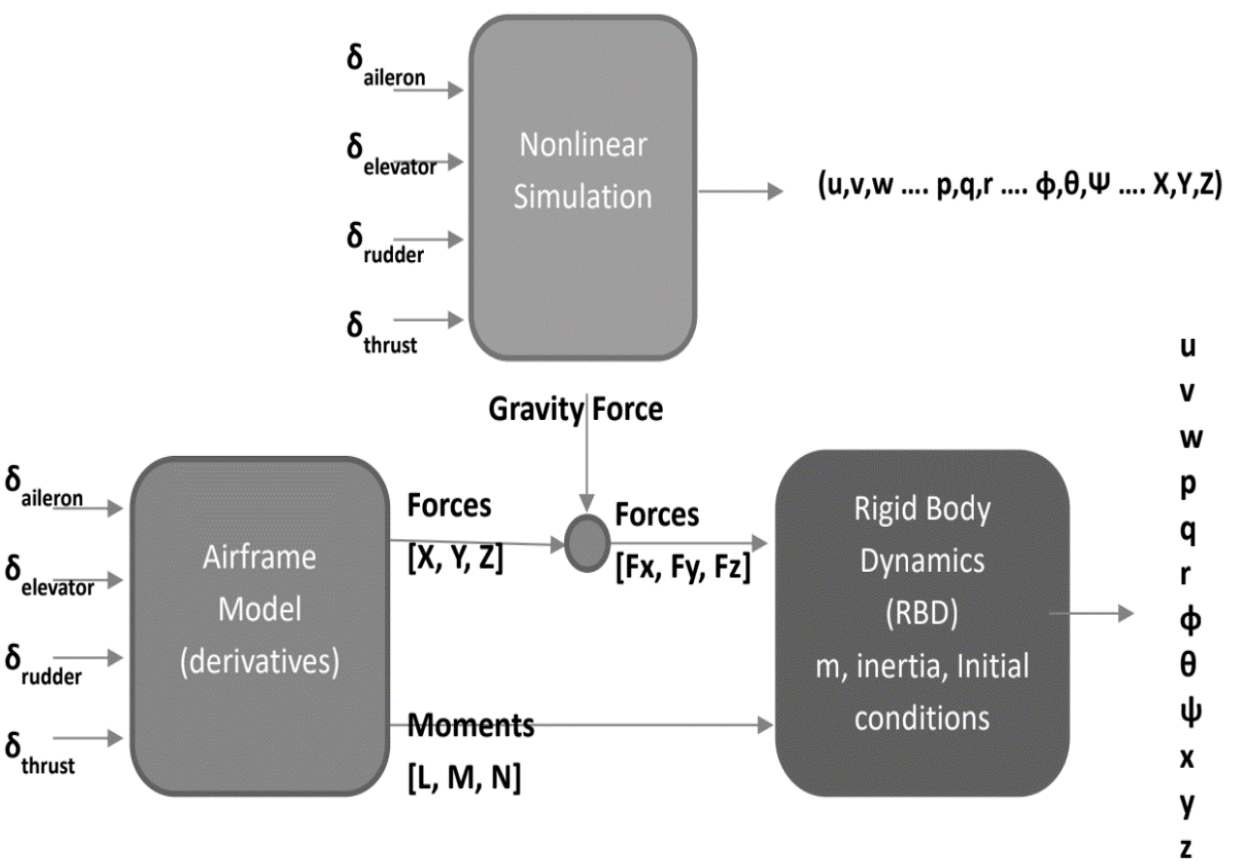
Where

$$\Delta X/m = \left(X_u\,\Delta u + X_w\,\Delta w + X_{\delta_e}\,\Delta\delta_e + X_{\delta_{th}}\,\Delta\delta_{th}\right)$$

$$X_o = mgS_{\theta_o}$$

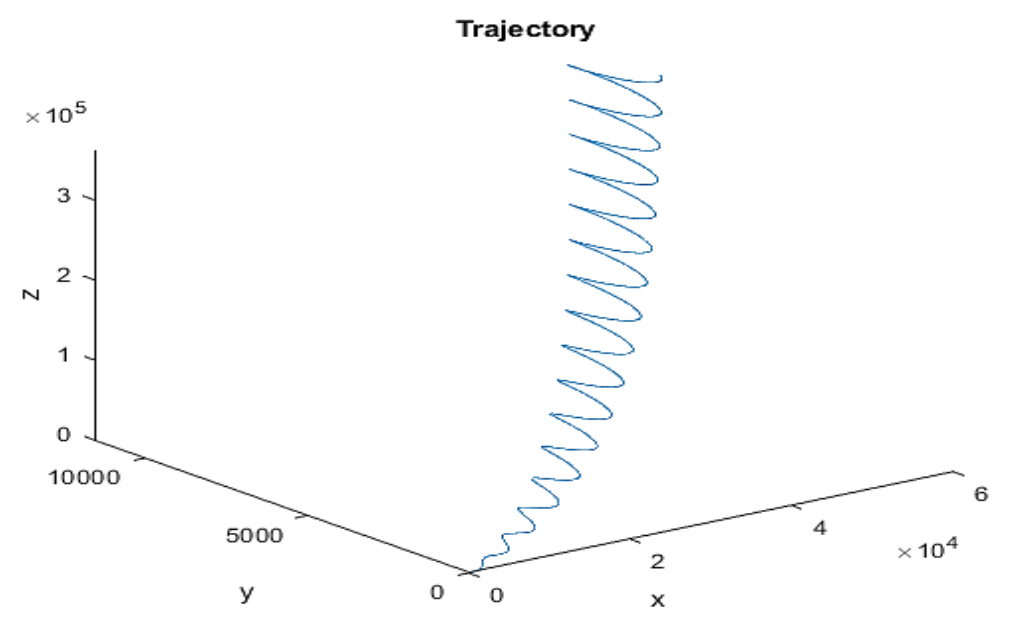
  - Force & Moments are function of stability derivatives & actions of control surfaces
  - X_o calculated from equilibrium equations at specific point(our FC)

- Then draw different trajectories for various values for control surfaces

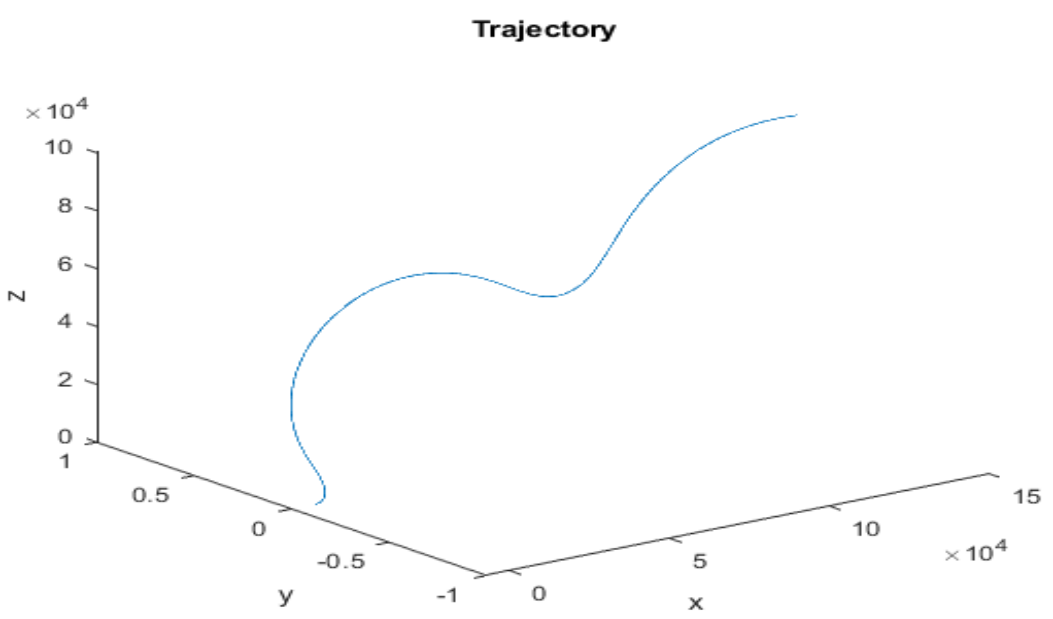


Responses

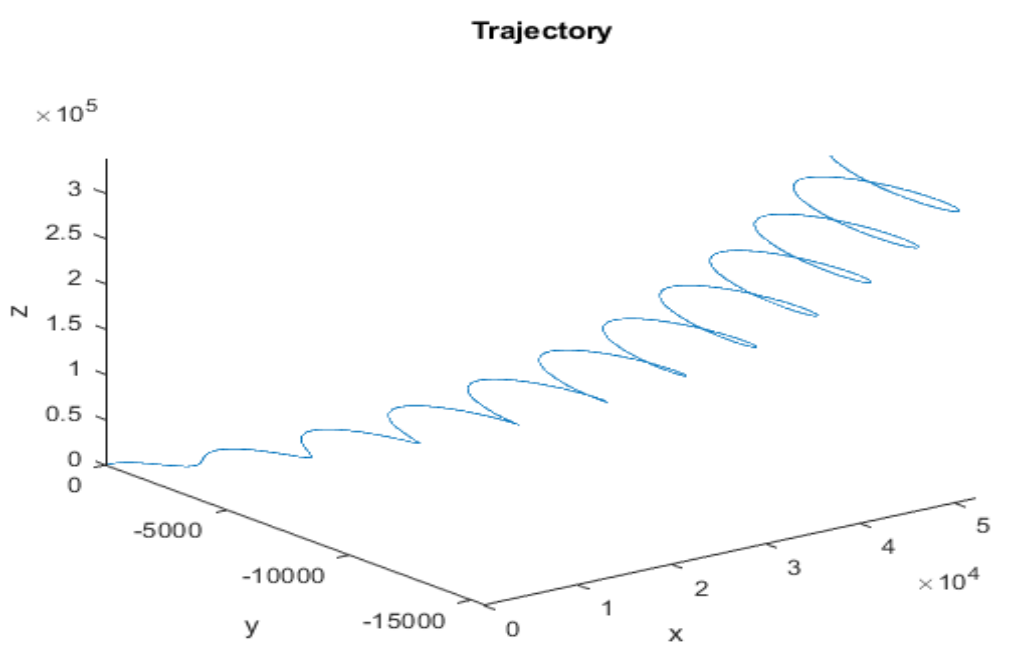
+5 aileron input



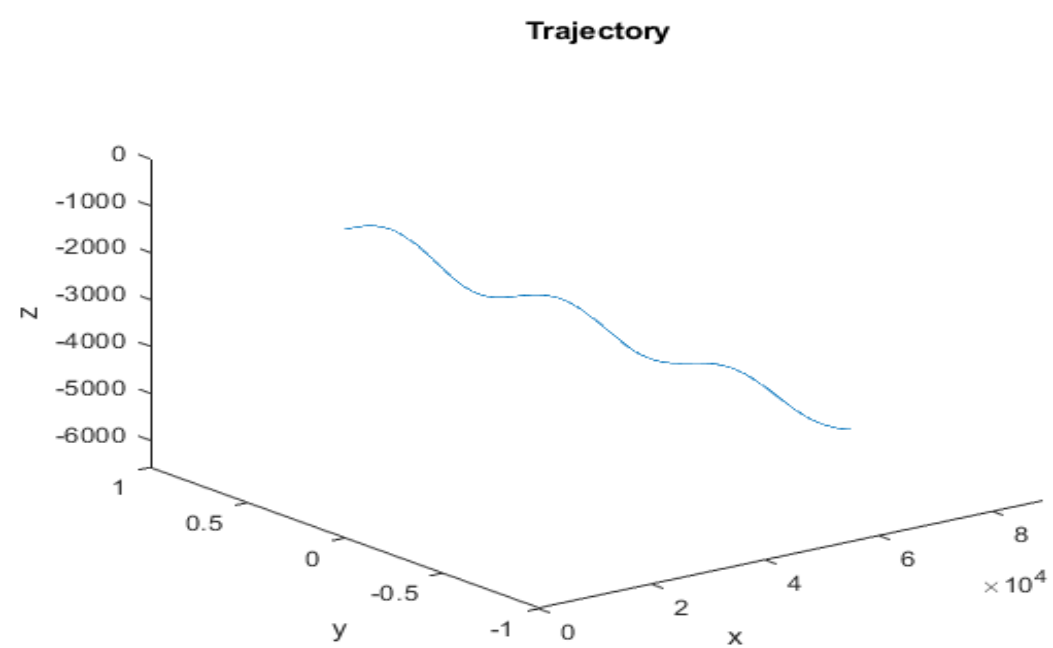
+5 elevator input



+5 rudder input



1000 thrust input

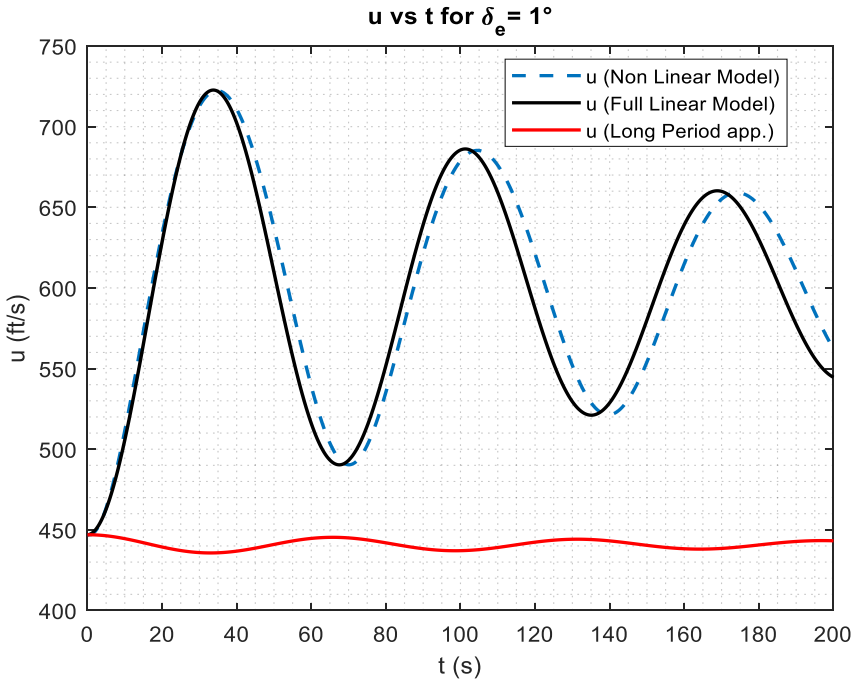


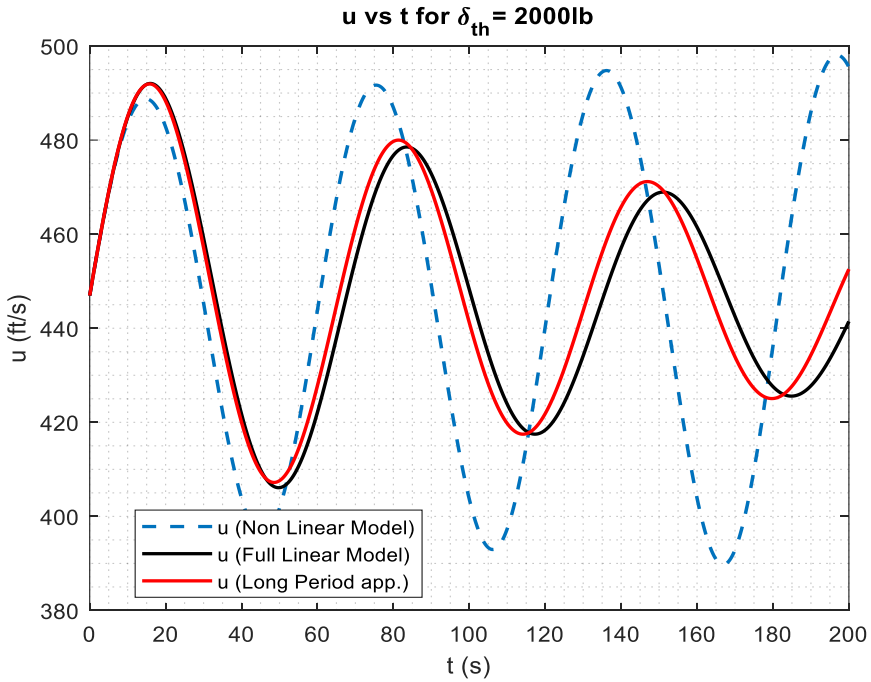
➢ TASK 4

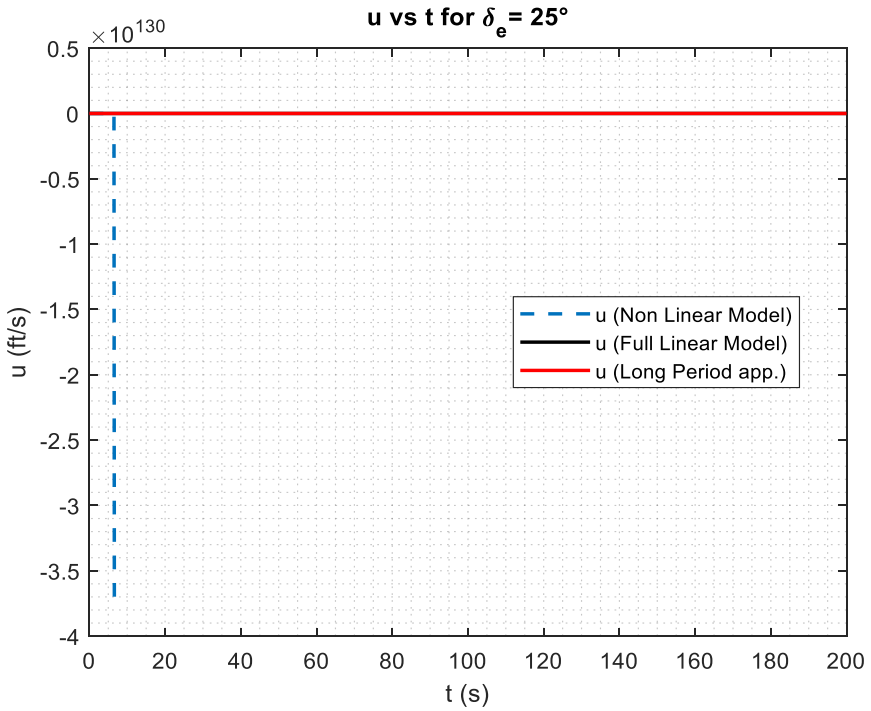
Overview

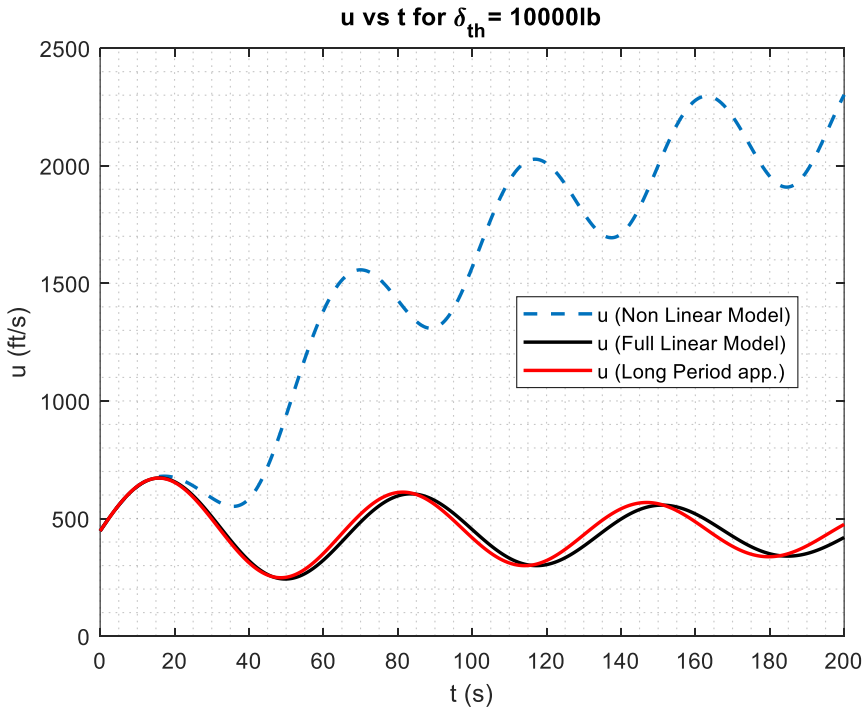
- **Linearization** of the 12 equations of motion
- **Approximations** of the longitudinal and lateral dynamics equations.
- **Step response** of our airplane using all the models of **longitudinal** dynamics we have obtained.
- **Step response** of our airplane using all the models of **lateral** dynamics we have obtained.
- **Transfer function** of our airplane using all models of the **longitudinal** dynamics including the Root locus and Bode plot for each.
- **Transfer function** of our airplane using all models of the **lateral** dynamics including the Root locus and Bode plot for each.

Step response (longitudinal) δ_e , δ_{th}

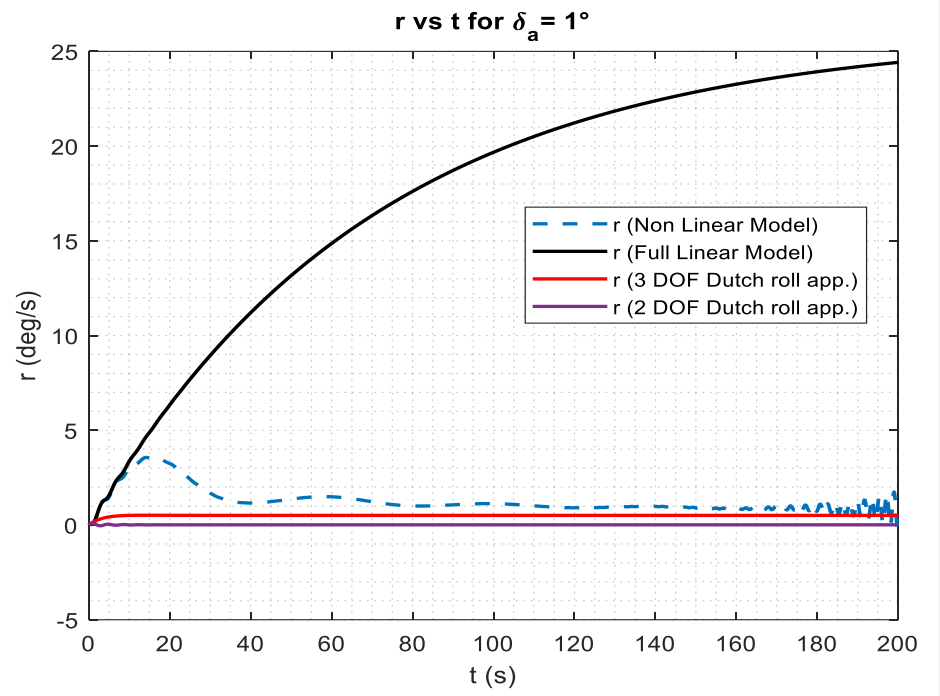


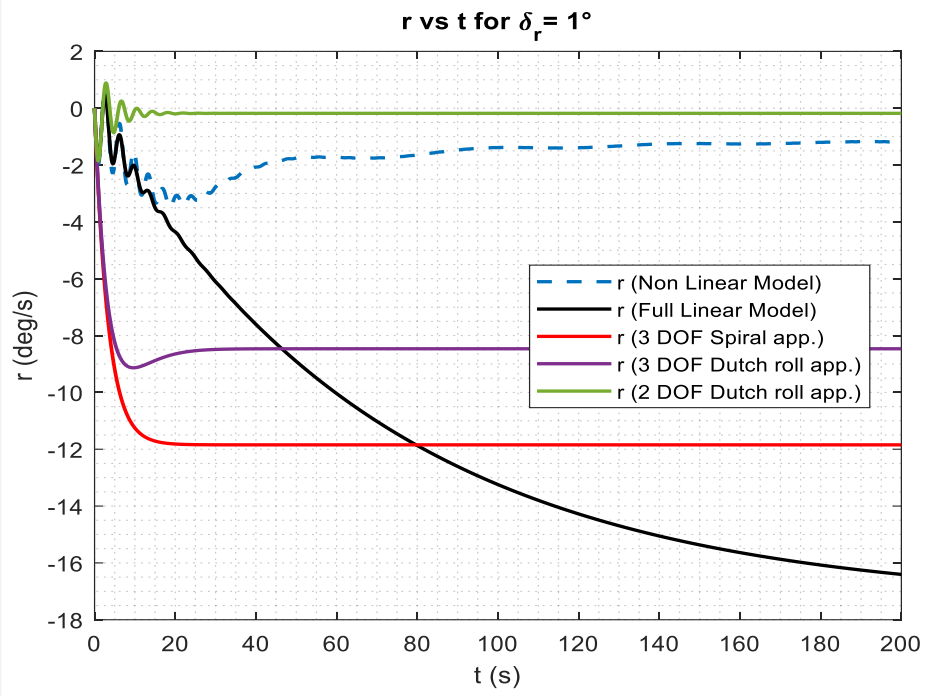


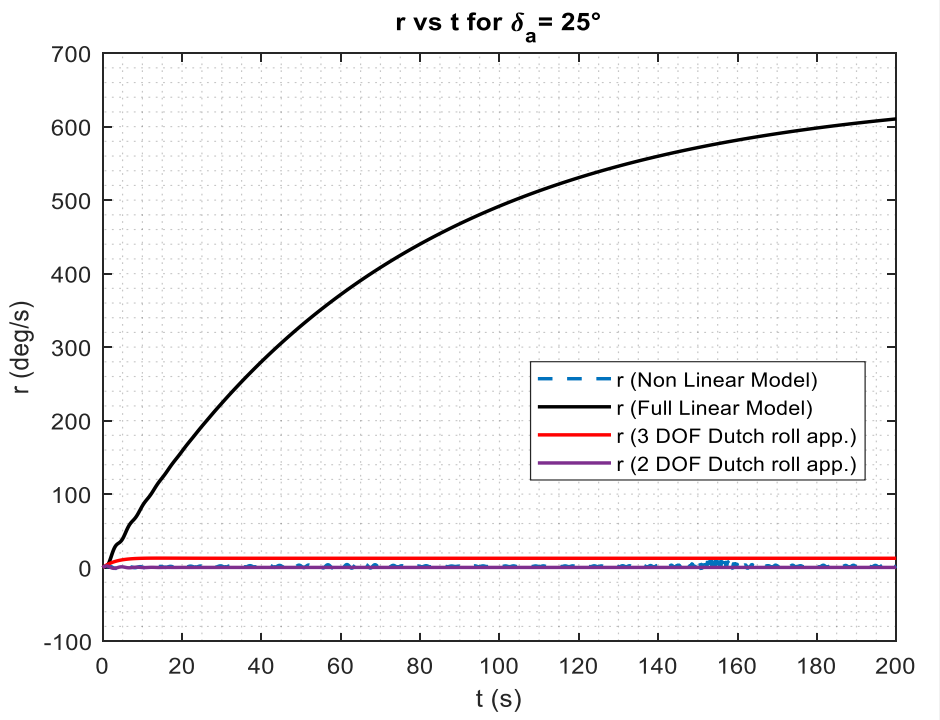


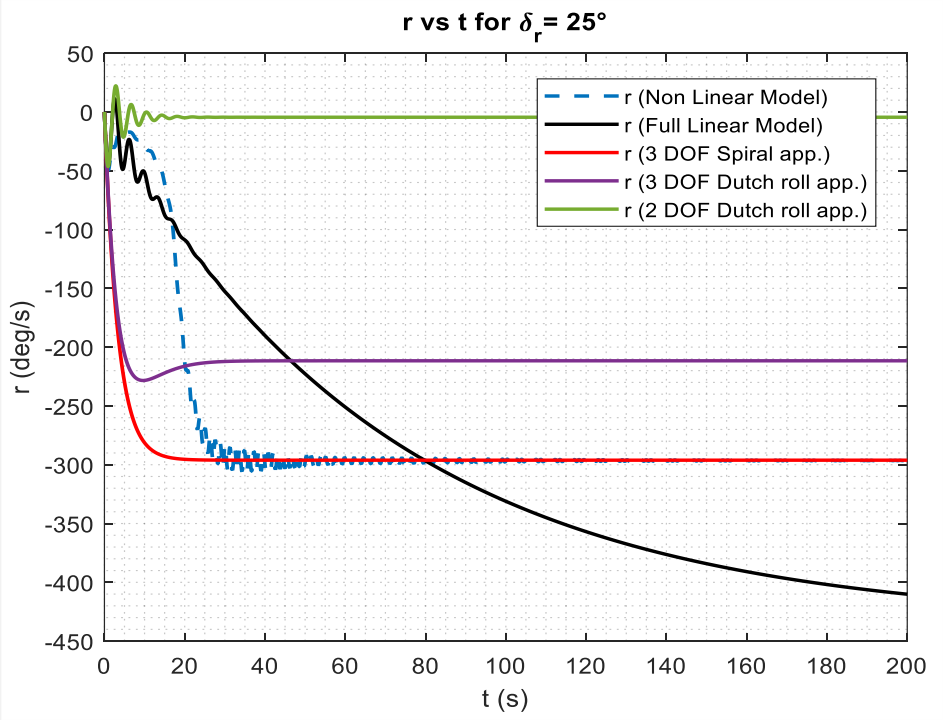


Step response (lateral) δ_a , δ_r





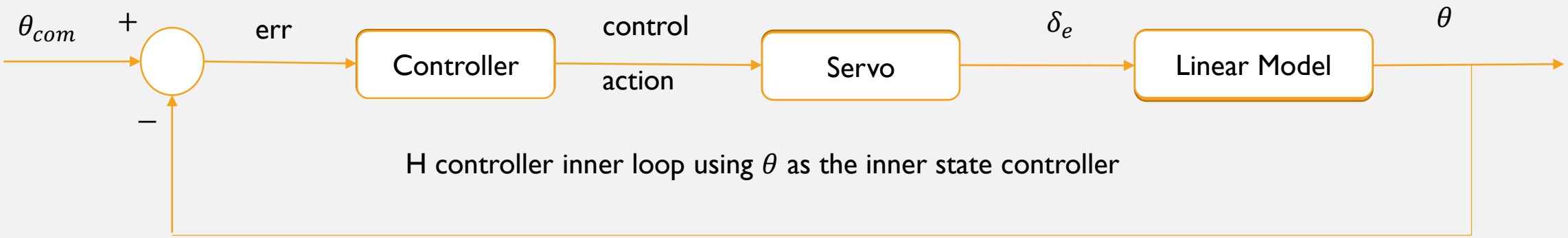




TASK 5

Longitudinal Autopilot Design

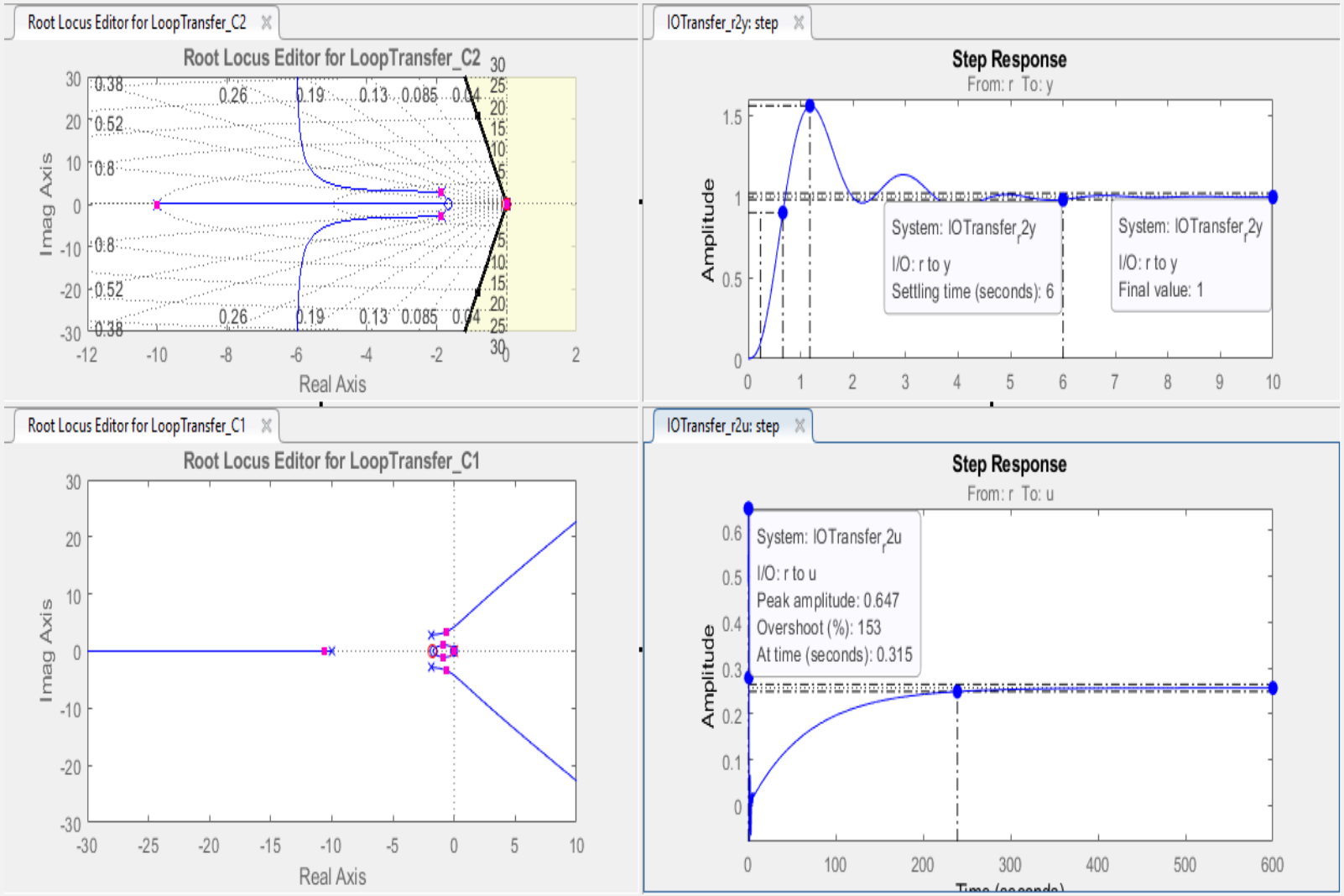
- The main objective of the Longitudinal controller is to be able to change the main longitudinal states like (h-u) using feedback controllers and inner states to get suitable control action with best performance.



