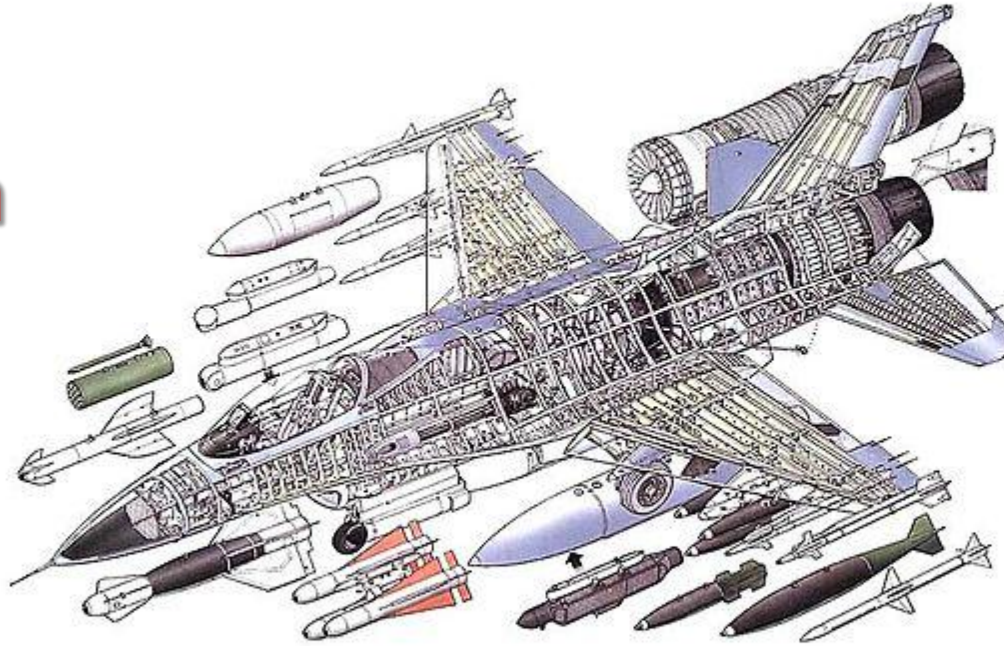
MECH 6091 – Flight Control Systems

Final Course Project

F-16 Autopilot Design



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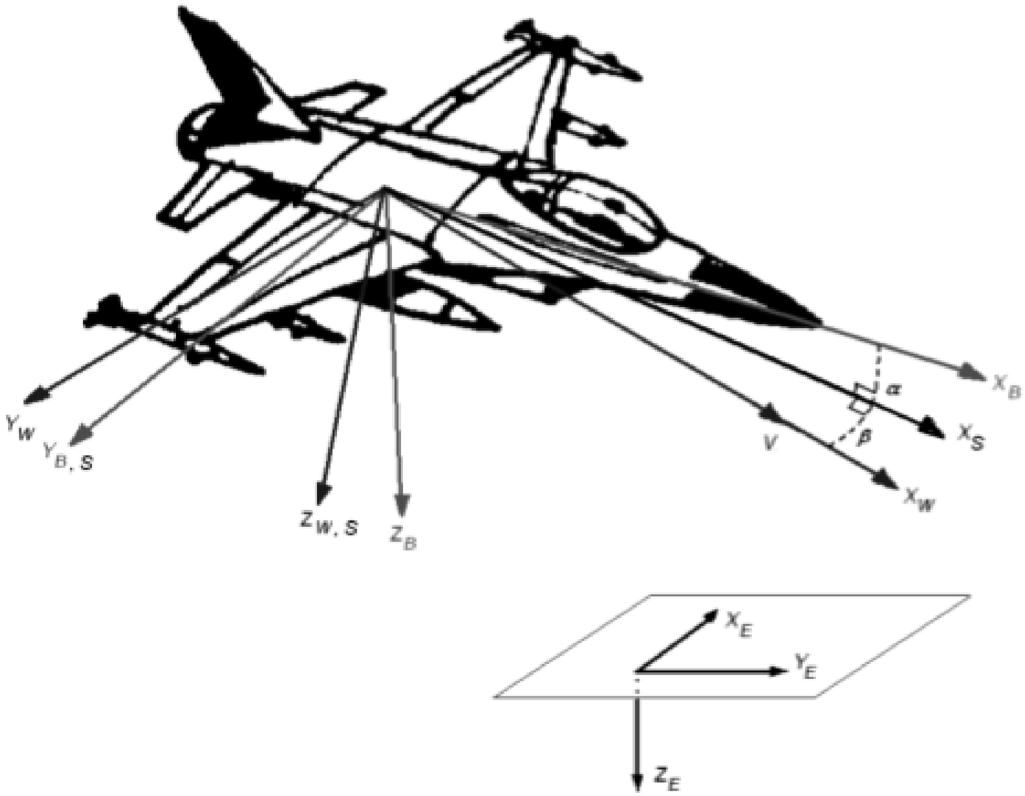
AGENDA

- Theoretical Background
- F-16 Model and Linearization
- Controller Design
- Results and Conclusions
- Q&A

Theoretical Background

- Reference Frames



Theoretical Background

- Aircraft Variables

Assumptions:

1. The aircraft is a rigid-body.
2. The earth is flat and non-rotating.
3. The mass is constant during the time interval over which the motion is considered.
4. The mass distribution is symmetric relative to the longitudinal plane.

Theoretical Background

- Equations of Motions EOM

Force: $$F = \frac{d}{dt}(mV)\Big]_B + \omega \times mV$$

Moment: $$M = \frac{dH}{dt}\Big]_B + \omega \times H$$

Theoretical Background

- Stability Requirements

$$C_{m_\alpha} < 0$$

- Longitudinal EOM

$$m\left(\dot{U} + QW - RV\right) = -mg\sin\theta + \left(-D\cos\alpha + L\sin\alpha\right) + T\cos\phi_T$$

$$\dot{Q}I_{yy} - PR\left(I_{zz} - I_{xx}\right) + \left(P^2 - R^2\right)I_{xz} = M_A + M_T$$

$$m\left(\dot{W} + PV - QU\right) = mg\cos\phi\cos\theta + \left(-D\sin\alpha - L\cos\alpha\right) - T\sin\phi_T$$

Theoretical Background

- Linearized Longitudinal EOM

$$m\dot{u} = -mg\theta\cos\Theta_1 + f_{A_x} + f_{T_x}$$

$$I_{yy}\dot{q} = m_A + m_T$$

$$m\left(\dot{w} - U_1 q\right) = -mg\theta\sin\Theta_1 + f_{A_z} + f_{T_z}$$

F-16 Nonlinear Model

- F-16 Russell Model:
  - 12 State Variables
  - 4 Input Variables

- F-16 Longitudinal Linear Model:
  - 5 State Variables
  - 1 Input Variables

- MATLAB *linmod* command used for linearization

- Low-Fidelity model

Longitudinal EOM in State Space Form

$$x(t) = \begin{bmatrix} h \\ \theta \\ Vt \\ \alpha \\ q \end{bmatrix} \qquad u(t) = [\delta_e] \qquad y(t) = \begin{bmatrix} h \\ \theta \\ Vt \\ \alpha \\ q \end{bmatrix}$$

$$\begin{bmatrix} \dot{h} \\ \dot{\theta} \\ \dot{V}_t \\ \dot{\alpha} \\ \dot{q} \end{bmatrix} = A \begin{bmatrix} h \\ \theta \\ Vt \\ \alpha \\ q \end{bmatrix} + B[\delta_e] \qquad \begin{bmatrix} h \\ \theta \\ V_t \\ \alpha \\ q \end{bmatrix} = C \begin{bmatrix} h \\ \theta \\ Vt \\ \alpha \\ q \end{bmatrix} + D[\delta_e]$$

