AE 246
Boeing 747-400 Supertanker

Angle of Attack & Roll Angle Hold Autopilots

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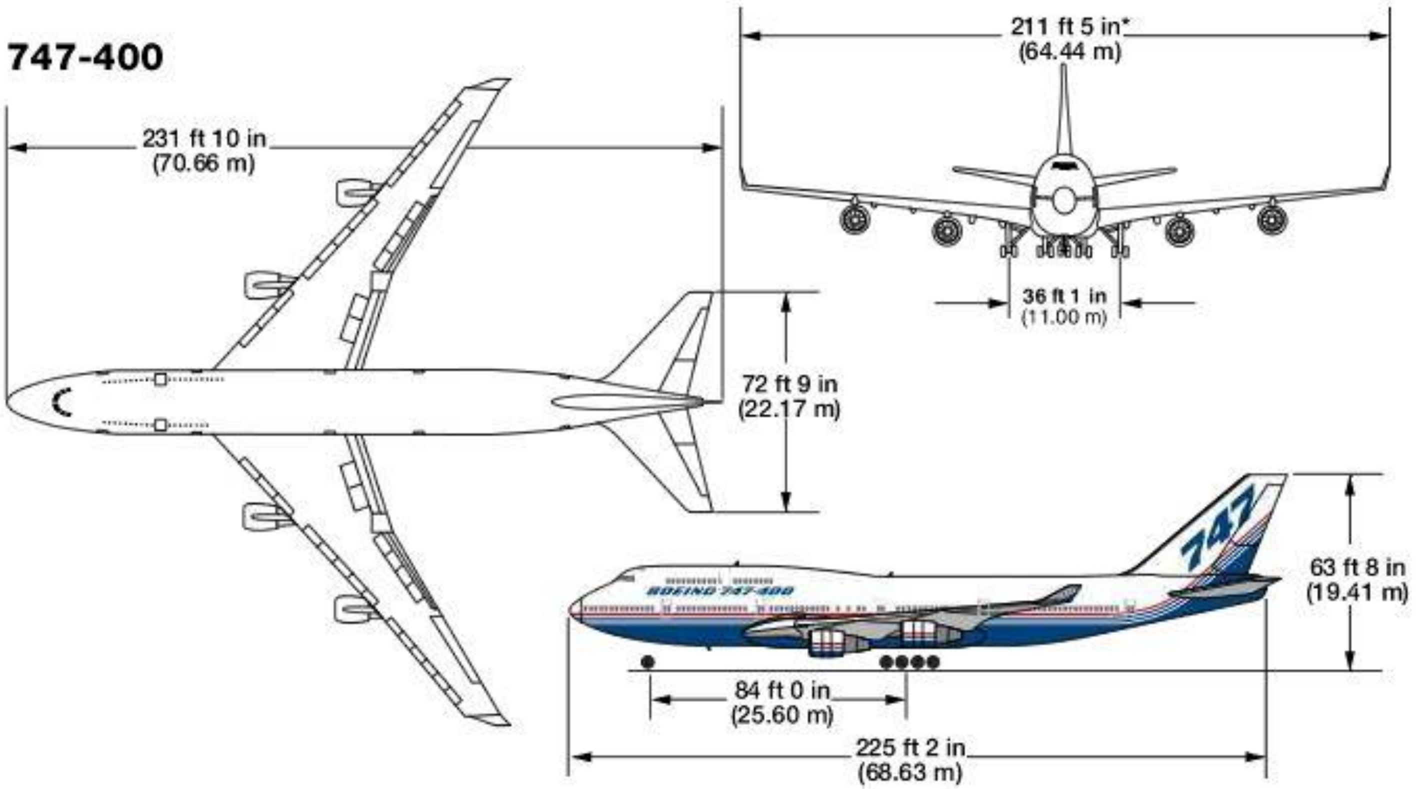
Agenda

- Introduction
- Problem Description
- Longitudinal Open-Loop Stability Analysis
- Lateral Open-Loop Stability Analysis
- Longitudinal Closed-Loop Stability Analysis
- Lateral Closed-Loop Stability Analysis
- Conclusion

Introduction

- Wildfires are getting worse each year.
- Aerial firefighting is important to put out fires in hard-to-reach areas.
- Strong winds and poor visibility make it difficult for aircraft to stay in operation.
- Looking into 747-400 Supertanker pitch and roll autopilot control to help correct for strong wind gusts and large aircraft disturbances.

Problem Description: Aircraft Model & Flight Conditions



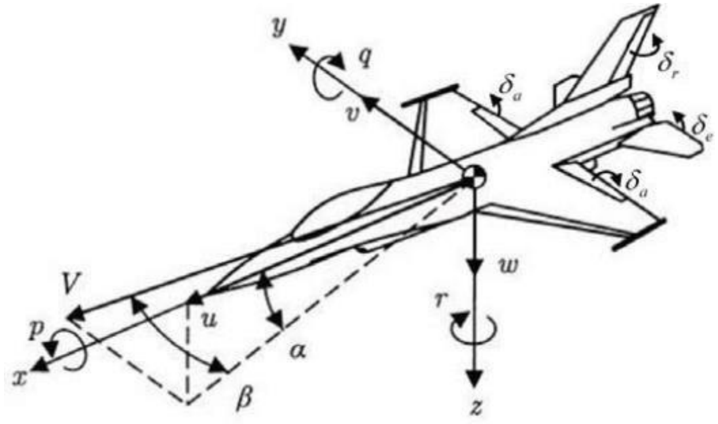
Aircraft Specifications:

- Wingspan - 211.42 ft
- Length - 231.85 ft
- Height - 63.67 ft
- Max Weight- 800,000 lb
- $\overline{c}$ - 27.3 ft
- Max aileron - +/-26°
- Elevator - -31° to +20°

Flight Conditions:

- Altitude - Sea Level
- Airspeed - M = 0.45, 502 ft/s
- Weight - 800,000 lb
- Configuration - Clean
- Q - 300 PSF

Problem Description: Coordinate System & Assumptions



Assumptions:

- Straight, level flight
- Steady-State Conditions
- Thrust is constant

Longitudinal:

$$\dot{x} = \begin{bmatrix} \dot{u} \\ \dot{a} \\ \dot{q} \\ \dot{\theta} \end{bmatrix}$$

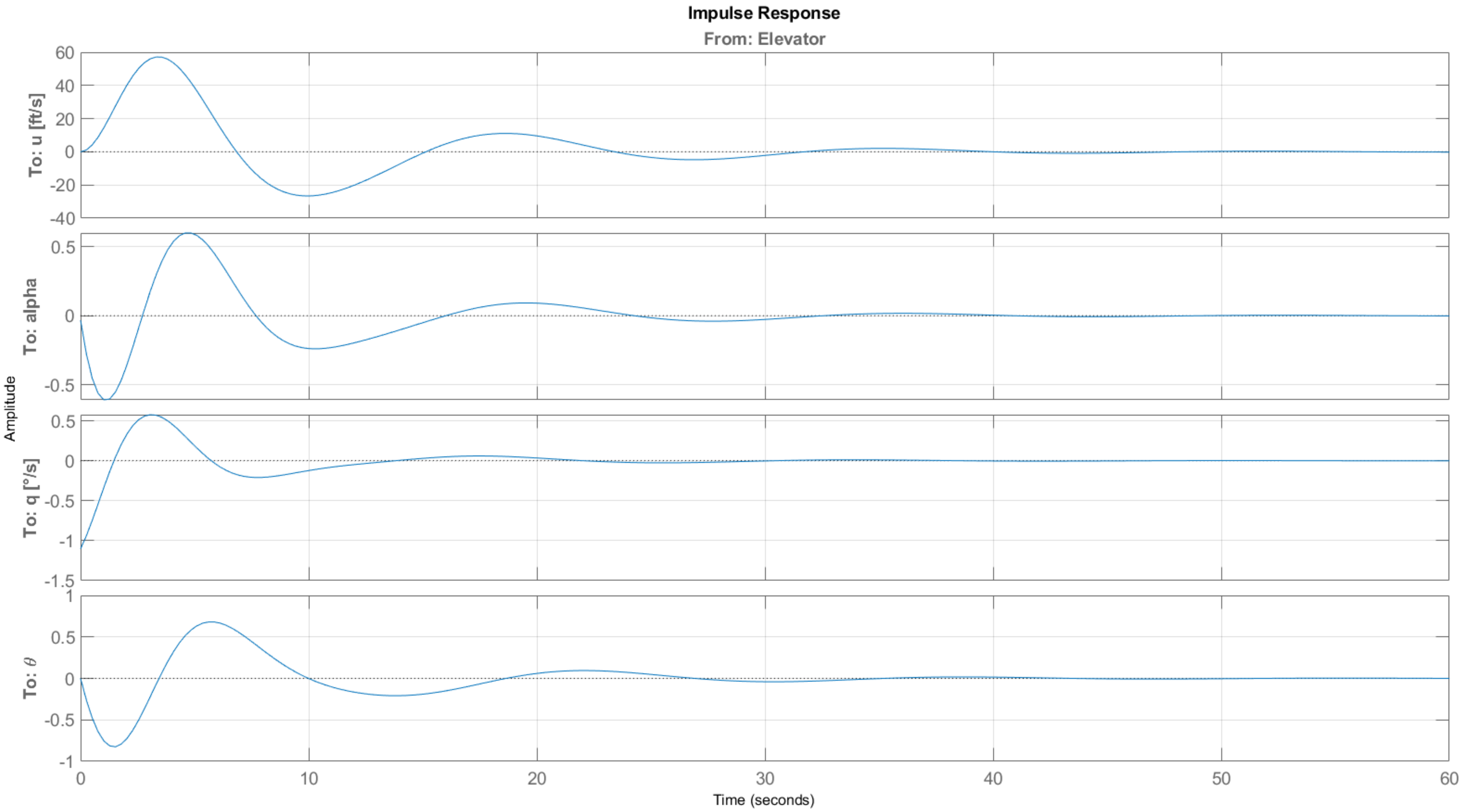
$$A = \begin{bmatrix} Xu & Xa & 0 & -g \\ \frac{Zu}{U1} & \frac{Za}{U1} & 1 & 0 \\ Mu + \frac{M\dot{a} * Zu}{U1} & Ma + \frac{M\dot{a} * Za}{U1} & Mq + Madot & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Lateral:

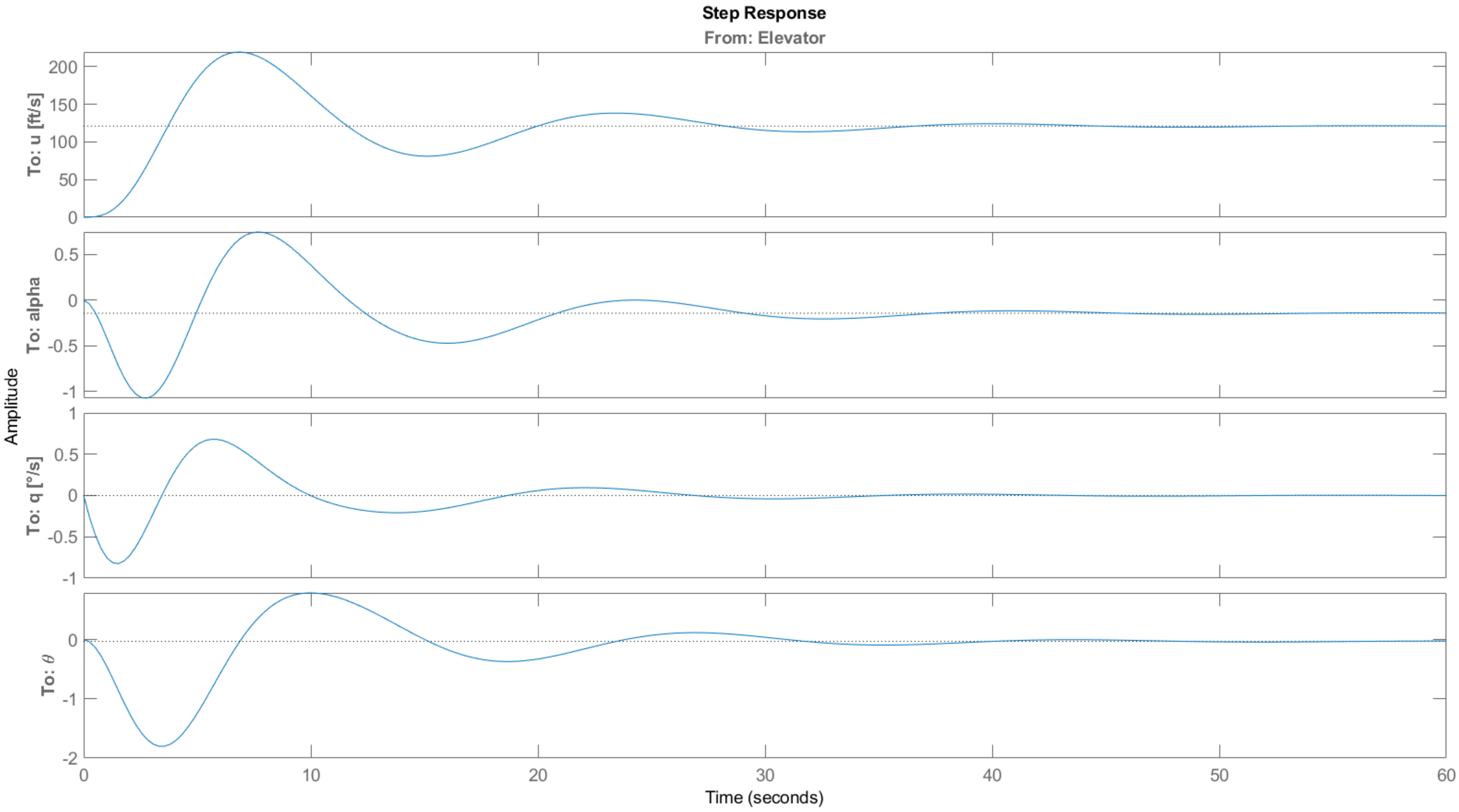
$$\dot{x} = \begin{bmatrix} \dot{\phi} \\ \dot{p} \\ \dot{\beta} \\ \dot{r} \\ \dot{\psi} \end{bmatrix}$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ 0 & Lp & L_{\beta} & L_r & 0 \\ \frac{g\cos\theta_1}{U1} & \frac{Y_p}{U1} & \frac{Y_{\beta}}{U1} & \frac{Y_r}{U1} \text{-1} & 0 \\ 0 & N_p & N_{\beta} & N_r & 0 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}$$

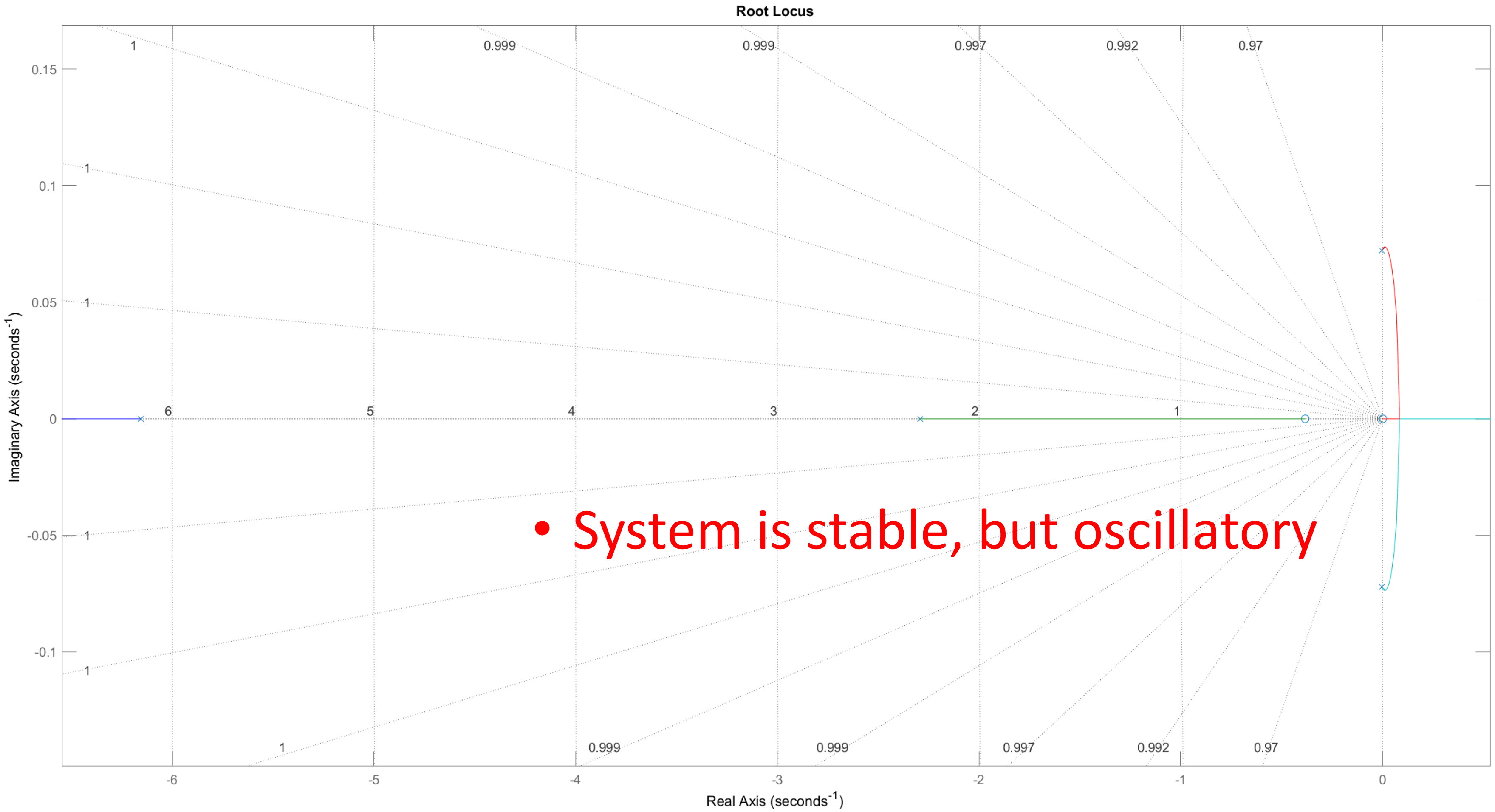
Impulse Response - Longitudinal Open-loop Analysis