- **<u>Pitch controller</u>**

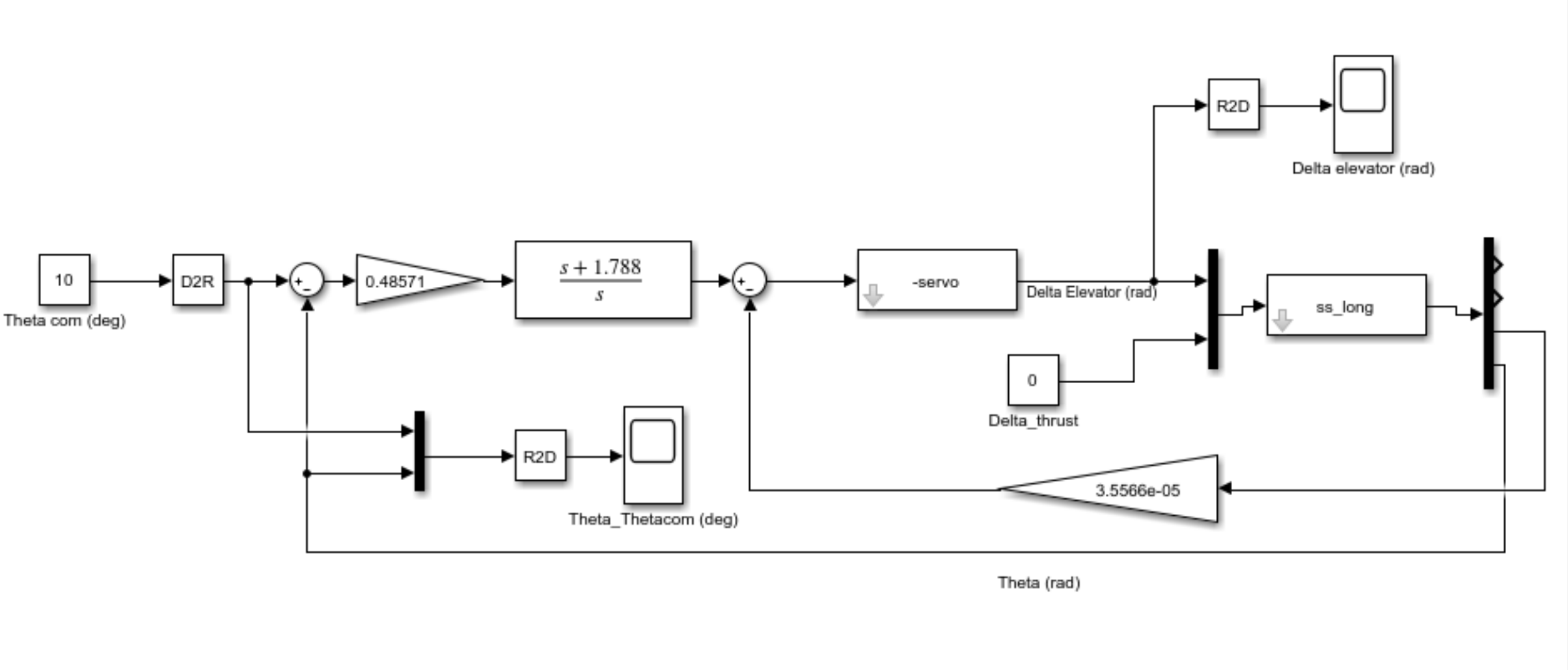
$$\therefore \left.\frac{\theta}{\theta_{command}}\right)_{OL} = \frac{(159.4s^2 + 269.3\,s + 3.922)}{(s^5 + 13.74\,s^4 + 48.99\,s^3 + 116.4\,s^2 + 1.596\,s + 1.005)}$$

Pitch Controller



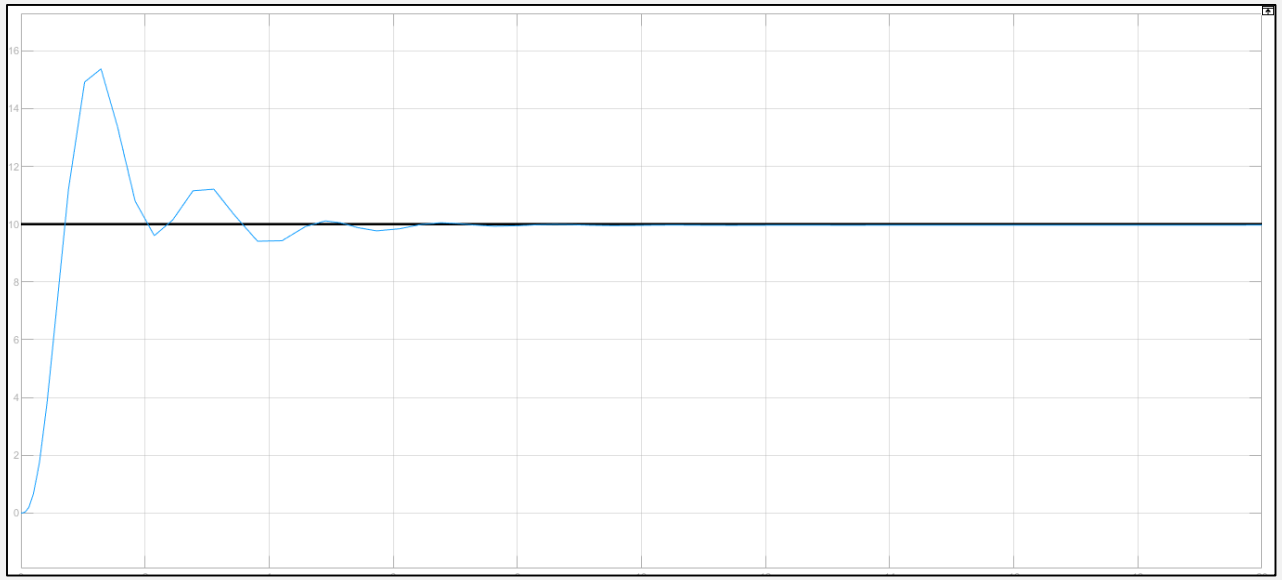
The best achieved response was $T_s = 6\ sec$
$with\ maximum\ control\ action = 0.647$

Simulink implementation

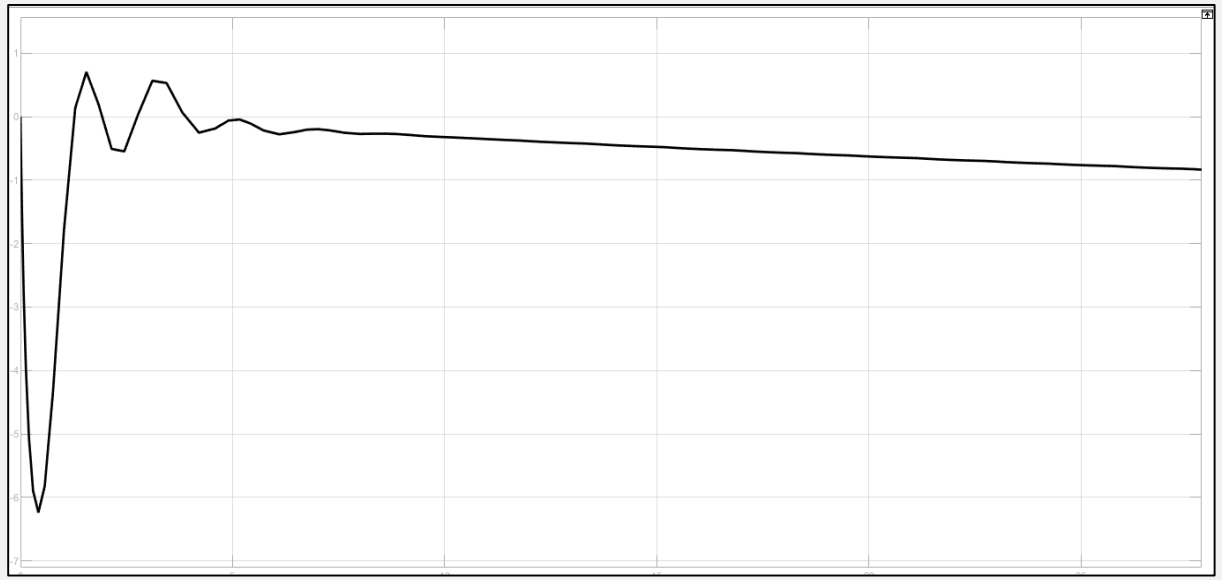


Rustles from Simulink

Delta theta actual, delta theta com



Elevator control action

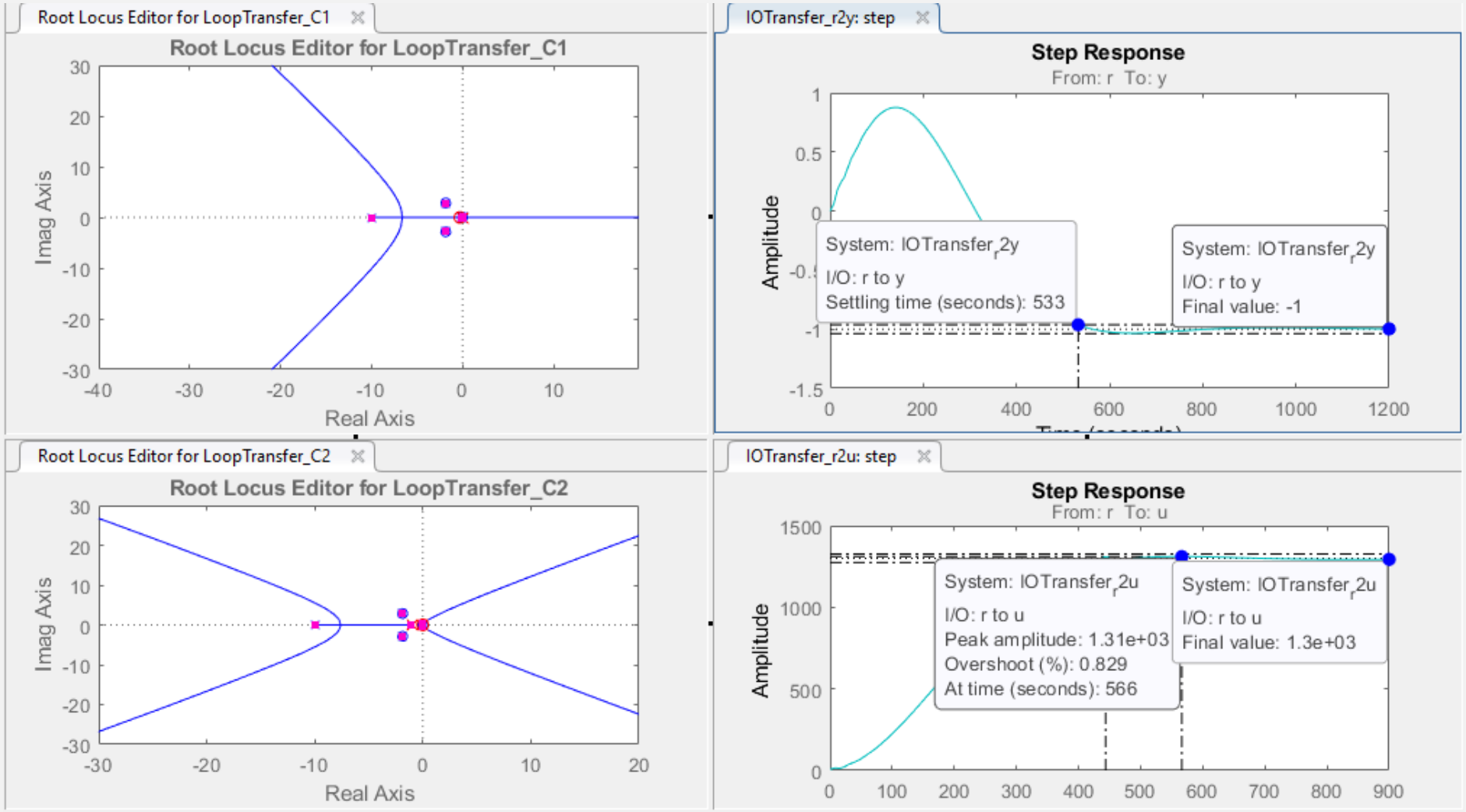


Velocity Controller

- **Necessity of velocity control**

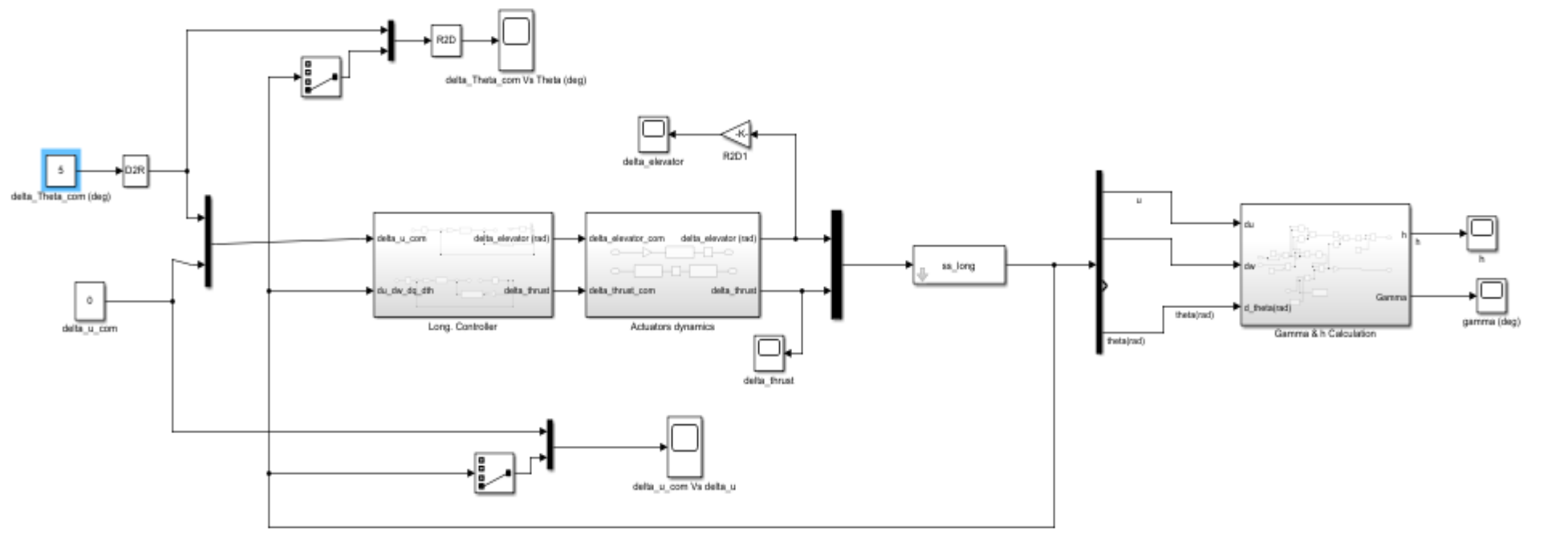
logically, when a $+ve$ pitch angle is commanded, it is expected that the airplane will gain altitude, but this will not always happen, usually when a $+ve$ pitch angle is commanded the airplane will lose altitude if there is no velocity controller, We can't judge the airplane behavior depending on the pitch angle θ only, as it includes two angles; the angle of attack "α" (trim angle) & the climb angle, where $\theta=\alpha+\gamma$ & $\alpha=fn(u,w)$, thus, the speed must be controlled to control α, and accordingly control the climb angle γ and the altitude.

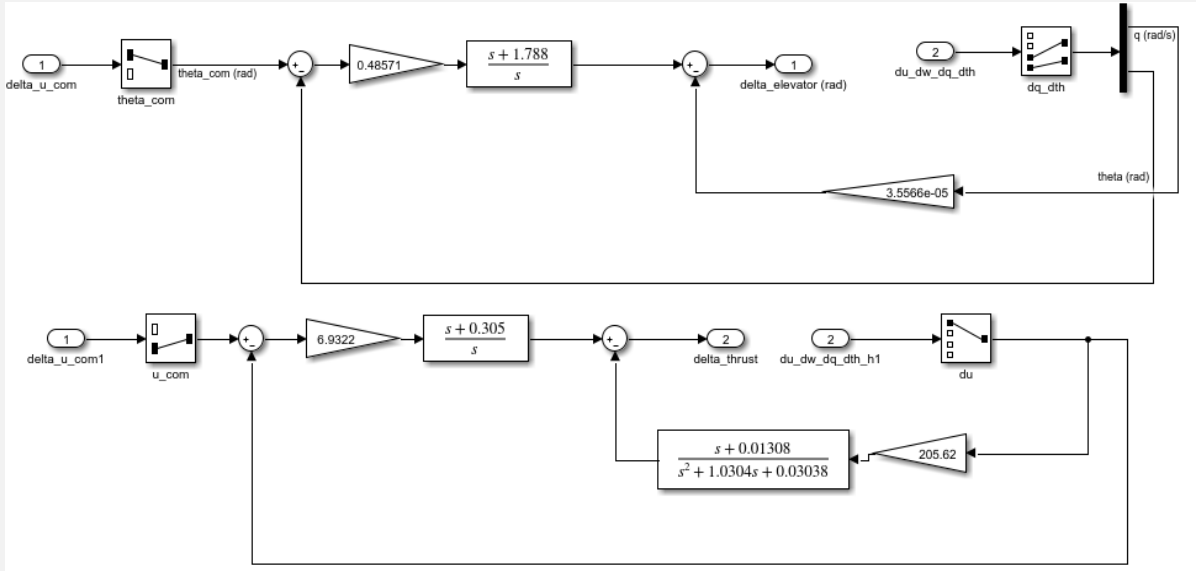
$$\left(\frac{u}{u_{com}}\right)_{OL} = \frac{(0.00235\, s^3 + 0.008749\, s^2 + 0.02719\, s\ - 7.725e - 05)}{(\ s^6 + 13.84\, s^5 + 50.36\, s^4 + 121.3\, s^3 + 13.24\, s^2 + 1.164\, s\ + 0.1005)}$$



The Best settling time achieved is $T_s = 533\ sec.$

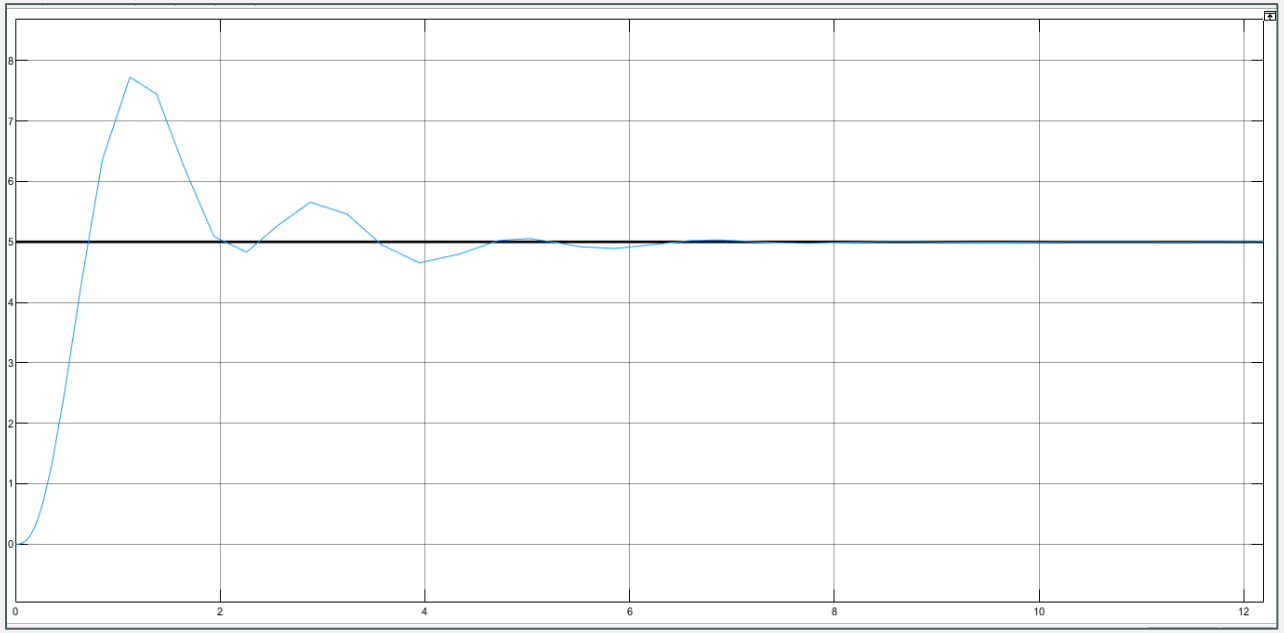
Velocity Controller implementation



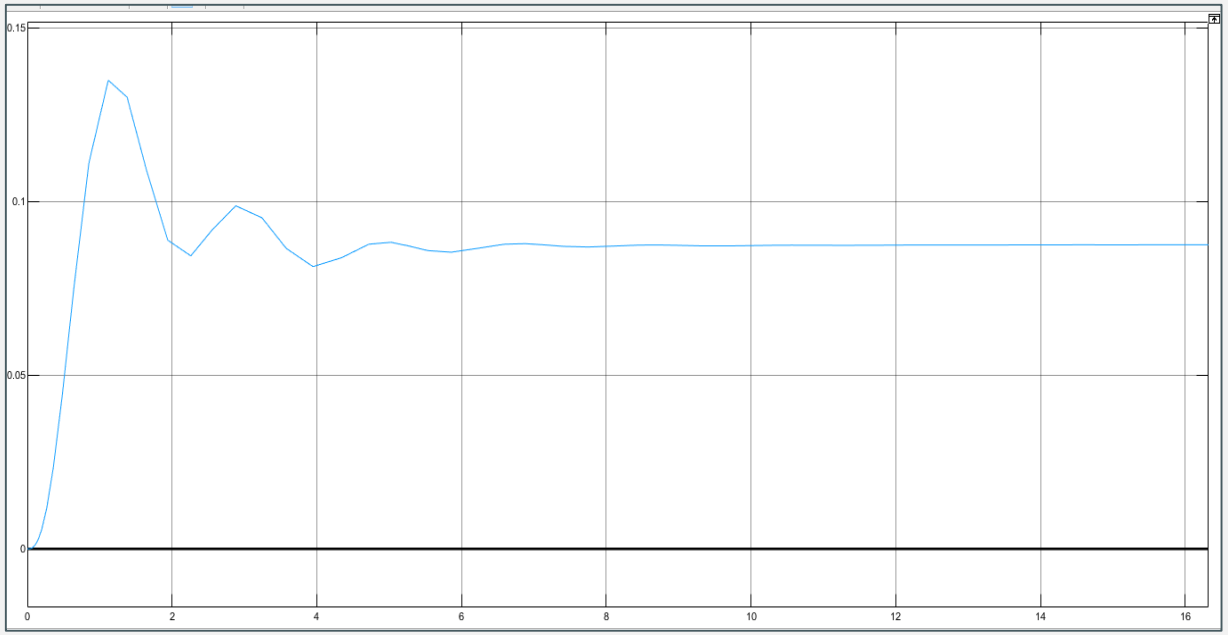


Pitch & Velocity controllers

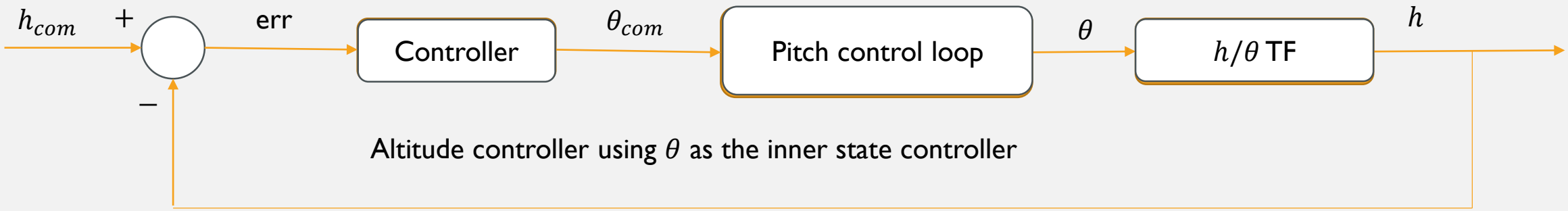
Delta theta actual, delta theta com



Delta u com, delta u

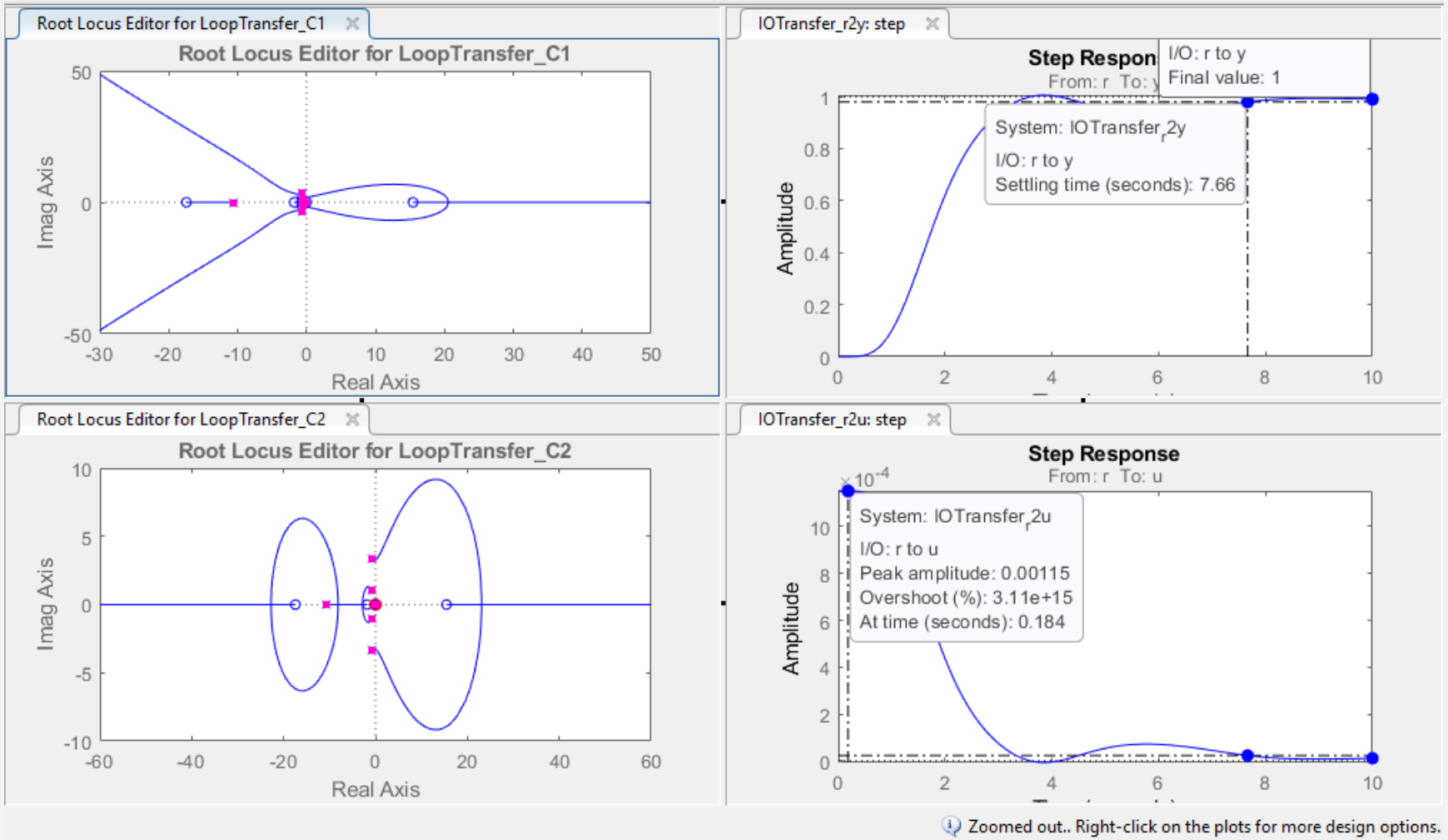


Altitude Controller



Altitude controller using θ as the inner state controller

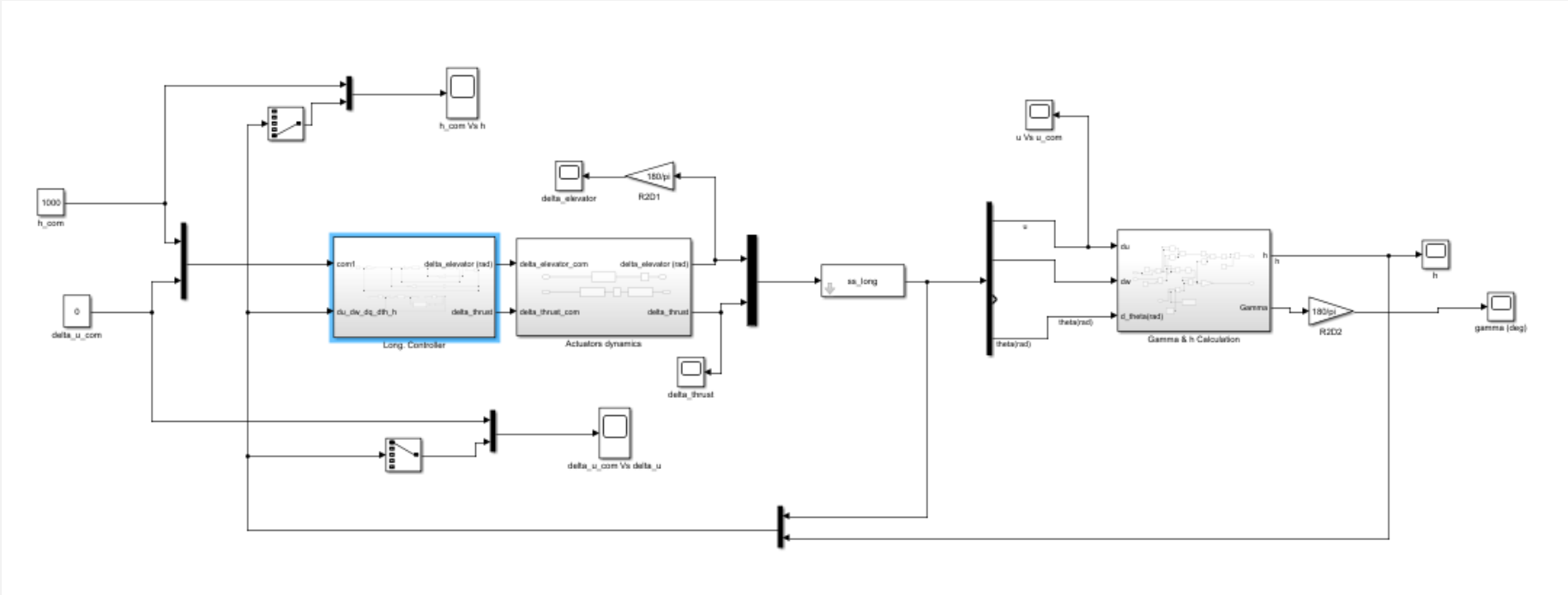
$$\left(\frac{h}{h_{com}}\right)_{OL} = \frac{-215.7\,S^4 - 818.7\,S^3 + 5.729e04\,S^2 + 1.044e05\,S + 947.7}{S^7 + 13.74S^6 + 48.99S^5 + 193.8S^4 + 270.8S^3 + 236.8S^2 + 3.407S}$$

