Performance and Robustness Tradeoffs for Scramjet-Powered Hypersonic Vehicles

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NASA FAP Annual Meeting - Hypersonics Project
October 7-9, 2008

Contributors

Arizona State University: J. Dickeson (NASA PhD Fellow), S. Sridharan, Dr. O. Cifdaloz (Post-doc)
Vibroacoustics Solutions: Dr. A. Kelkar, Dr. J. Vogel
Mission Critical Technologies: J. Benavides
Other: Dr. P. Voulgaris (UIUC), Dr. B. Ridgely (Raytheon), D. Soloway (NASA)

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Outline

- Motivation
- State-of-the-Art: Prior and Current Efforts
- Fundamental Issues and Challenges
- Sample Engineering Longitudinal Model for Generic Hypersonic Vehicle
  - Model Description
  - Static and Dynamic Analysis
  - Control Design Tradeoffs
  - Nonlinear Issues
- Summary and Conclusions

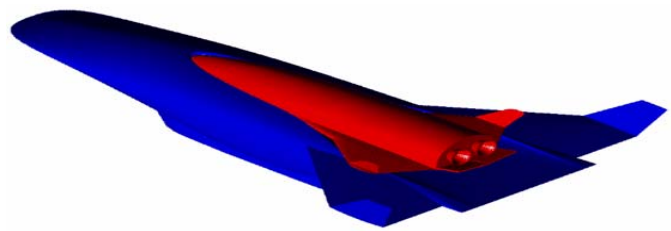
Motivation

Air-breathing hypersonic vehicles represent next critical step toward achieving
- reliable affordable access to space and global reach vehicles

- Rocket-based systems must carry oxygen - more expensive (limits payload), less reliable

  Airbreathing ... need not carry oxygen - less expensive (reduce TOGW), more reliable, offers increased I_{sp} and lower cost-per-pound-to-orbit

- NASA Emphasis: two-stage-to-orbit (TSTO) concepts; e.g. NASA reference vehicle (RV)



Dr. J. Robinson, et. al.

- Issue: Significant aero-thermo-elastic-propulsion interactions and uncertainty
  - requires control-relevant integrated multidisciplinary (IM) MAD approach

NOTES: 1. To suitably limit scope, we focus on scramjet-powered vehicles (Mach 5-16) and a single vehicle

2. Final IM-MAD approach will be applicable to TSTO

STATE OF THE ART

State of the Art: Programs

- **1986-1993 - NASP X-30:** $3*B* SSTO effort involving DOD and NASA; No flights
- **1996 - Hyper-X Program:** Initiated to advance hypersonic air-breathing propulsion
- **2002 - Scramjet**
  Supersonic combustion of scramjet in flight first demonstrated July 30, 2002
  by Univ of Queensland Centre for Hypersonics (HyShot program)
- **2004 - X-43A Flights**
  Hyper-X program culminated with historic (March 27, November 16)
  2004 Mach 7, 10 X-43A scramjet-powered flights (McClinton, 2007)
  ...ushered in era of airbreathing hypersonic flight
- **Hypersonic International Flight Research Experimentation (HIFIRE)**
  Ongoing collaboration between NASA, AFRL, Australian Defence Science and Technology Organization (DSTO), Boeing Phantom Works, University of Queensland
  Will involve 10 flights over 5 years
- **X-51A Scramjet Engine Demonstrator - WaveRider (SED-WR)**
  AFRL, Boeing, Pratt & Whitney, Rocketdyne
  single HC-fueled scramjet, fixed-geometry inlet, air-launched expendable missile, to be launched by B-52 at ∼35Kft, accelerated by solid-propellant rocket motor (MGM-140) to Mach 4.5 scramjet ignition speed, target speed: ∼Mach 6-7, first flight: ∼ Aug 2009

Fundamental Issues and Challenges

Aero-Thermo Interactions (Anderson, 2006)

- Drag can be reduced by making body more slender (increased fineness); this increases structural heating, reduces flexible mode frequencies
  ...can degrade control system performance...may cause instability!
  ...may require suitable (high fidelity) models for active modal control
- Hypersonic vehicle design is heat-driven, not drag-driven
  Reason: within hypersonic regime ($M > 5$) <u>heating varies as V^3; drag as V^2</u>

Scramjet Propulsion (Heiser & Pratt, 1994)

- Airbreathing systems need not carry oxidizer - significantly reduces TOGW
  - for given payload $W_{payload}$: $\frac{W_{rocket}}{W_{payload}} \approx 25 \quad >> \quad \frac{W_{airplane}}{W_{payload}} \approx 6.5$ (4% vs 15.4%)
  - offers potential for significantly (vis-a-vis rockets)
    - increased specific impulse $I_{sp} \stackrel{\text{def}}{=} \frac{Impulse}{W_{propellant}}$
      (I_{sp} for H >> I_{sp} for HC fuels $\Rightarrow$ Much higher Mach numbers for H - larger volume)
    - <u>lower cost-per-pound-to-orbit</u> (currently $\$10K/lb$ for rocket based systems)

Fundamental Issues and Challenges

Integrated Airframe and Engine - "Engineframe"

- Entire underbelly part of flowpath - long forebody provides compression lift, mass capture
- Will fly at highest allowable $\bar{q}$ (structure permitting) to maximize mass capture
- Aft body expansion nozzle recovers thrust
- May require tight AOA control for proper operation (particularly at off-design conditions)
- Aft situated c.g. results in instability - requires minimum BW to stabilize

Trajectories within Airbreathing Corridor (Heiser & Pratt, 1994)

- About 30kft wide (vertically); dynamic pressure: $\overline{q} \in [500, 2000]$ psf
  - lower bd dictated by available lifting area; upper bd by structural limits
  - At Mach 16, lower bd requires flight below 150kft
- **Need for Flight Path Angle (FPA) Control**
  - Assume corridor-centered flight at Mach 10. If FPA deviates by $\sim 2.9°$ for 30 sec, vehicle will leave corridor! (Static calculation; doesn't capture dynamical issues!)
  - Can be disastrous - particularly in presence of uncertain low-frequency flexible modes
  - Issue: RHP zero (elevator to FPA) may limit FPA BW...may require additional control surface to follow rapid FPA commands; e.g. a canard (beware severe thermal issues)

Prior and Ongoing Work

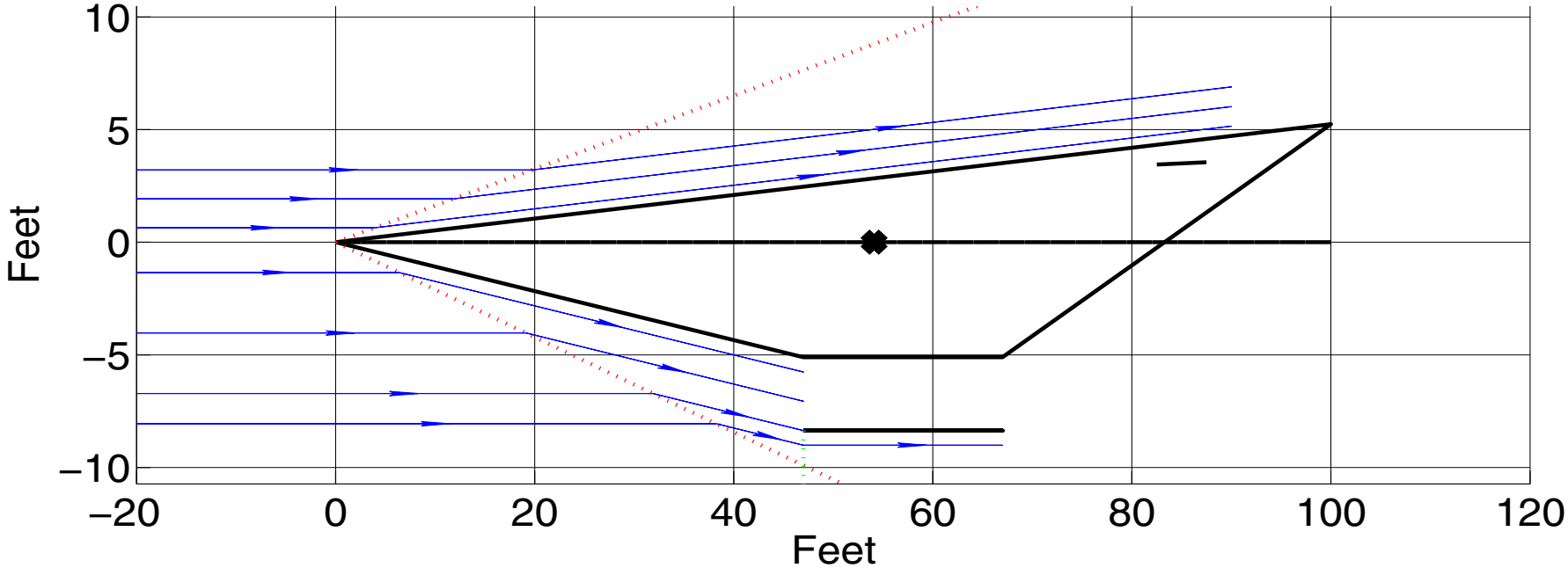
- 1994, Chavez-Schmidt (Arizona State University)
  - 3DOF longitudinal (plus flexing) model
  - simple scramjet engine

    isentropic diffuser, internal-external nozzles, 1D Rayleigh flow combustor
    thermal choking (unity combustor exit Mach)
    convenient plume assumption
  - FEM based structural model (based on similar full scale vehicle)
- 2003-2008, Mirmirani, Colgren, Keshmiri, et. al.
  - engineering and CFD methods, 6DOF, winged cone
- 2004-2008, Bolender, Doman, Oppenheimer, et. al.
  - builds on 1994 Chavez-Schmidt model (overview given below)
- 2008, VSI-Control3D; Univ. Michigan-OSU
  - Two Ongoing NASA (collaborative) Modeling NRAs
  - engineering and CFD methods, 6DOF
  - general vehicle configurations; e.g. NASA RV, etc.