Control Input Limits

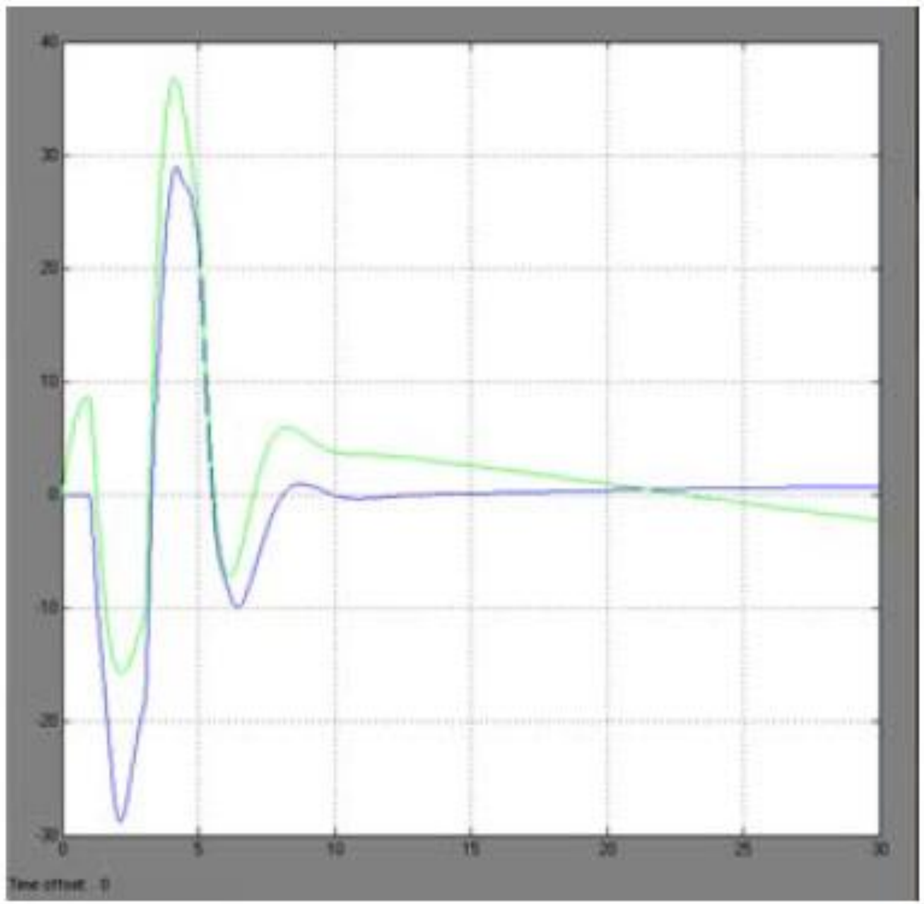
Control input	Minimum value	Maximum value	Units
δ_t	10000	19000	Lbs
δ_e	-25	25	Deg
δ_a	-21.5	21.5	Deg
δ_r	-30	30	Deg

Nonlinear vs. Linear Model

15k ft @ 600 ft/s

5 deg Elevator Disturbance

Pitch rate



Controller Design

FLIGHT QUALITY REQUIREMENTS – MIL-F-8785C

- Flight Category B – Cruise
- Level 1 – Clearly adequate for mission flight phase

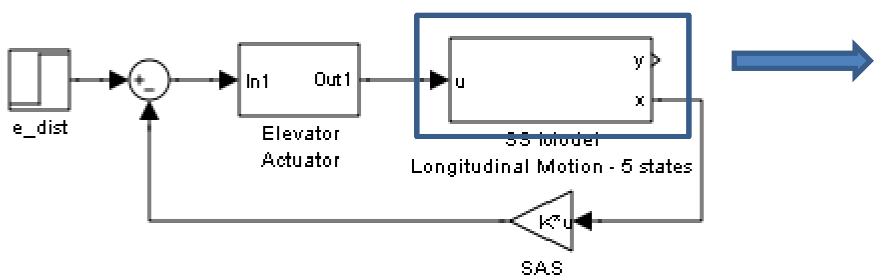
Parameter	Current	MIL Target	Desired
SP – ζ	0.464	[0.3, 2]	≥ 0.7
SP – ω_n	1.63 rad/s	[1.1, 7] rad/s	≥ 3 rad/s
SP – τ	1.32 s	--	
P – ζ	0.057	> 0.04	≥ 0.3
P – ω_n	0.066	NA	≥ 0.5 rad/s
P – τ	262 s	--	≤ 7s (t_s≤30s)

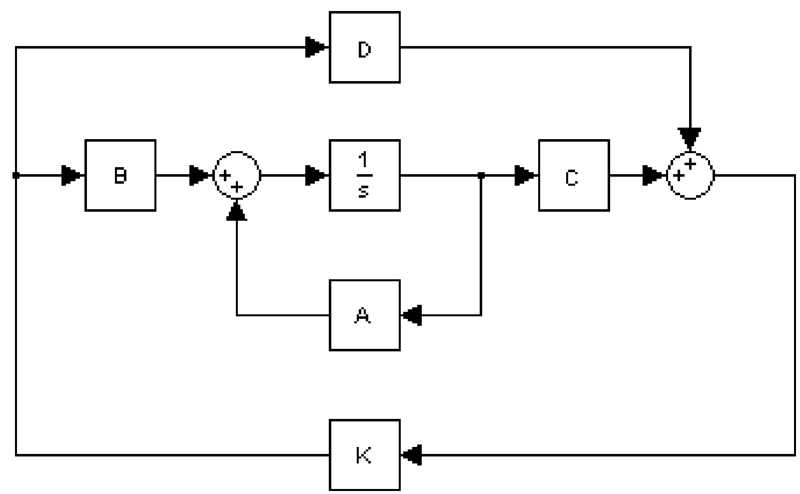
Controller Design – SAS

- Full-Feedback State (All states are available)