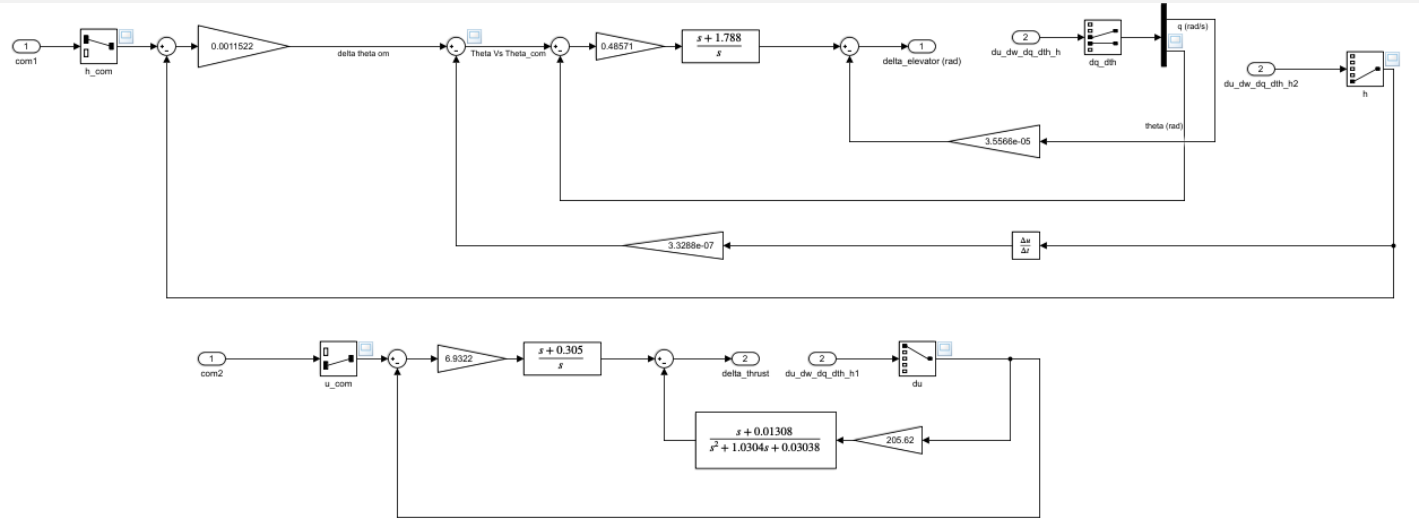


The Best settling time achieved was $T_s = 7.66\ sec.$

The maximum control action was $\theta_{com} = 0.00115 rad$

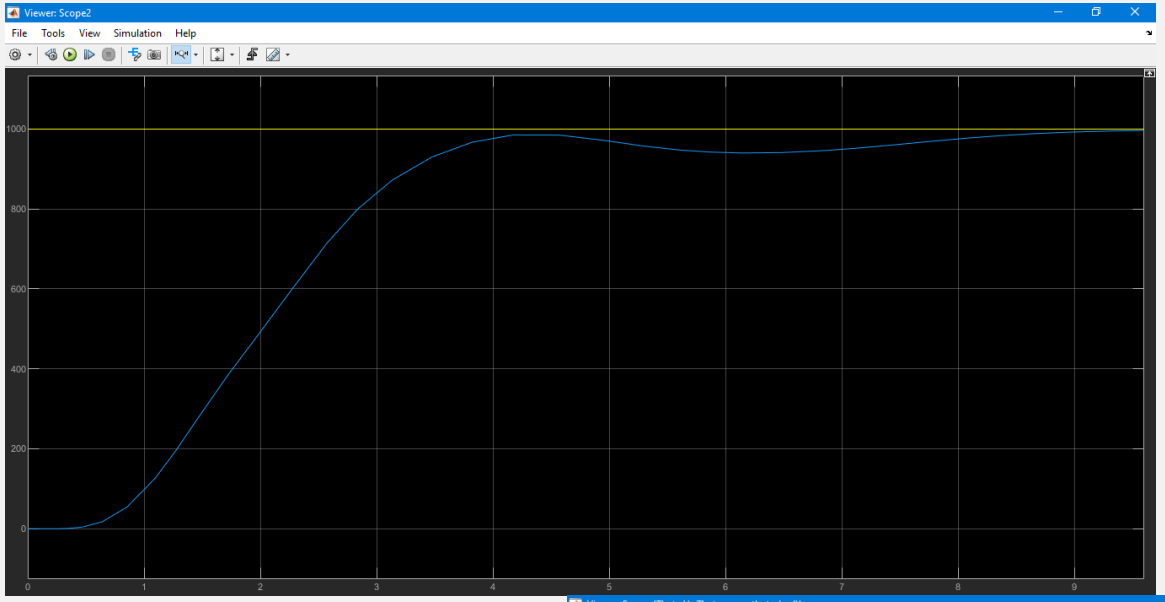
Altitude Controller implementation

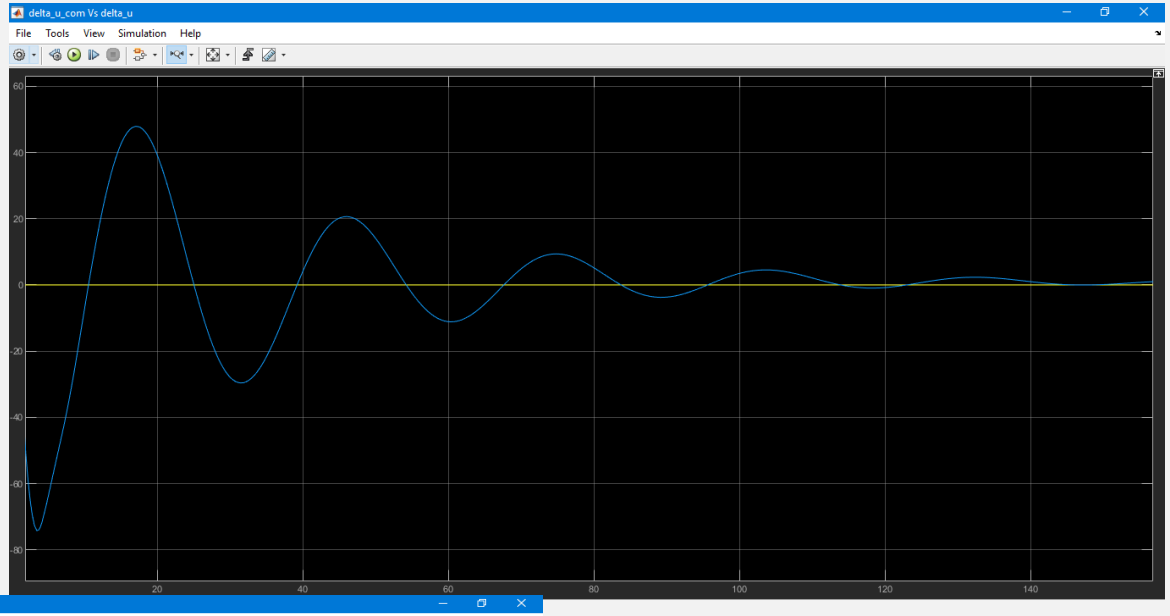


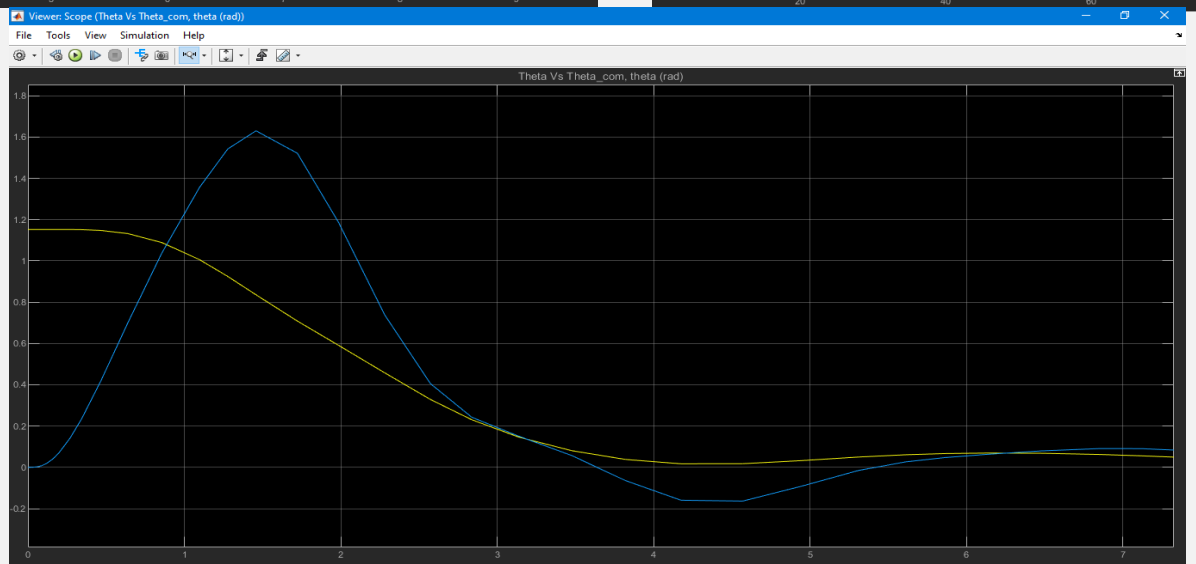


Test Longitudinal Controller

$$\Delta h_{com} = 1000\ ft \because h_0 = 0 \ \therefore h_{com} = 1000\ ft\ , \Delta u_{com} = 0$$







➢ TASK 6

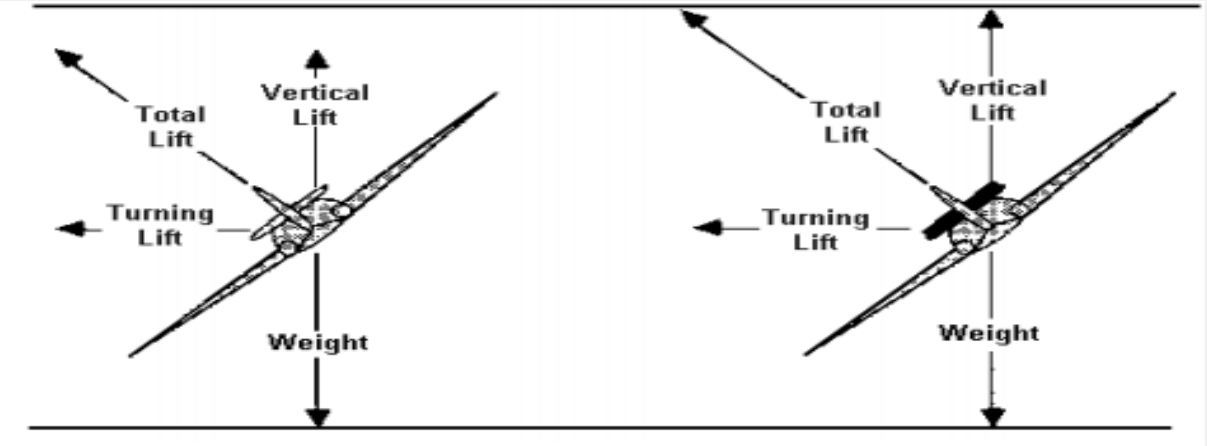
Lateral Autopilot Design

Coordinated turn means that the lateral acceleration is equal to zero $(\beta = 0)$

The main reasons that we want to make $\beta = 0$ is for

1. The safety of passengers (centrifugal force effect)
2. The safety of the aircraft components
3. Also for reducing the power consumption as it will be a drag is absence of coordinated turn

Coordinated level turn Is the same a coordinated turn but with holding the altitude at a desired value

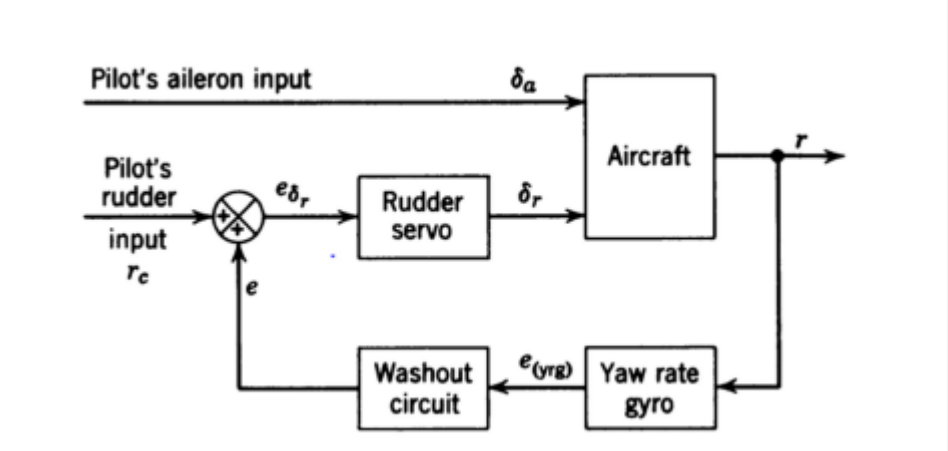


Yaw Damper Design

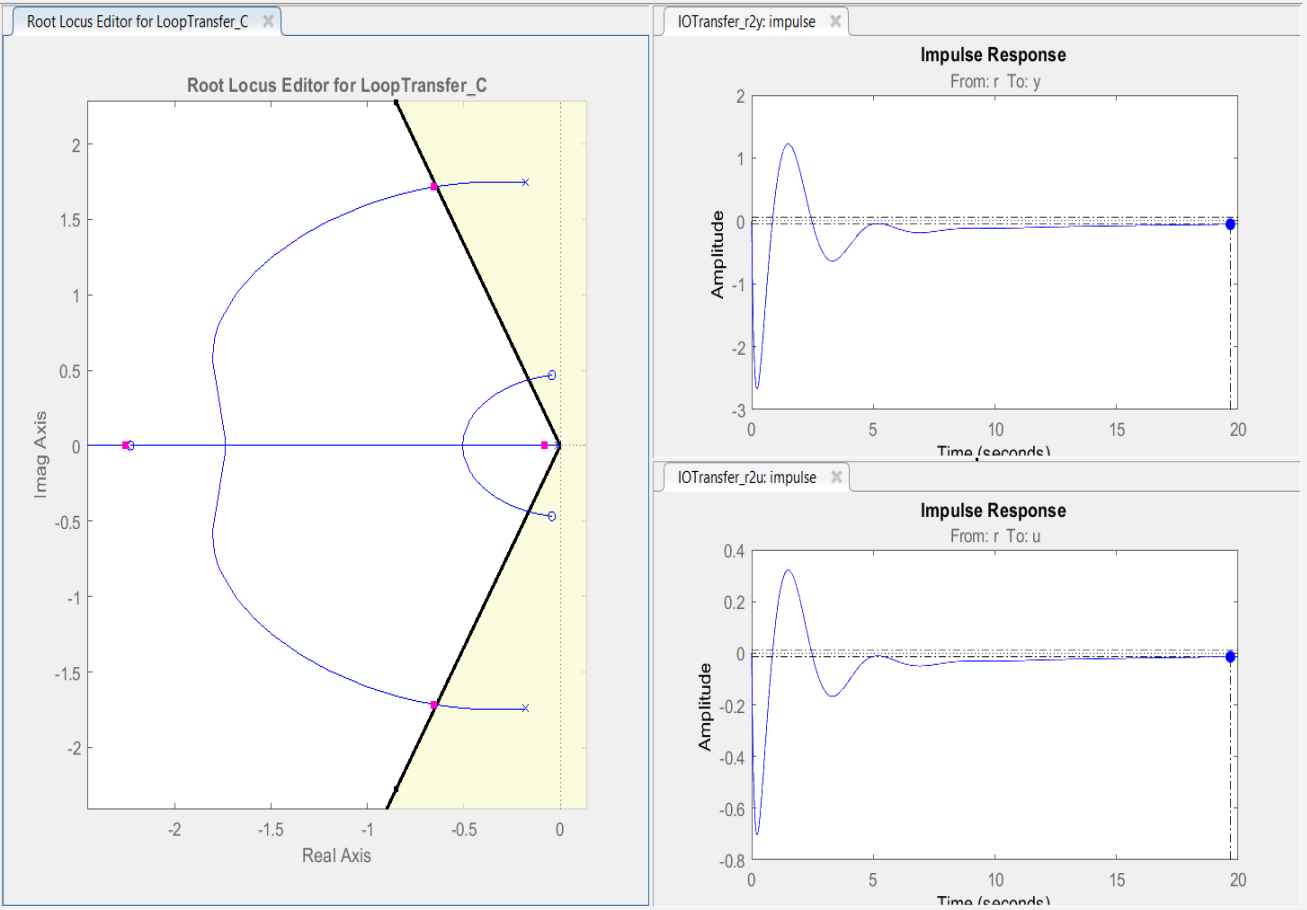
The washout Circuit ($e_s \neq 0$)

$$\frac{k\,s}{s+a}$$

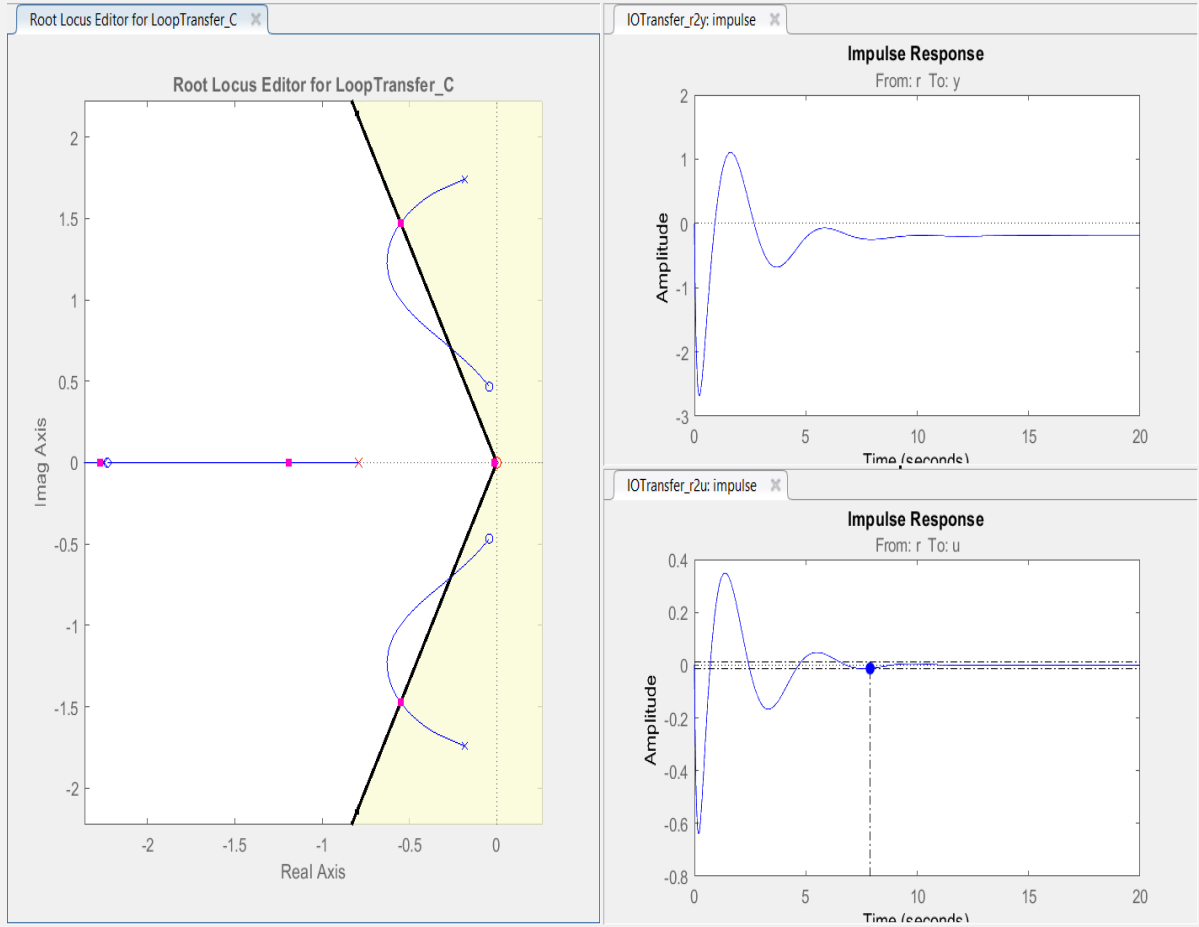
```
OL_r_rcom =

          -35 s^3 - 81.03 s^2 - 14.39 s - 17.14
  ---------------------------------------------------------
  s^5 + 12.62 s^4 + 30.14 s^3 + 46.15 s^2 + 69.6 s + 0.985

Continuous-time transfer function.
```



The Results without washout circuit $e_{ss} = 0$

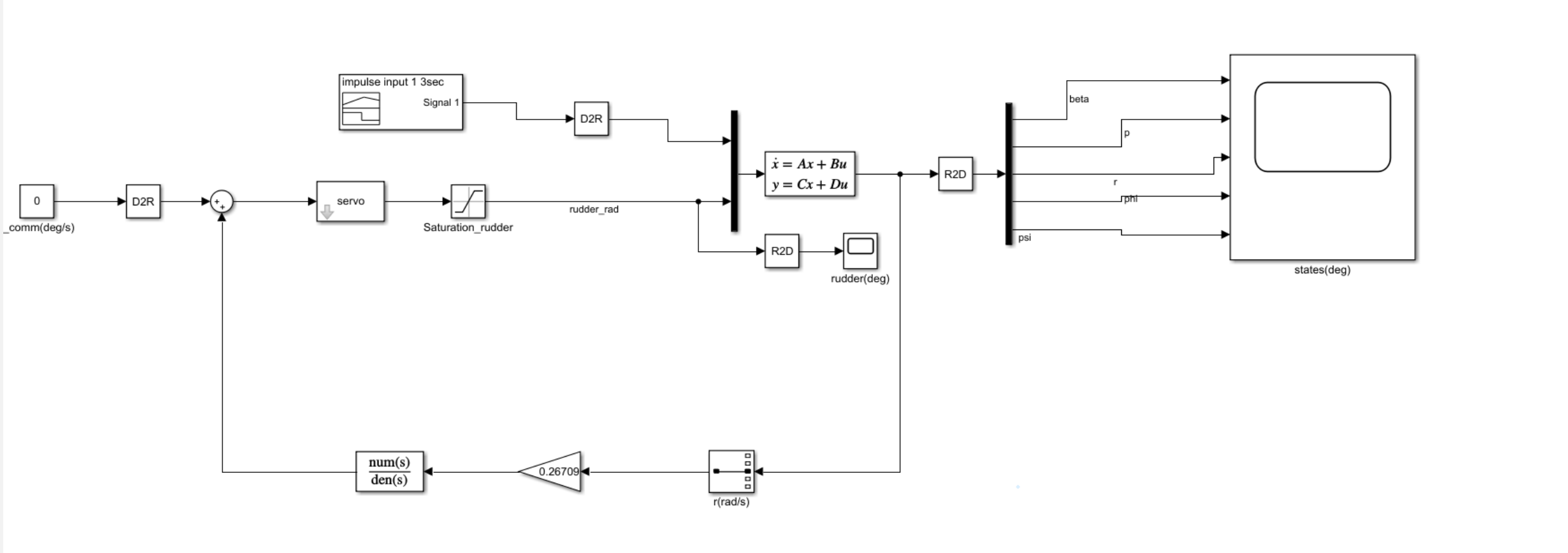


The Results with washout circuit $C = \frac{0.26709s}{s + 0.791}$



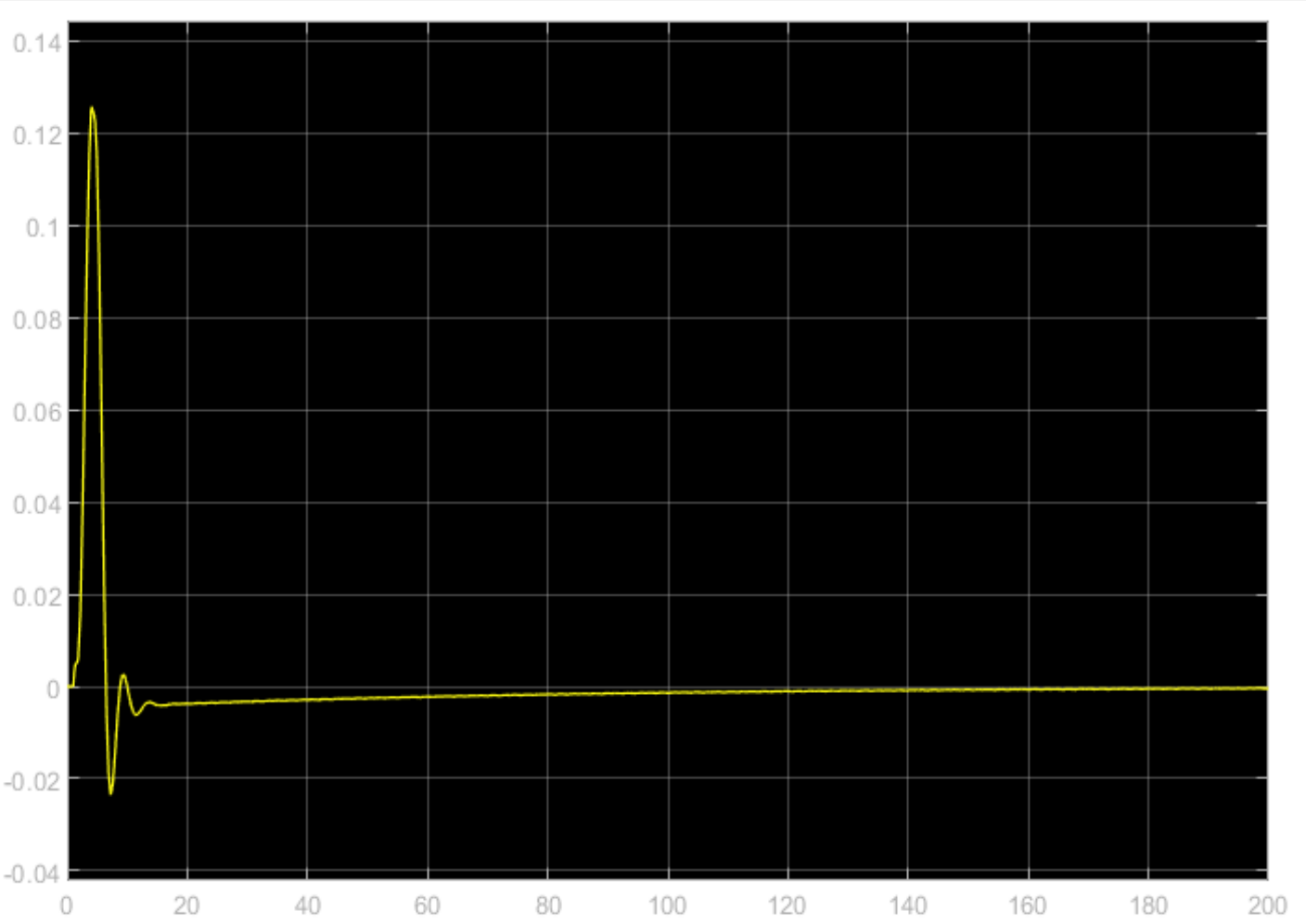
Testing the Yaw damper on the lateral state space Model

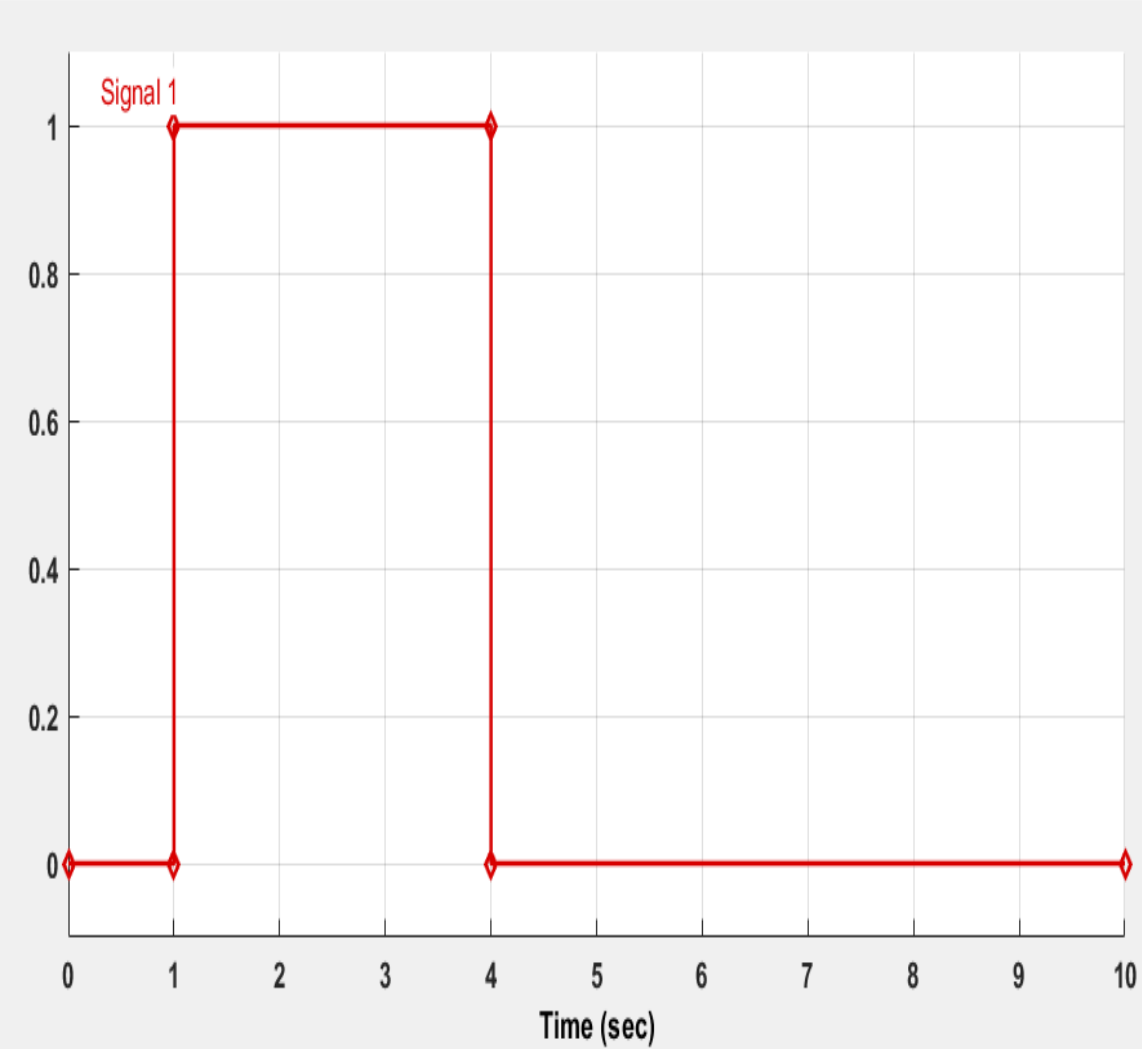
Simulink



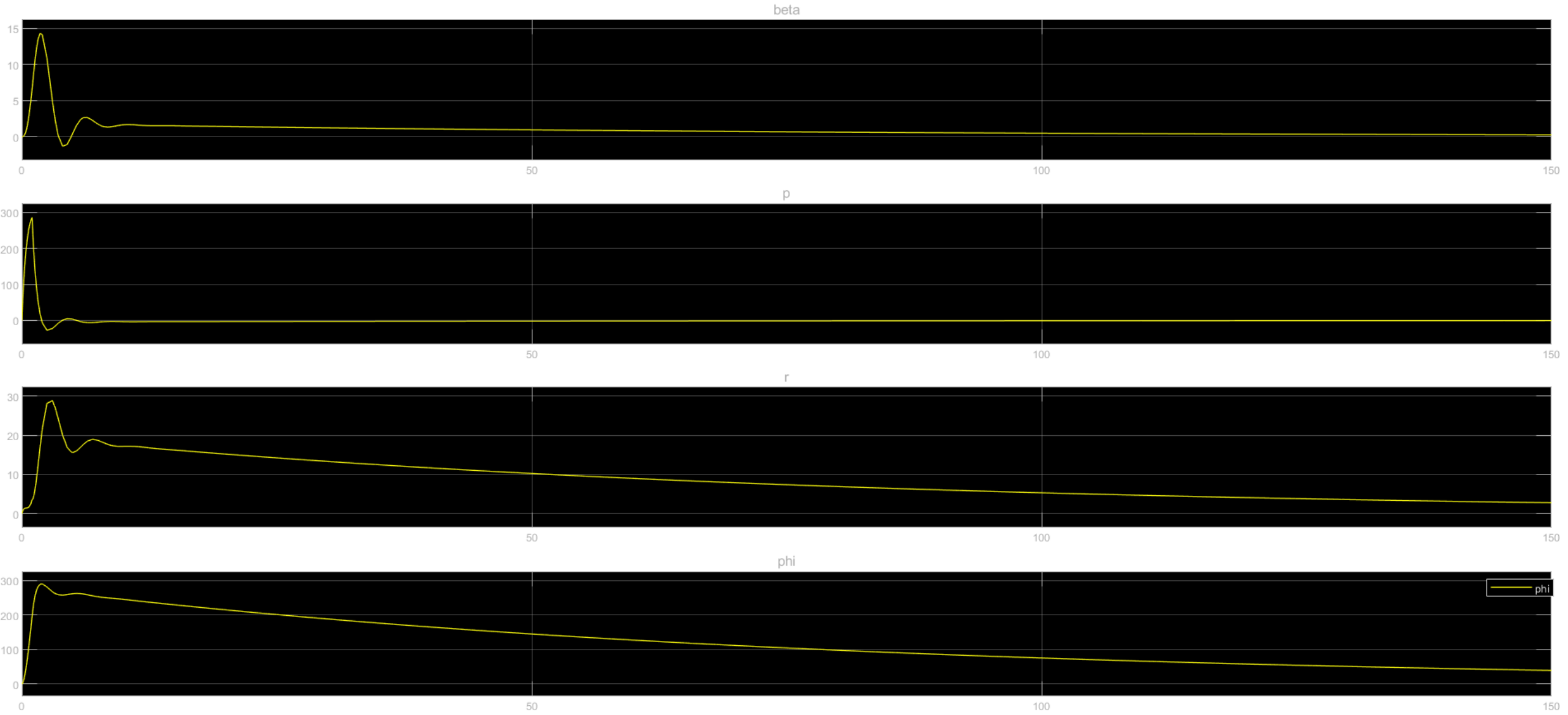
Control action for rudder and input signal

(Rudder limit: -15<δr<15)





φ & r settle at a value $\neq 0$



Roll Controller

The TF $\frac{\Delta\varphi}{\delta_r}$ has been changed during yaw controller for coordinated airplane, we will get the new TF from Matlab function called feedback it will give us the closed loop dynamics for new $\frac{\Delta\varphi}{\delta_r}$ after the effect of yaw damper.