SAMPLE ENGINEERING MODEL

Bolender, Doman, Oppenheimer

Overview of Model



- 3DOF longitudinal + structual (Bolender, Doman, Oppenheimer, et. al, 2005-2008)
- Model components
  - inviscid compressible oblique-shock and Prandtl-Meyer expansion theory
  - unsteady effects: linear piston theory
  - viscous drag effects: Eckerts temperature reference method (turbulent)
  - structural: assumed modes method (free-free beam)
  - propulsion: 1994 Chavez, Schmidt
  - 4 possible controls - elevator, fuel equivalence ratio (FER), diffuser area ratio, canard
- Propulsion improvement: GNC2008 Torrez, Driscoll, Bolender, Doman, Oppenheimer.
- For this paper, 2 controls (elevator, FER) model, diffuser area ratio = 1, canard removed

Fundamental Questions Asked

- Where can vehicle be trimmed (altitude, Mach)?...focus on level-flight
- How do trim properties change over trimmable region?
- How do dynamic properties change over trimmable region?
  - poles, zeros, right half plane zero-to-pole ratio
  - frequency response, control coupling
- What control design tradeoffs do we expect?
  - closed loop bandwidth vs. reference command magnitude
  - robustness with respect to uncertain flexible dynamics
- How do nonlinear issues impact control design tradeoffs?

Contributions of Work

Model Used: Bolender, Doman, Oppenheimer, et. al. (3 DOF + flexing) longitudinal model (2004-2008)

Publications

"Modeling & Control of Scramjet-Powered Hypersonic Vehicles: Challenges, Trends, & Tradeoffs," Published and presented at AIAA GNC Conference and Exhibit, Honolulu, Hawaii, Aug. 18-21, 2008

"Constraint Enforcement for Scramjet-Powered Hypersonic Vehicles with Significant Aero-Elastic-Propulsion Interactions," Submitted for publication to American Control Conference, St. Louis, Missouri, June 10-12, 2009

Trim (Static) Properties

- Trimmable Region: ∼Mach 5-12, 70-115 kft
  (subset of airbreathing corridor, Mach 5-16, 70-120 kft, $\overline{q} \in [500, 2000] psf$ [Heiser and Pratt,1993])
- Show importance of FER Margin

$$FERM \stackrel{\text{def}}{=} min(Thermal\ Choking\ FER, 1) - TrimFER$$

and how it depends on mach, altitude, flow turning angle (AOA+forebody deflection).
$FERM_{TC}$ decreases with decreasing Mach, increasing altitude, increasing FTA (AOA+forebody deflection).
$FERM_{unity}$ decreases with increasing Mach, increasing altitude (independent FTA).

Dynamic Properties

- Pitch-up instability due to forward cp (long forebody compression ramp) and rear shifted cg.
- Requires minimum bandwidth (BW) for stabilization
  - More unstable at lower altitudes and higher Machs
  - Instability (and poles) invariant along constant dynamic pressure profiles

Contributions of Work

Dynamic Properties

- Right half plane (non-minimum phase) zero associated with elevator-FPA map; vehicle initially loses altitude prior to climbing when elevator is deflected upwards
- Limits maximum achievable (FPA tracking) BW
  - RHP zero decreases with increasing altitude and decreasing Mach (like RHP pole)
  - RHP zero monotonically (albeit slightly) along constant dynamic pressure profiles

Control Design Tradeoffs (LQR)

- While state feedback can be used to eliminate minimum BW constraint at error, acceptable command following and disturbance attenuation requirements require a minimum BW (at error); also, still require minimum BW at controls
- FPA BW limited by RHP zero (inverse response) effects and flexible dynamics
  - Elevator+FER allows for decrease in FPA settling time by 3% (5.15 sec to 5.0 sec)
  - Elevator+canard (no FER) allows for 23% decrease (5.15 sec to 3.97 sec)...but canard may burn off!
- FPA robustness with respect to uncertainty in flexibility
  - Elevator alone allows for 11.2% decrease in flexility (EI) before instability
  - Elevator+FER allows for 17.1% decrease in flexibility (52% improvement)
  - Elevator+FER+canard allows for 19.5% decrease of flexibility

Nonlinear Issues

- Methods Used: LQR, Generalized Predictive Control
- FER Margin limits controller BW and/or reference command magnitudes (mainly velocity; FPA to much lesser extant)
- Elevator saturation can induce instability for large controller BW/reference FPA command magnitudes
  - constraint enforcement methodologies needed to ensure stability and best possible tracking

TRIMMABLE REGION AND STATIC TRIM PROPERTIES

Trimmable Region

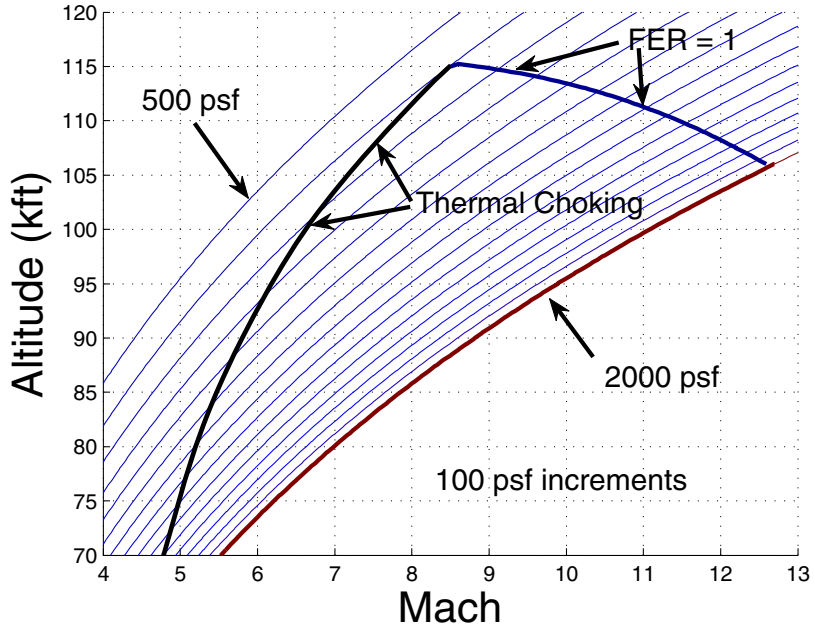


Figure 1: Trimmable Region: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle

- Airbreathing corridor: $\overline{q} \in [500, 2000]\ psf$ [Heiser and Pratt, 1993]
- Trimmable region - subset of airbreathing corridor (approx Mach 5-12, 70-115 kft)
- Structual Contsraint: $\overline{q} = 2000 \frac{lbs}{ft}$ (not absolute!)
  - Nominal flight condition: Mach 8, 85 kft, $\overline{q} = 2076\ psf$, (to facilitate comparison with prior research)
- FER Constraints:
  - FER = 1, (model does not capture thrust reduction for FER > 1)
  - Thermal choking (combustor exit Mach = 1)

Trim Analysis

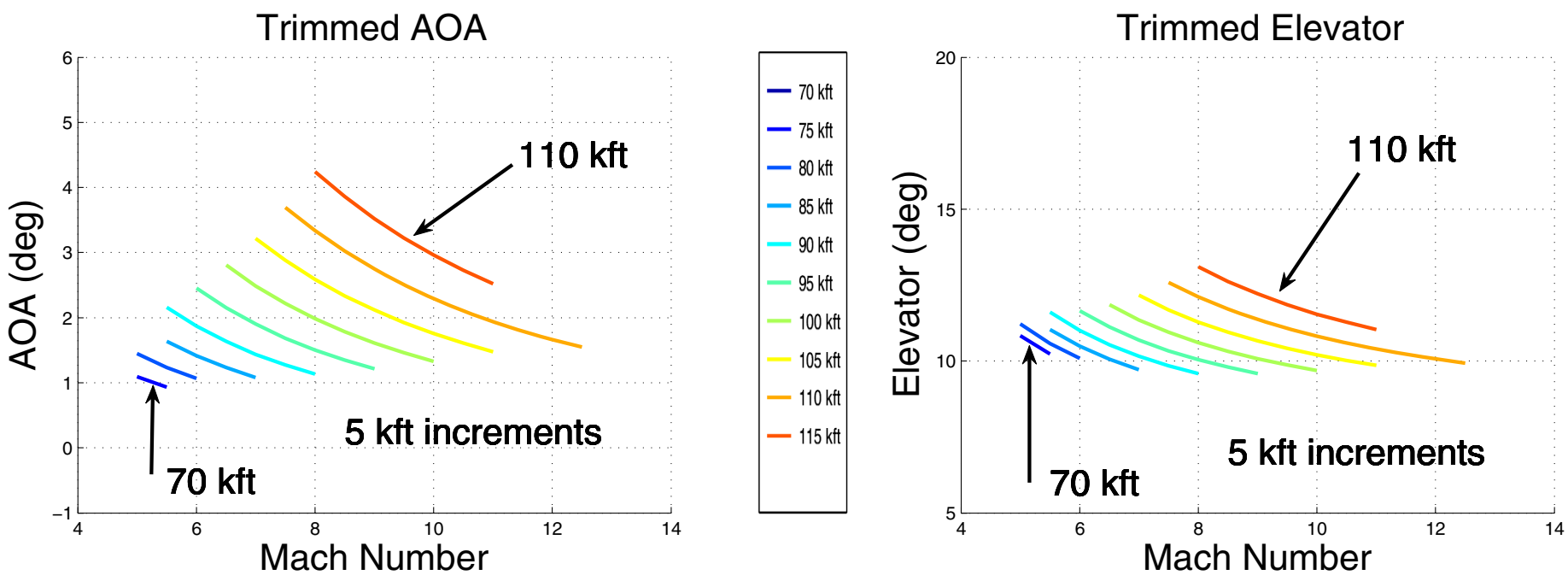


Figure 2: Trim AOA and Elevator Deflection: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle

- Both AOA and elevator deflection decreases monotonically with increasing Mach, and increases monotonically with increasing altitude
- Left endpoints: thermal choking
- Right endpoints:
  - $\overline{q} = 2000\ psf$ for 70-104 kft
  - FER = 1 for 104-115 kft