Step Response - Longitudinal Open-loop Analysis



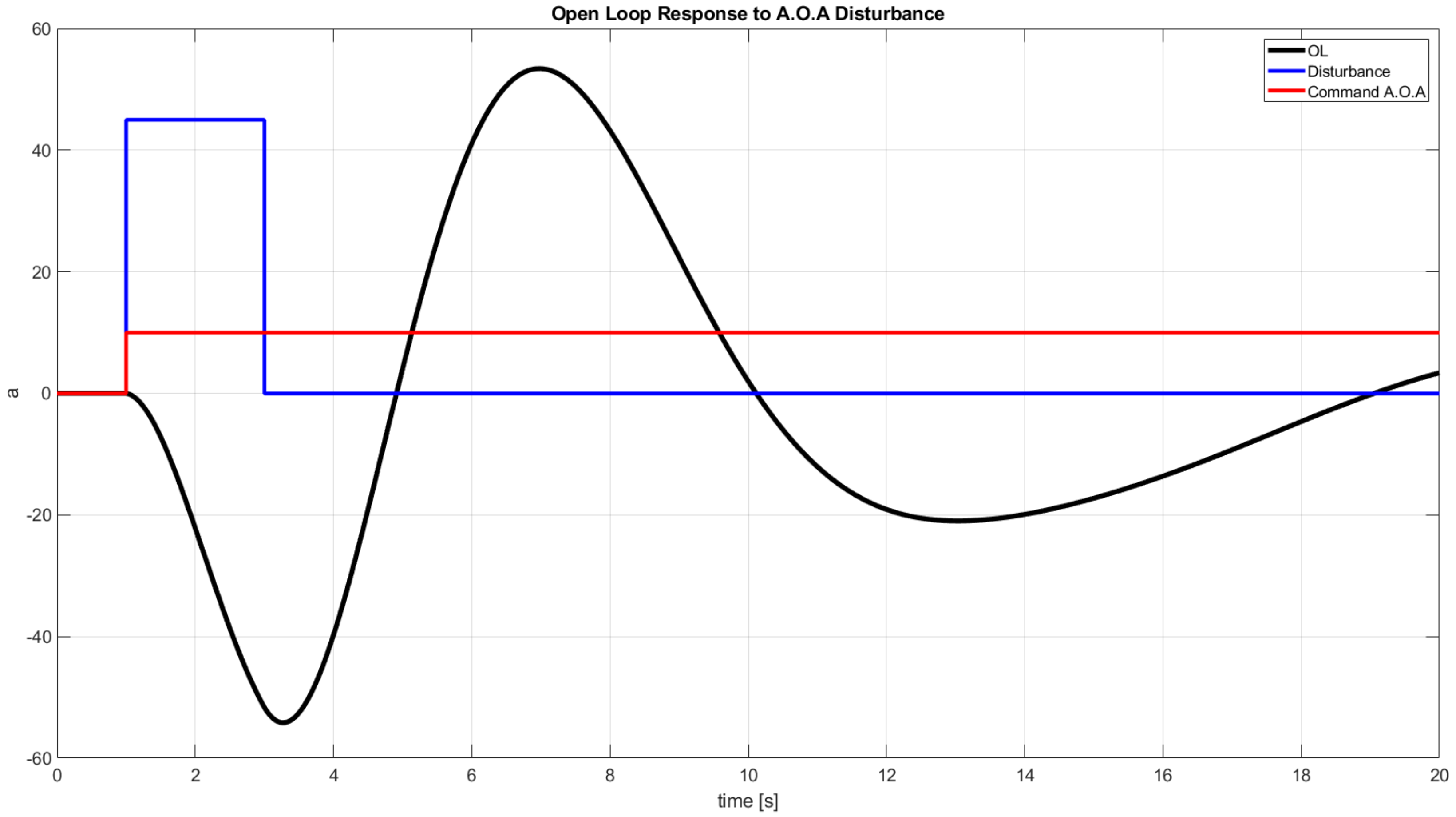
Longitudinal Open-loop Stability Analysis - Elevator deflection to Angle of Attack



- System is stable, but oscillatory

Longitudinal Open-loop Stability Analysis Pitch Command

- Open Loop Response to 10° control input

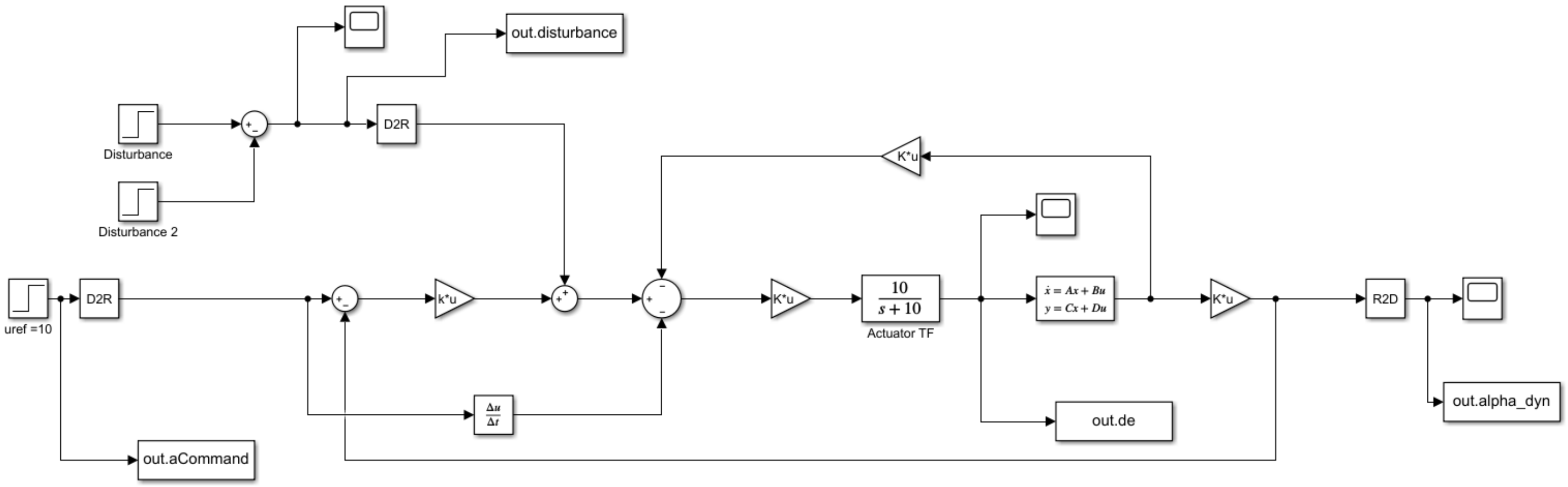


Longitudinal Closed-loop Stability Analysis Controller Design

Controllability:

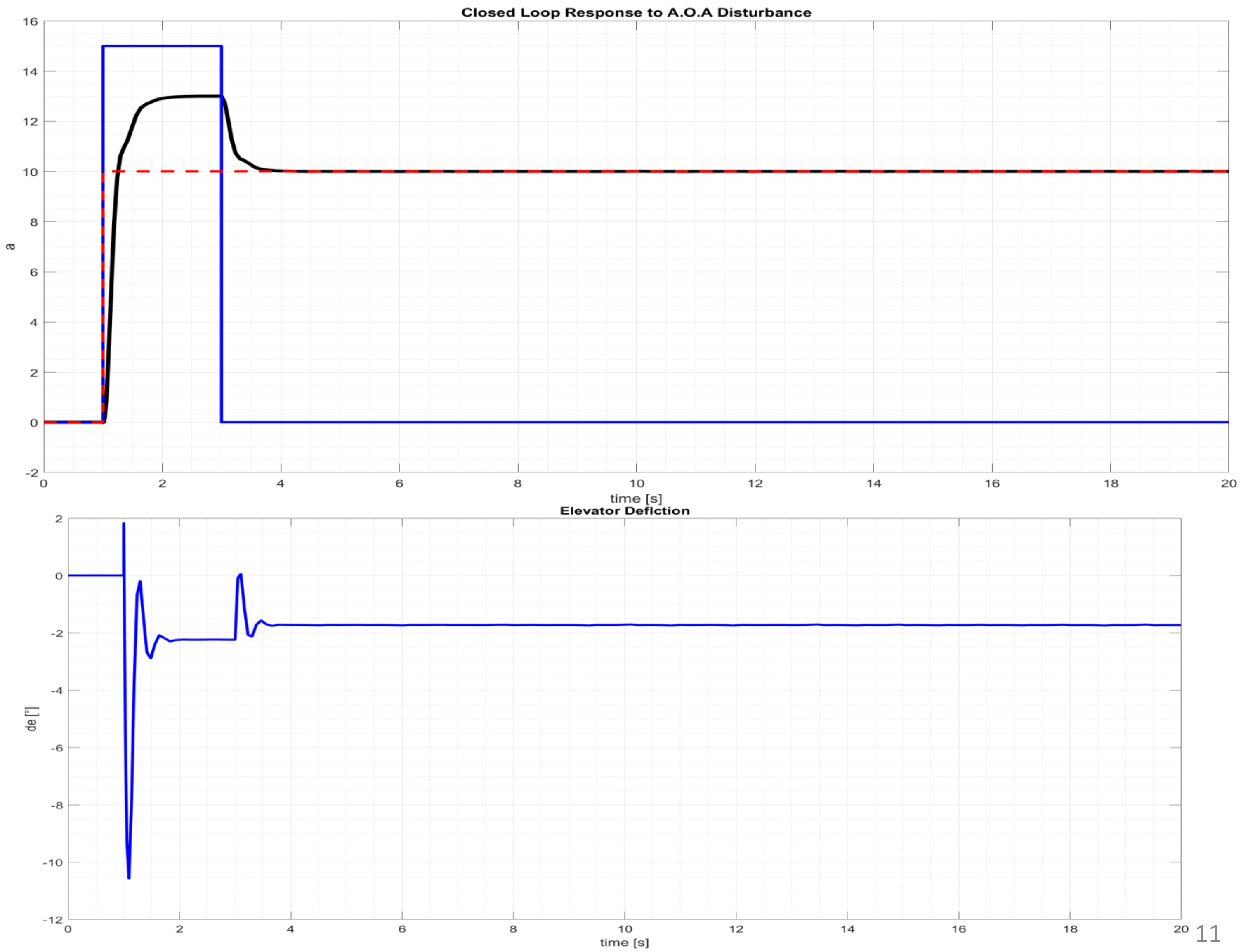
```
>> ctrlLong = ctrb(longSIMO)

ctrlLong =

    1.1800   -0.0075   35.1797 -284.0646
   -0.0434   -1.0637    9.5984  -66.0790
   -1.0947    8.8349  -59.1840  375.3366
         0   -1.0947    8.8349  -59.1840

>> ctrlCheck = rank(ctrlLong)

ctrlCheck =

     4
```

Dynamic Inversion Control System Design



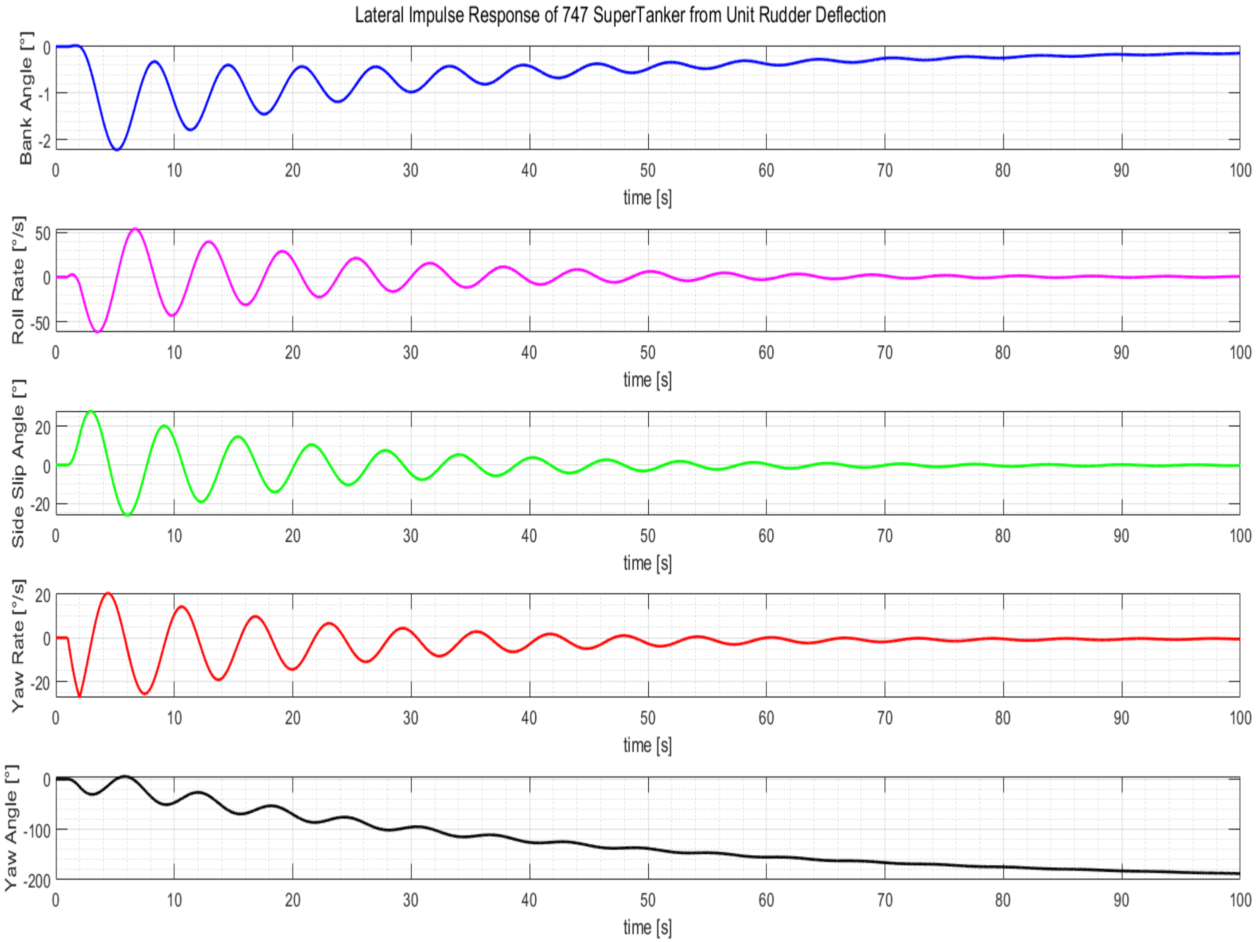
Longitudinal Closed-loop Stability Analysis Pitch Command

- Closed Loop Response to 10° control input
  - Dynamic inversion controller restores angle of attack to commanded angle
  - Elevator deflection stays within system capabilities