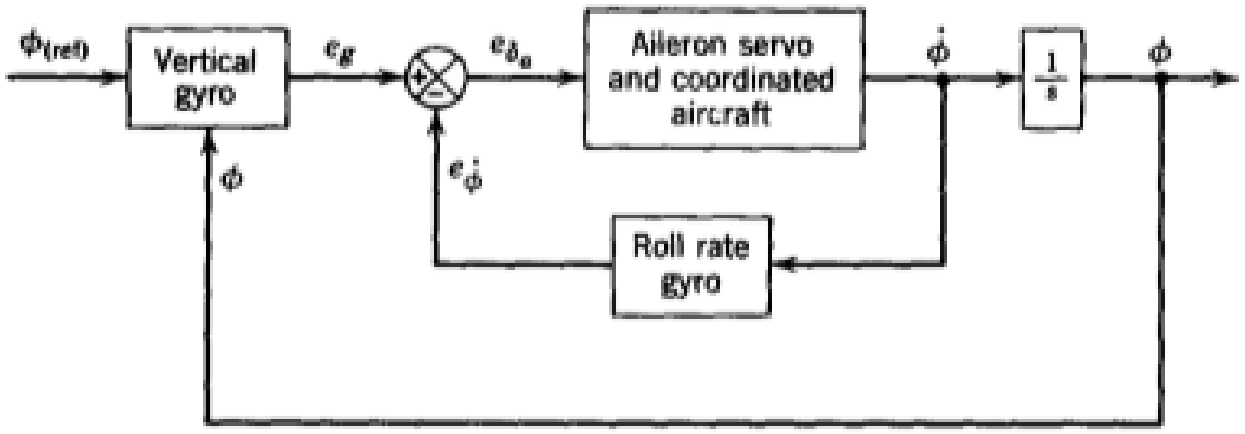
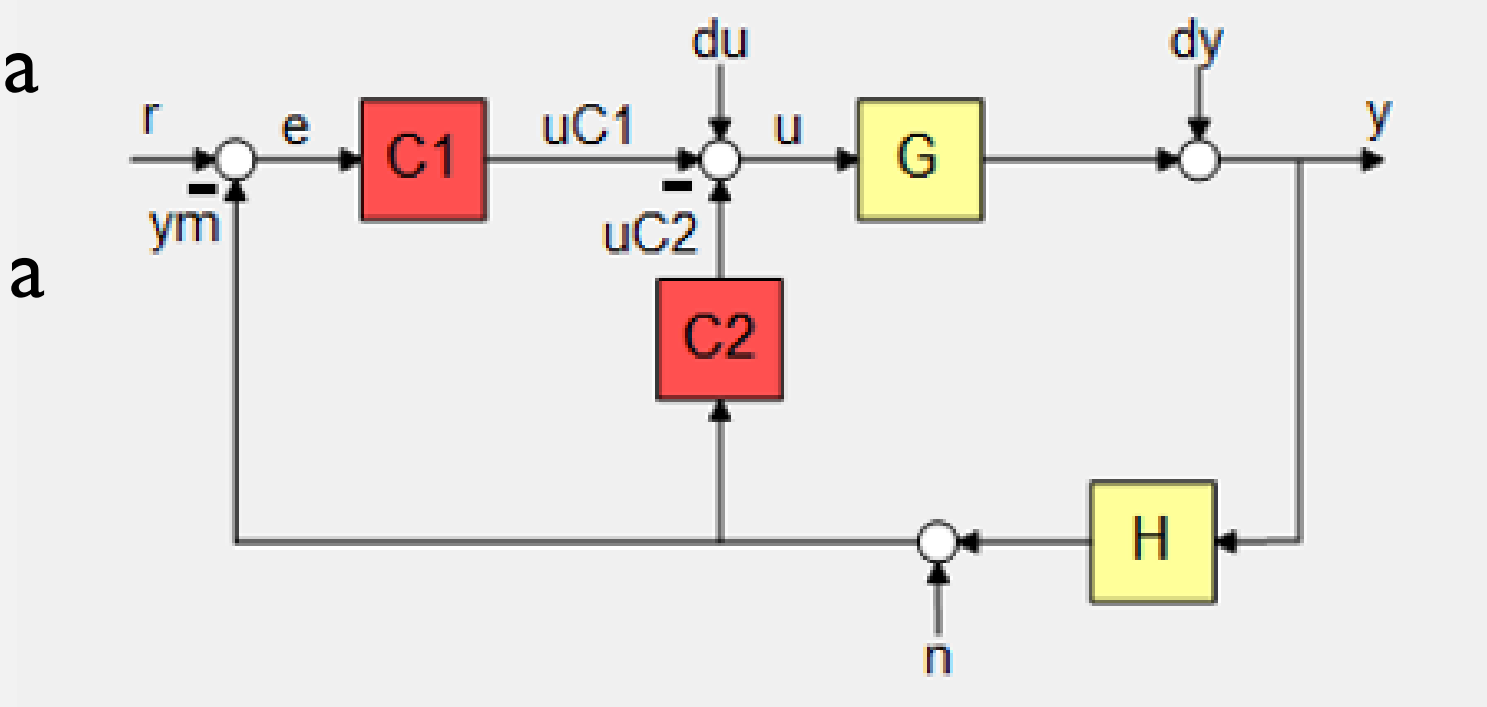


Figure 4-39 *Block diagram of roll angle control system.*

```
OL_phi_phicom =

                 1260 s^4 + 1.42e04 s^3 + 3.19e04 s^2 + 4.542e04 s + 2.859e04
  ---------------------------------------------------------------------------------------
  s^8 + 33.41 s^7 + 417.7 s^6 + 2422 s^5 + 6890 s^4 + 1.142e04 s^3 + 1.221e04 s^2 + 6077 s + 77.91
```

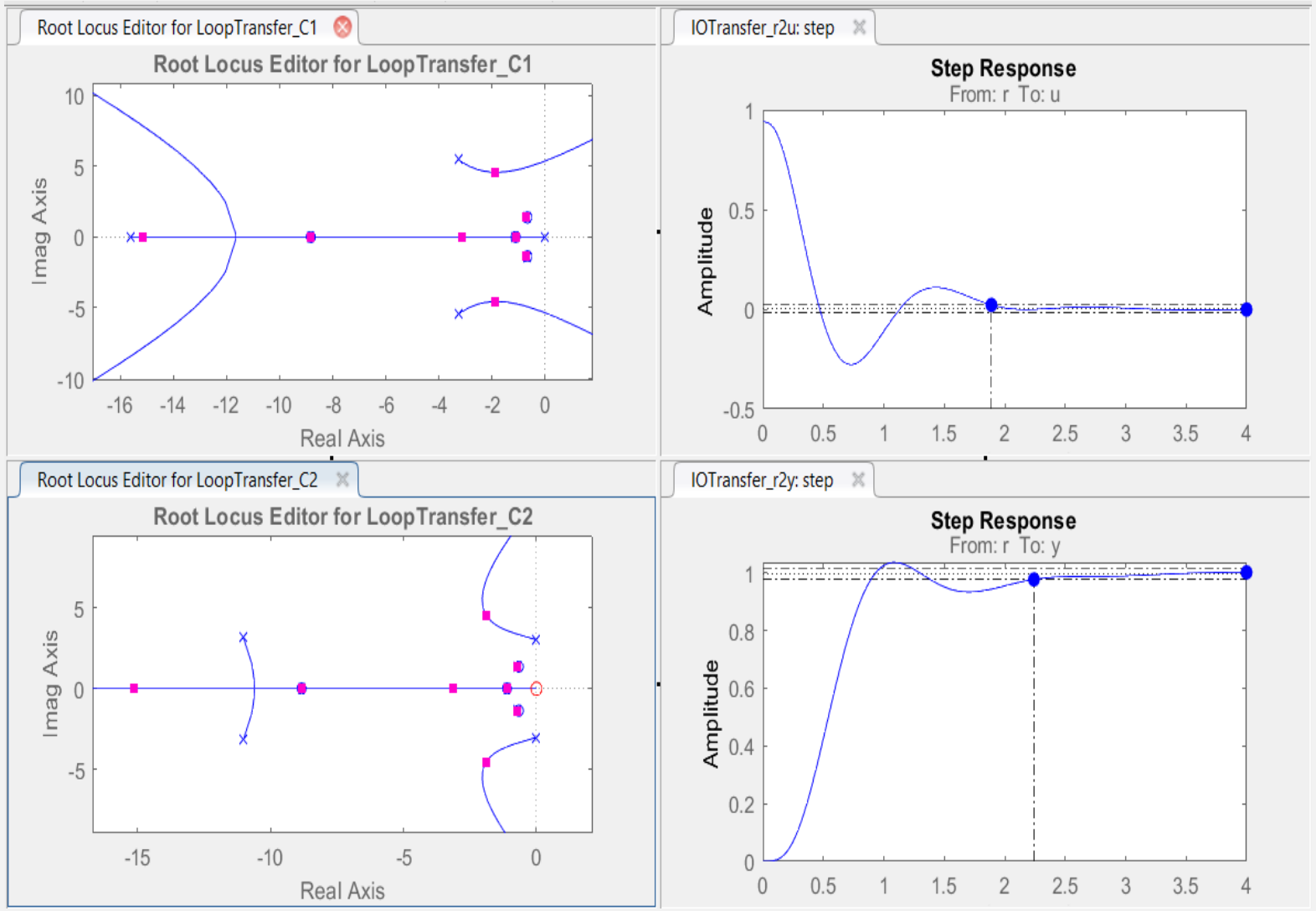
Roll Controller

we have chosen to tune on a **PD controller** to get minimum settling time with a proper control action.
After tuning the controllers will be

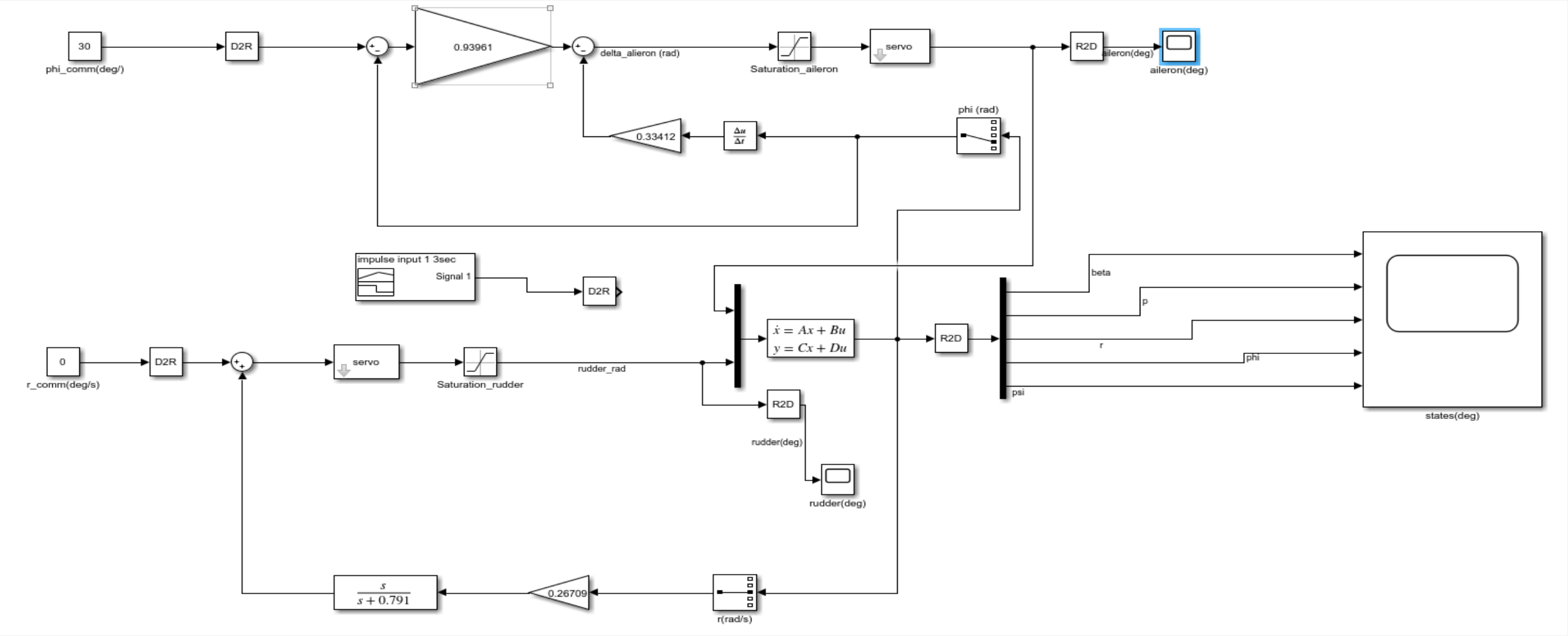


$$Kp = 0.93961(C1)$$
$$Kd = 0.33412(C2)$$

The results with PD controller

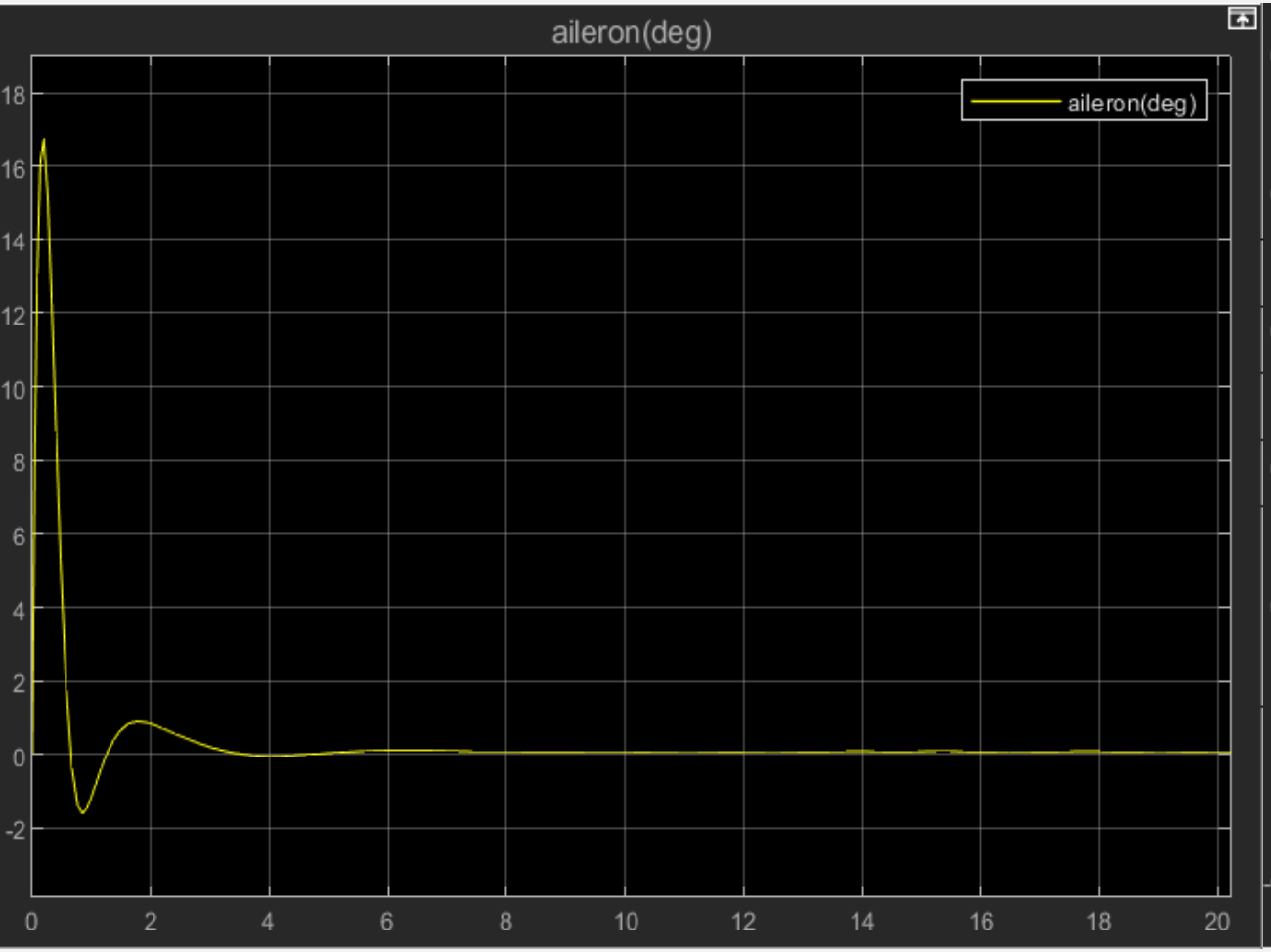


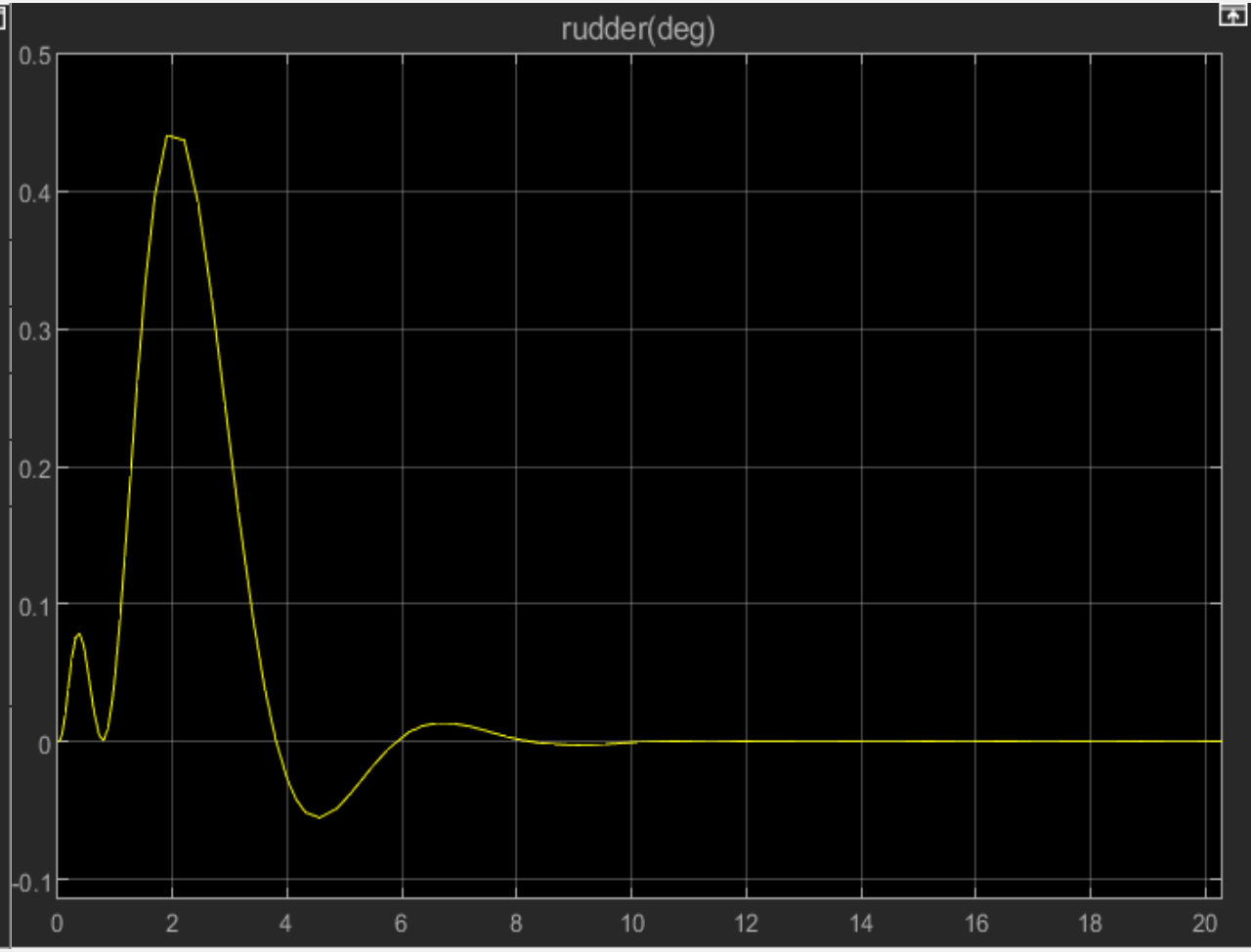
Simulink Test (Roll and Yaw) - Pd Controller



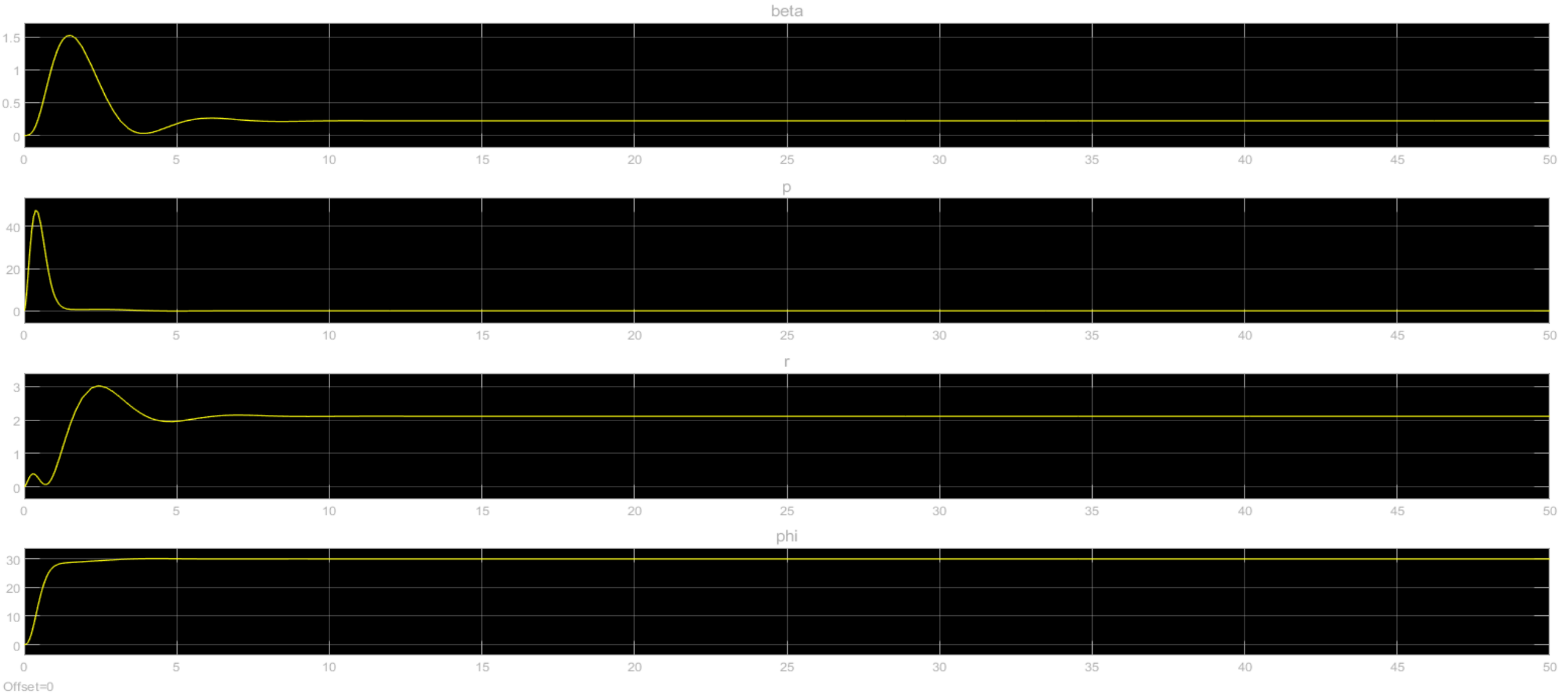
Control Actions for Rudder and Aileron

(Aileron limit: -50<δa<50)





States In (Deg) Phi Desired =30
R & Beta Settles At Value ≠ 0



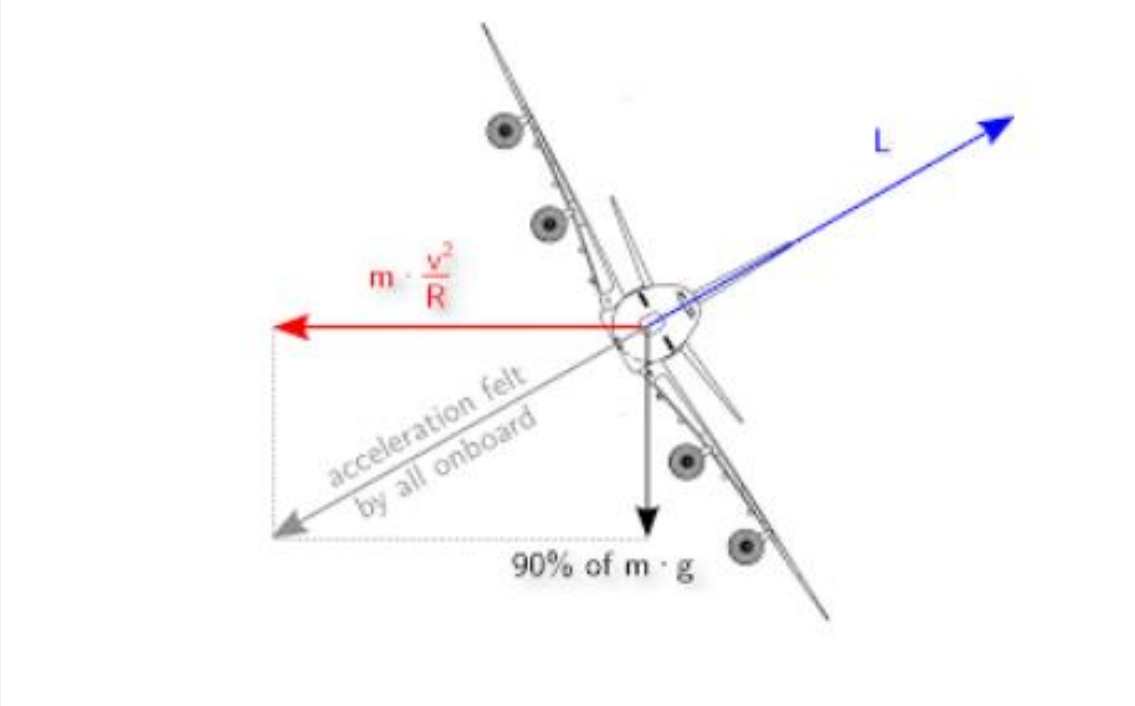
Coordination

There is a certain value for bank angle (phi) to achieve coordination, after some manipulations with equations, this value of phi is

$$\varphi \cong \frac{U_o}{g}\,\dot{\psi}$$

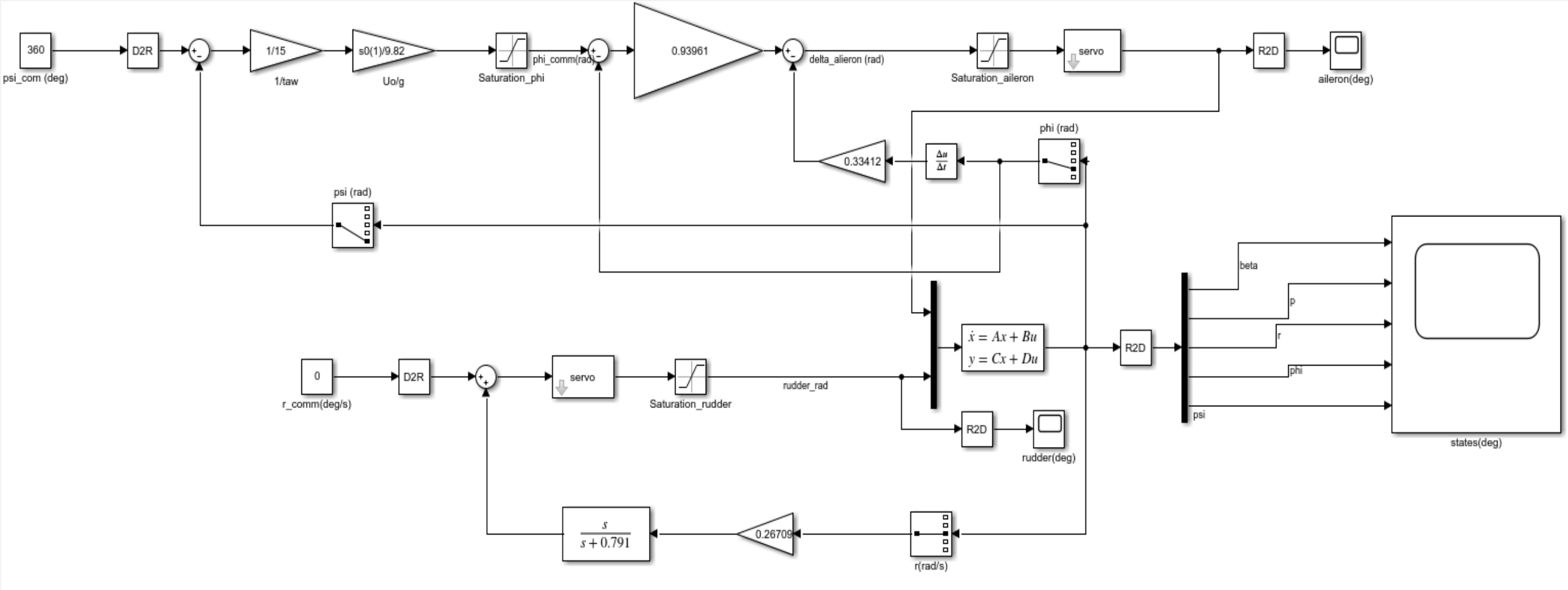
With: $\psi/_{\psi_d} = \frac{1/_\tau}{s+1/_\tau}$ & $15 \leq \tau \leq 20$

$$\therefore\ \varphi_d = \frac{U_o}{\tau\, g}\,(\psi_{desired} - \psi)$$

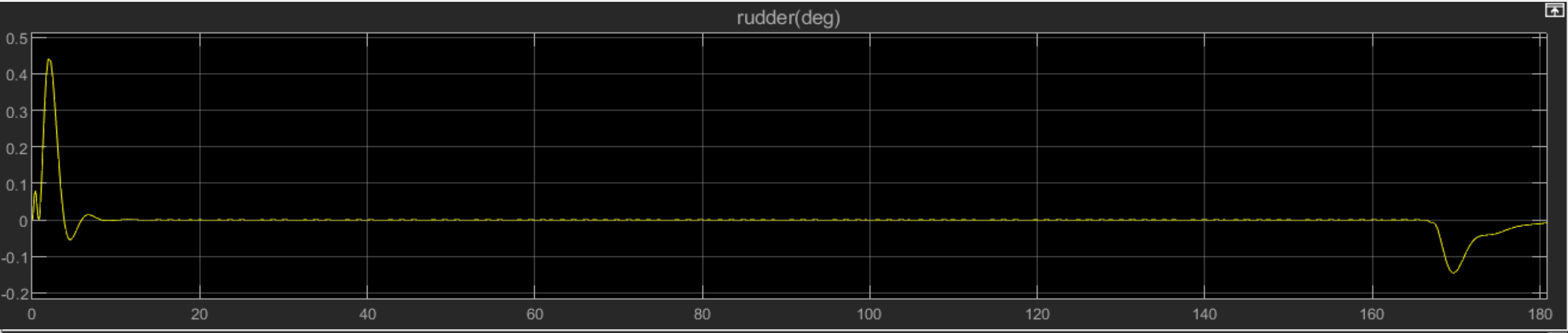


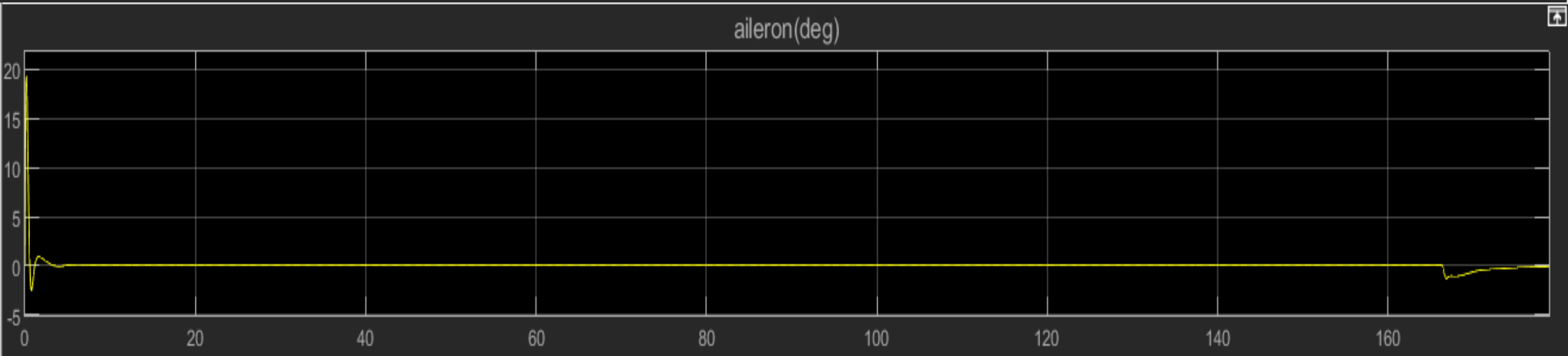
Simulink results (All controllers together)