- Pole Placement Method

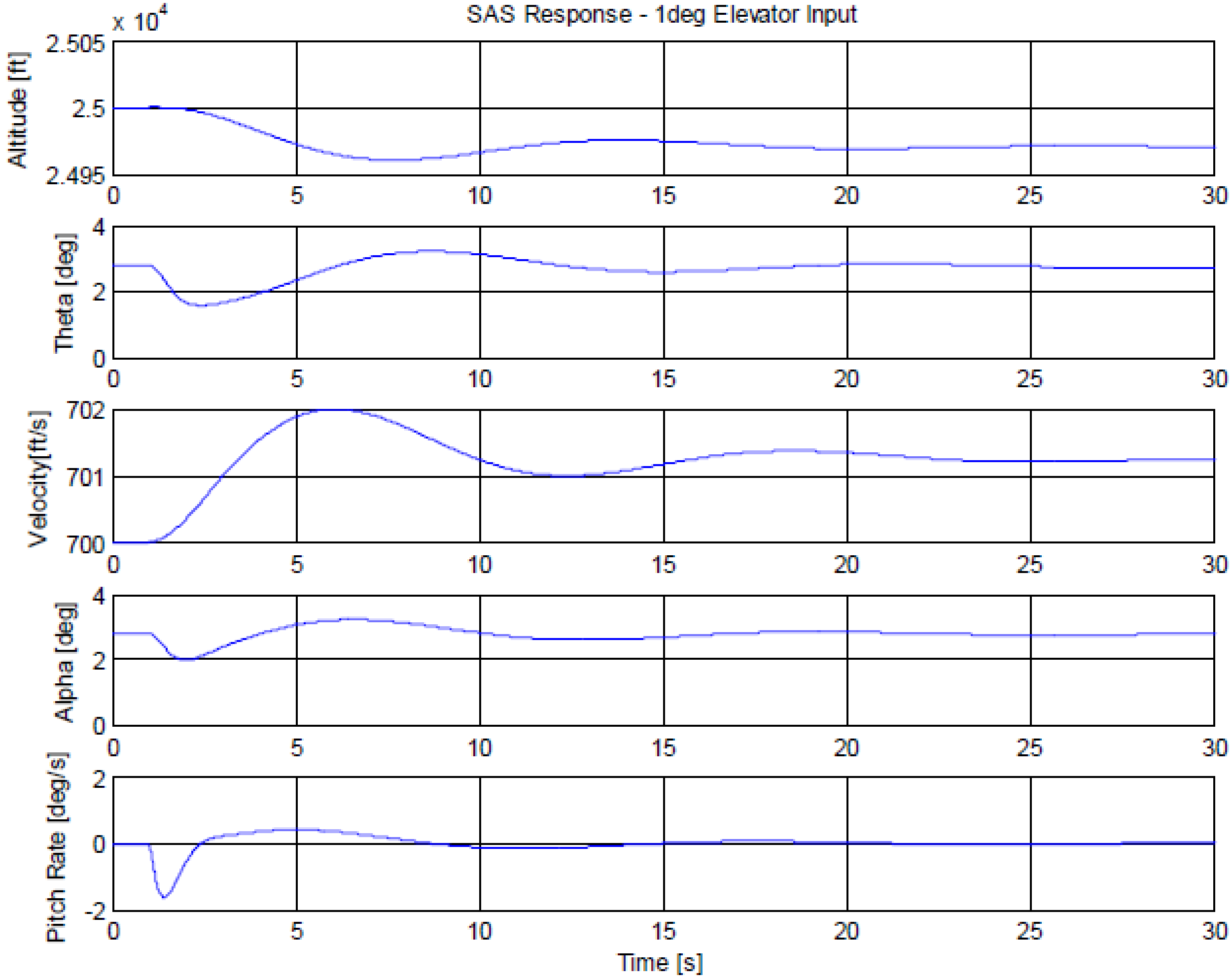
- Necessary and Sufficient Condition for Arbitrary Pole Placement





Controller Design – SAS

25k ft @ 700 ft/s
1 deg Elevator Disturbance



Controller Design – SAS

- Stability improvement achieved
- Excellent disturbance rejection
- New characteristics:

Parameter	Desired	Achieved	
SP – ζ	≥ 0.7	0.7	✓
SP – ω_n	≥ 3 rad/s	3 rad/s	✓
P – ζ	≥ 0.3	0.287	
P – ω_n	≥ 0.5 rad/s	0.522	✓
P – τ	≤ 7s ($t_s \leq 30$s)	6.67 s	✓

Controller Design – Autopilot

- Altitude Reference Trajectory
  - Up to 5k ft increase/decrease tracking

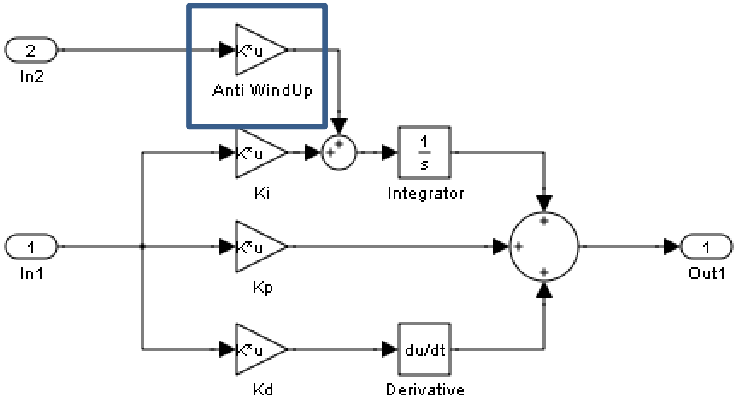
- Augmented A/C TF

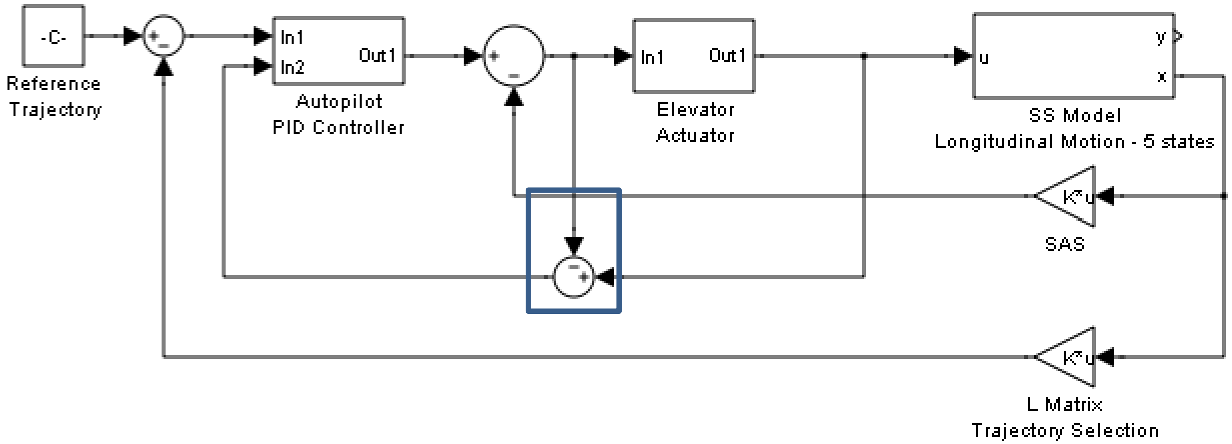
$$\frac{h(s)}{\delta_e(s)} = \frac{0.9443\, s^3 - 3.963\, s^2 - 69.09\, s - 0.2069}{s^5 + 4.501\, s^4 + 10.53\, s^3 + 3.852\, s^2 + 2.454\, s + 0.00245}$$

- Desired Response Characteristics:
  - Settling time < 30s
  - Overshoot <= 5%
  - Steady-State error = 0
  - Minimize oscillations

Controller Design – Autopilot

- PID Controller Design
- SISO tool + Manual Tuning
- Attention to Actuator Saturation!