Trim Analysis

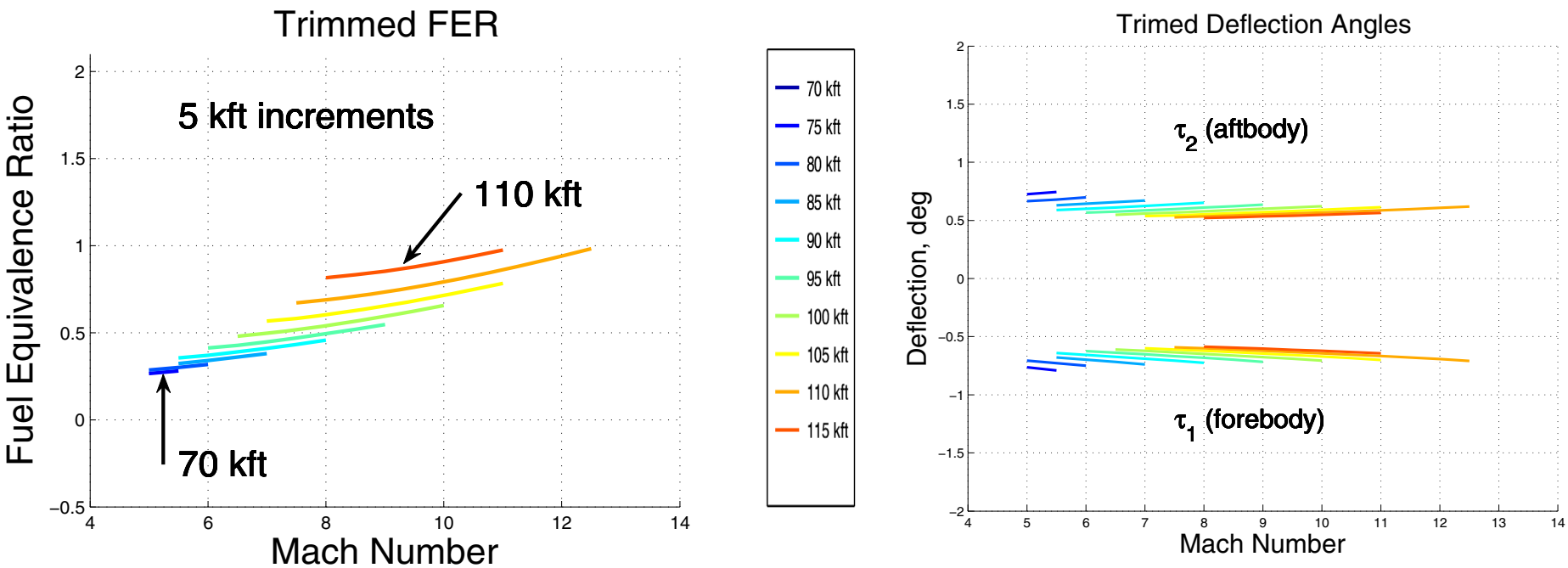


Figure 3: Trim FER and Flexing Deflection Angles: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle

- FER increases monotonically with ↑Mach and ↑altitude.
- Fore/aft deflection angle is always negative/positive, and relatively constant

DYNAMIC ANALYSIS: LINEAR

Dynamic Analysis

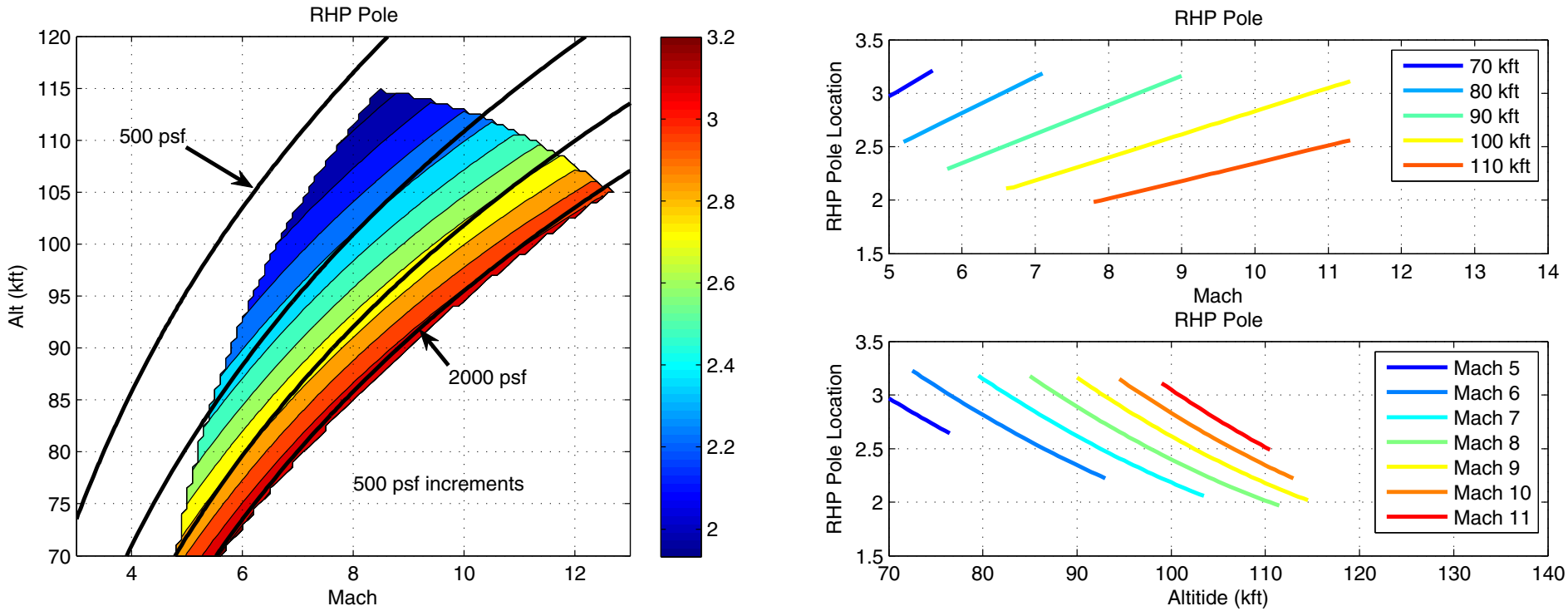


Figure 4: Right Half Plane Pole: Level Flight, 2 Control Flexible Vehicle

- RHP pole fairly constant along constant dynamic pressure profiles;
  - increases with increasing dynamic pressure (greater BW for stabilization)
- RHP pole increases linearly with increasing mach
- RHP pole decreases monotonically with increasing altitude

Dynamic Analysis

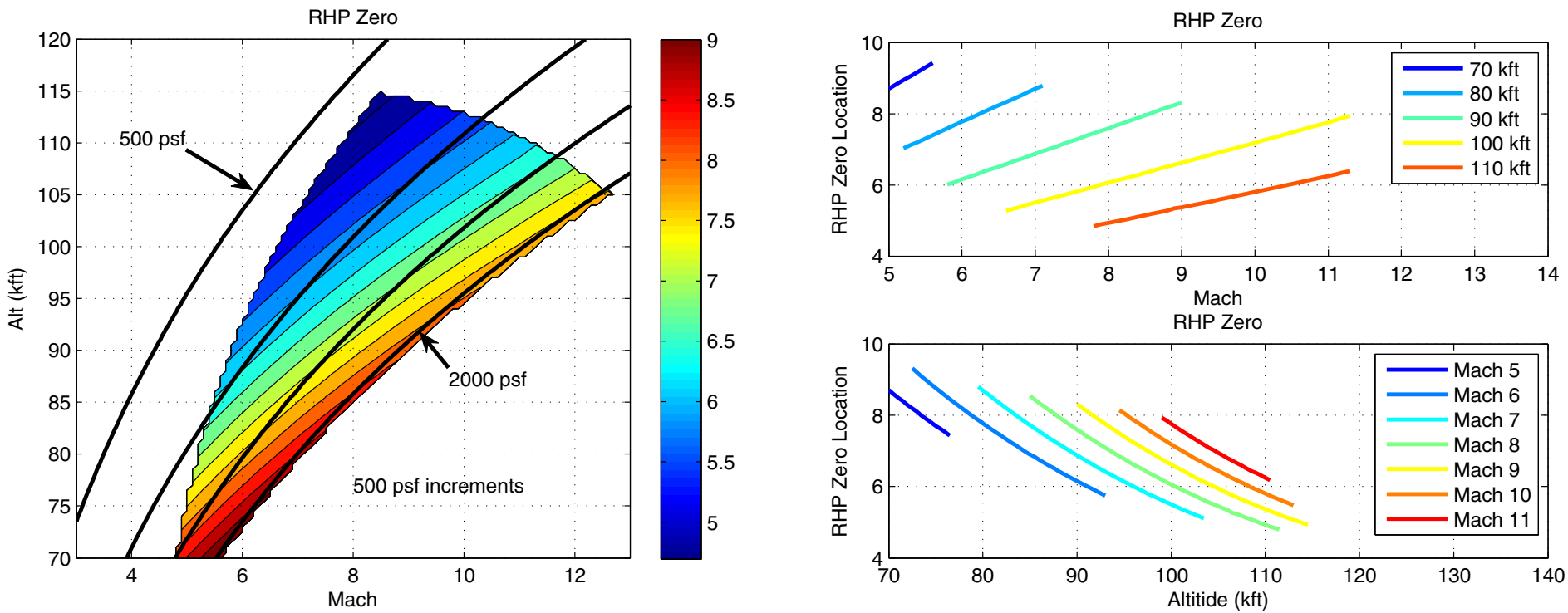


Figure 5: Right Half Plane Zero: Level Flight, 2 Control Flexible Vehicle

- RHP zero decreases with decreases dynamic pressure
- RHP zero increases linearly with increasing mach
- RHP zero decreases monotonically with increasing altitude