We choose $\tau = 15$ & $\psi_d = 360\ degree\ (Complete\ turn)$

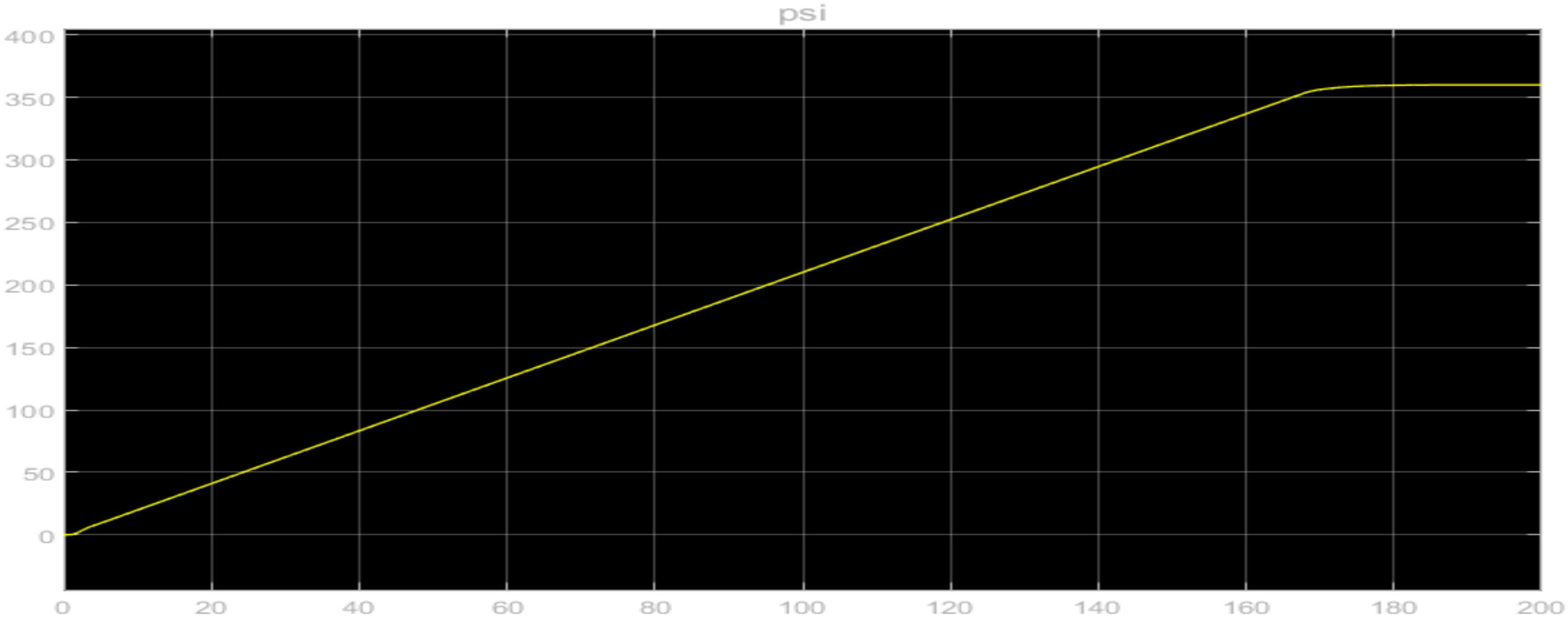


Control Actions for Rudder and Aileron

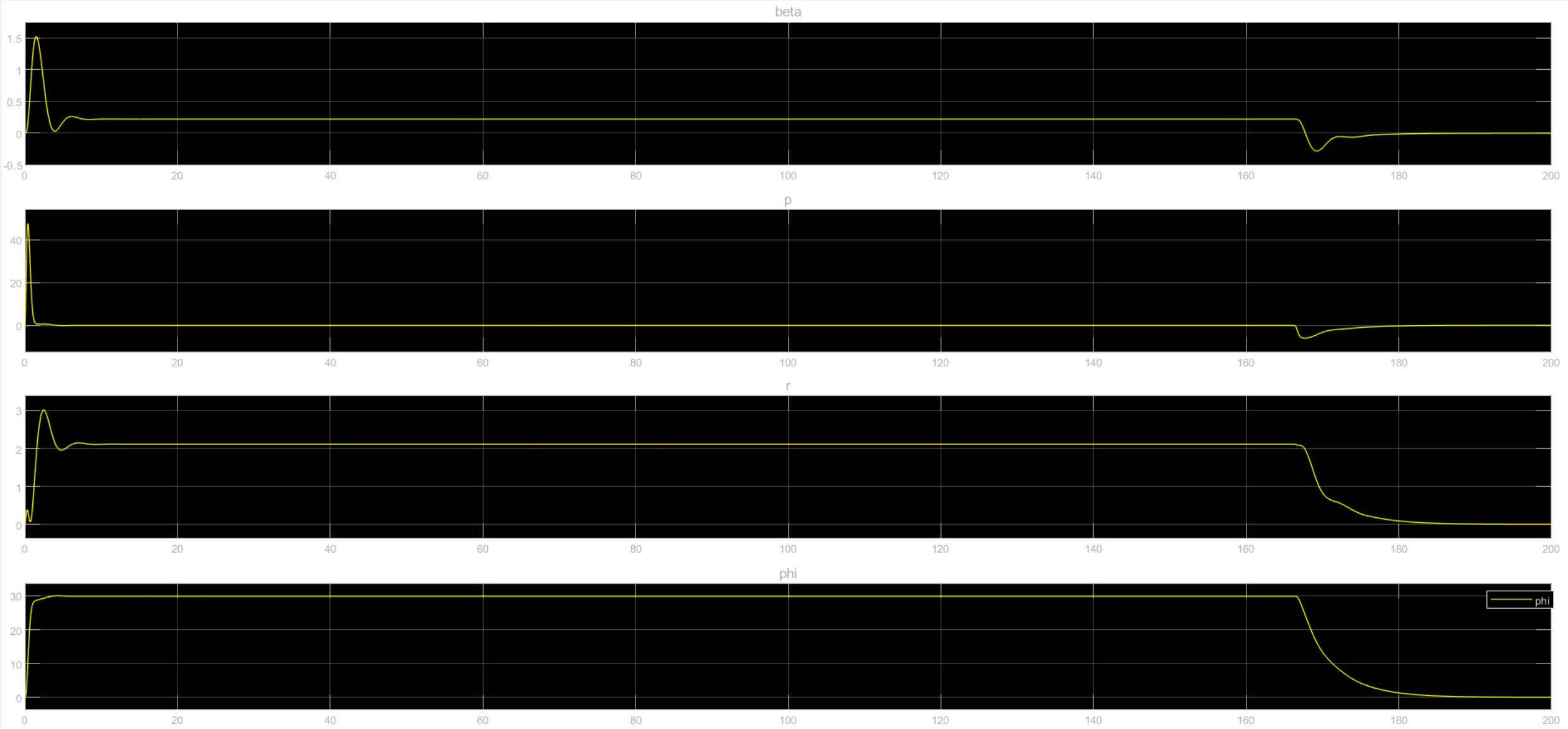




States (Deg) to make coordination turn take time less than 3 minutes



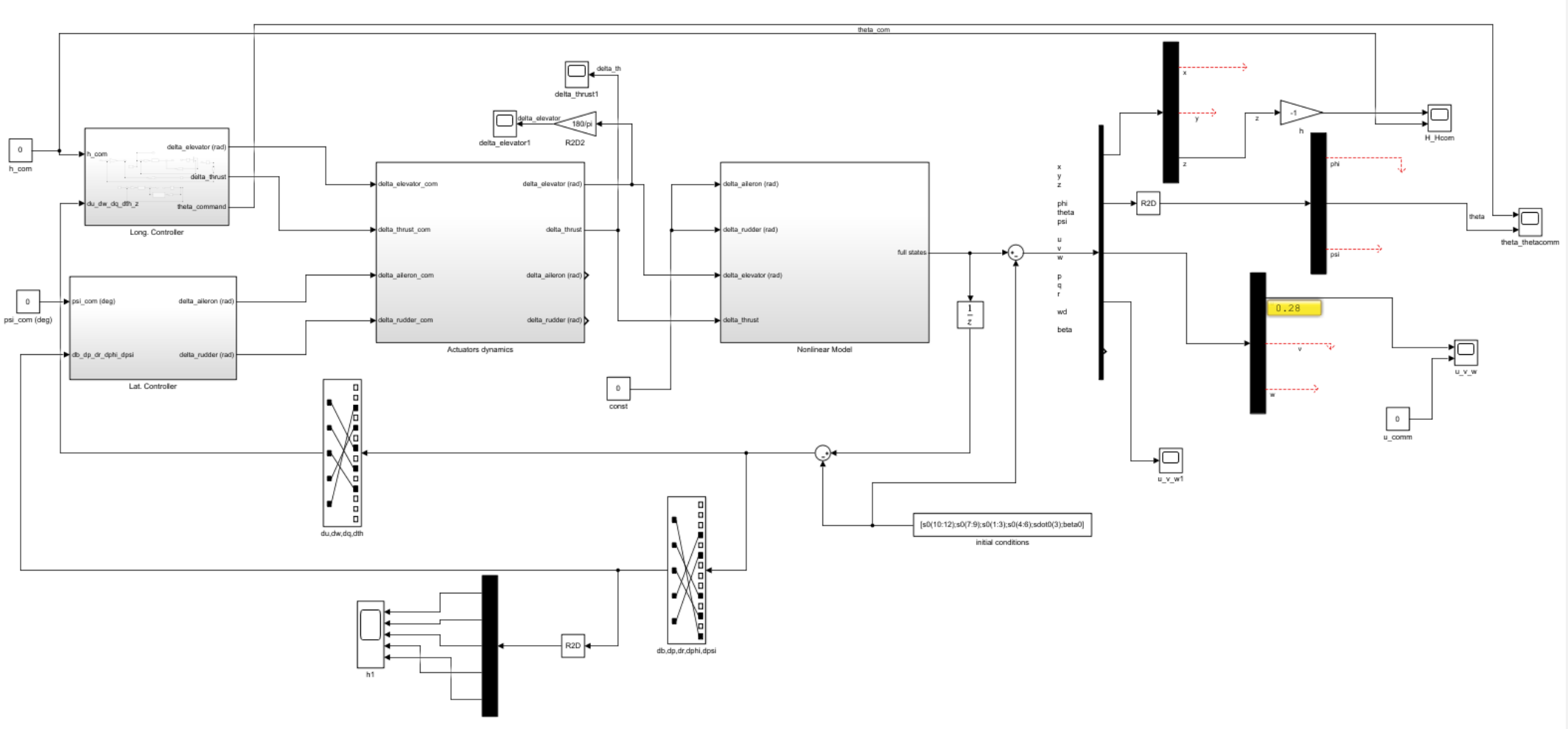
States (Deg) to make coordination turn take time less than 3 minutes



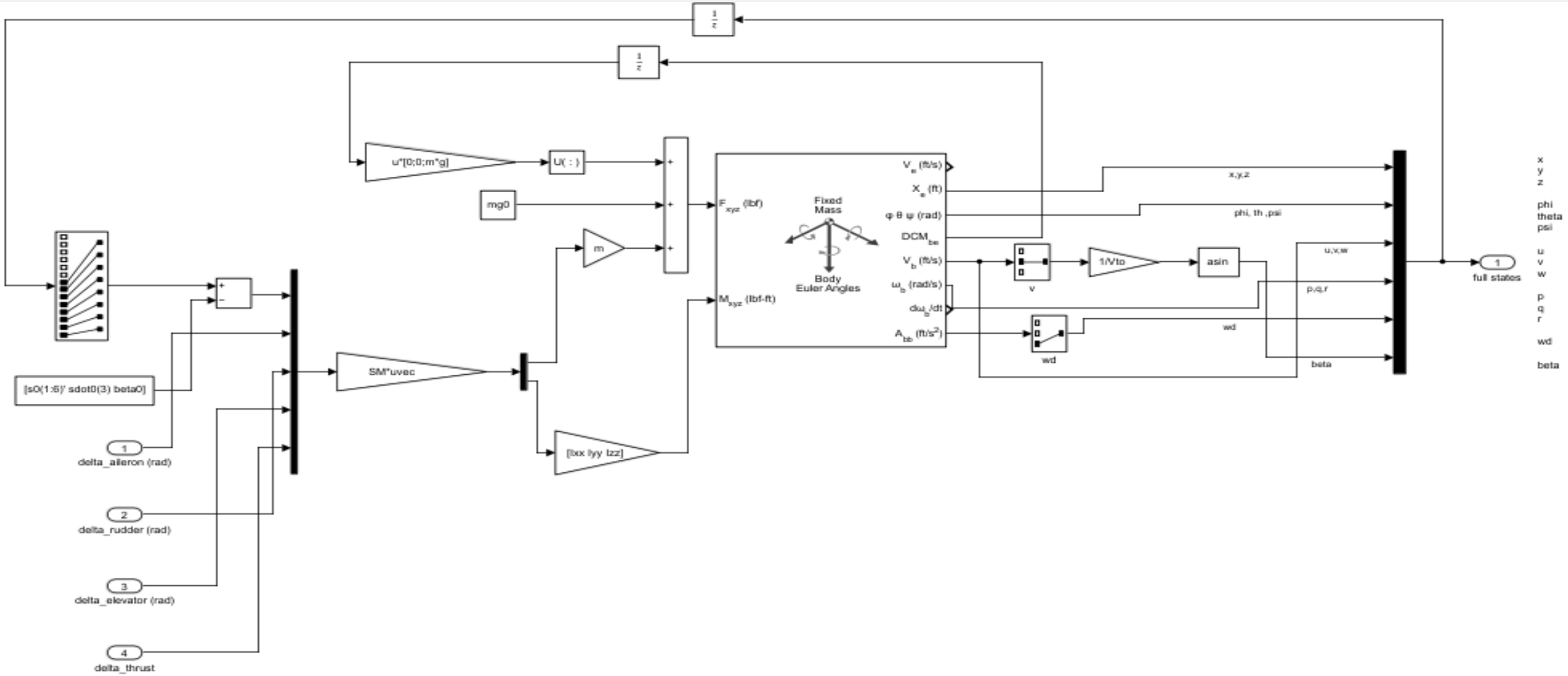
➢ TASK 7

Build Nonlinear Simulator

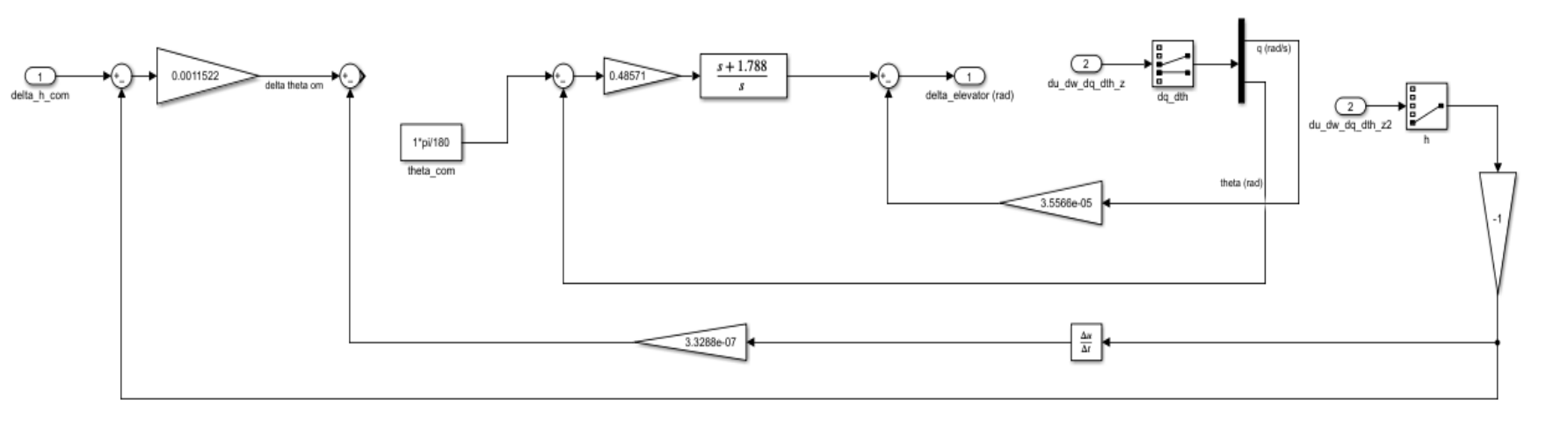
Full testing loop containing (Controller + Simulator)

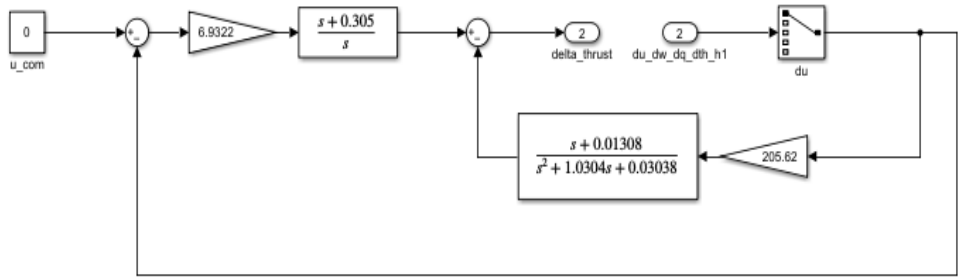


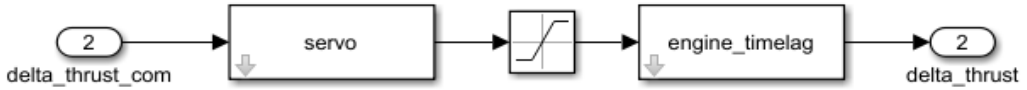
Nonlinear Simulator

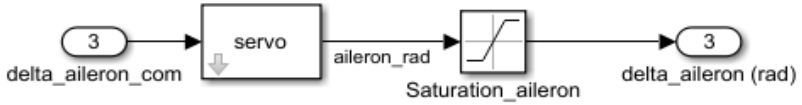


Longitudinal Controller& Actuators Dynamics





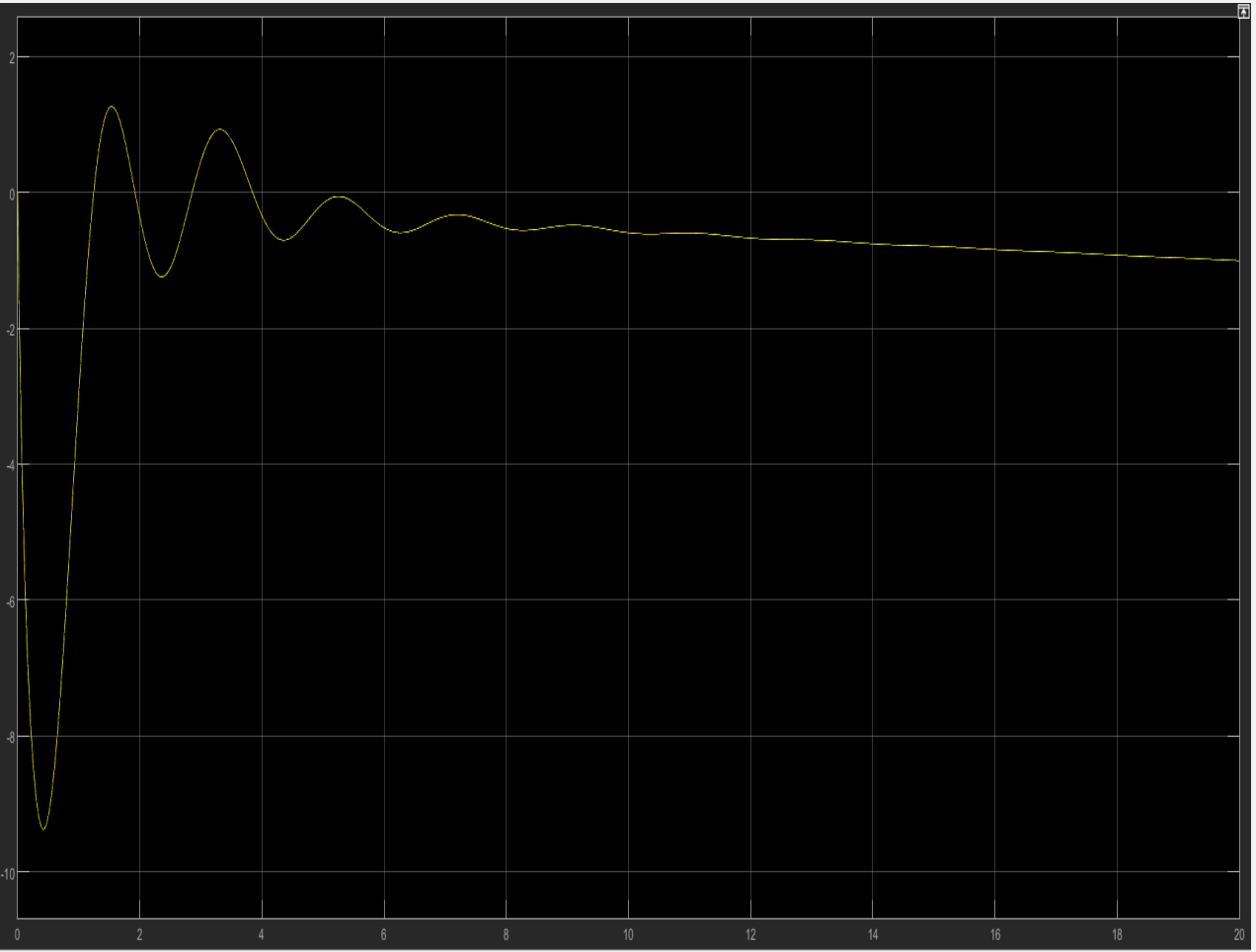




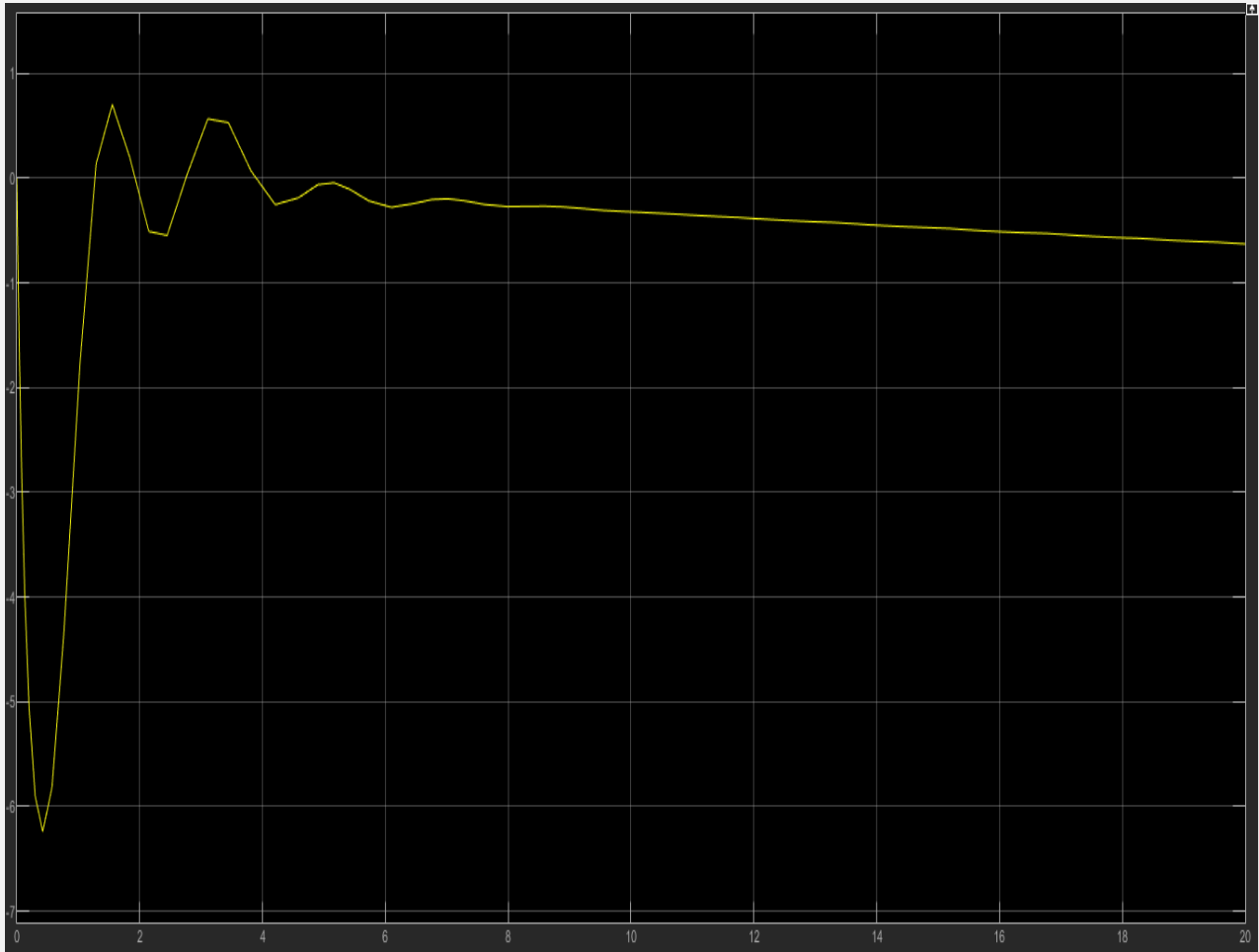
Pitch controller

$\Delta\theta_{com} = 15°$ **(delta elevator)**

Non linear model



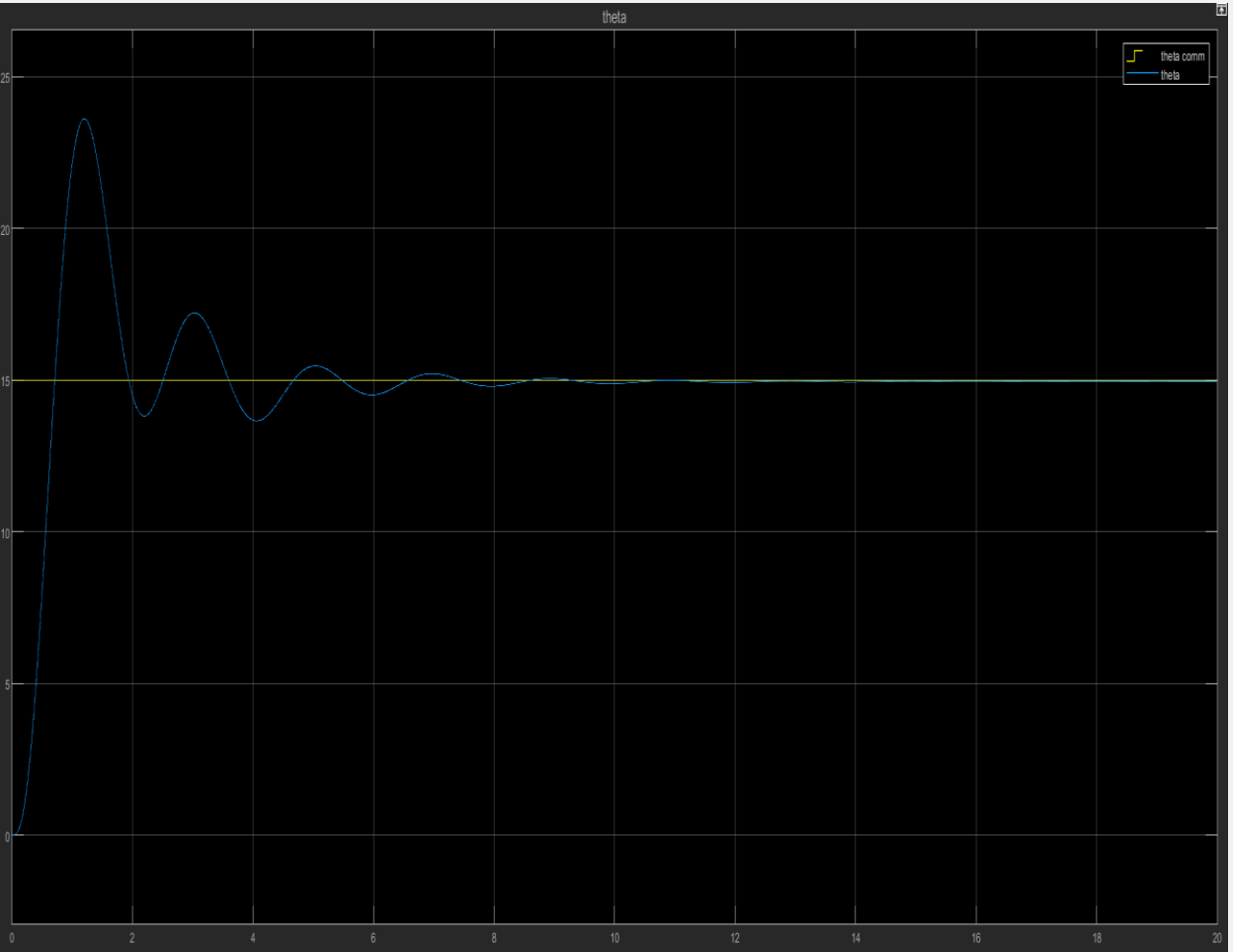
Linear model



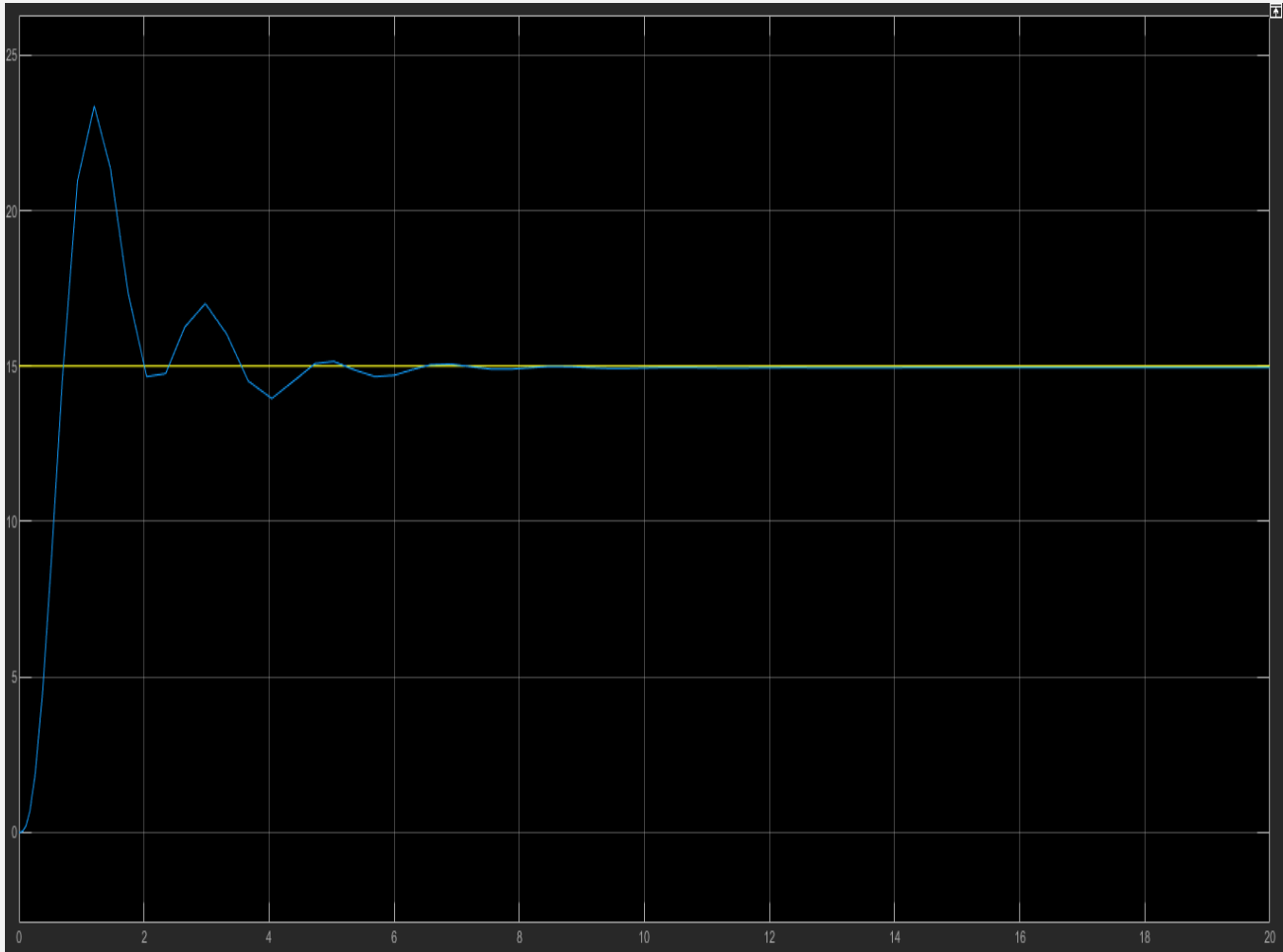
Pitch controller

(theta vs theta command)