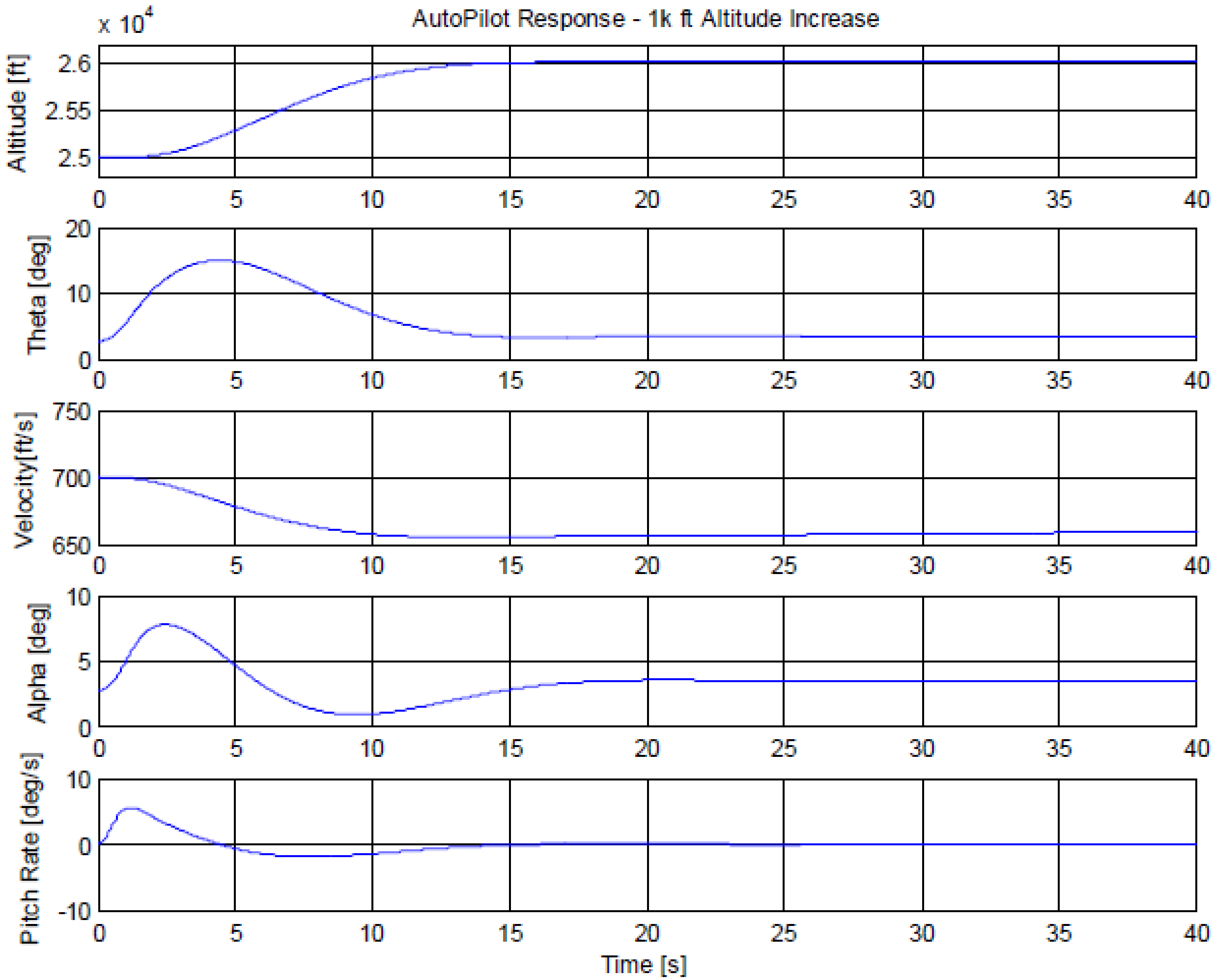




Anti-Windup included

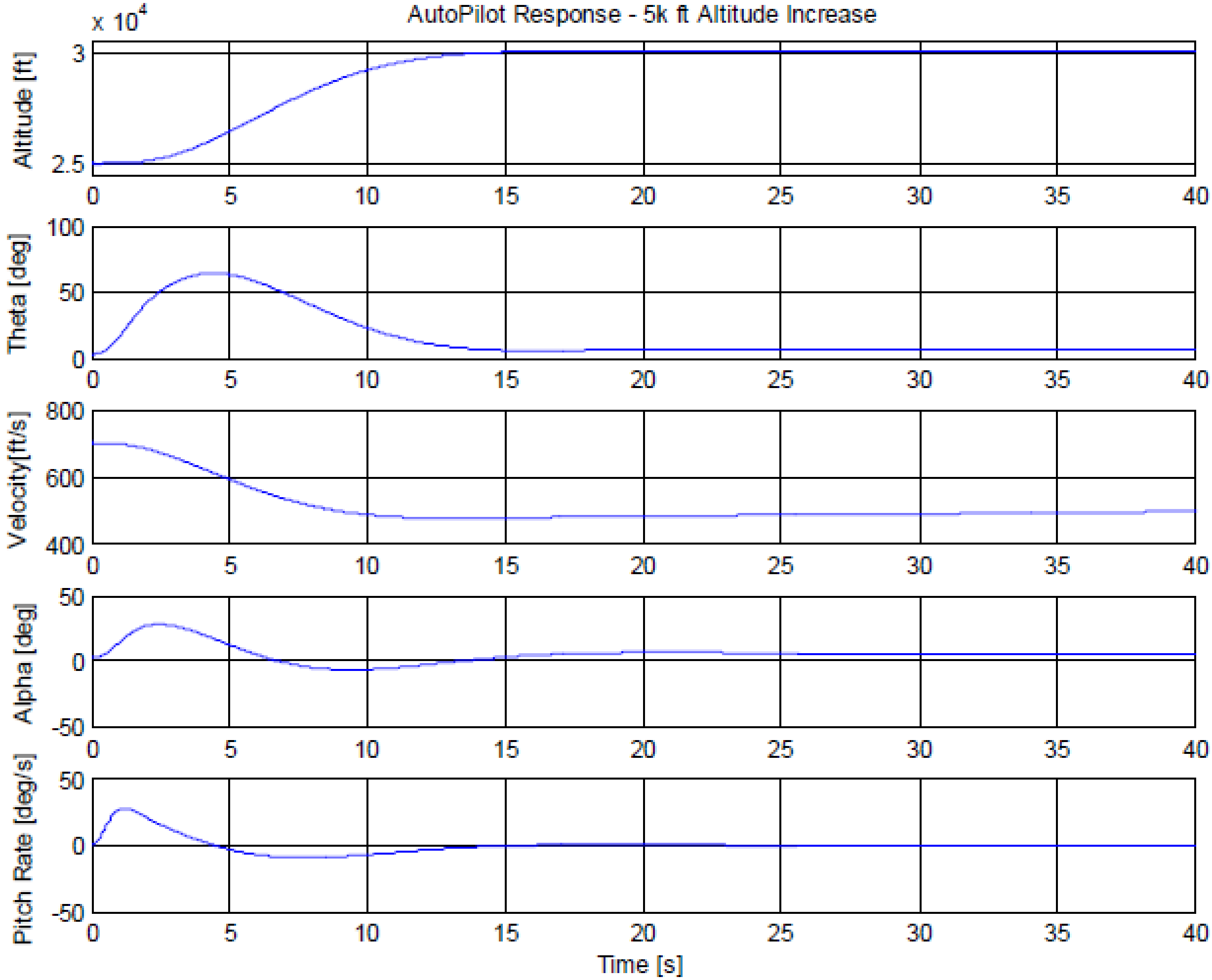
Controller Design – Autopilot

1k ft increase @ 700 ft/s
No Elevator Disturbance



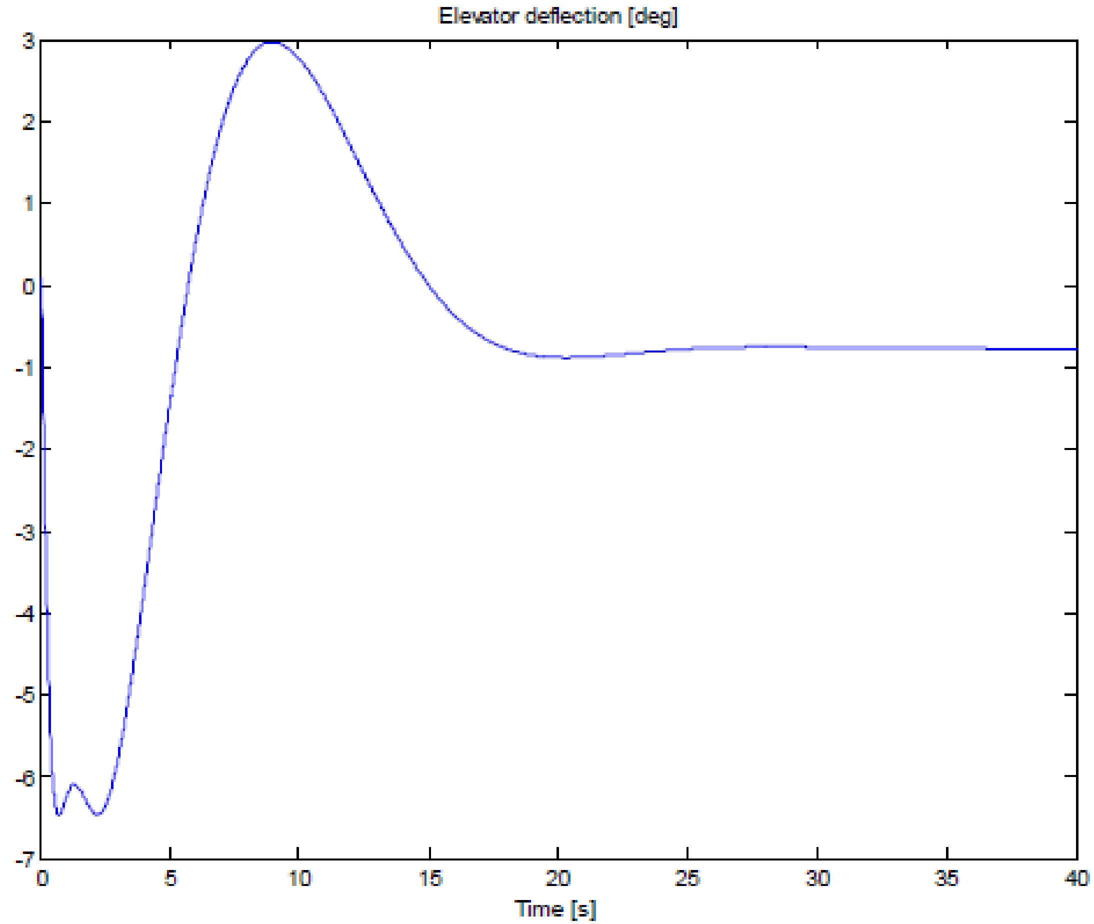