DYNAMIC ANALYSIS: FREQUENCY RESPONSE

Dynamic Analysis

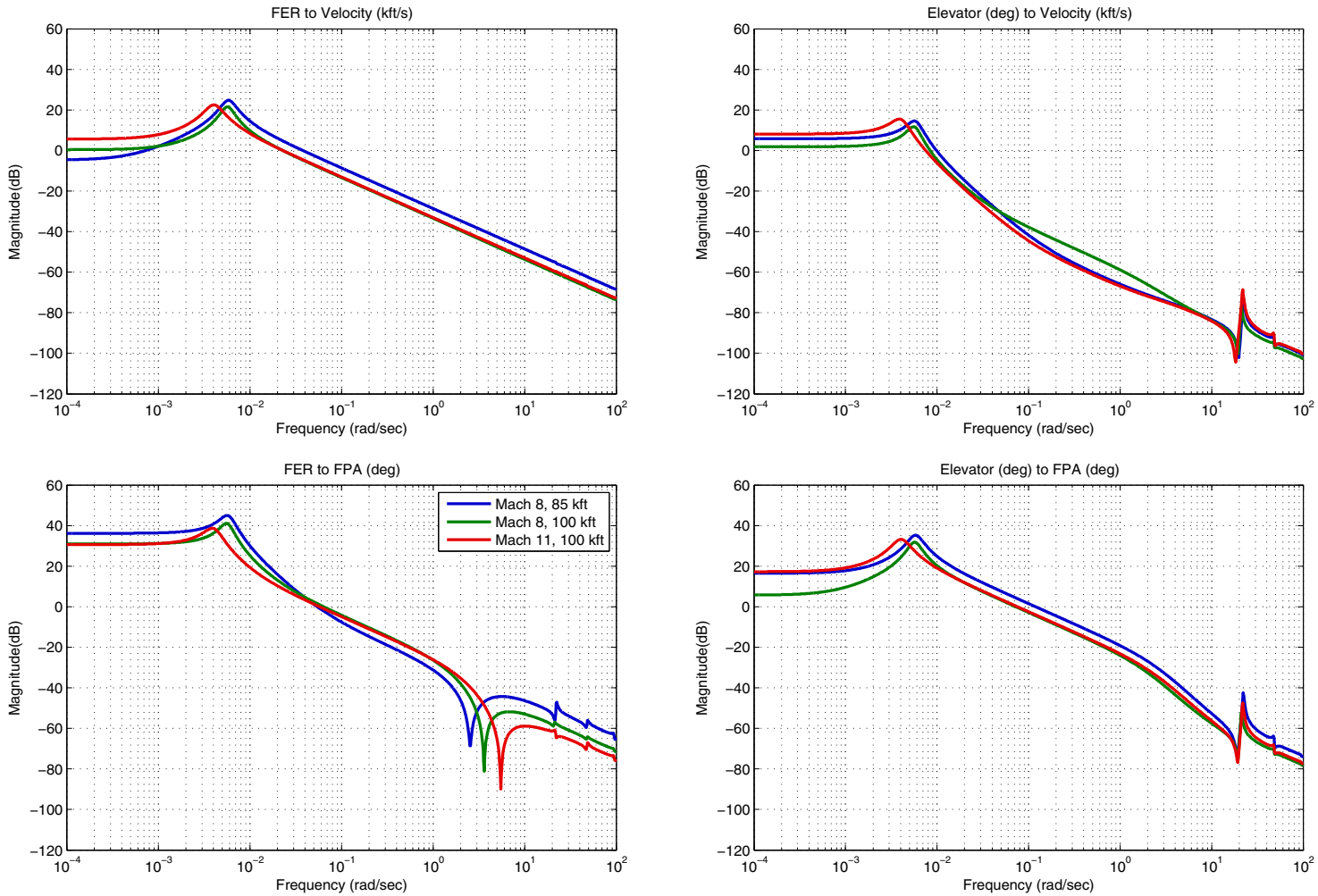


Figure 6: Plant Bode Magnitude Response, Mach 8, 85 kft: Level Flight, 2 Control Flexible Vehicle

Dynamic Analysis

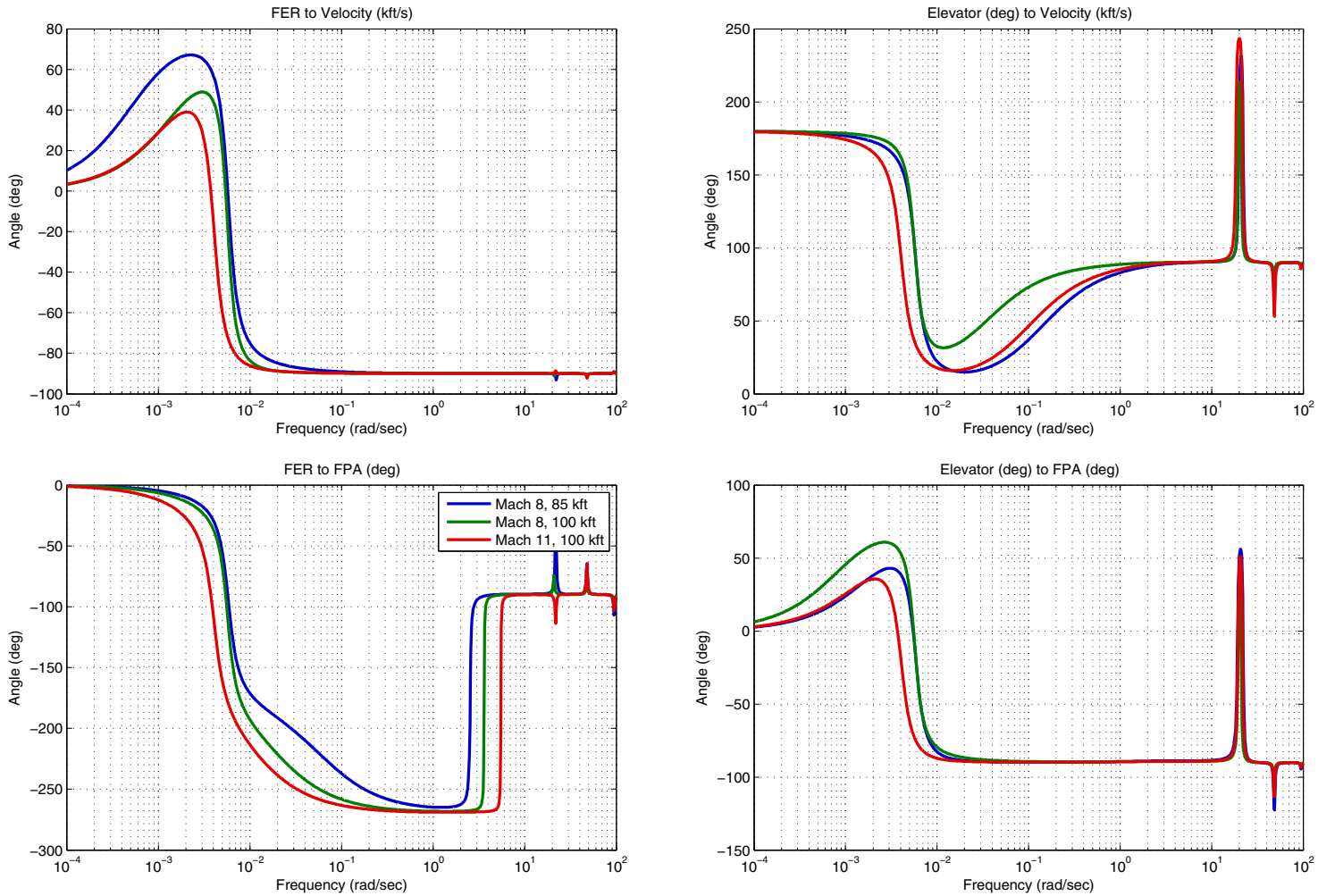


Figure 7: Plant Bode Phase Response, Mach 8, 85 kft: Level Flight, 2 Control Flexible Vehicle

DYNAMIC ANALYSIS: LQR SERVO METHODOLOGY

LQR Servo Methodology

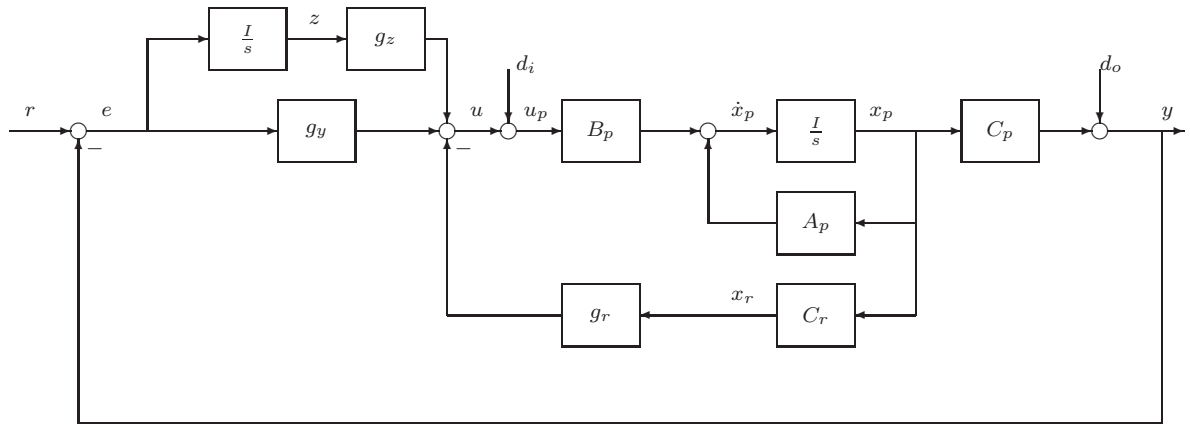


Figure 8: LQ Servo: Adapting LQR Control Law For Reference Command Following

$$\dot{x}_p = A_p x_p + B_p u \qquad y = C_p x_p \tag{1}$$

- $y = [\ v\ \gamma\ ]^T$ is the output vector
- $u = [\ FER\ \delta_e\ ]^T$ is the control vector
- $x_p = [\ y^T\ x_r^T\ ]^T = [\ v\ \gamma\ \alpha\ q\ ]^T$ is the plant state vector
- $x_r = [\ \alpha\ q\ ]^T = [\ 0_{2\times 2}\ \ I_{2\times 2}\ ]x_p = C_r x_p$ denotes the rest of the states in x_p (i.e. states in x_p excluding those in y)

The sensitivities are defined as follows:

Sensitivity @ output ($r \to e$): $S_o = [I + L_o]^{-1}$

Comp. sensitivity @ output ($r \to y$): $T_o = L_o\,[I + L_o]^{-1}$

Open loop @ output ($e \to y$): $L_o = PK$

Input disturbance to output: $S_o P = [I + L_o]^{-1}\,P$

Sensitivity @ input ($d_i \to u_p$): $S_i = [I + L_i]^{-1}$

Comp. sensitivity @ input ($d_i \to u$): $T_i = [I + L_i]^{-1}$

Open loop @ input ($u_p \to u$): $L_i = KP$

Reference to control :$KS_o = K\,[I + L_o]^{-1}$

DYNAMIC ANALYSIS:
CLOSED LOOP SENSITIVITY STUDIES
(Using only δ_e on FPA)

Sensitivity Magnitude Response (Elevator Only)