Non linear model



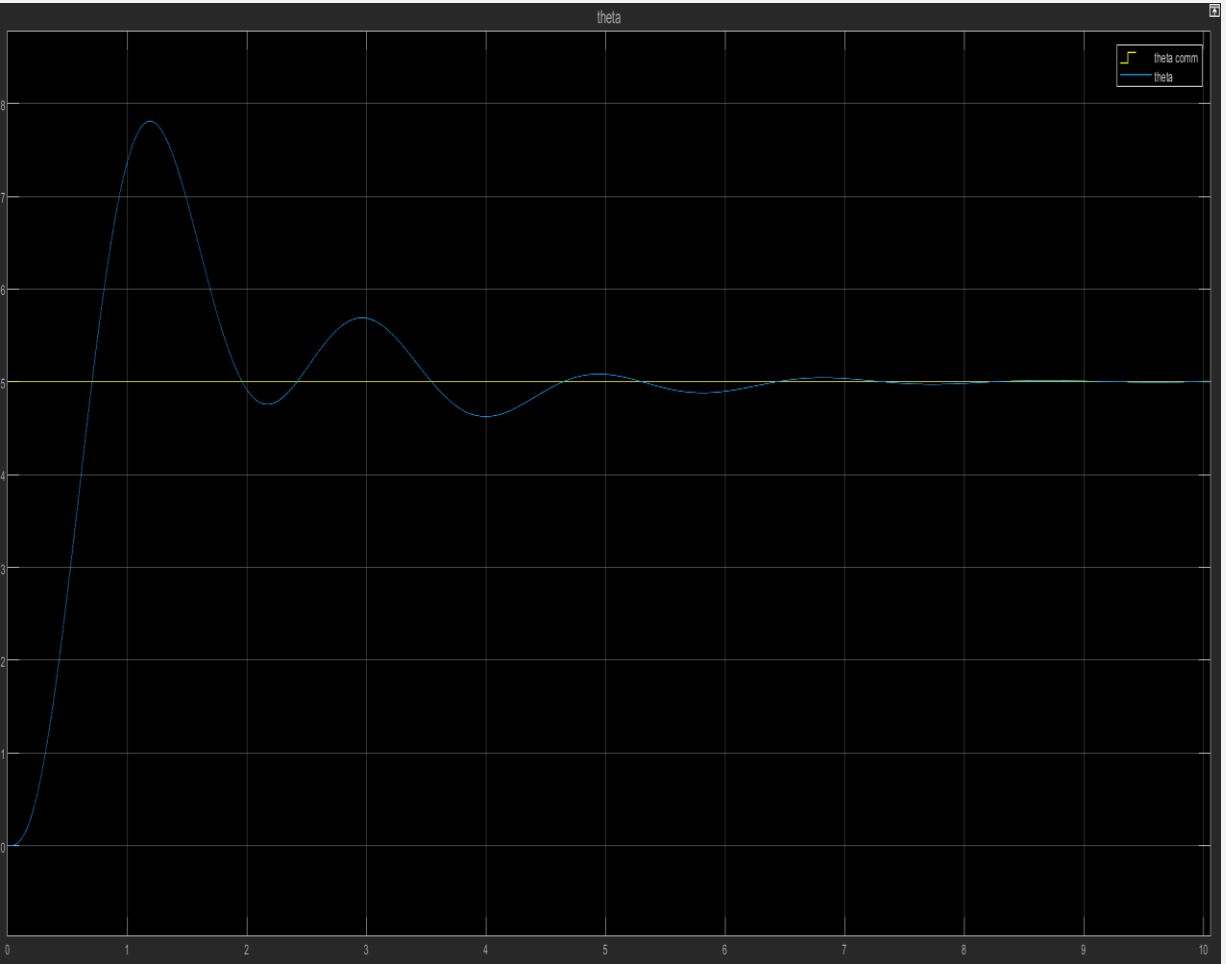
Linear model



Pitch controller + Velocity controller

($\Delta\theta_{com} = 5°$, Δu_{com}=0) (theta vs theta command)

Non linear model

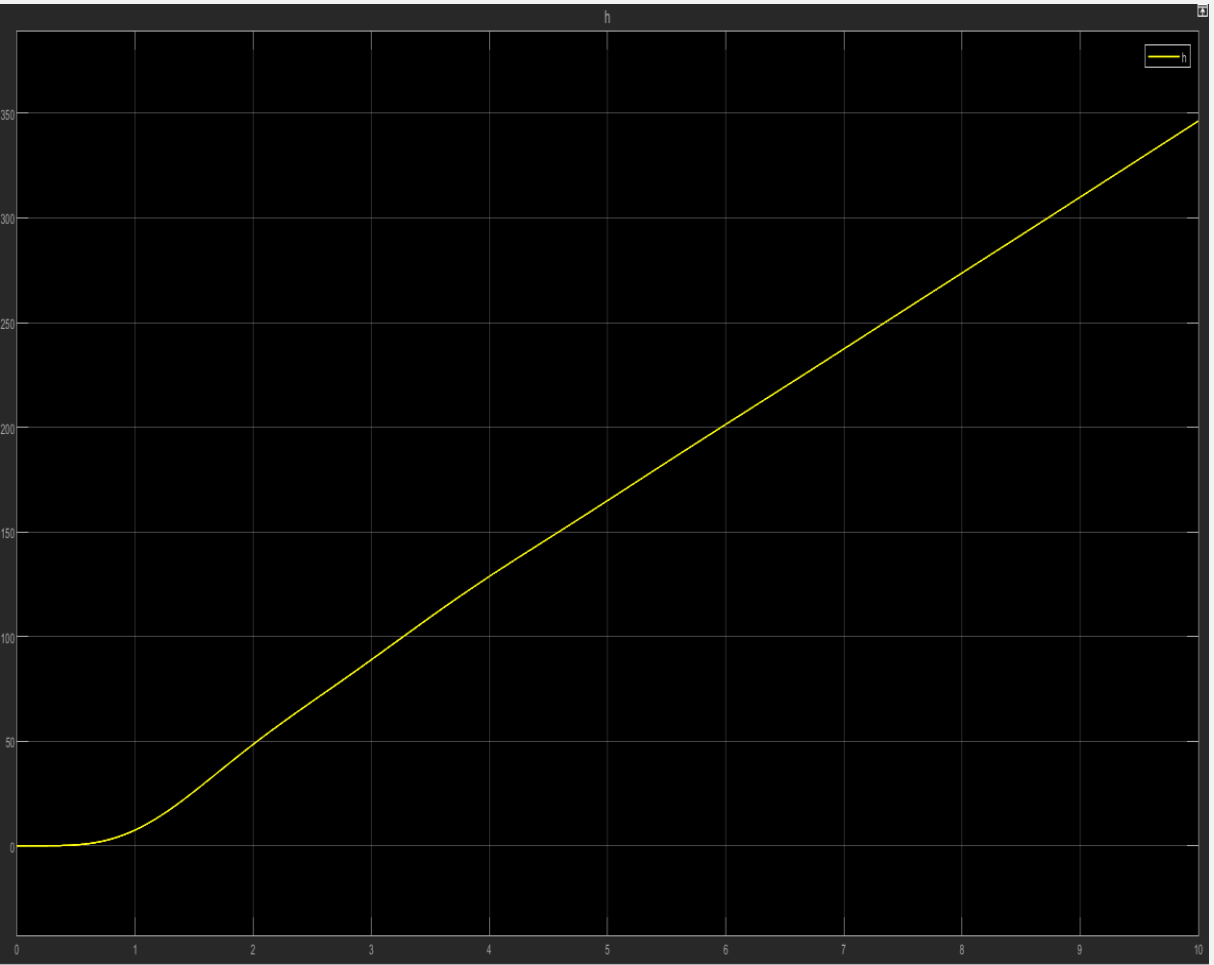


Linear model

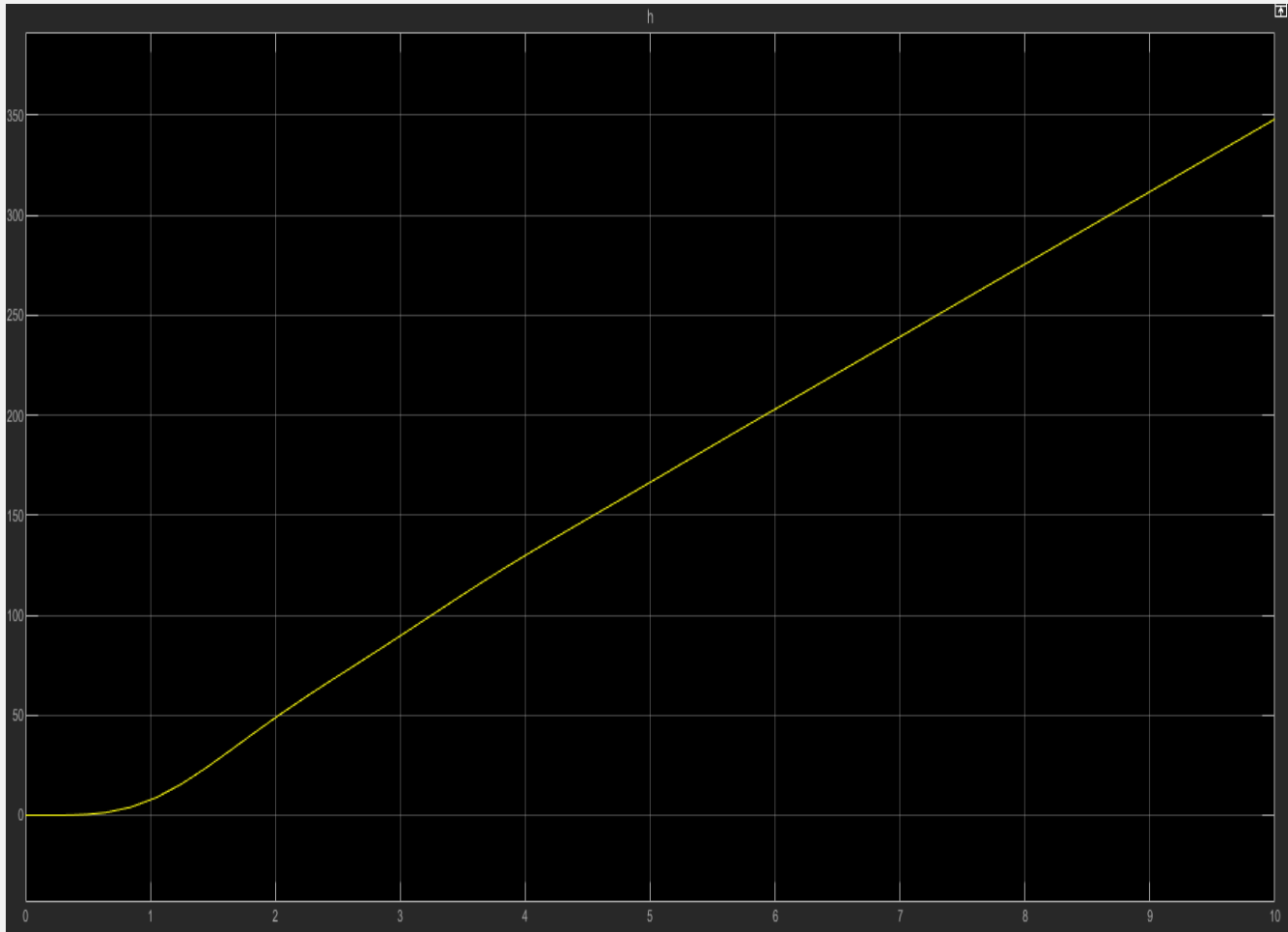
Pitch controller + Velocity controller

(Altitude h (ft))

Non linear model



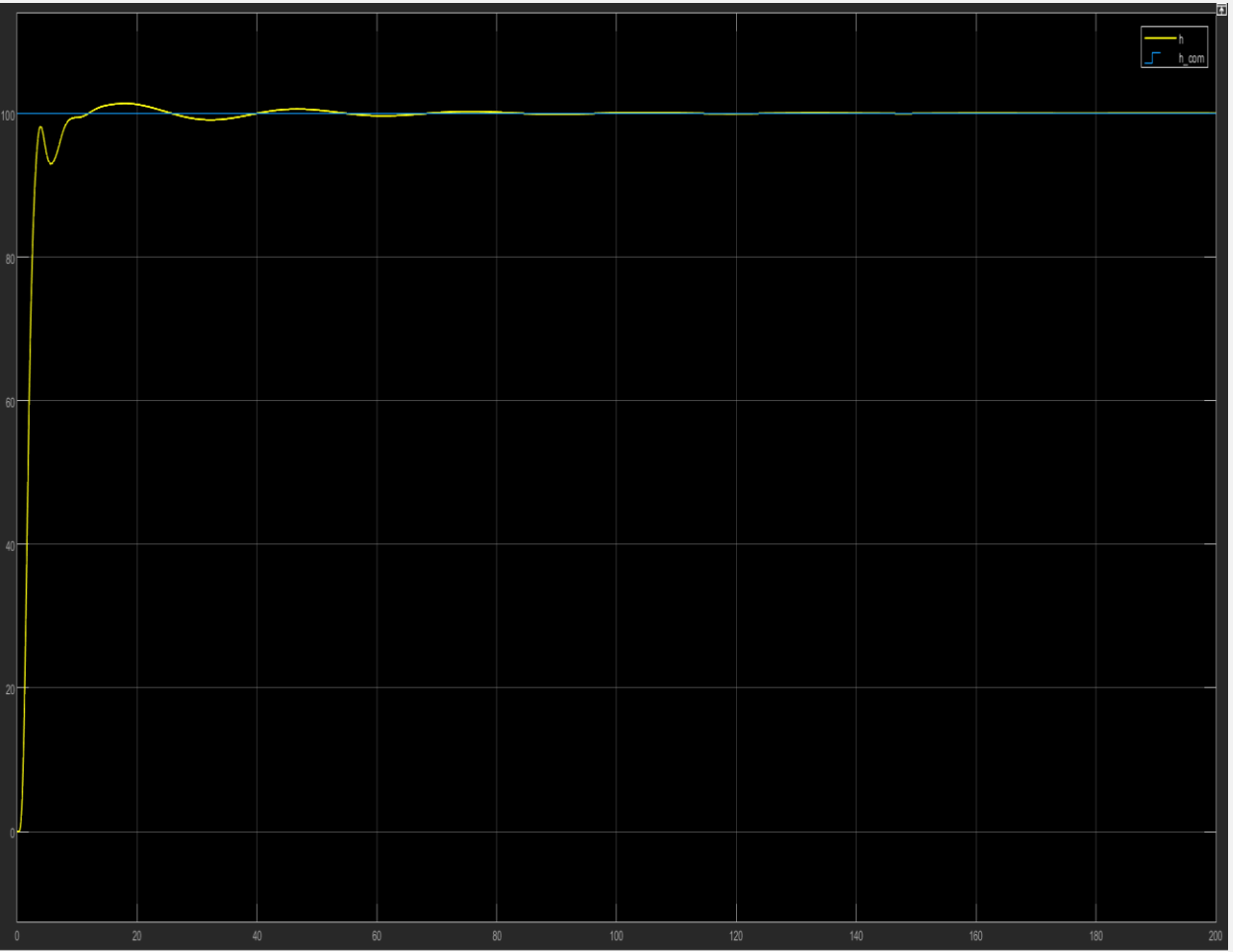
Linear model



Altitude Hold Controller

(h vs h command) (h_com= 100)

Non linear model

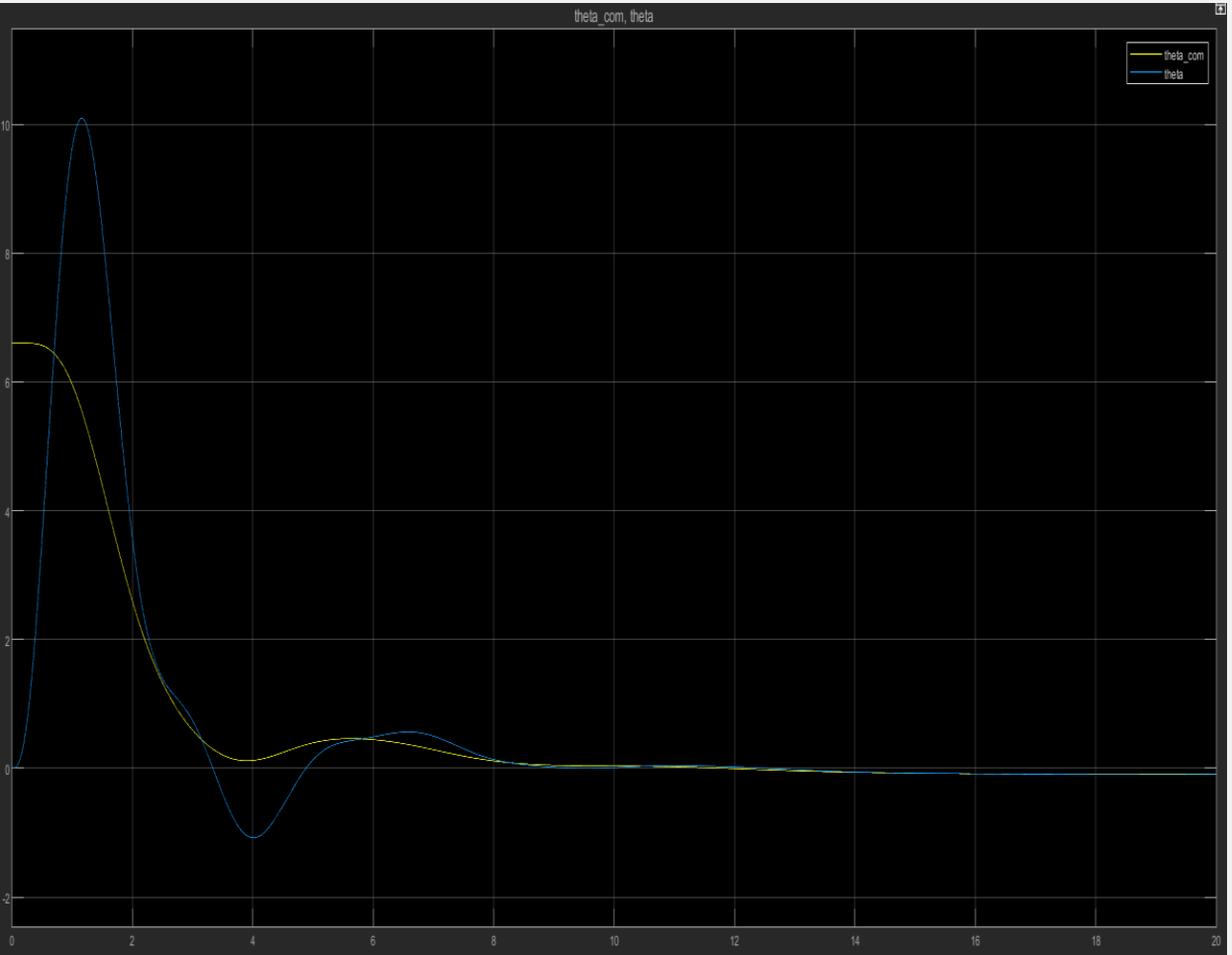


Linear model

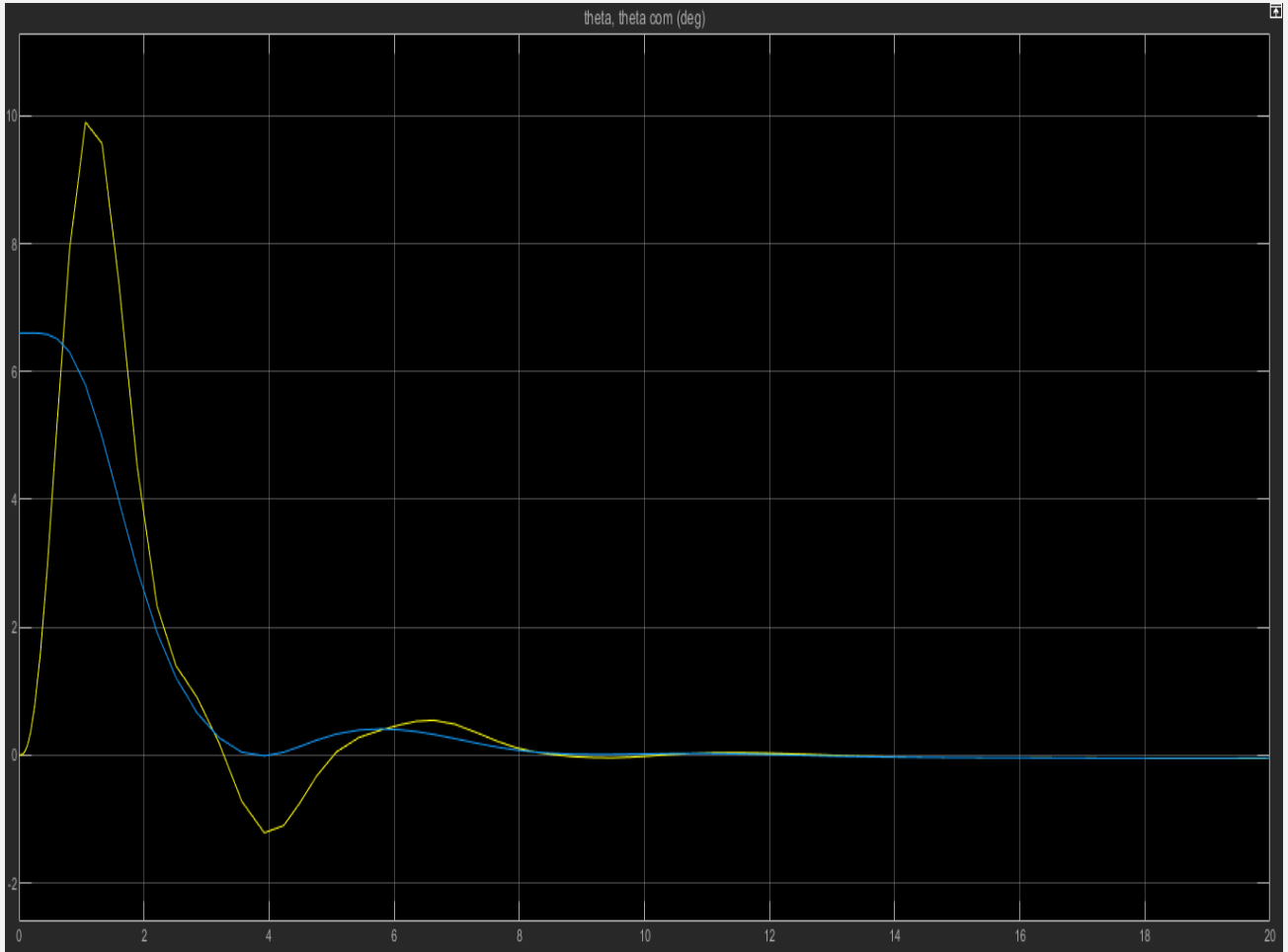
Altitude Hold Controller

(theta vs theta command)

Non linear model



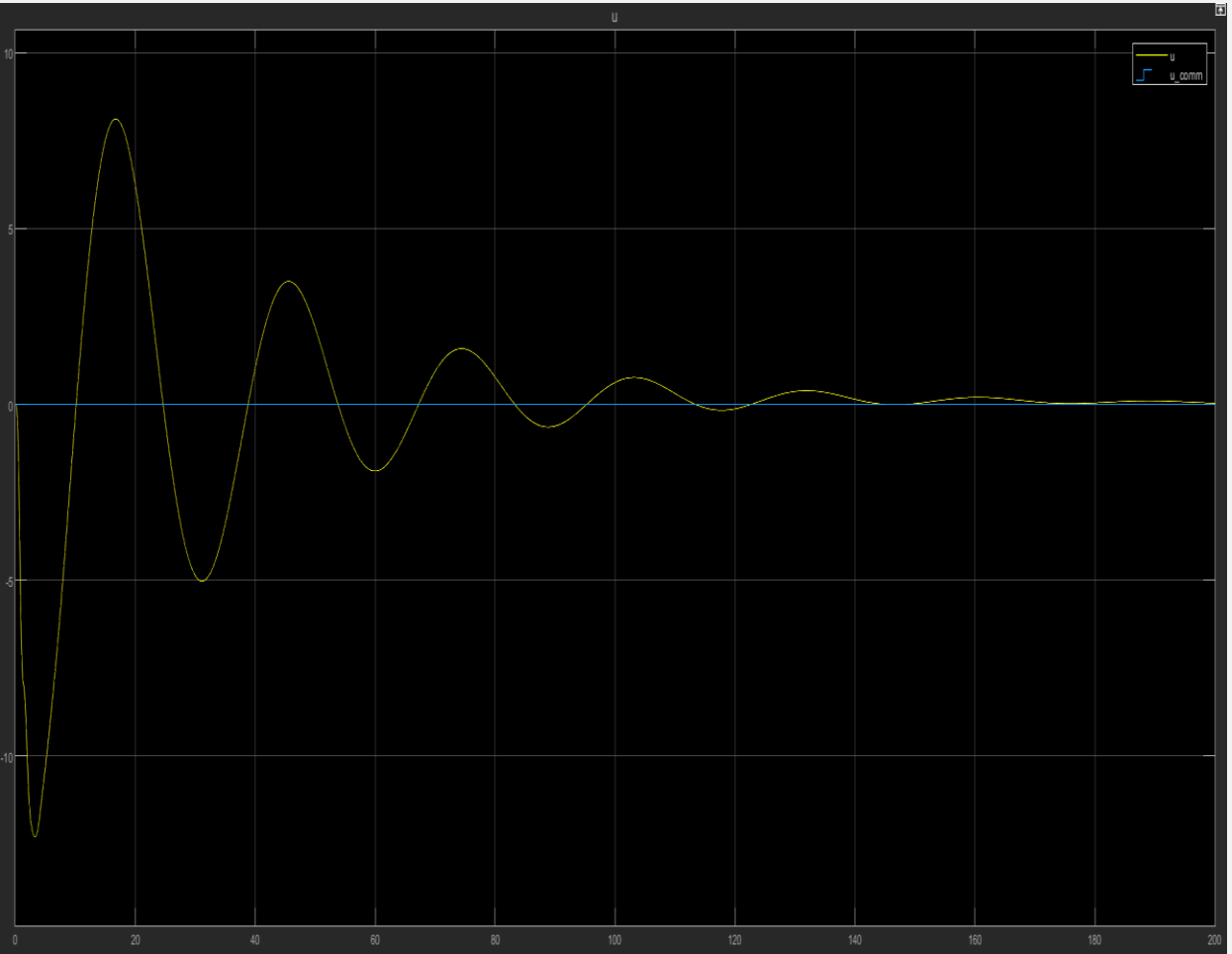
Linear model



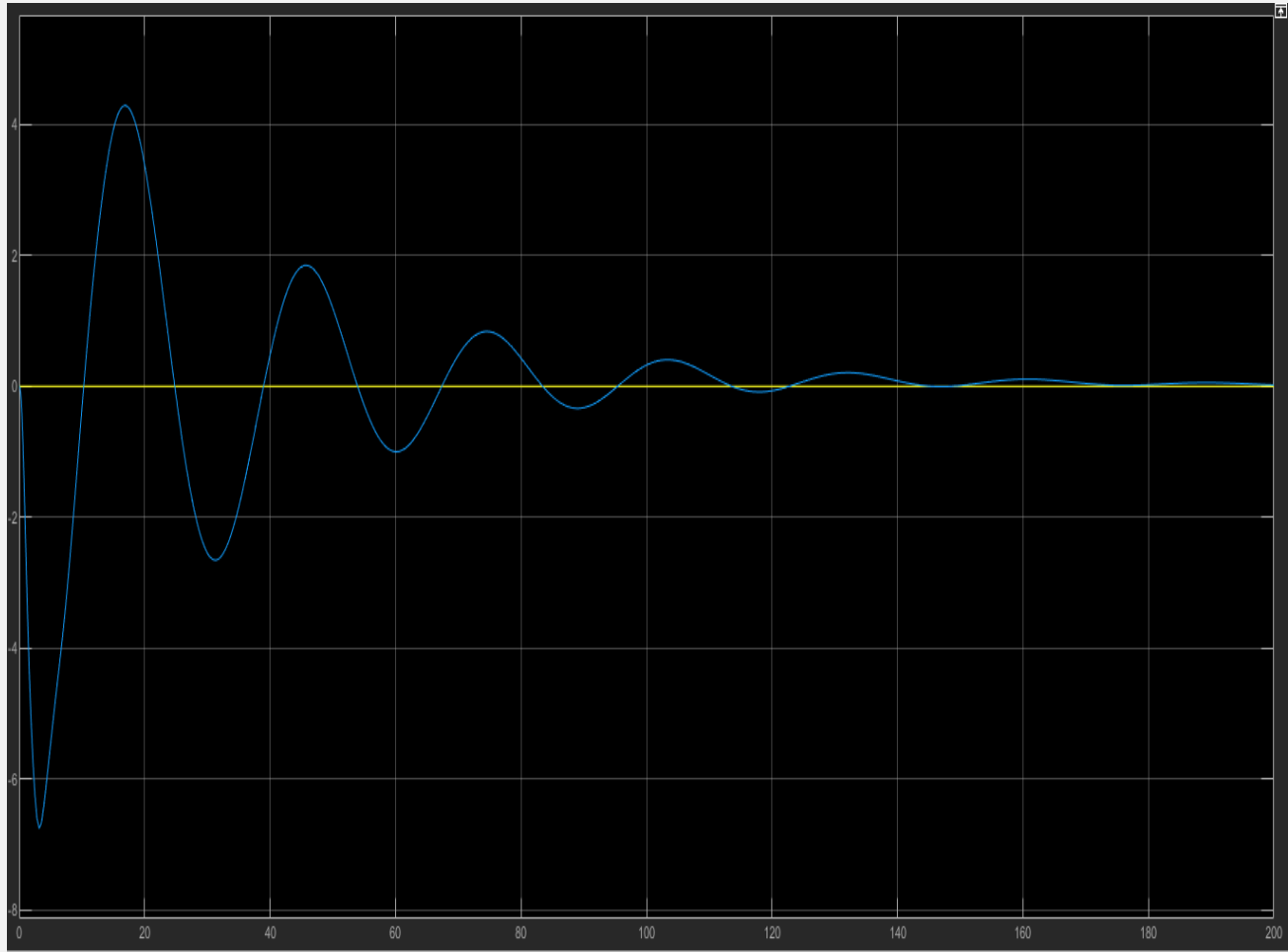
Altitude Hold Controller

(u vs u command)

Non linear model



Linear model

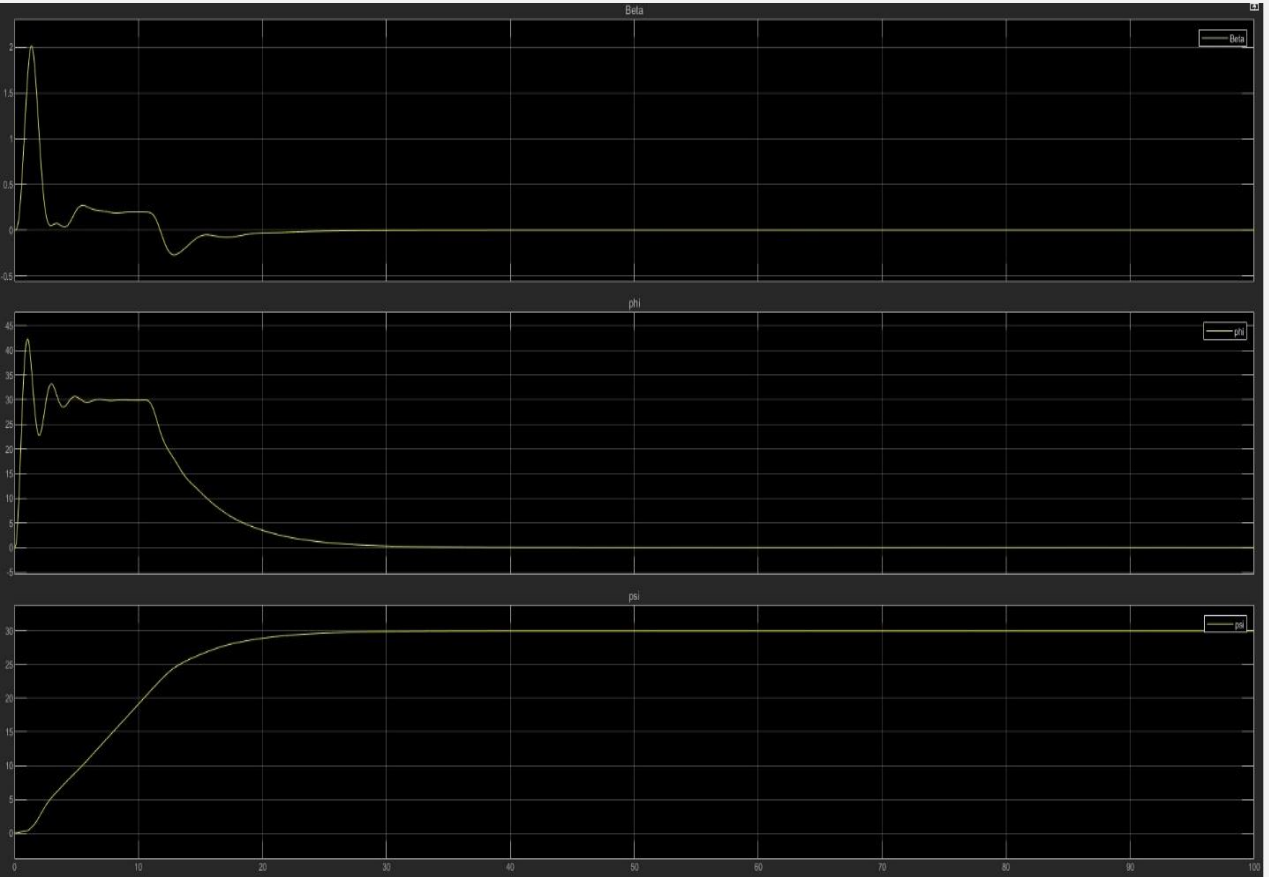


Lateral Controller

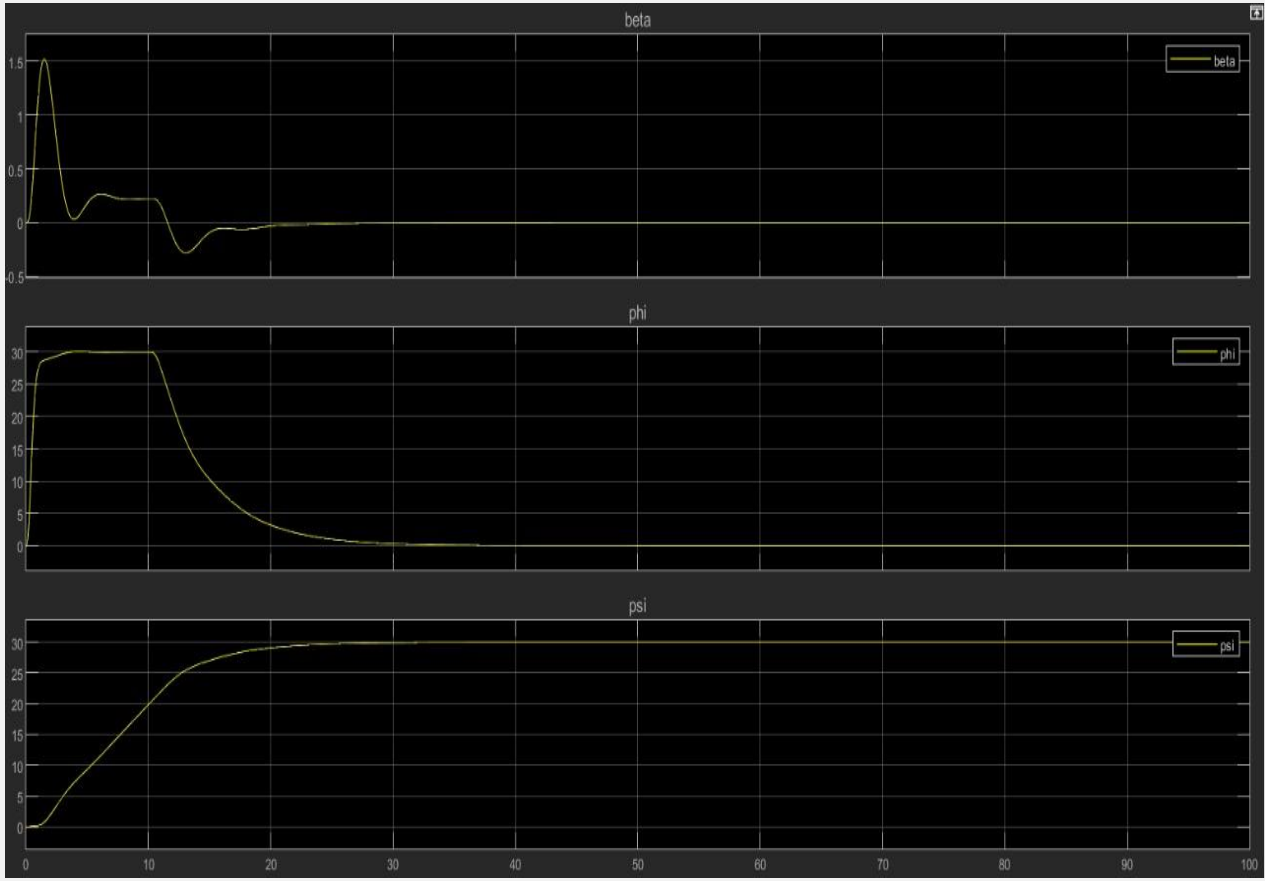
(psi_com= 30 deg)