Controller Design – Autopilot

5k ft increase @ 700 ft/s
No Elevator Disturbance



Controller Design – Autopilot

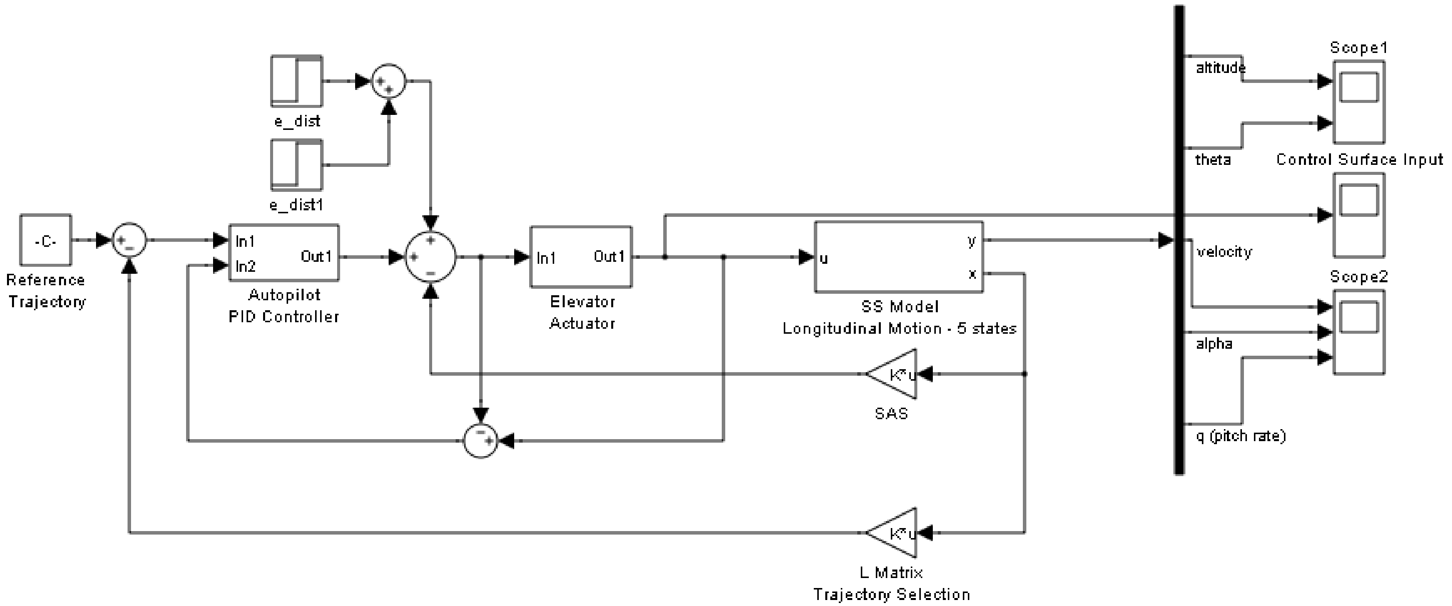
5k ft increase @ 700 ft/s
No Elevator Disturbance