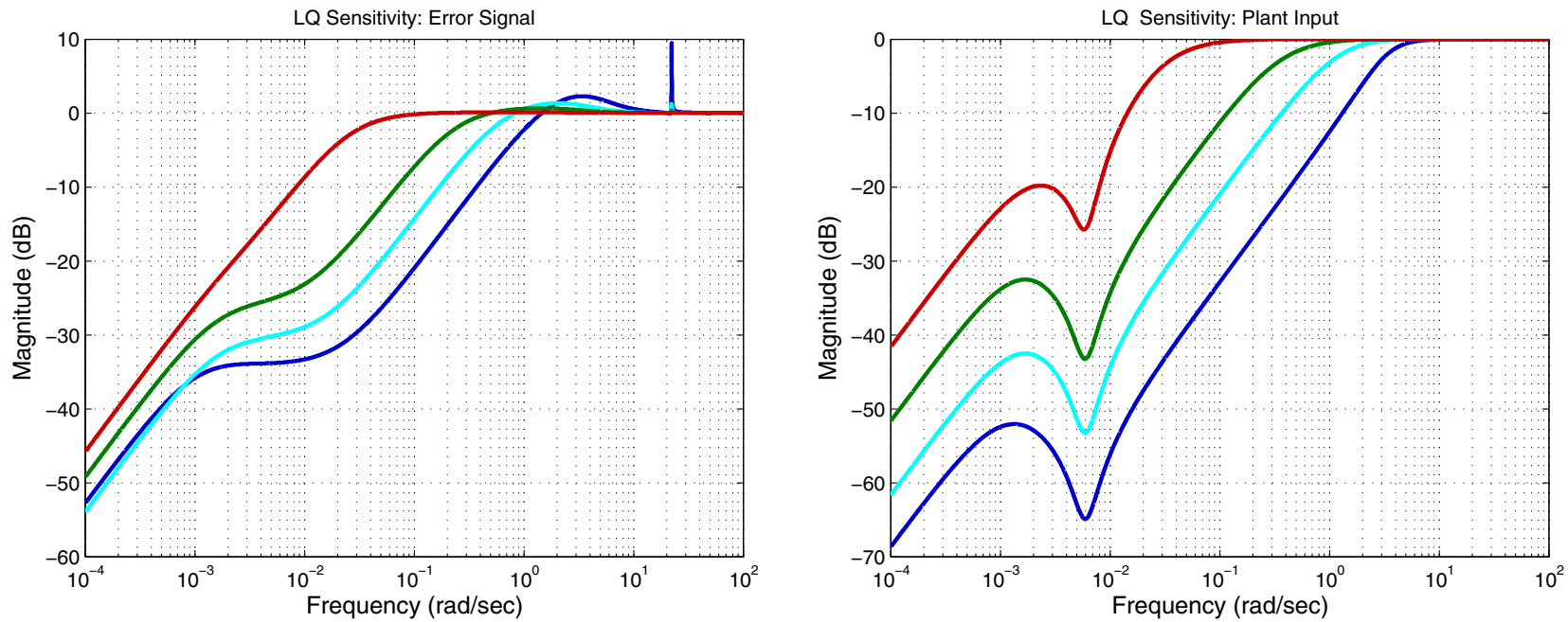


Figure 9: LQR Closed Loop Sensitivity (Mach 8, 85 kft)

- Min BW @ controls T_i, $\omega_g = 6.28$ (~ 2 times the unstable pole)to get $< 10\ dB$ peak in S_o
  - Attempts to decrease BW @ the input yields peaking in S_o before S_i
- Min BW @ error $S_o \approx 0$ given large enough BW @ T_i
- Max BW @ error S_o, $\omega_g = 1.47 \ll$ RHP Zero $= 8.5$
  - Limited by the RHP Zero and low frequency flexible modes ($\sim 20\frac{rad}{s}$)
  - ω_g limited by the simplicity of K, (PI like structure)
  - Adding FER as an input will allow for an increase in ω_g beyond 1.47 (not shown)

Sensitivity Magnitude Response (Elevator Only)

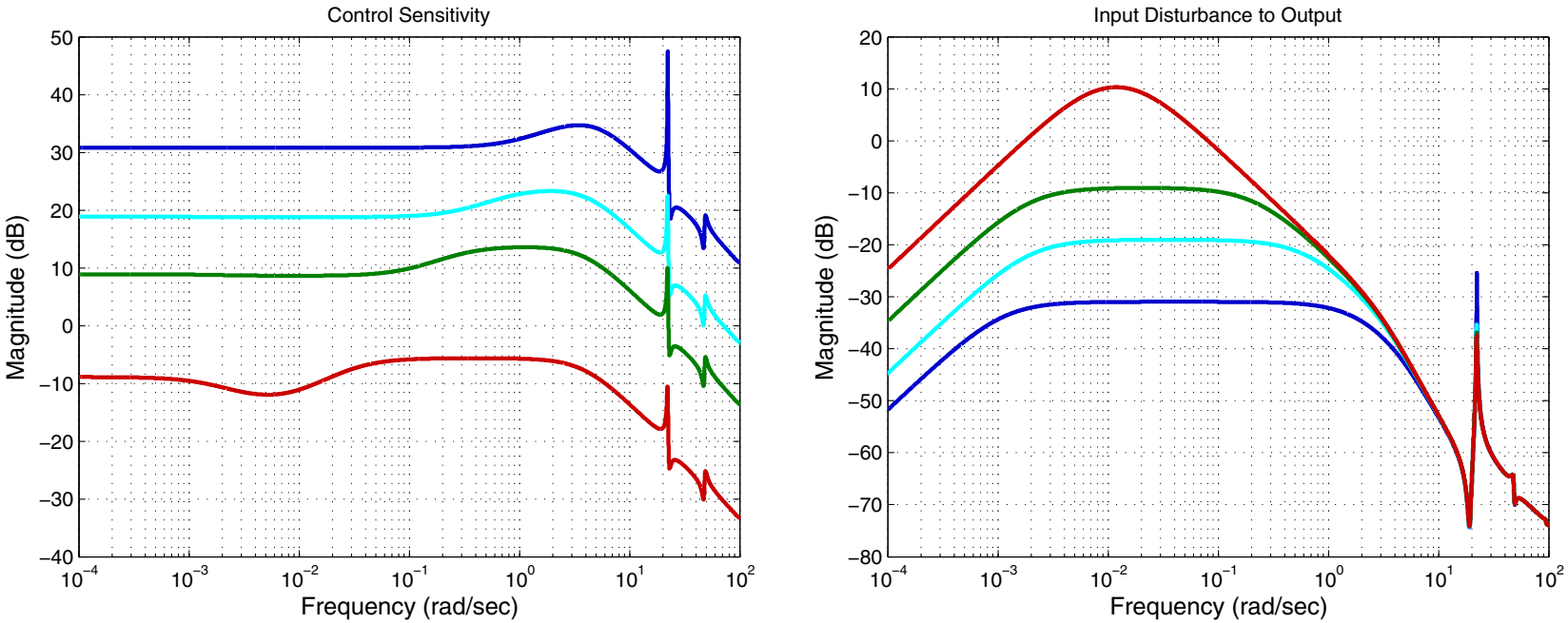


Figure 10: LQR Closed Loop KS_o, S_oP Sensitivity (Mach 8, 85 kft)

- Controls can grow unrealistically large before maximum BW issues are seen
- Minimum BW dictated by 10 dB response in S_oP (input disturbance to plant output)

Sensitivity Magnitude Response (Elevator Only)

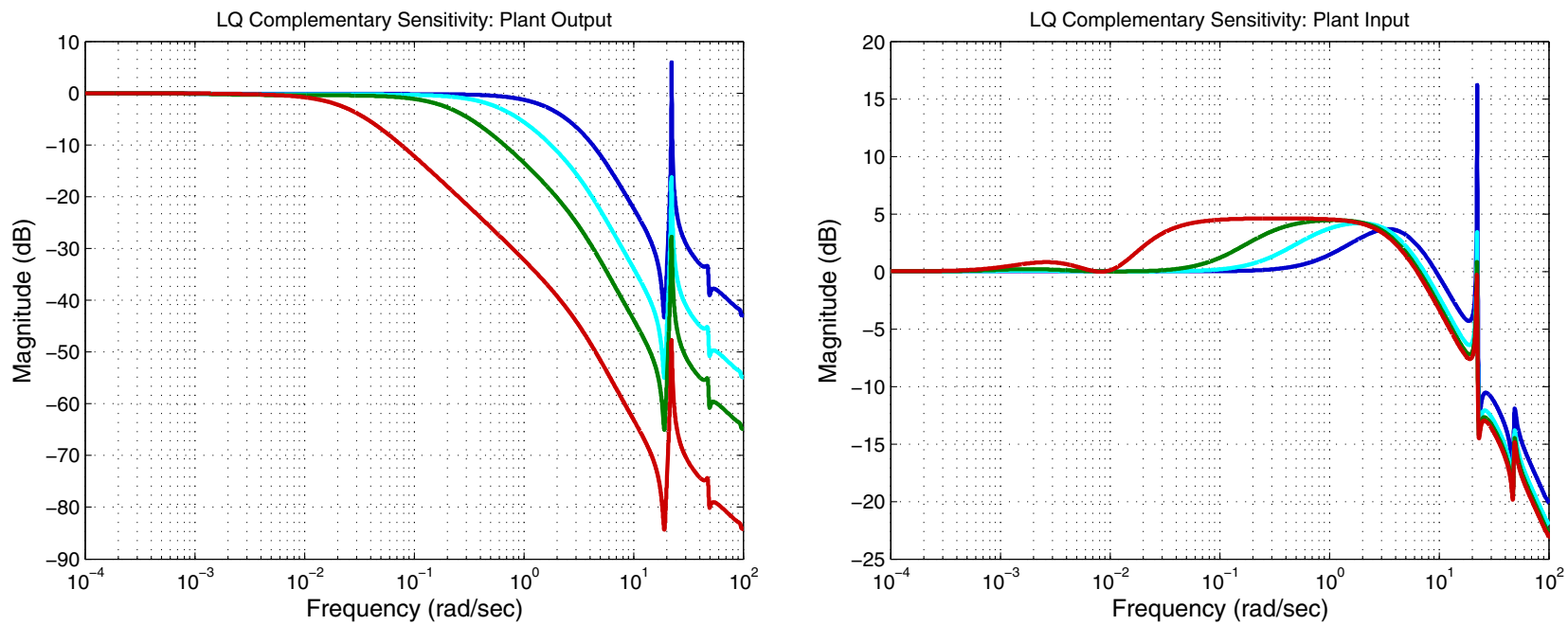


Figure 11: LQR Closed Loop Frequency Response, Complementary Sensitivity (Mach 8, 85 kft)

- Min BW @ controls T_i, $\omega_g = 6.28$ (~ 2 times the unstable pole)to get $< 10\ dB$ peak in S_o
  - Attempts to decrease BW @ the input yields peaking in T_o before T_i

Sensitivity Magnitude Response (Elevator Only)