$(\beta \ \& \phi \ \& \Psi)$

Nonlinear

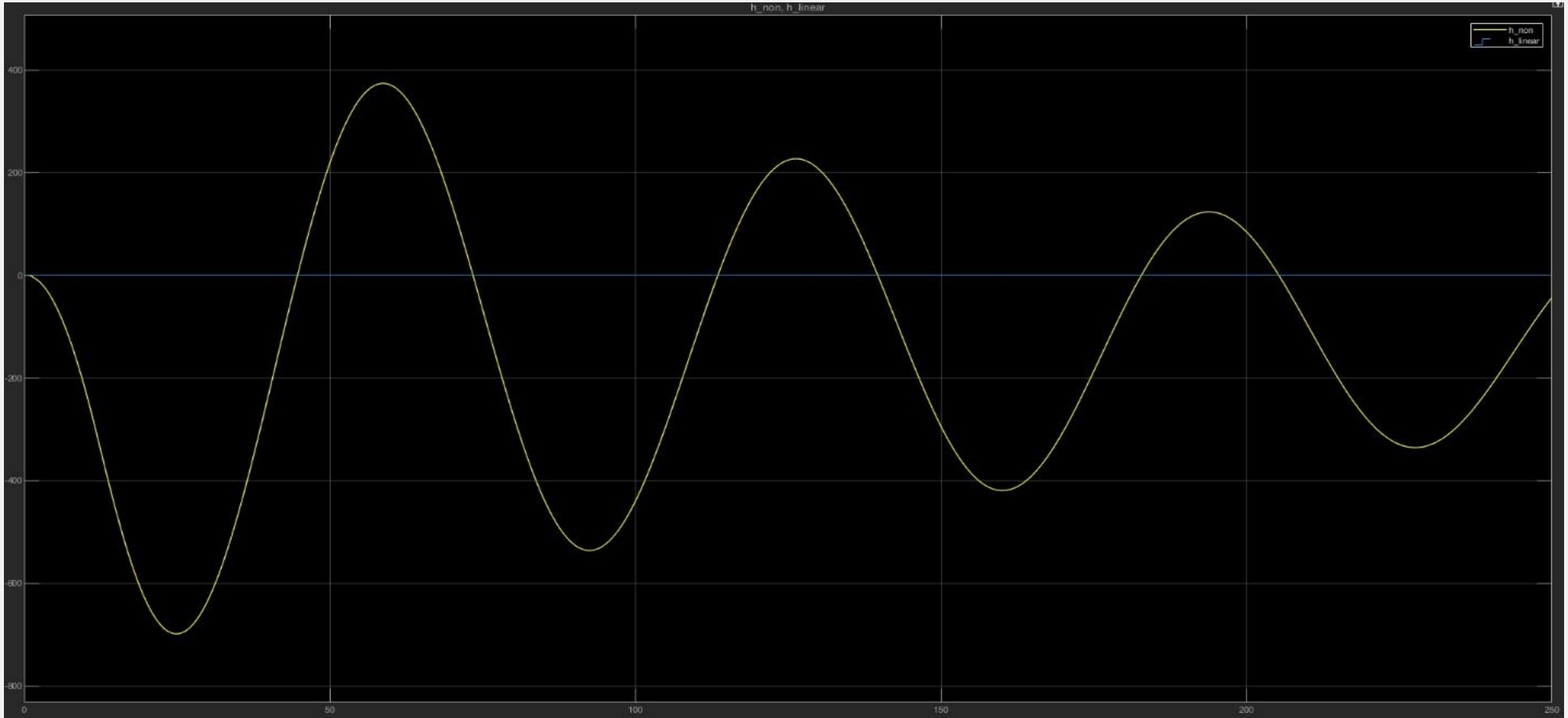


Linear



Lateral Controller

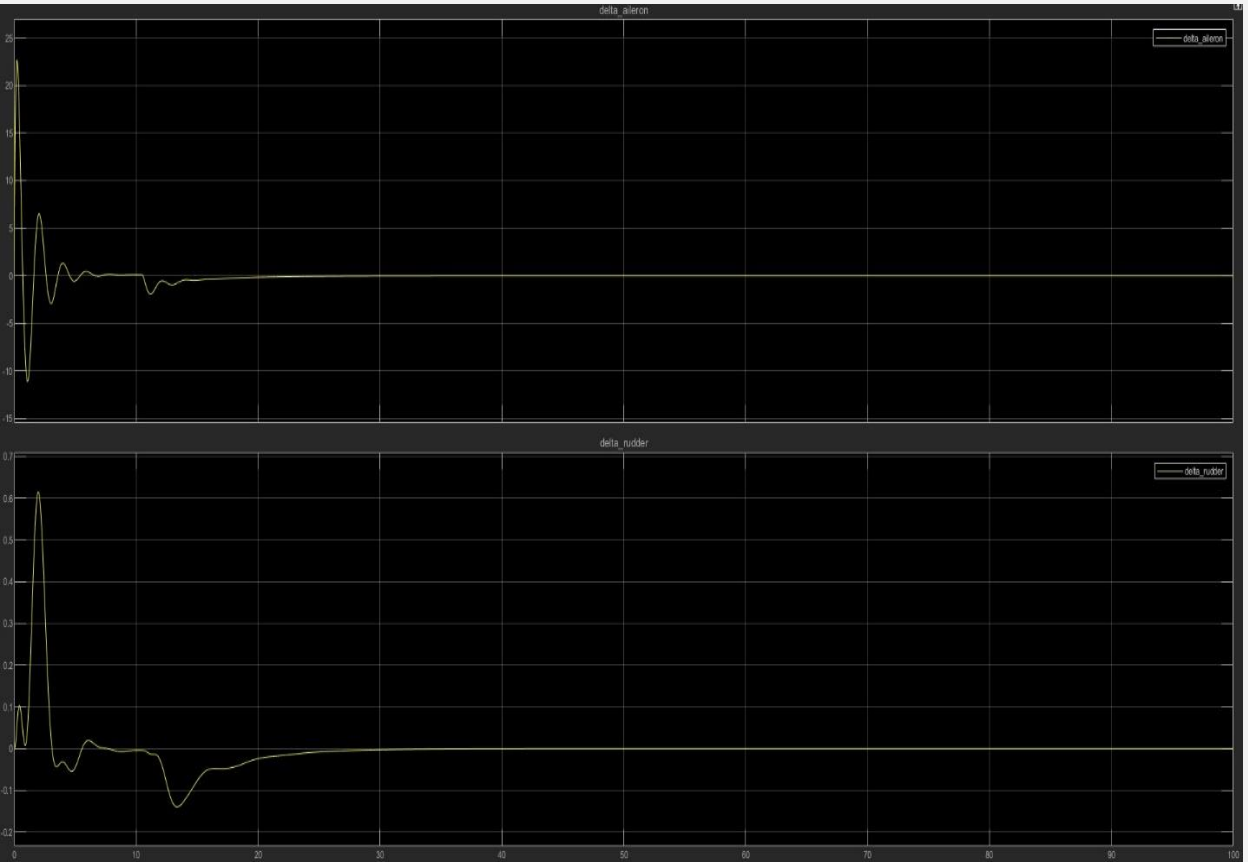
$h_{linear} - h_{nonlinear}$



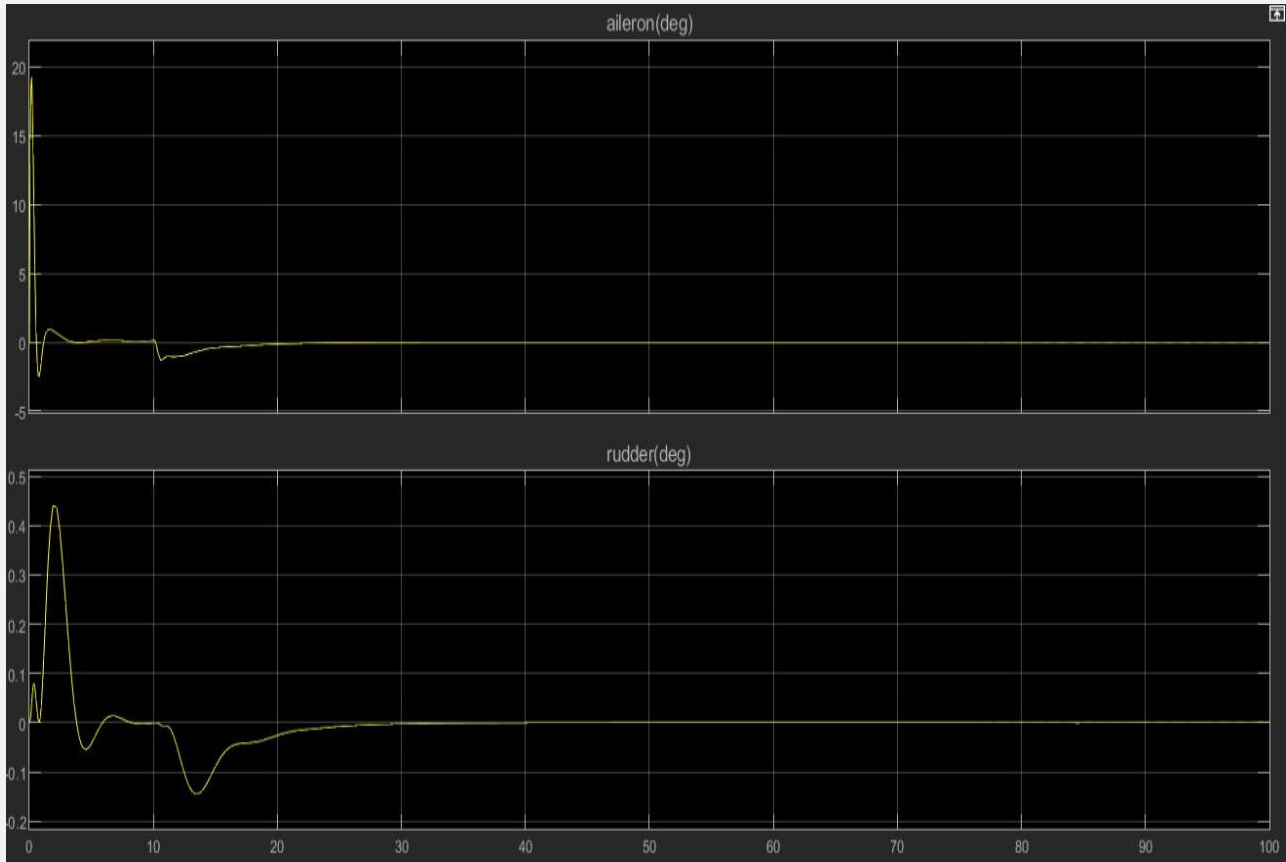
Lateral Controller

δr & δa

Nonlinear



Linear

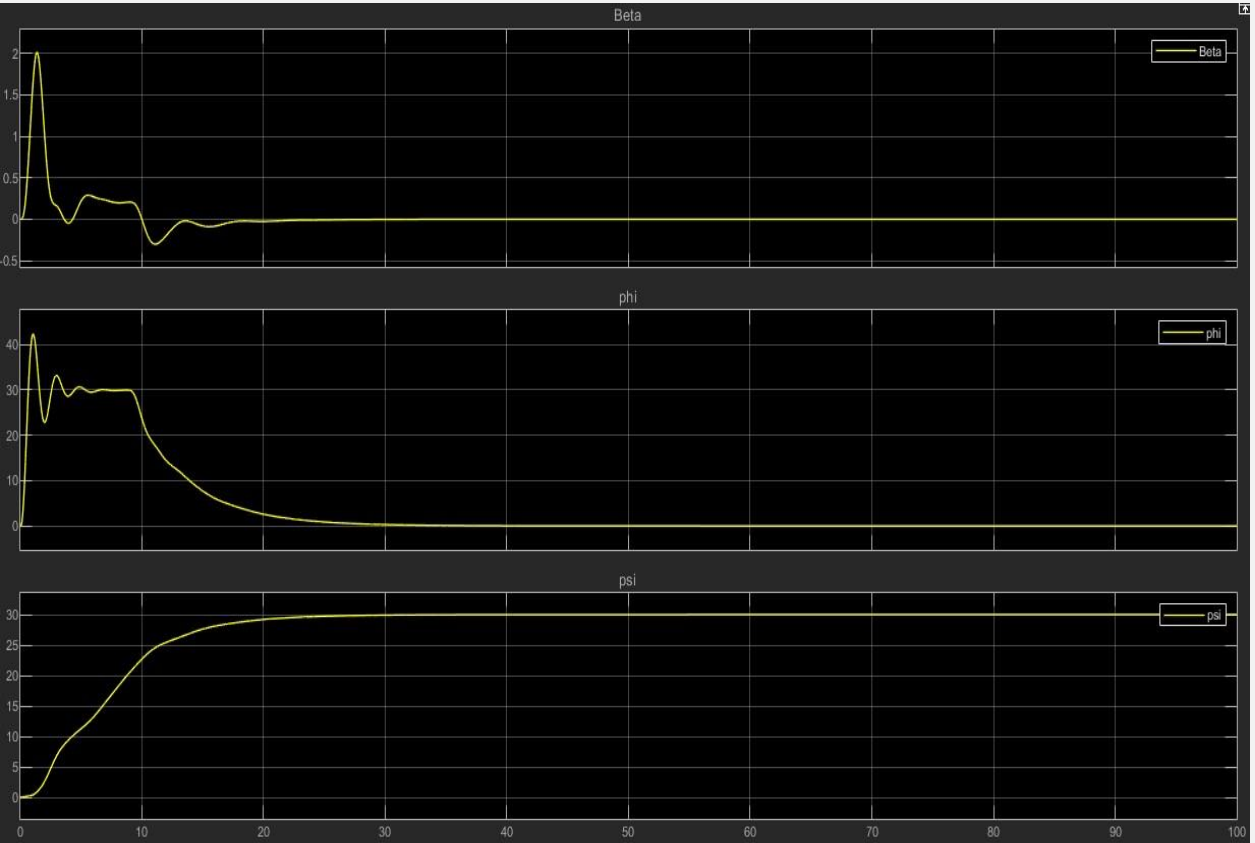


Lateral controller + Altitude Hold controller

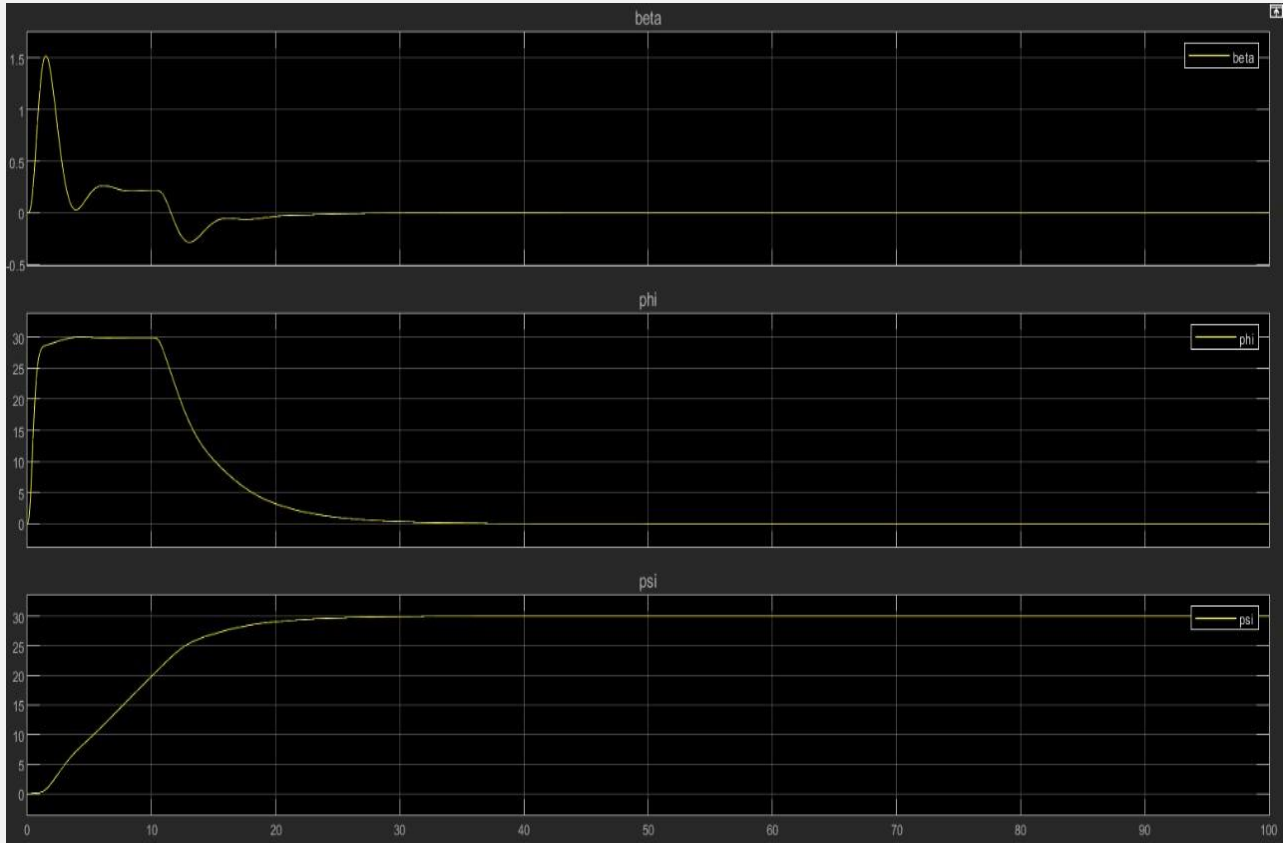
(psi_com= 30 deg)
(h_com= 0)

$(\beta \ \& \phi \ \& \Psi)$

Nonlinear

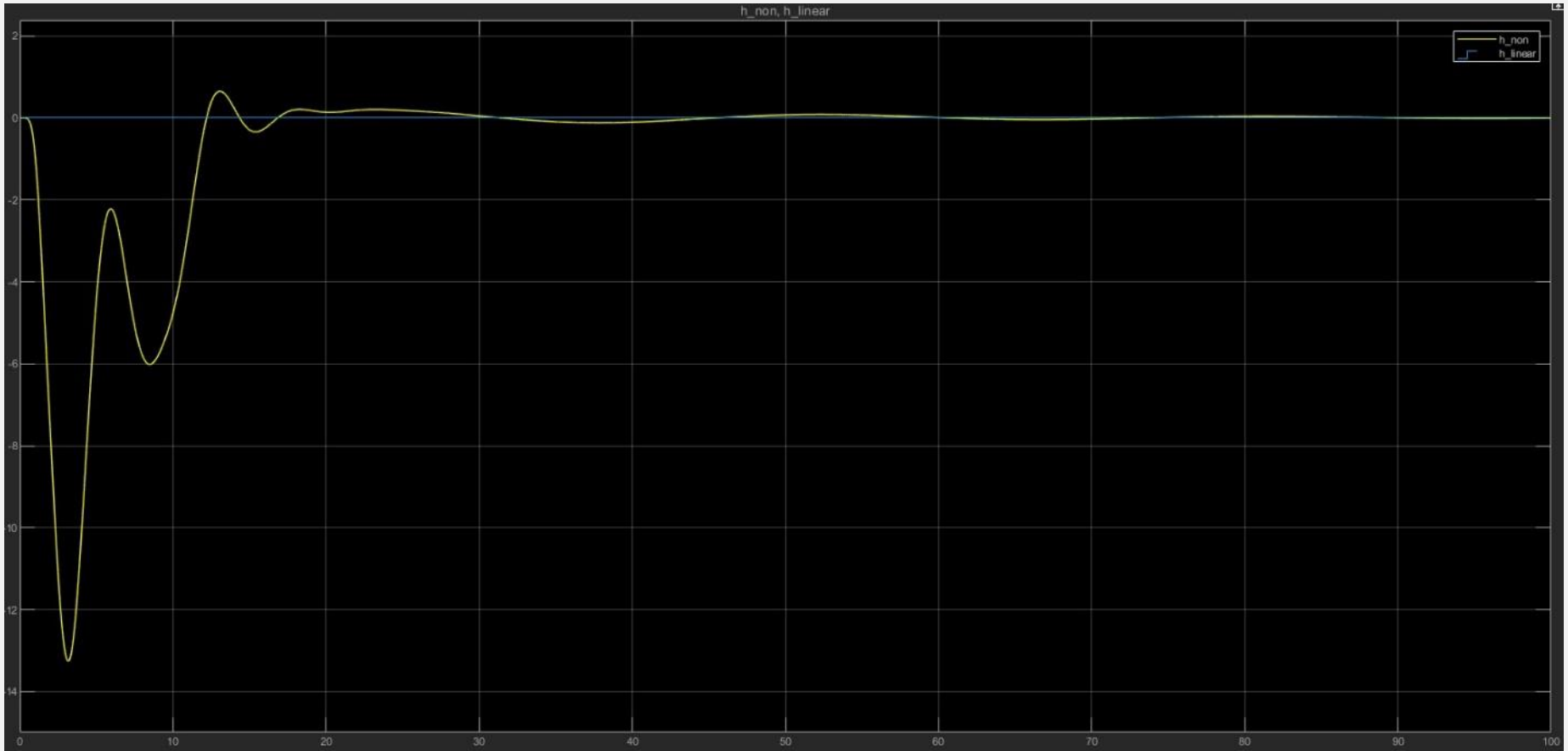


Linear



Lateral controller + Altitude Hold controller

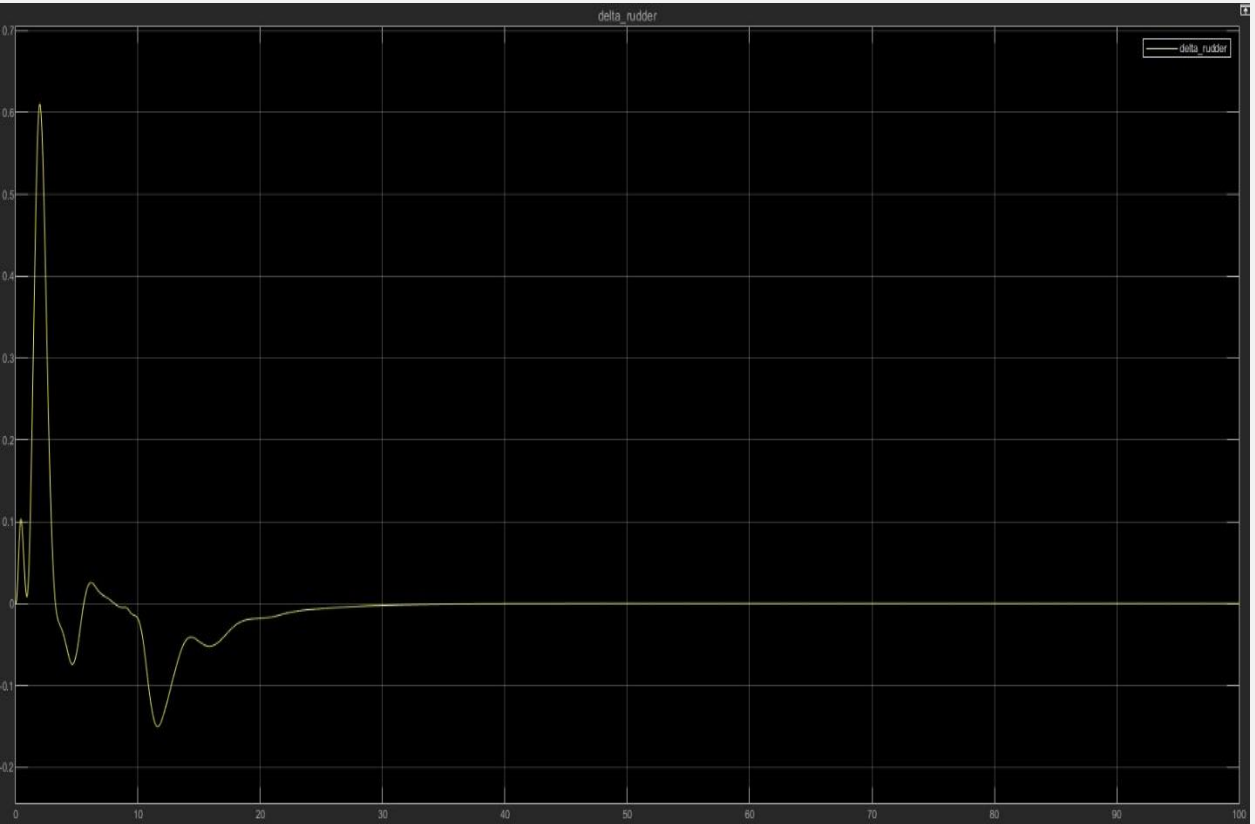
$h_{linear} - h_{nonlinear}$



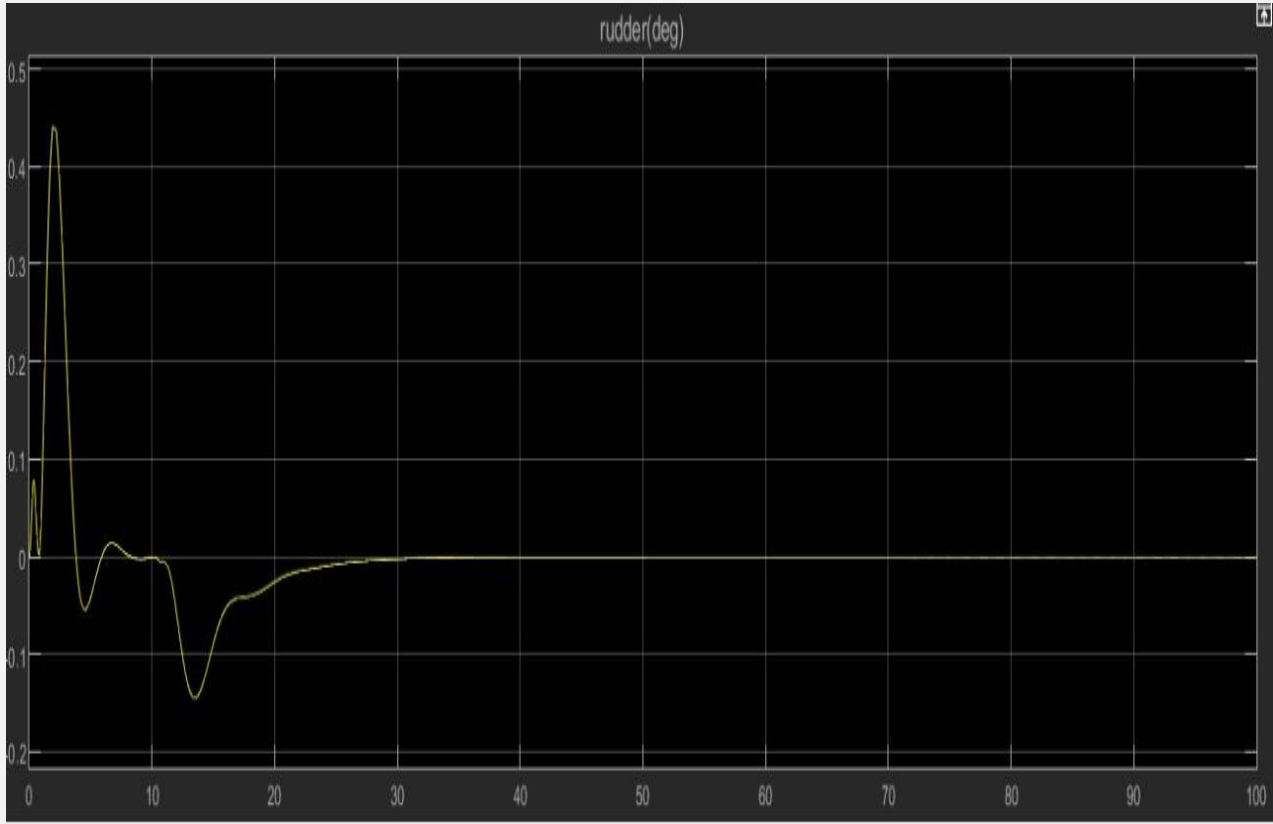
Lateral controller + Altitude Hold controller