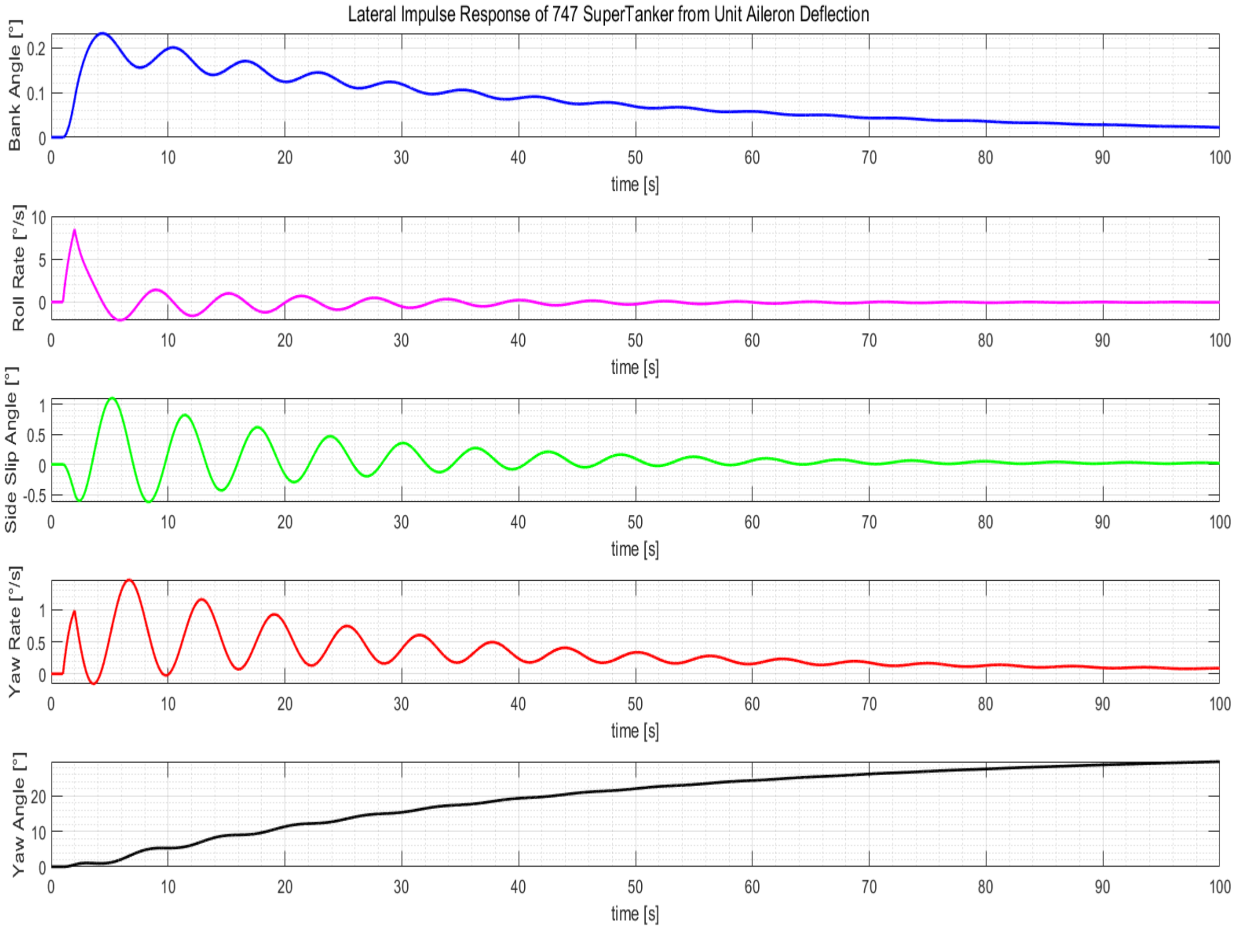


Impulse Response - Lateral Open-loop Analysis

Rudder

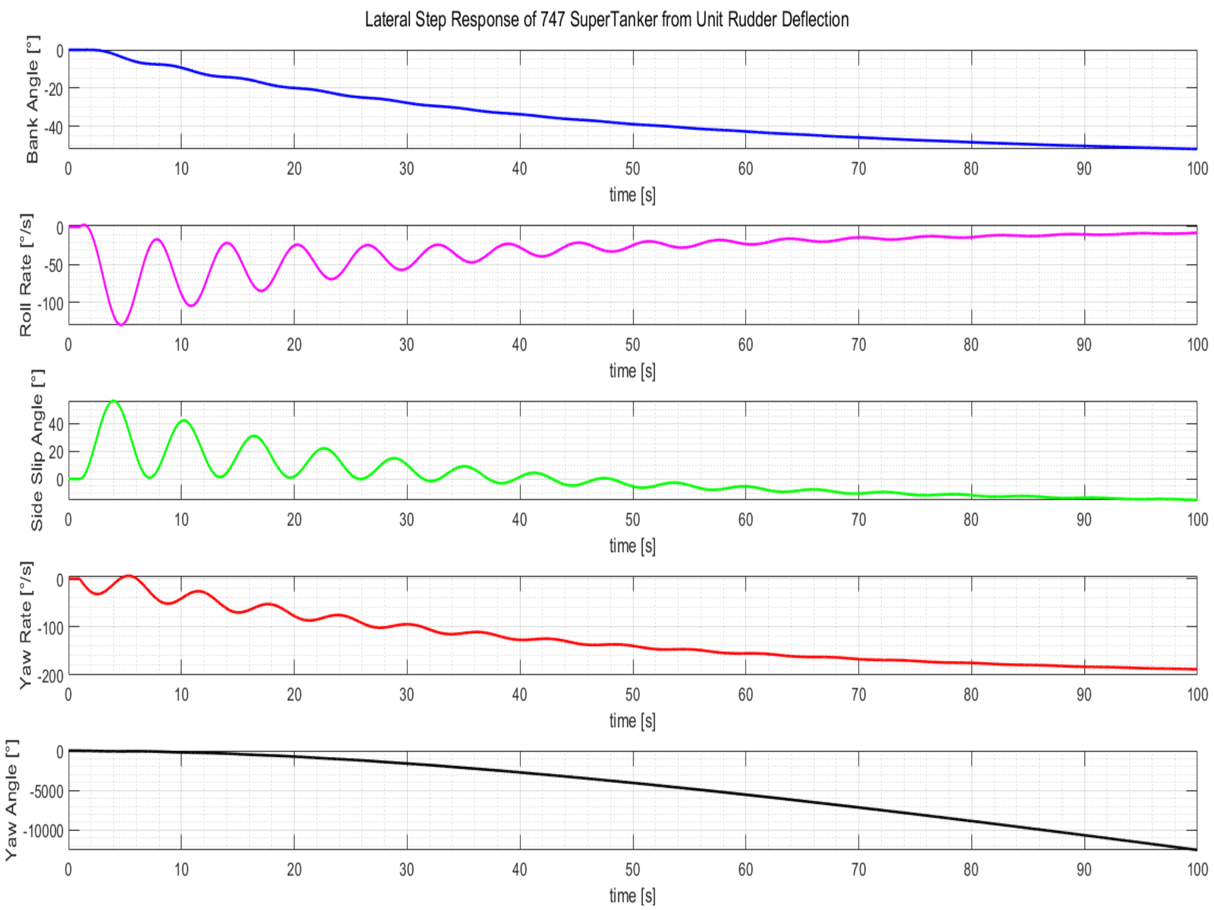


Aileron

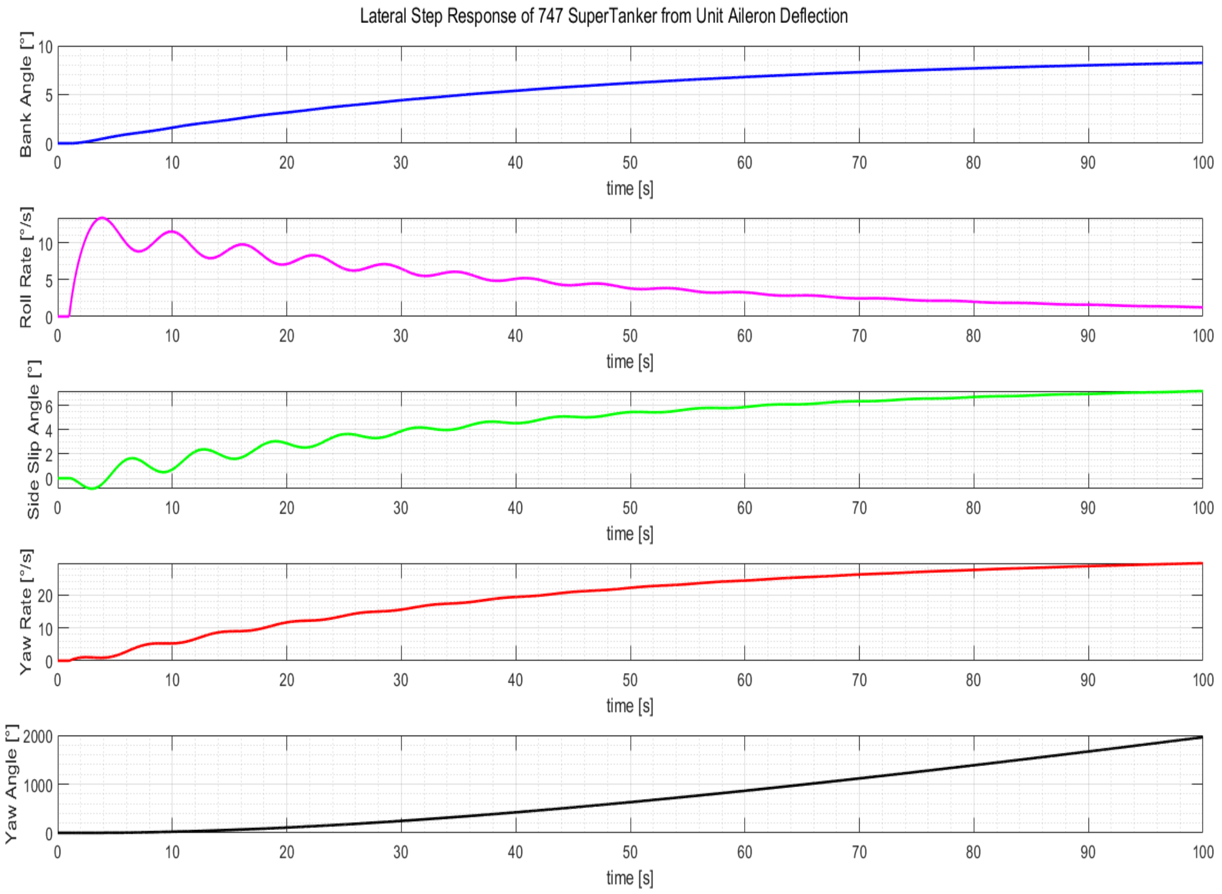


Step Response - Lateral Open-loop Analysis