Controller Design – SAS + Autopilot

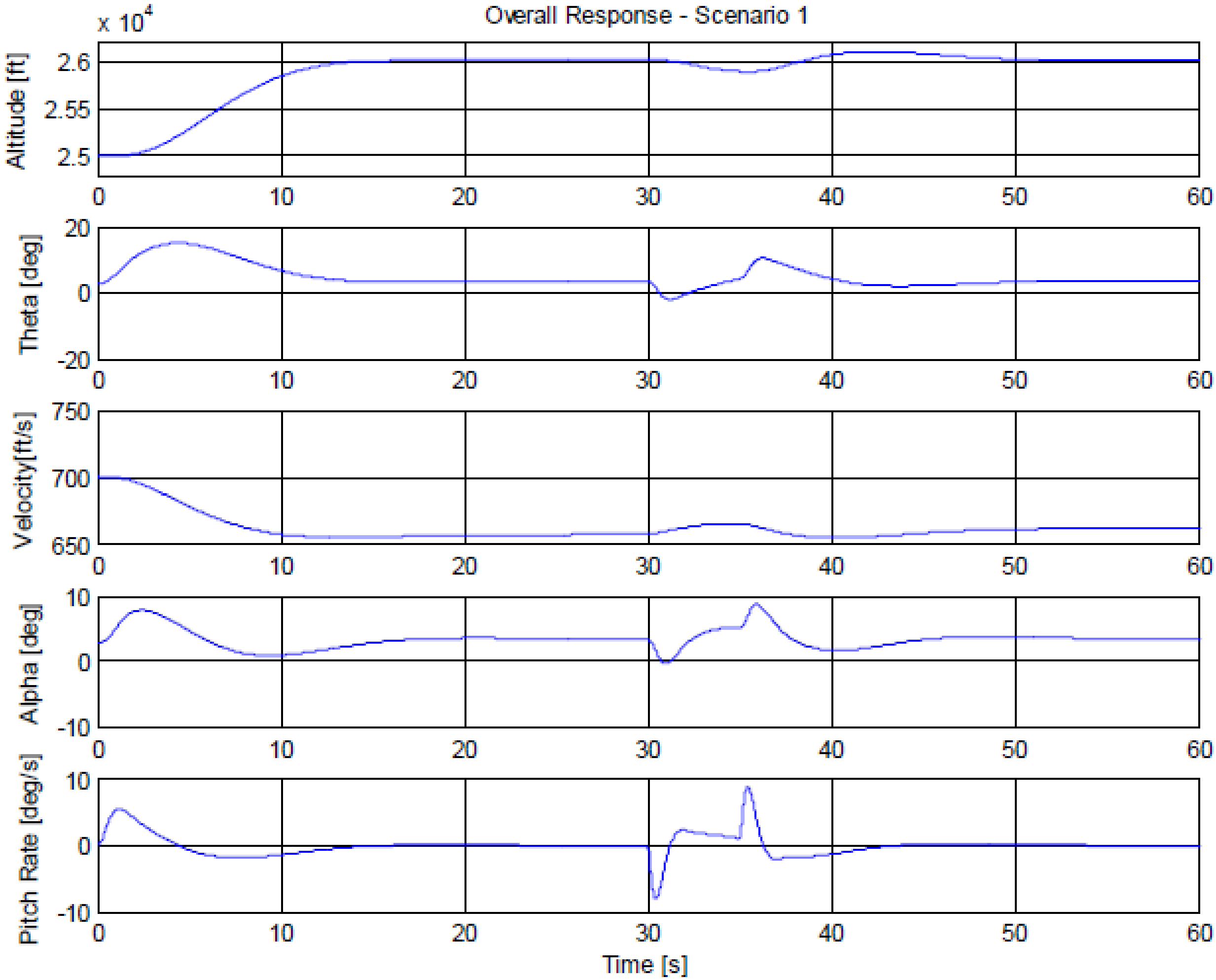
Scenario:

1. 1000 ft altitude increase, followed by
2. +5deg perturbation, followed by
3. -5deg perturbation