δrudder

Nonlinear



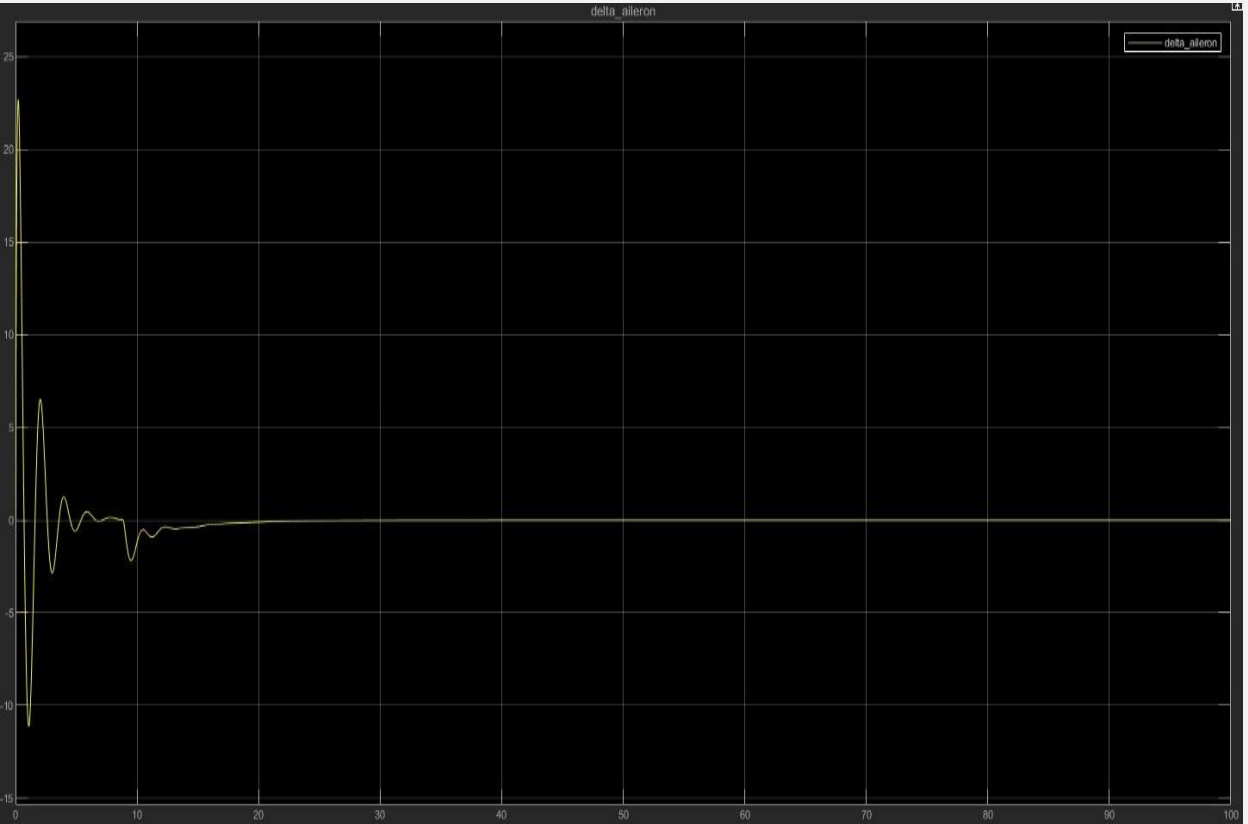
Linear



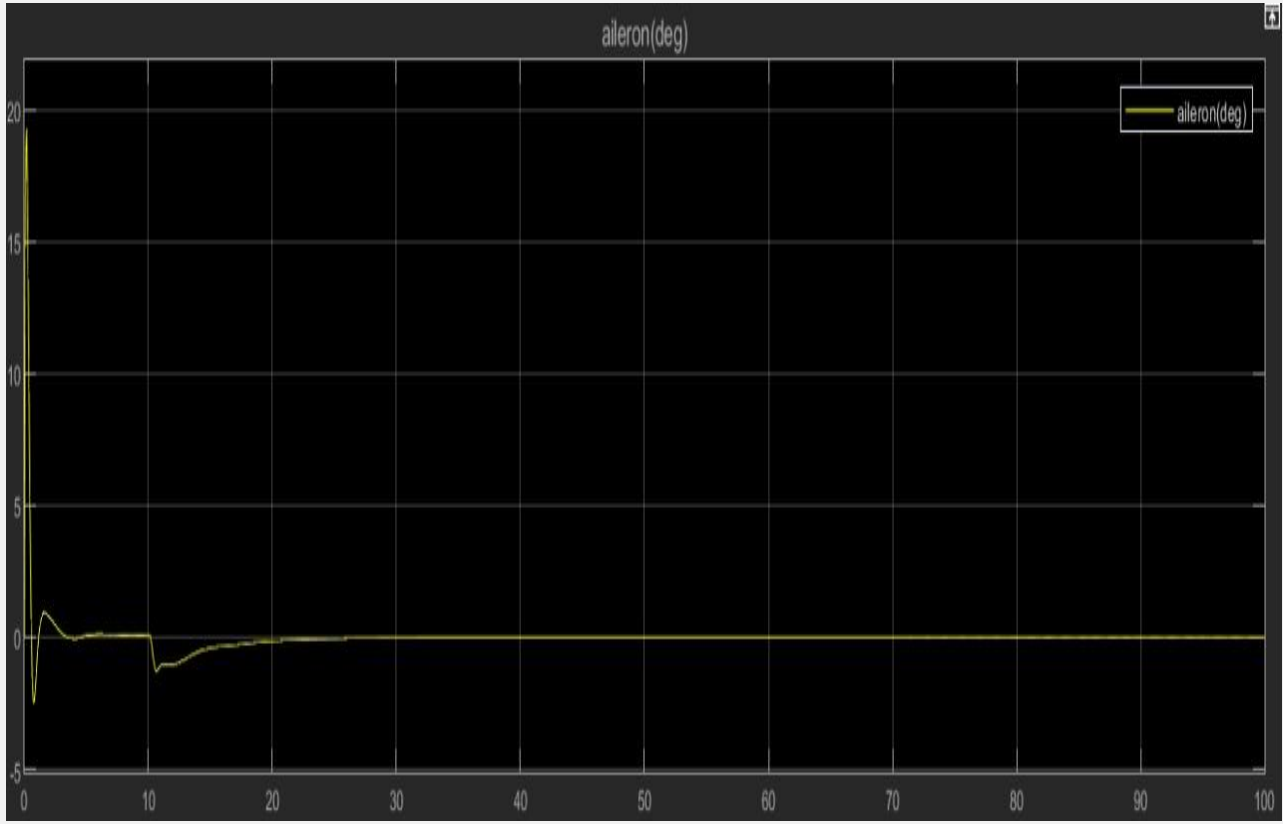
Lateral controller + Altitude Hold controller

δaileron

Nonlinear

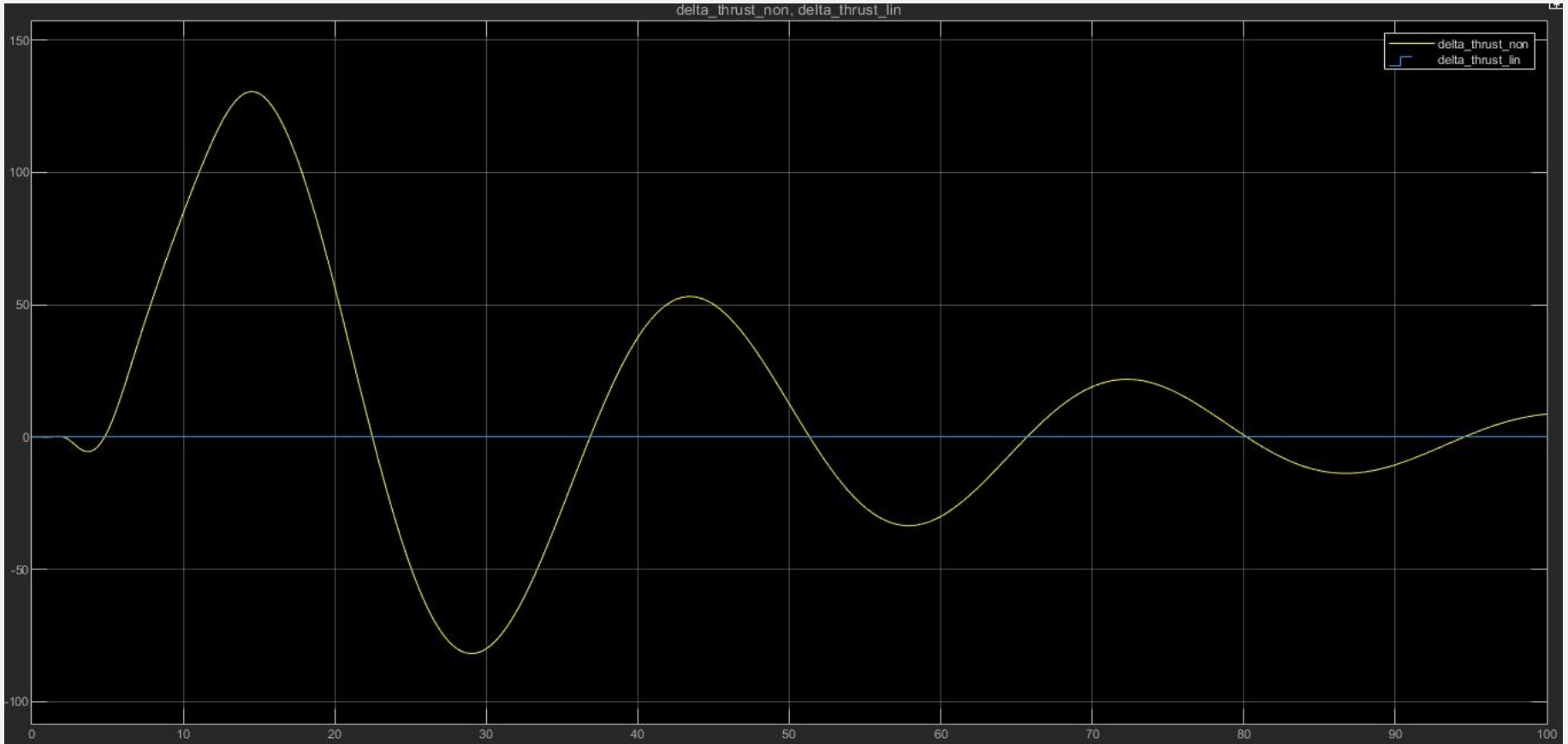


Linear



Lateral controller + Altitude Hold controller

$\delta thrust_{linear} - \delta thrust_{nonlinear}$

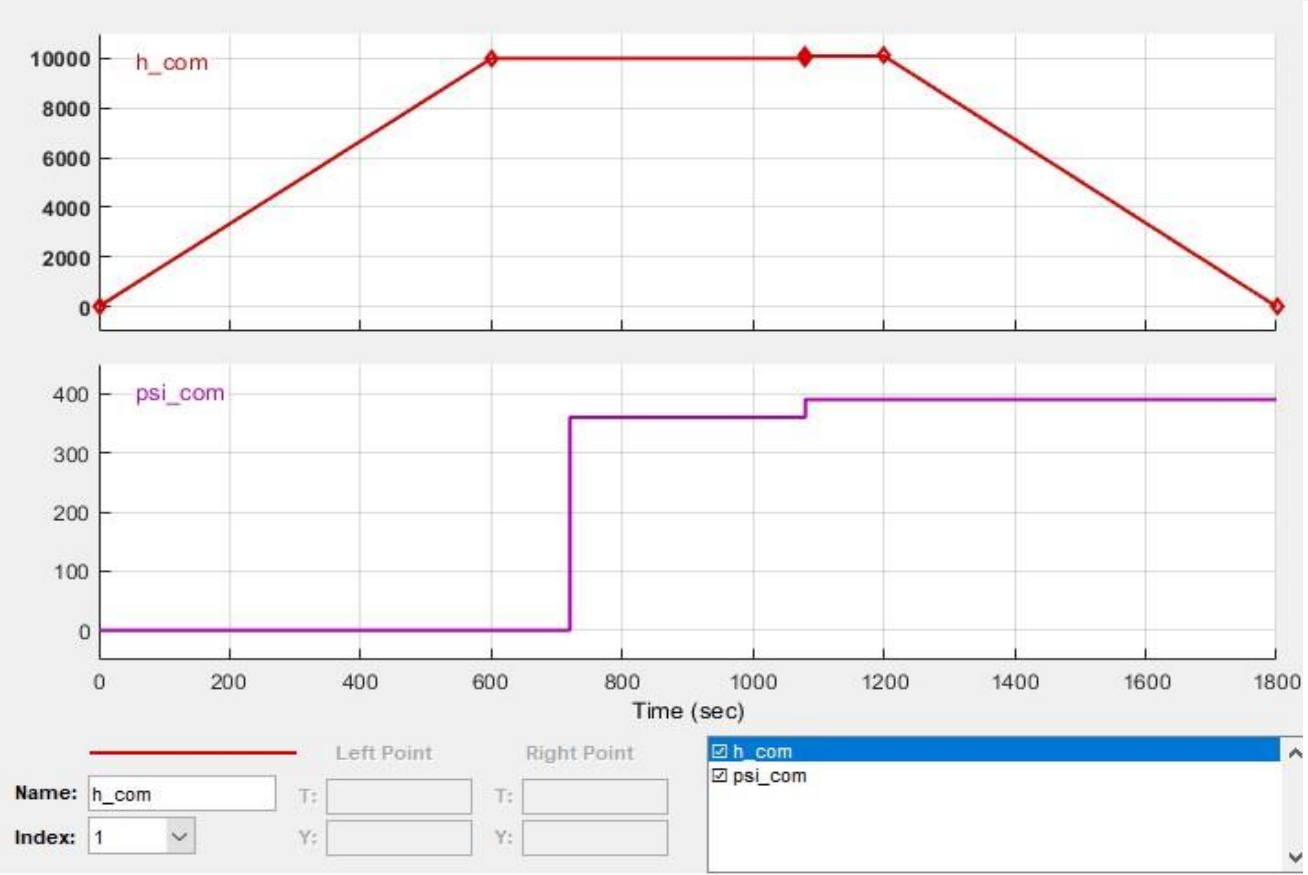


Lateral controller + Altitude Hold controller

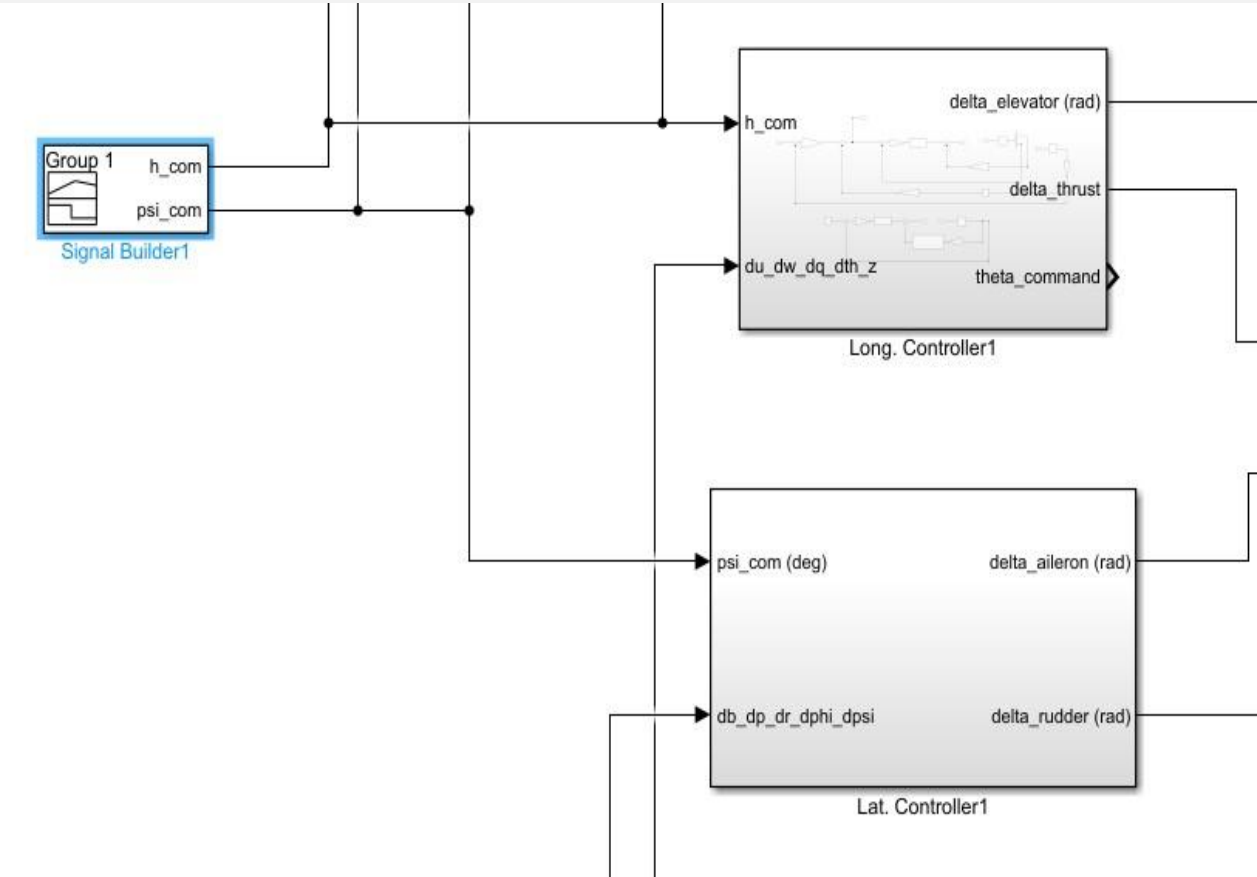
$\delta elev_{linear} - \delta elev_{nonlinear}$

Complete Autonomous Mission

Input signal



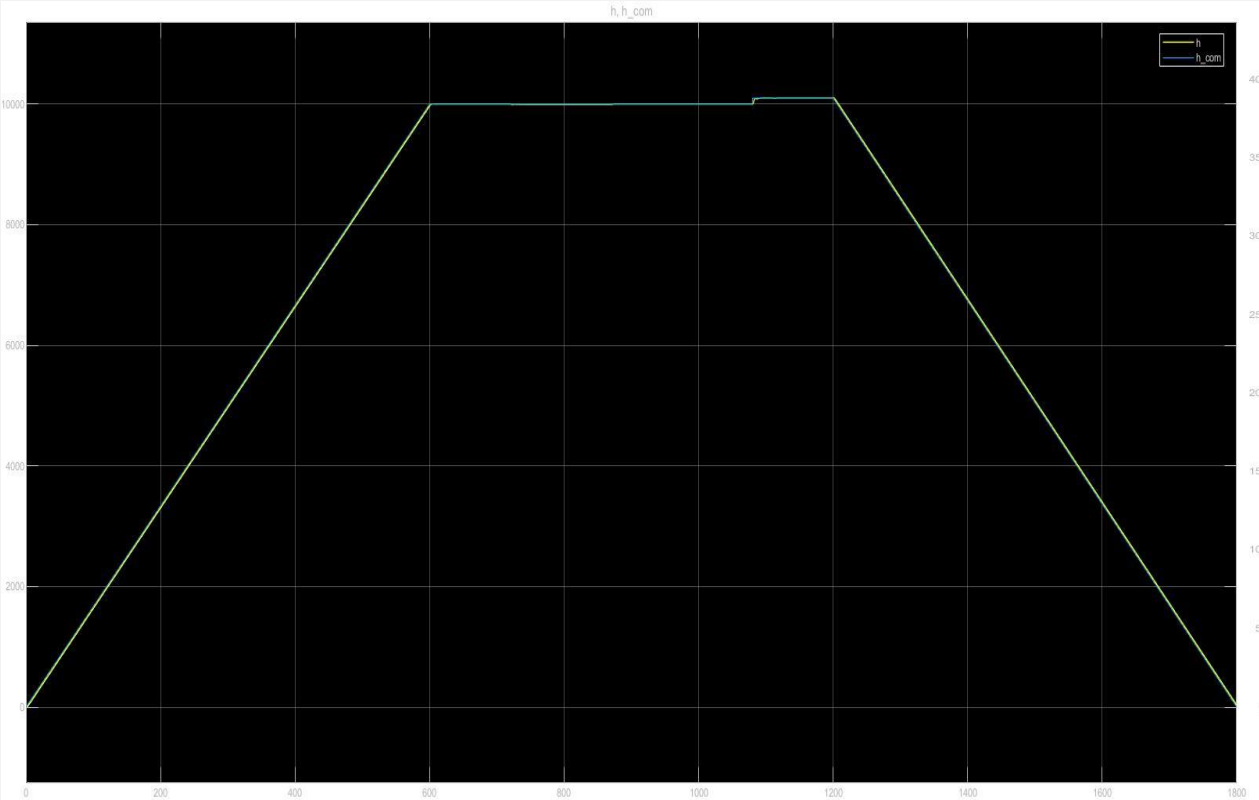
Simulink

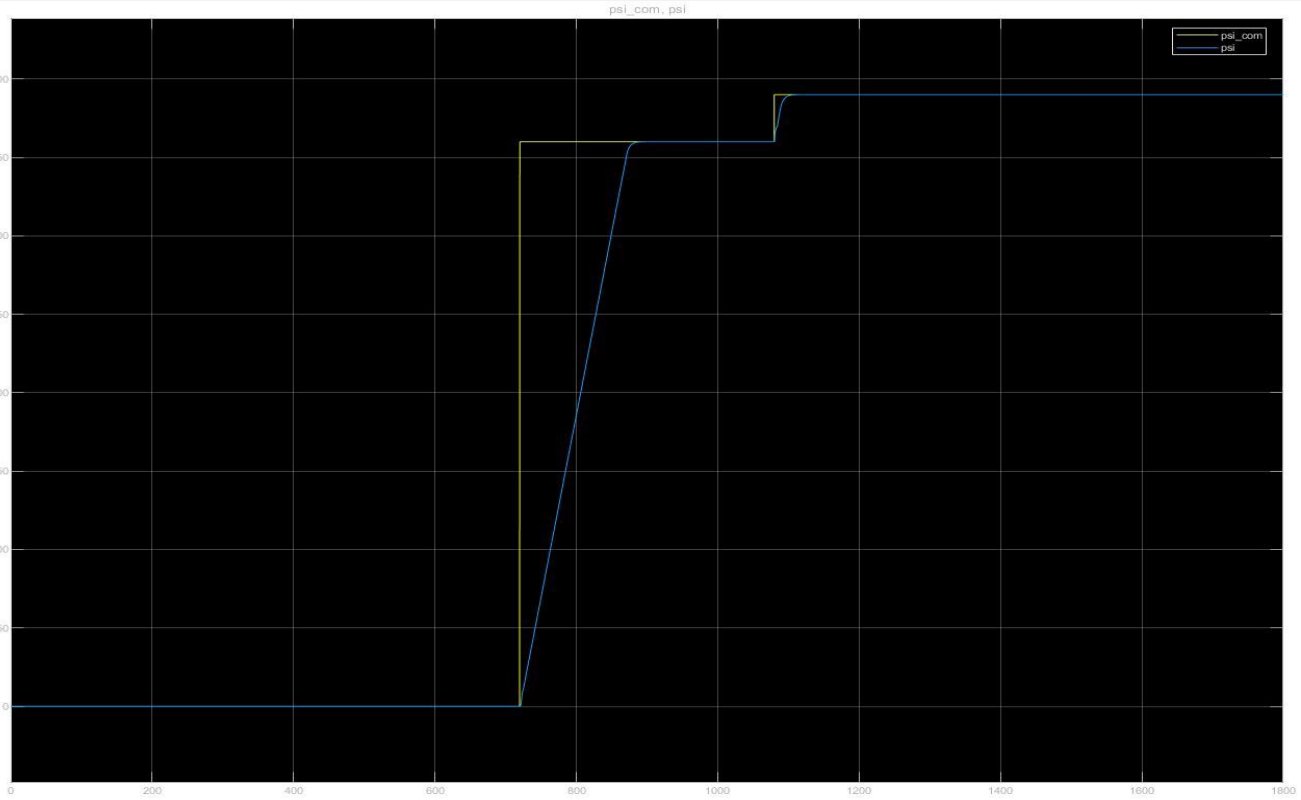


Complete Autonomous Mission

h_{com} - h

psi - psi_{com}

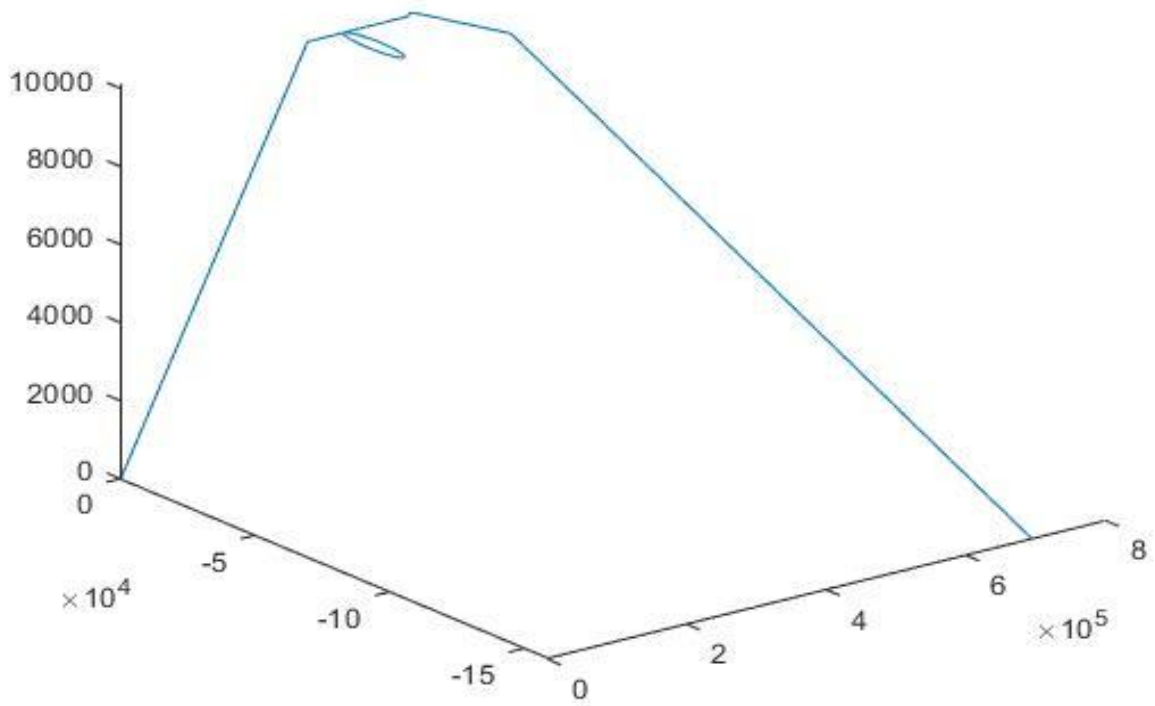




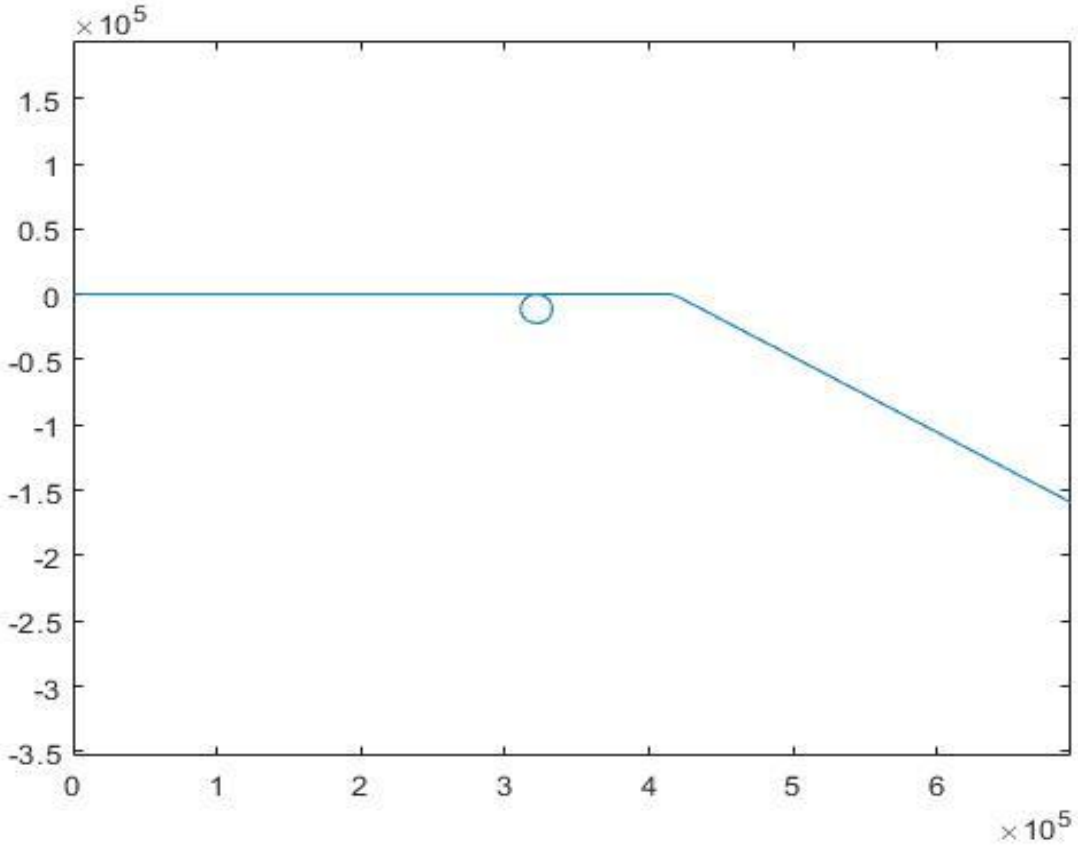
Complete Autonomous Mission

Trajectory

3d



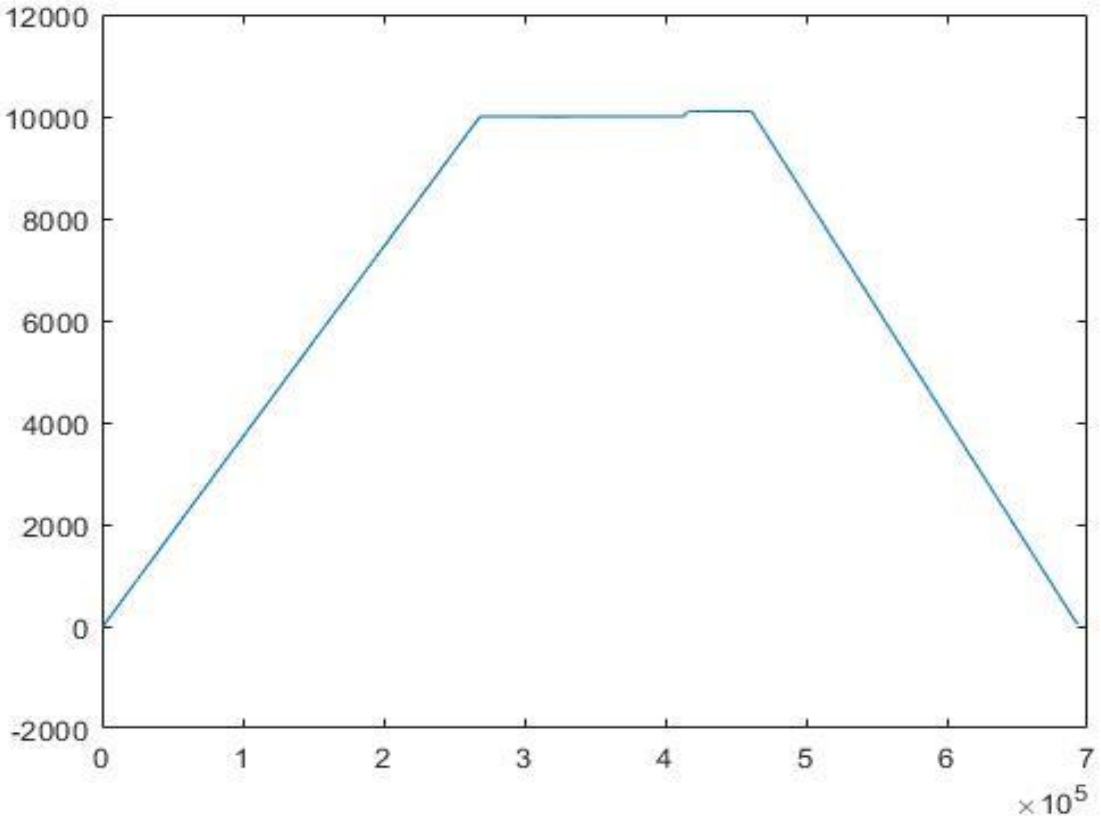
X-Y plane



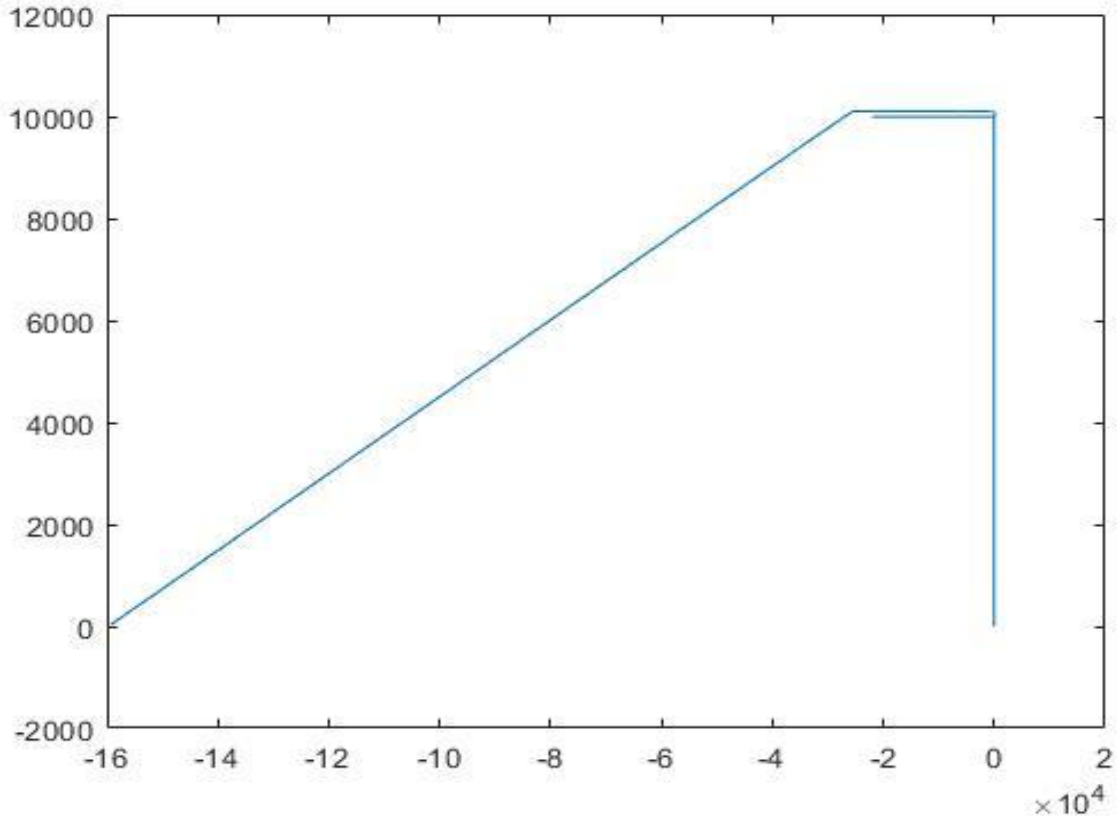
Complete Autonomous Mission

Trajectory

X-Z plane



Y-Z plane



Thank you