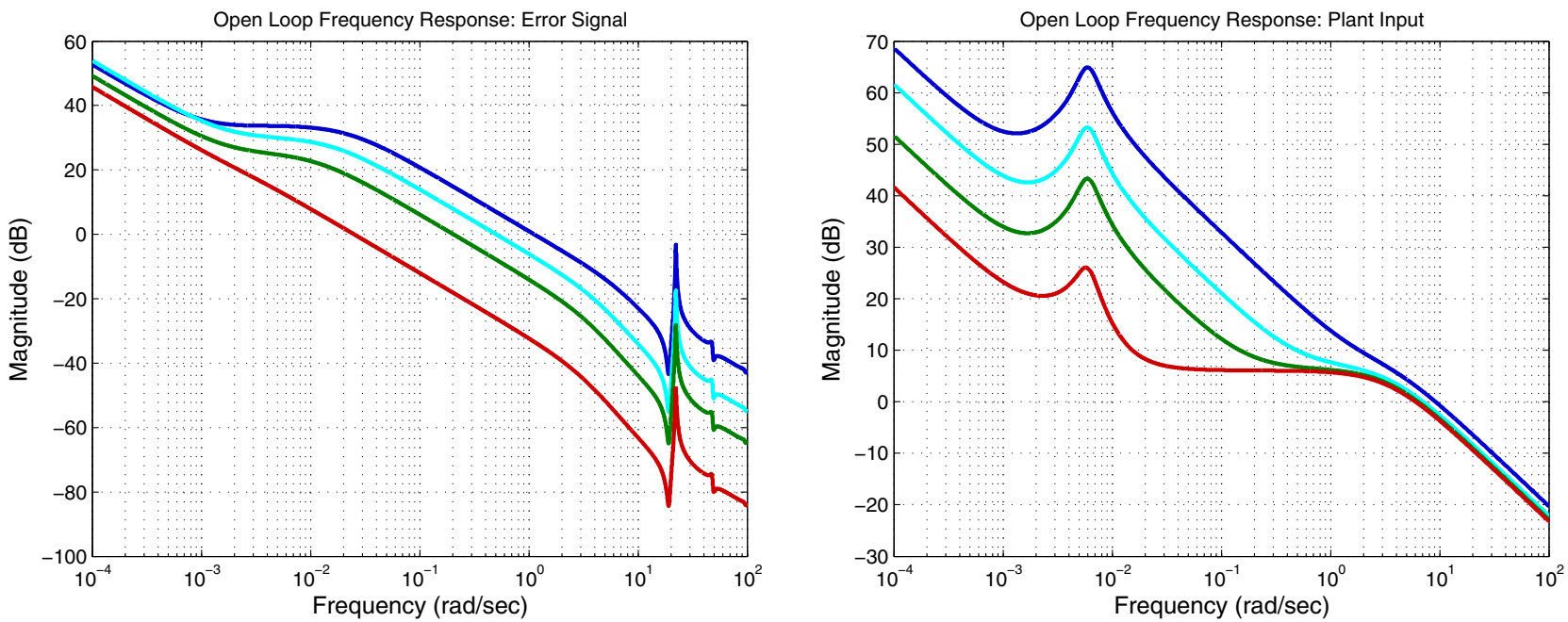


Figure 12: LQR Closed Loop Frequency Response, Open Loop (Mach 8, 85 kft)

- Min BW @ controls L_i, $\omega_g = 5.98$

Time Responses (Elevator Only)

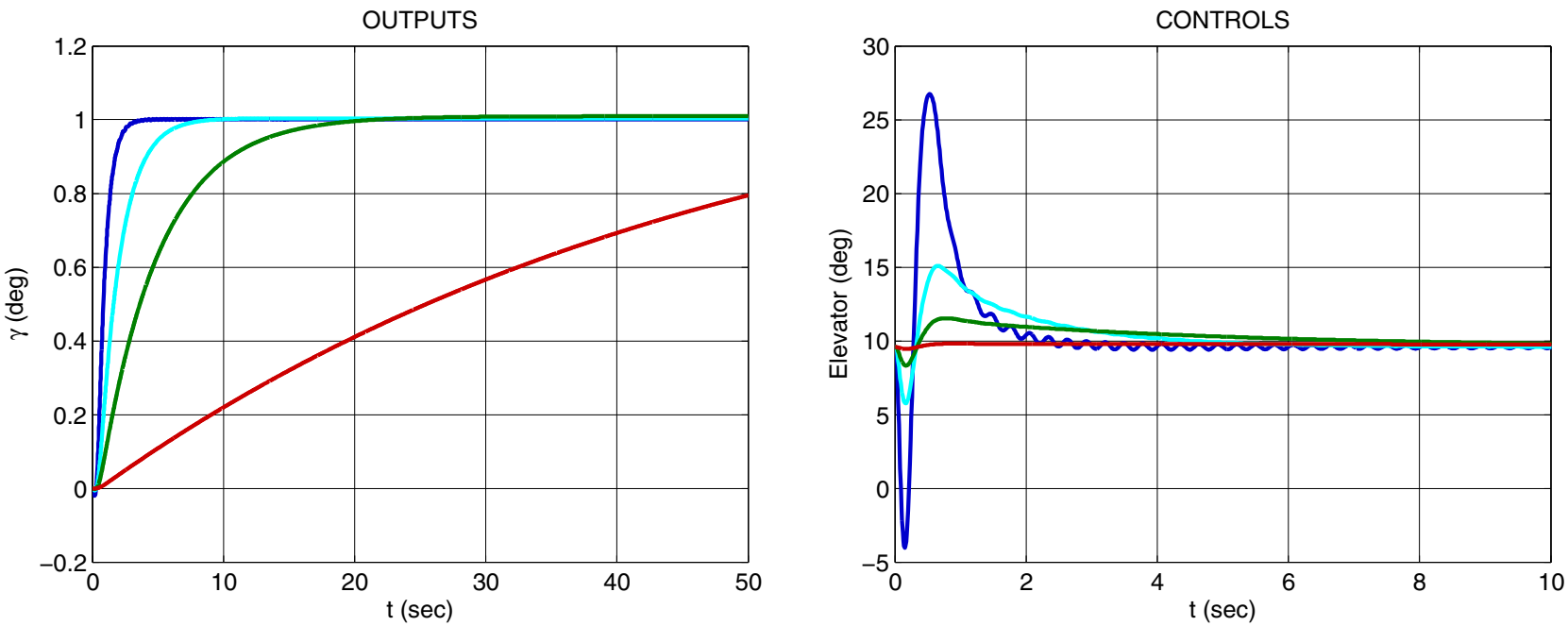


Figure 13: LQR Closed Loop Time Response, Flight Path Angle Command (Mach 8, 85 kft)

- Slowest BW design settles in 360 seconds (not shown)
- Fastest BW design begins to excite flexible modes as seen in the control response
- Fastest BW design settles in 2.15 seconds

DYNAMIC ANALYSIS:
CLOSED LOOP LQR
TWO INPUT, TWO OUTPUT (TITO)

Time Response (TITO System)

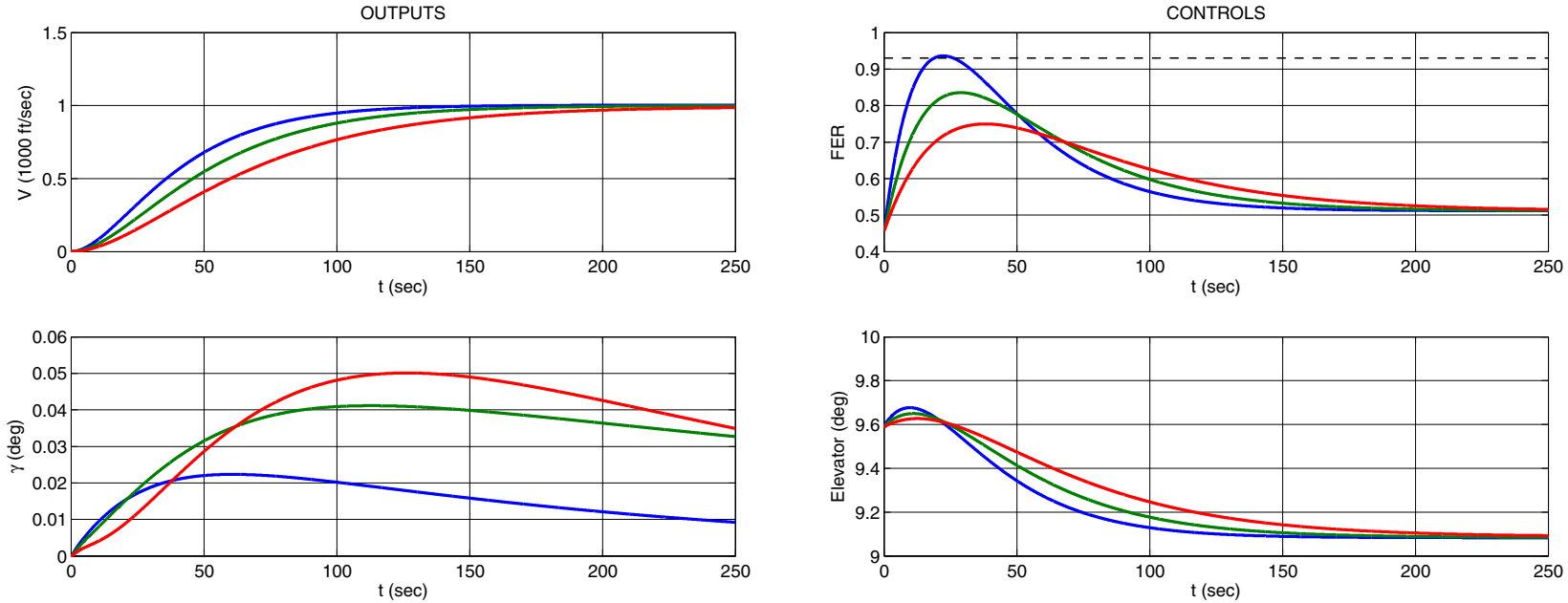


Figure 14: LQR Closed Loop Time Response, Velocity Command (Mach 8, 85 kft)

- Output and control response to velocity commands for the three designs (referred to as fast, nominal, slow)
- Control responses show equilibrium control + small signal control
- Thermal choking occurs at FER = 0.92 (for a turning angle equal to the trim turning angle)
- As the controller bandwidth increases, the transient values of the FER control increases
- Transient responses for the elevator are similar for all three designs

Time Response (TITO System)