Rudder

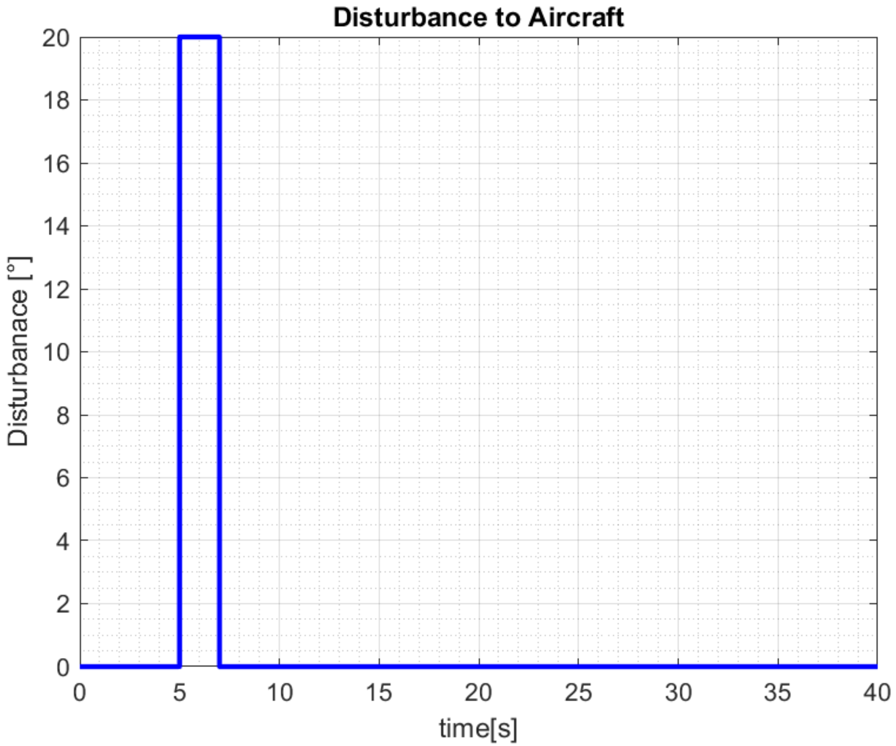


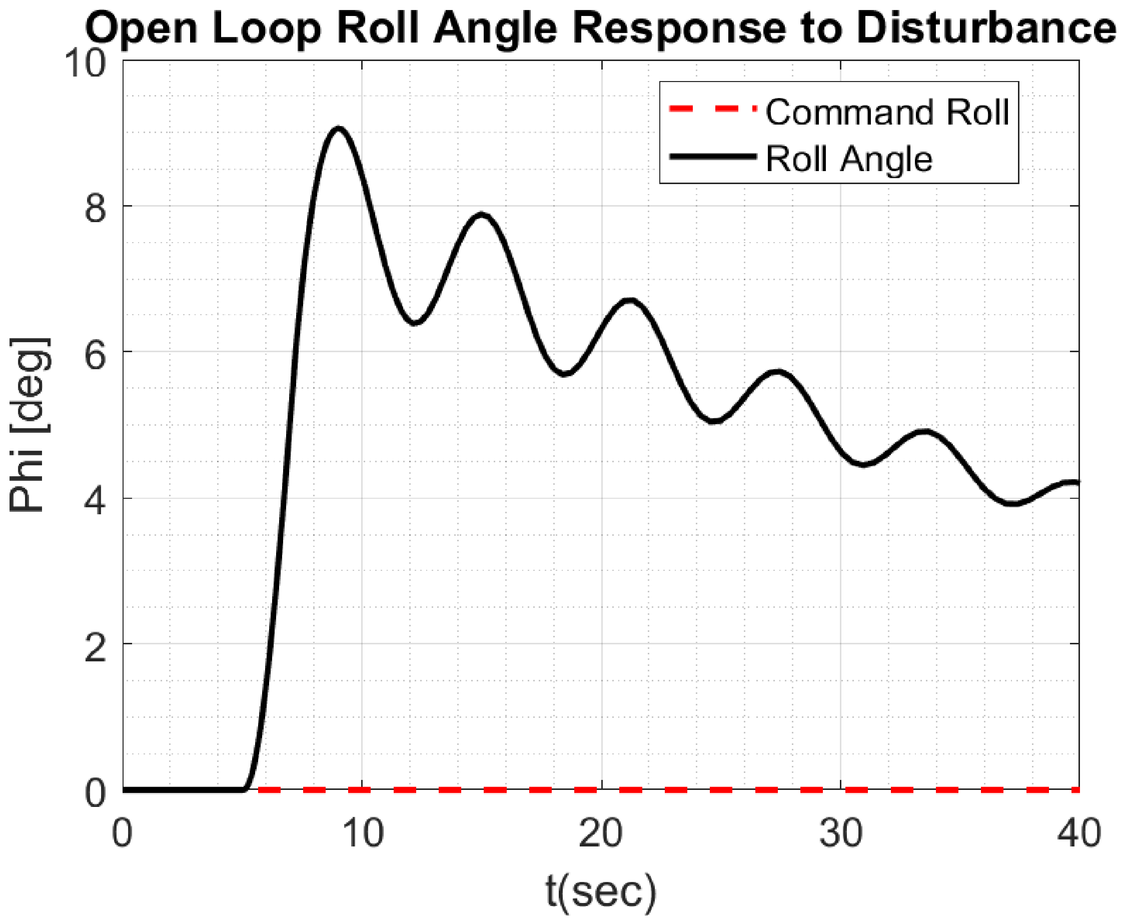
Aileron



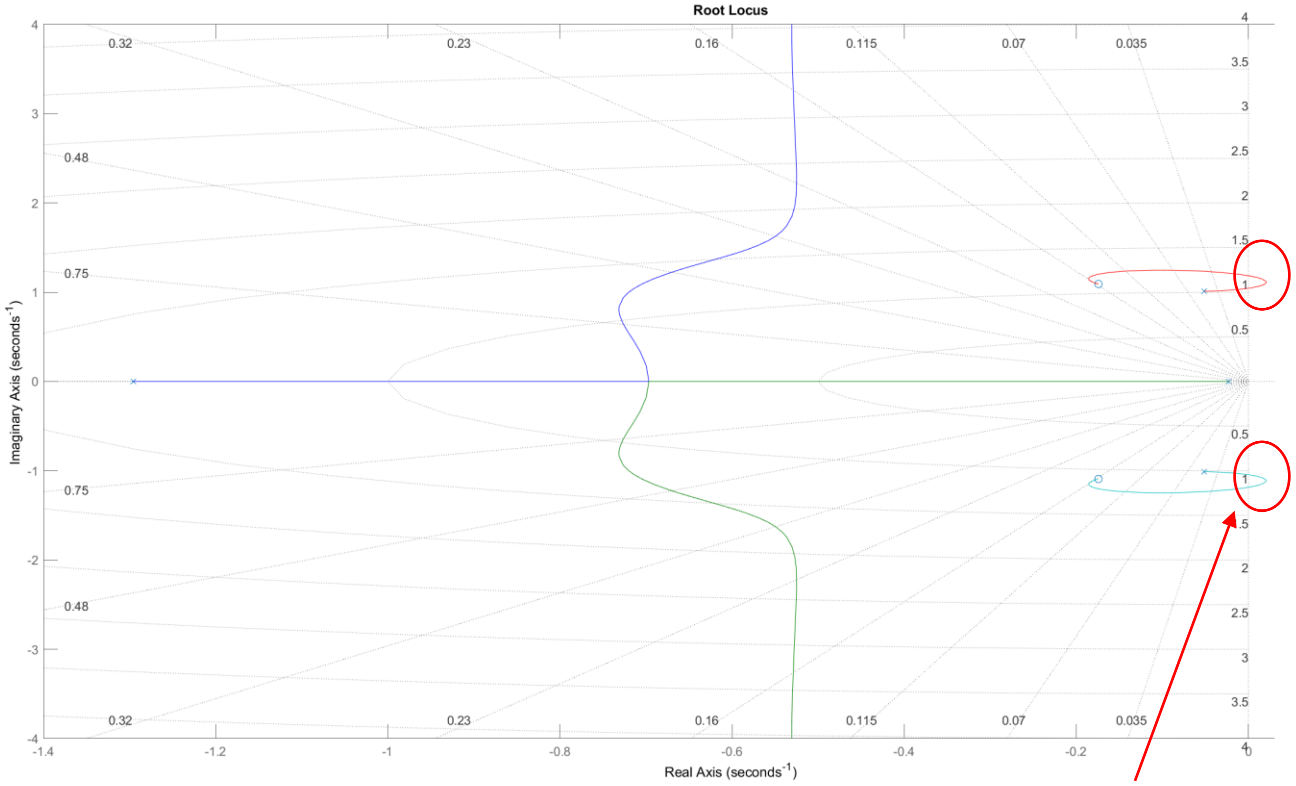
Lateral Open-loop Stability Analysis Pitch Command