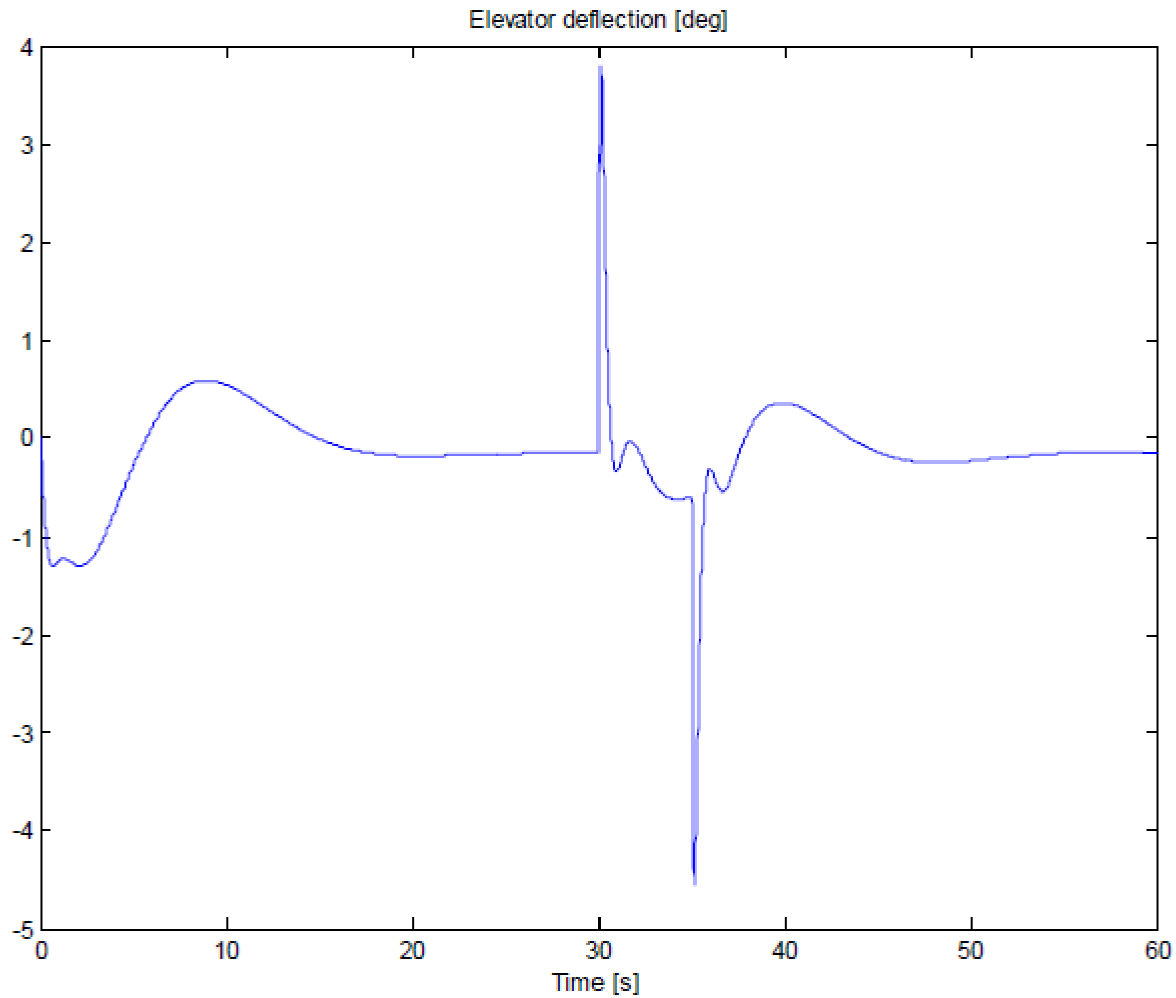
Controller Design – SAS + Autopilot

Scenario 1



Controller Design – SAS + Autopilot

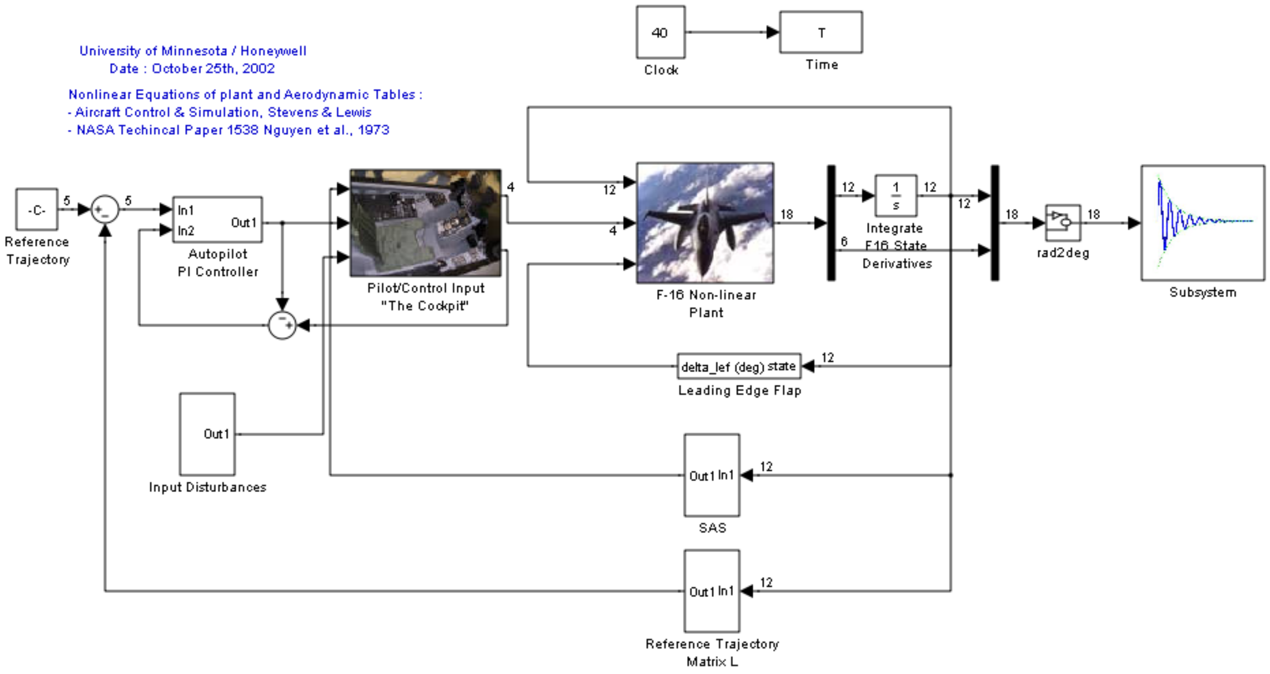
Scenario 1



Controller Design – Nonlinear Model

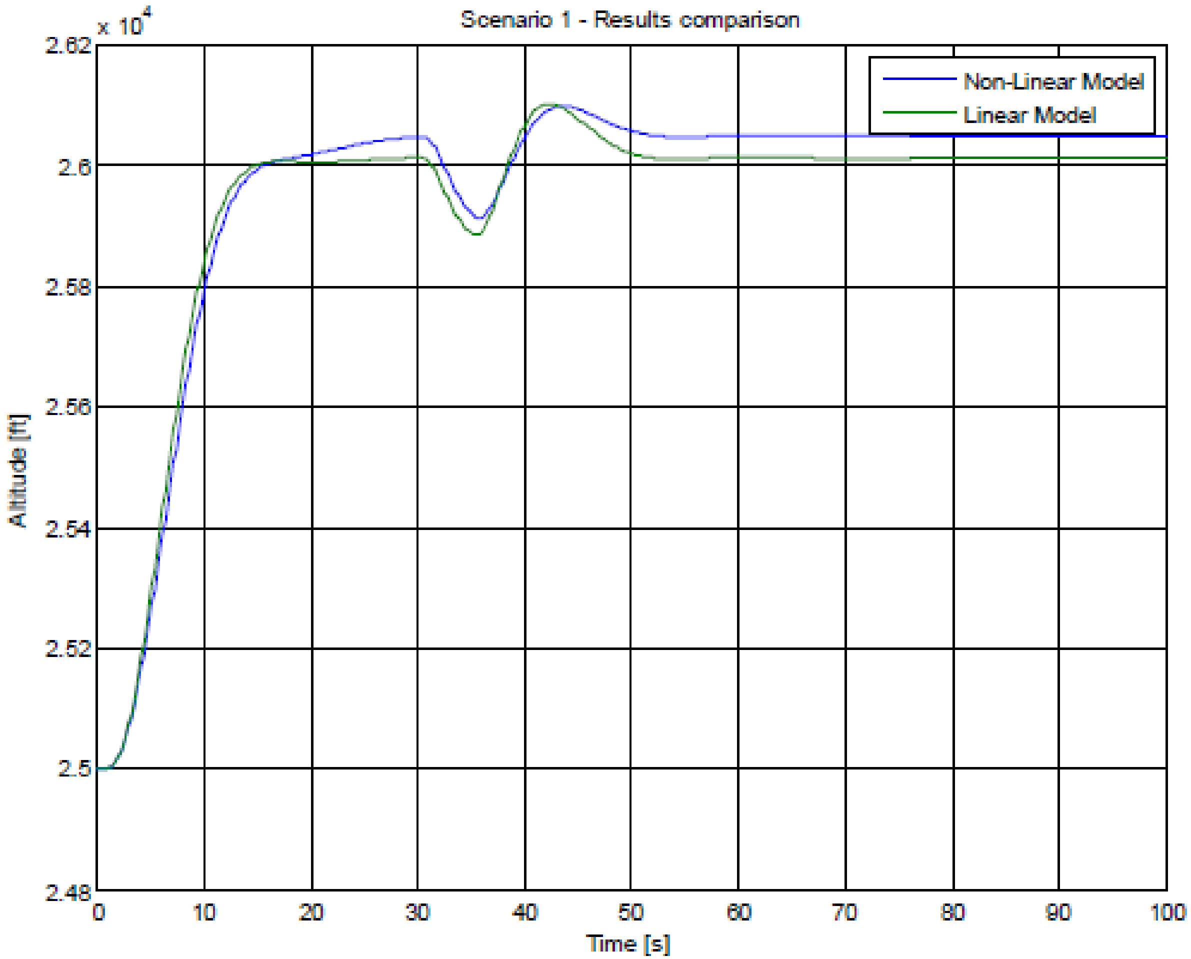
Compare:

- Linearized Model + LTI Controller
- Nonlinear Model + LTI Controller



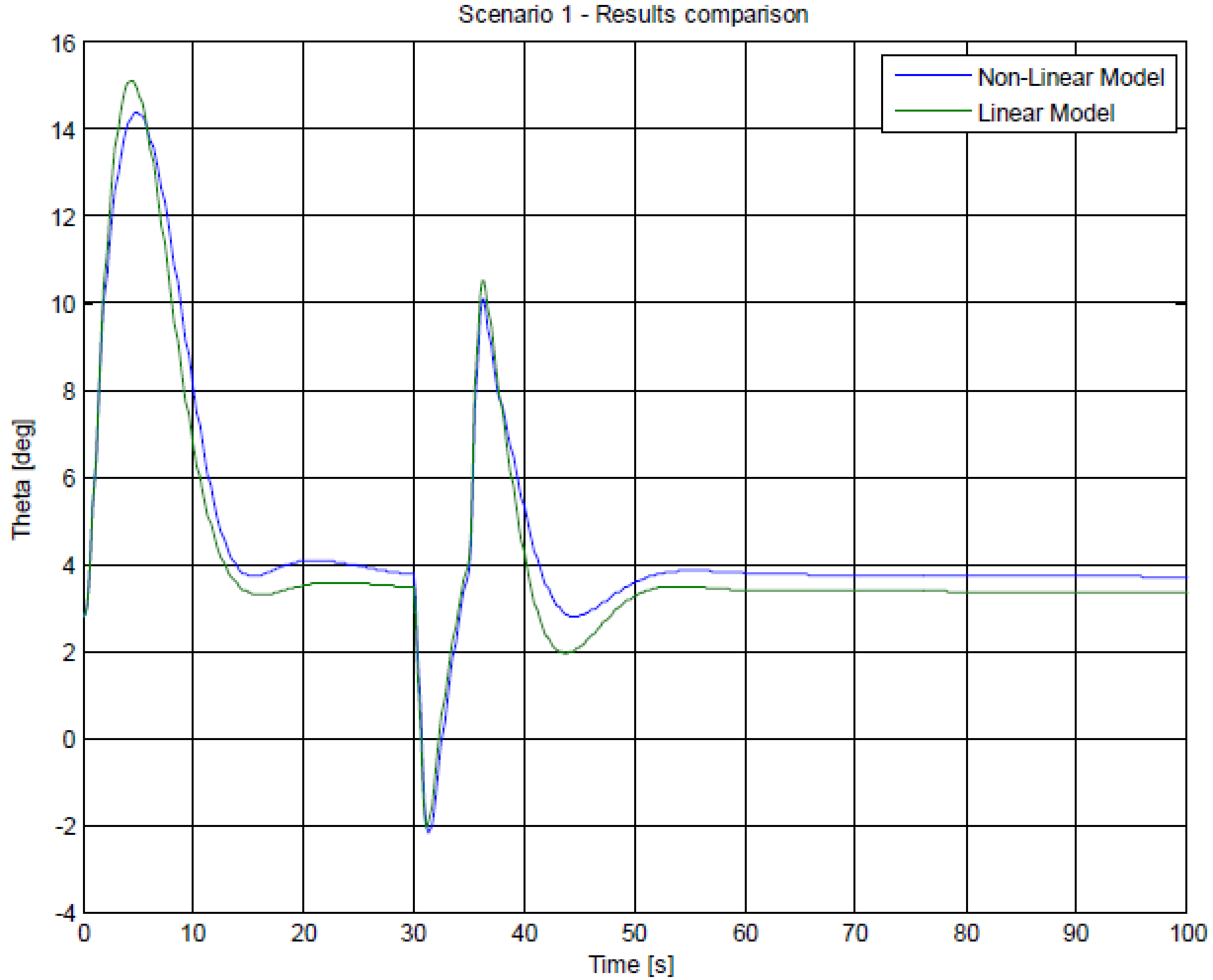
Controller Design – Nonlinear Model

Scenario 1 – Altitude



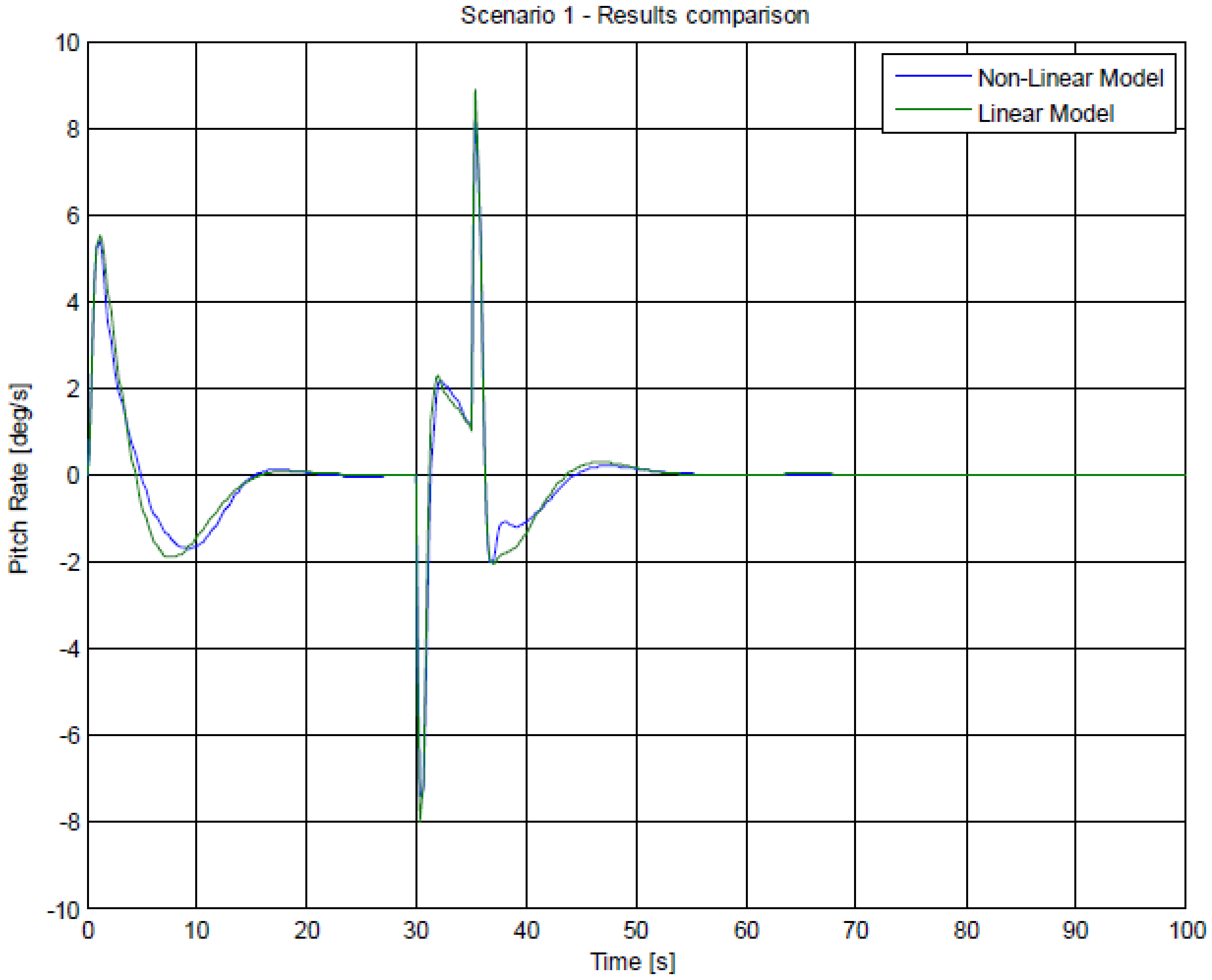
Controller Design – Nonlinear Model

Scenario 1 – Theta



Controller Design – Nonlinear Model

Scenario 1 – Pitch Rate



Conclusions

- A good linearization method is extremely important
- FFS eases SAS design -> In real life, not all states are available (estimators required)
- Nonlinear model shows longitudinal/lateral coupling
- **Satisfactory overall results**
- Future work: Scheduled PID and Lateral Motion

Q&A