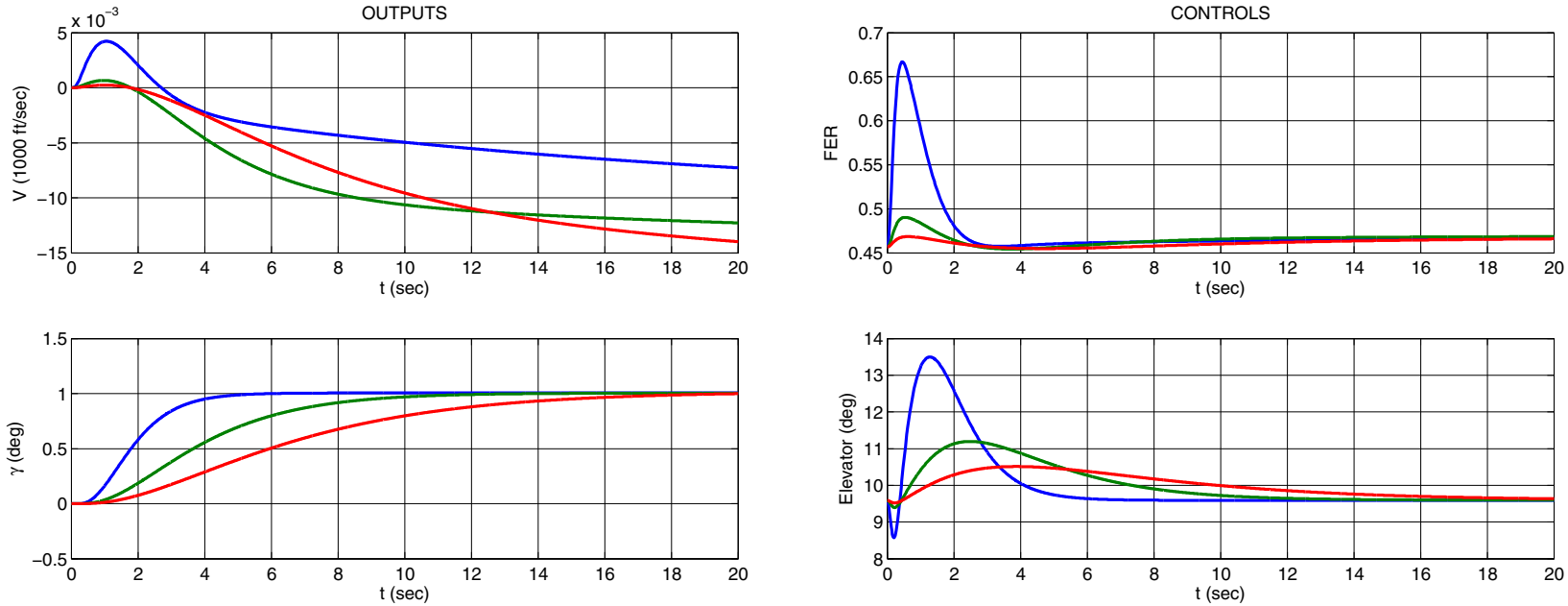


Figure 15: LQR Closed Loop Time Response, Gamma Command (Mach 8, 85 kft)

- Output and control response to flight path angle commands for the three designs
- For the slow and nominal designs, the elevator deflection transient increases while the FER transient remains small
- As the controller bandwidth is further increased, a noticeable jump in the FER transient is observed

Singular Value Response (TITO System)

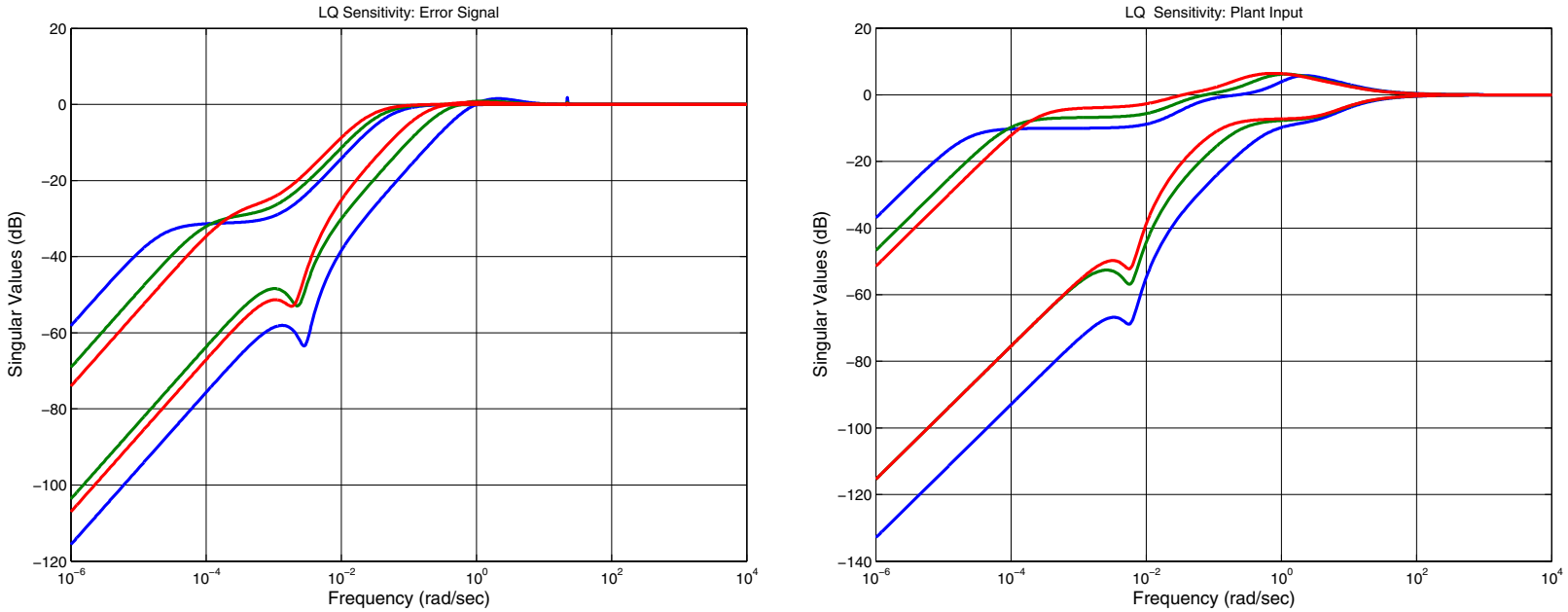


Figure 16: LQR Frequency Response, Sensitivity at Error Signal (Mach 8, 85 kft)

- Sensitivity at the input and output
- The maximum sensitivity is located at 1 rad/s and has a value of 2.5 dB for fast design, and 0.5 dB for the slow design

Singular Value Response (TITO System)

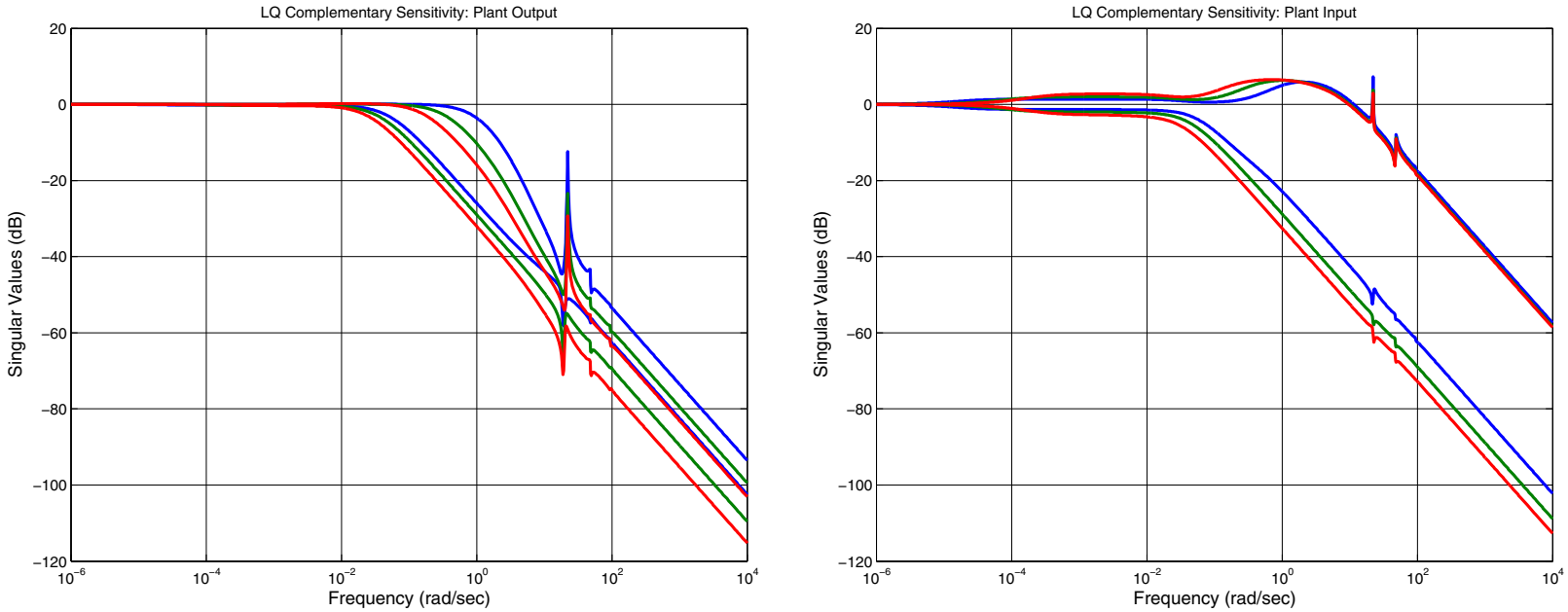


Figure 17: LQR Frequency Response, Sensitivity at Error Signal (Mach 8, 85 kft)

- Complentary sensitivity at the input and output
- The maximum sensitivity at the input is located at 1 rad/s and has a value of 5.98 dB for all 3 designs design

Singular Value Response (TITO System)