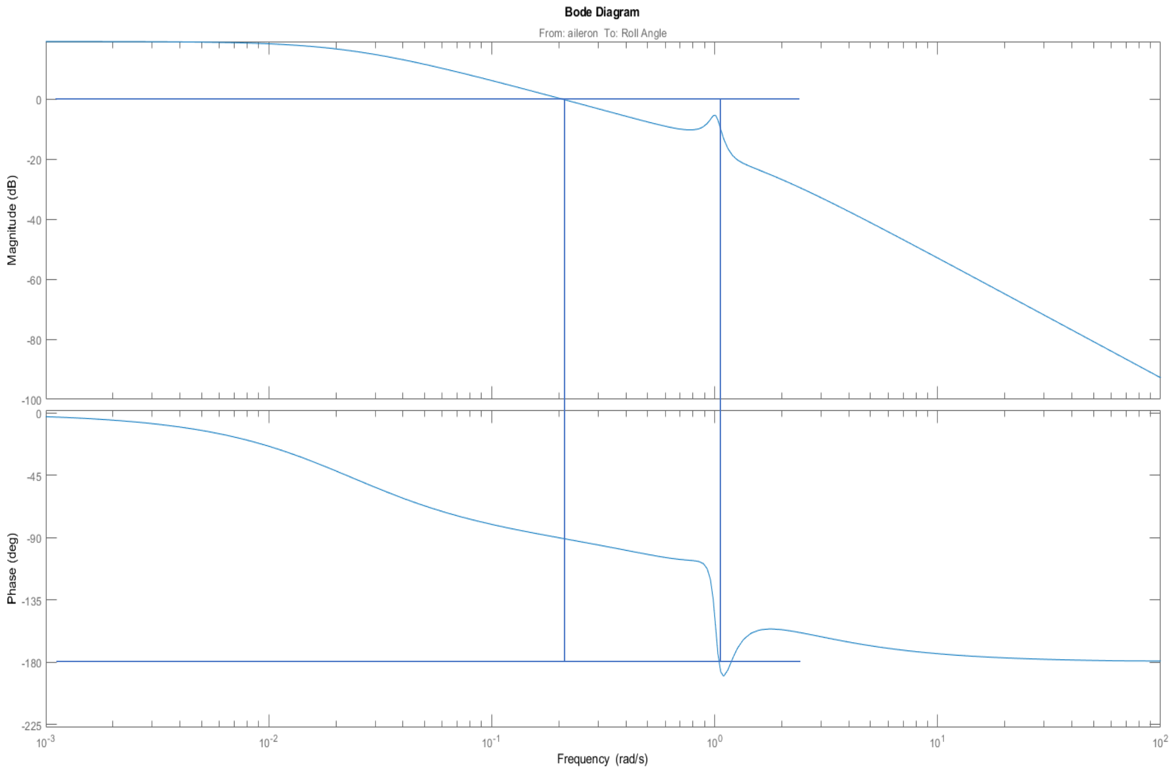
- Open Loop Response to 0° control input with 20° disturbance





Lateral Closed-loop Stability Analysis - Roll Angle Hold Autopilot





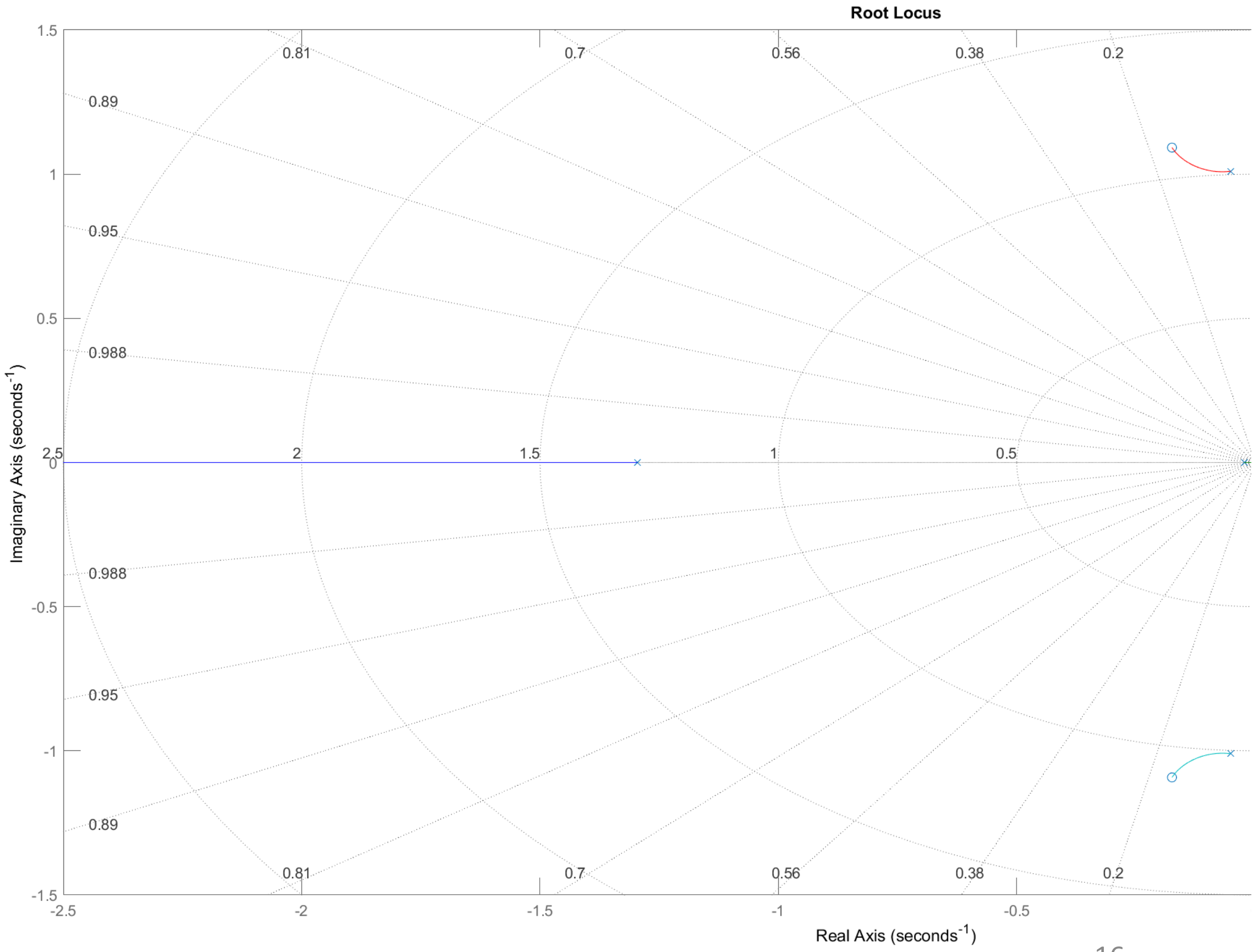
- System quick to go unstable
- Complex conjugate poles result in oscillation

Lateral Closed-loop Stability Analysis - Roll Angle Hold Autopilot

- Analyze Affects of Positive Feedback Loop:
  - Poles stay on the left half of the s-plane

Controllability:

```
ctrlLat =

         0         0    0.2540    0.2290   -0.5173   -0.2457   -1.3288    0.3573    2.1598   -0.5256
    0.2540    0.2290   -0.5173   -0.2457   -1.3288    0.3573    2.1598   -0.5256   -0.7996    0.6479
    0.0000         0    0.6140   -0.0285   -0.1510    0.0393   -0.5257   -0.0178    0.0963    0.0171
   -0.6140    0.0285    0.1331   -0.0232    0.5011   -0.0000   -0.1518    0.0066   -0.5409    0.0211
         0         0   -0.6140    0.0285    0.1331   -0.0232    0.5011   -0.0000   -0.1518    0.0066

>> ctrlCheck

ctrlCheck =

     5
```



Lateral Closed-loop Stability Analysis Controller Design

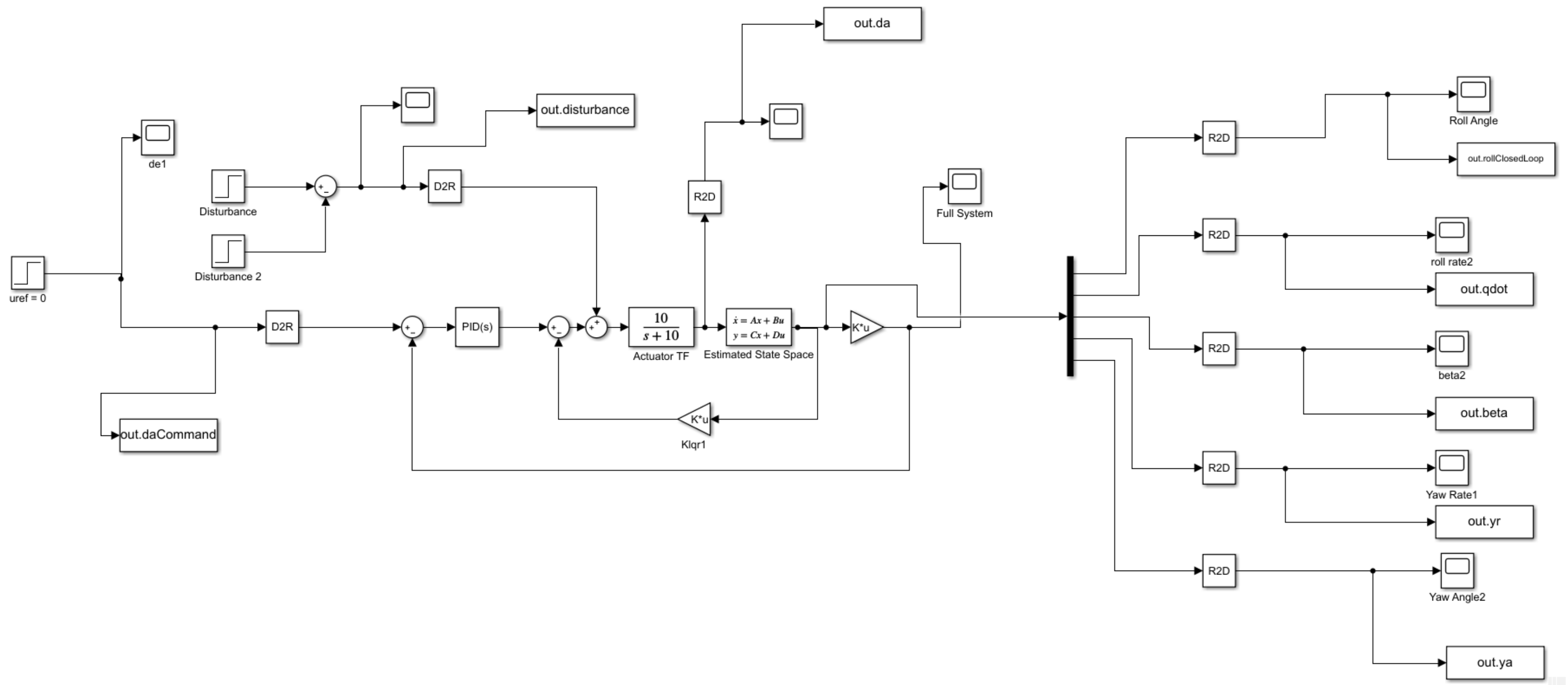
- Roll Approximate System
  - Aileron to Roll Angle Transfer Function:

$$\frac{0.229}{s^2 + 1.12s}$$

  - Aileron Actuator Transfer Function:

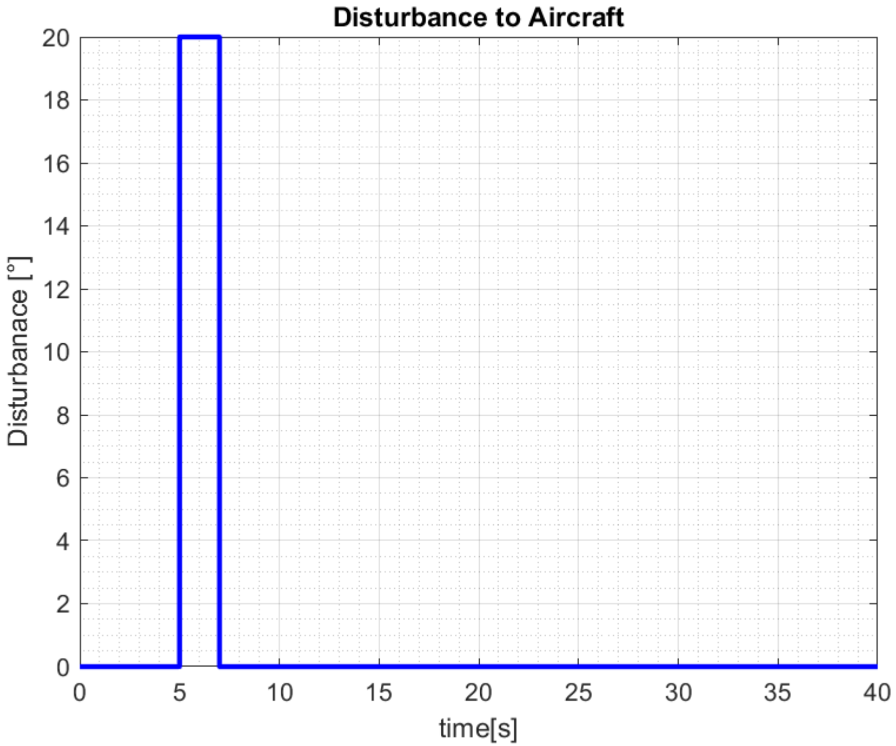
$$\frac{10}{s + 10}$$

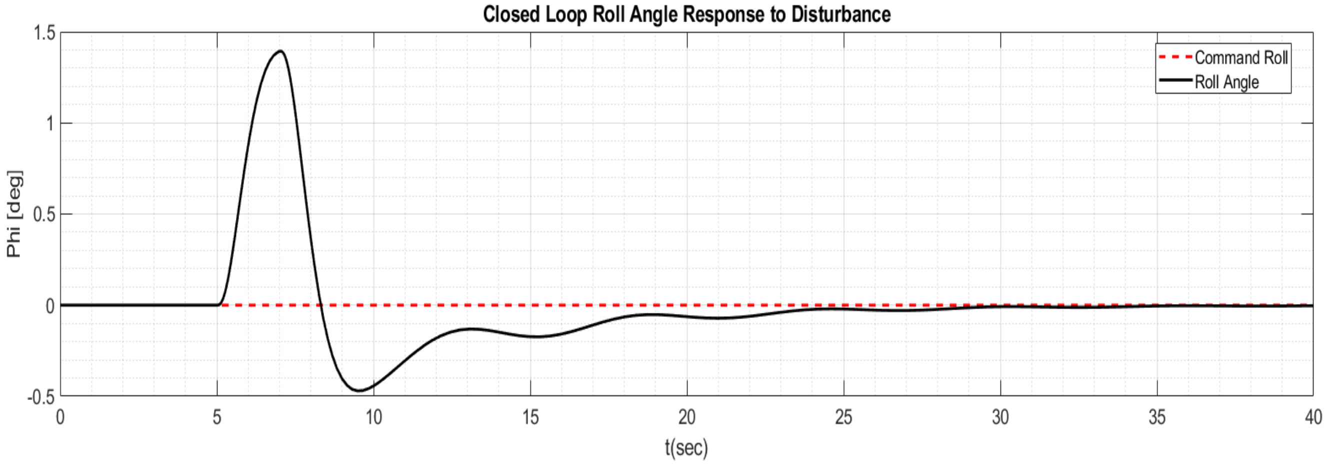
LQR-PID Roll Angle Hold Controller with roll angle feedback

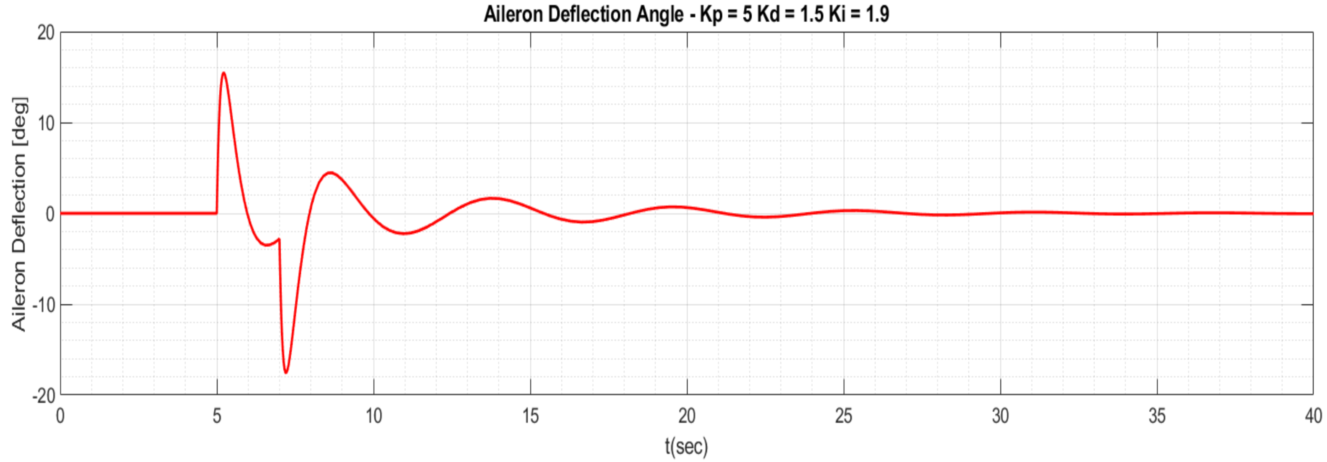


Lateral Closed-loop Stability Analysis Results

- Closed Loop Response to 0° control input with 20° disturbance







Conclusion

- Dynamic Inversion
  - Quickly corrects disturbances in angle of attack and returns aircraft to desire reference signal.
  - With a 15° disturbance, the aircraft only requires 11° of elevator input to correct the attitude
- LQR-PID
  - With a 20° roll disturbance, the aircraft corrects the attitude with 15° of aileron input.
  - Due to the high proportional gain, the rise time of the system is pretty quick. The resulting response oscillates for a bit and has a slightly long settling time. This can be fixed by increasing the derivative gain, however it will result in a higher aileron deflection.

References

[1] http://www.tc.faa.gov/its/worldpac/techrpt/ar04-44.pdfWith a 15° disturbance, the aircraft only requires 11° of elevator input to correct the attitude

[2] Akyazi, O., Usta, M. A., & Akpinar, A. S. (2013). A Self-Tuning Fuzzy Logic Controller for Aircraft Roll Control System. *International Journal of Control Science and Engineering, 2*(6), 181-188. doi:10.5923/j.control.20120206.06

[3] http://www.aerospaceweb.org/aircraft/jetliner/b747/

[4] Aircraft Handling Qualities Data - https://www.robertheffley.com/docs/Data/NASA%20CR-2144--Heffley--Aircraft%20Handling%20Qualities%20Data.pdf