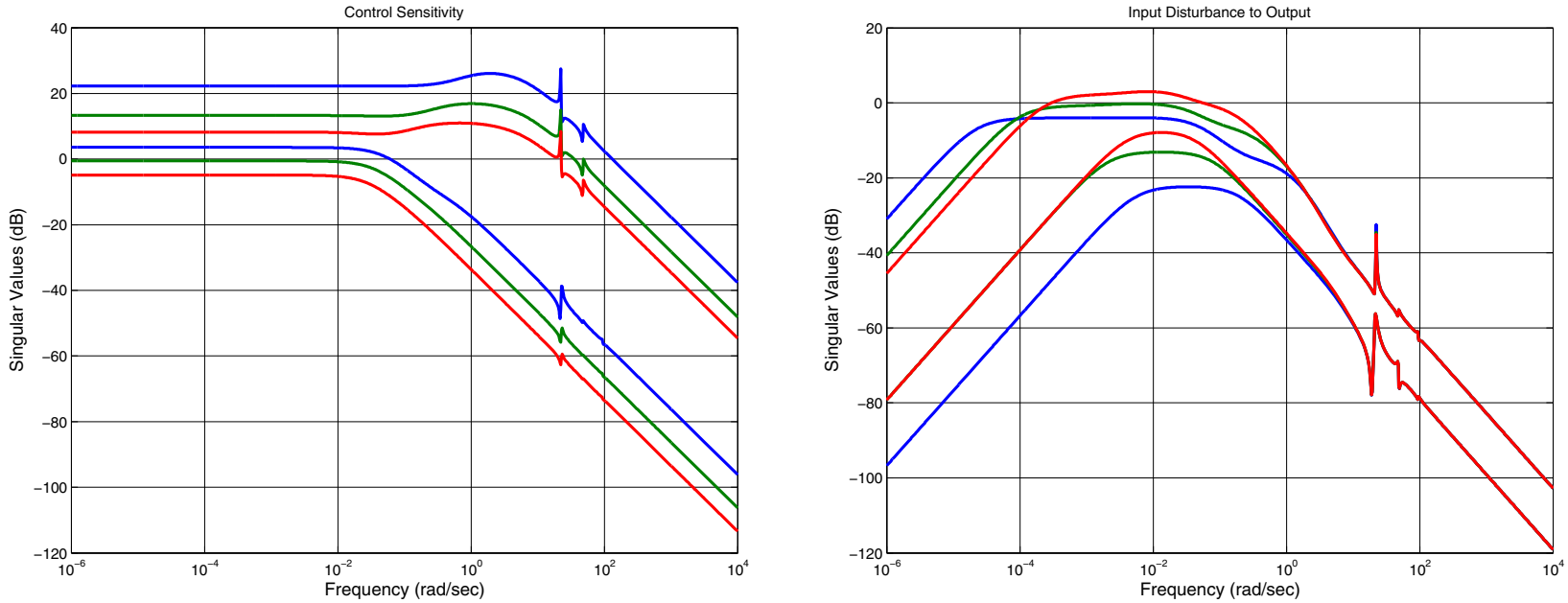
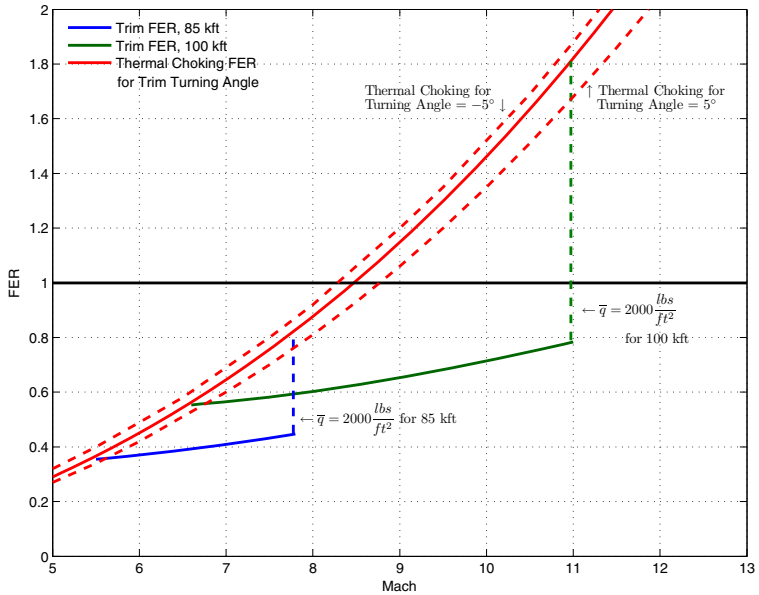


Figure 18: LQR Frequency Response, Control Sensitivity and Input Disturbance to Output (Mach 8, 85 kft)

- Control sensitivity and input disturbance to output properties for the closed loop response
- Control sensitivity values increase with increasing controller bandwidth
- Input disturbance rejection properties improve as controller bandwidth is increased

NONLINEAR ISSUES: FER MARGIN

FER Margin



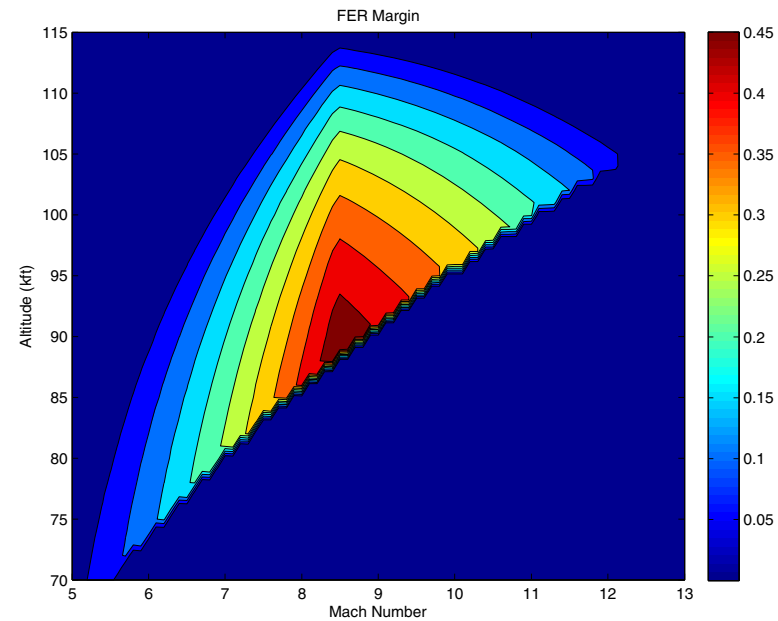


Figure 19: FER for Trim and Thermal Choking: Level Flight, Unsteady-Viscous Flow, 2 Control Flexible Vehicle

- Thermal Choking FER Margin

$$FERM_{TC} = Thermal\ Choking\ FER - Trim\ FER$$

- Thermal Choking FER almost independent of altitude (not shown) for the above Mach ranges.
- Unity FER Margin

$$FERM_{Unity} = 1 - Trim\ FER$$

- <u>$FERM_{TC}$ decreases with decreasing Mach, increasing flow turn angle, decreasing altitude</u>
- <u>$FERM_{Unity}$ decreases with increasing mach & altitude</u>

$$FER\ Margin = min(FERM_{TC}, FERM_{Unity})$$

- $(\frac{L}{D})_{max}$ at Mach 6.6, 100 kft, but results in FER Margin = 0!!!

NONLINEAR SIMULATIONS: GENERALIZED PREDICTIVE CONTROL

GPC Time Response

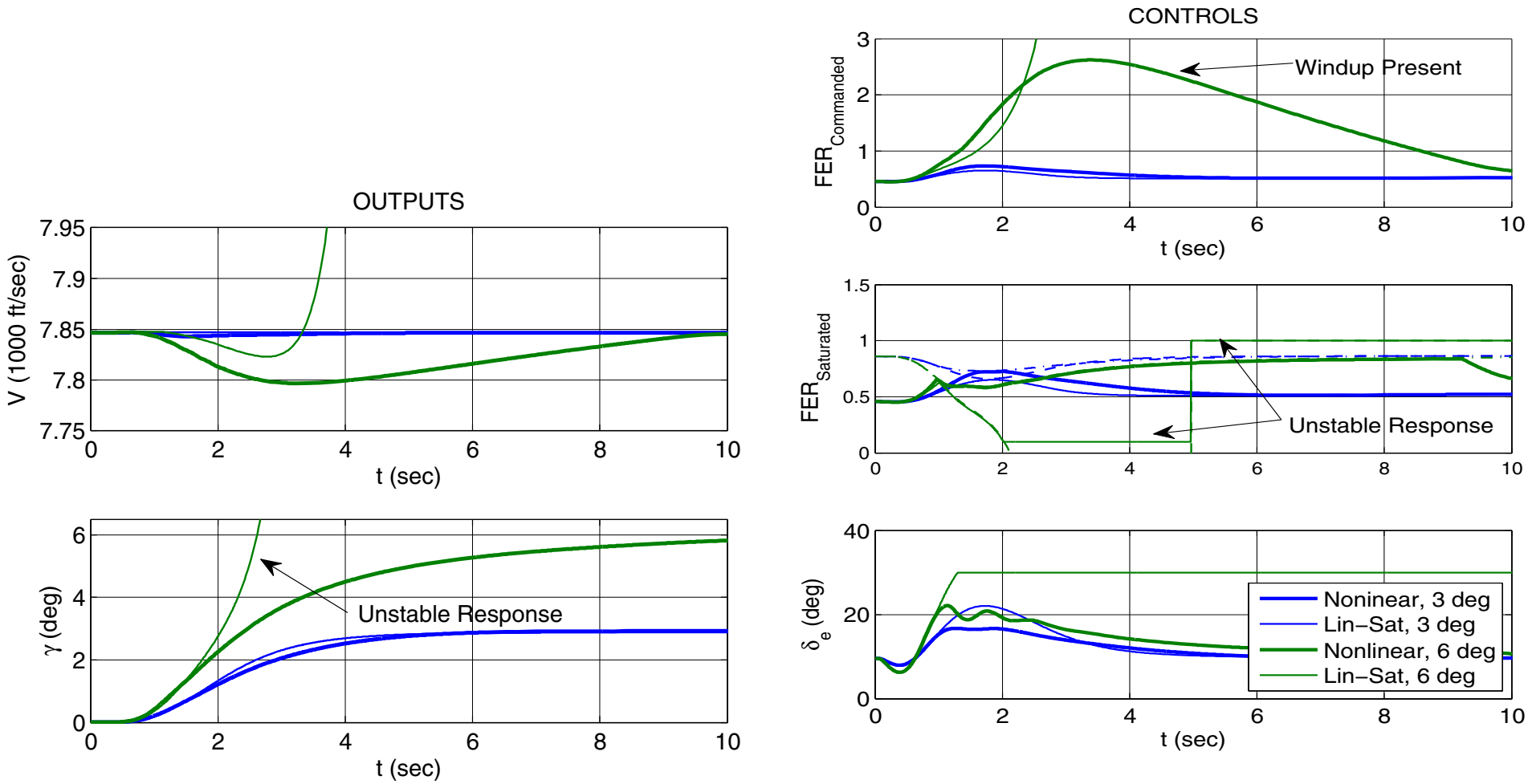


Figure 20: Nonlinear and Lin-Sat Responses to 3°, 6° FPA Commands - No Constraint Enforcement

- Nonlinear and lin-sat responses
- No constraint enforcement is included
- For the large FPA commands, the lin-sat responses go unstable while the nonlinear responses do not go unstable.

GPC Time Response

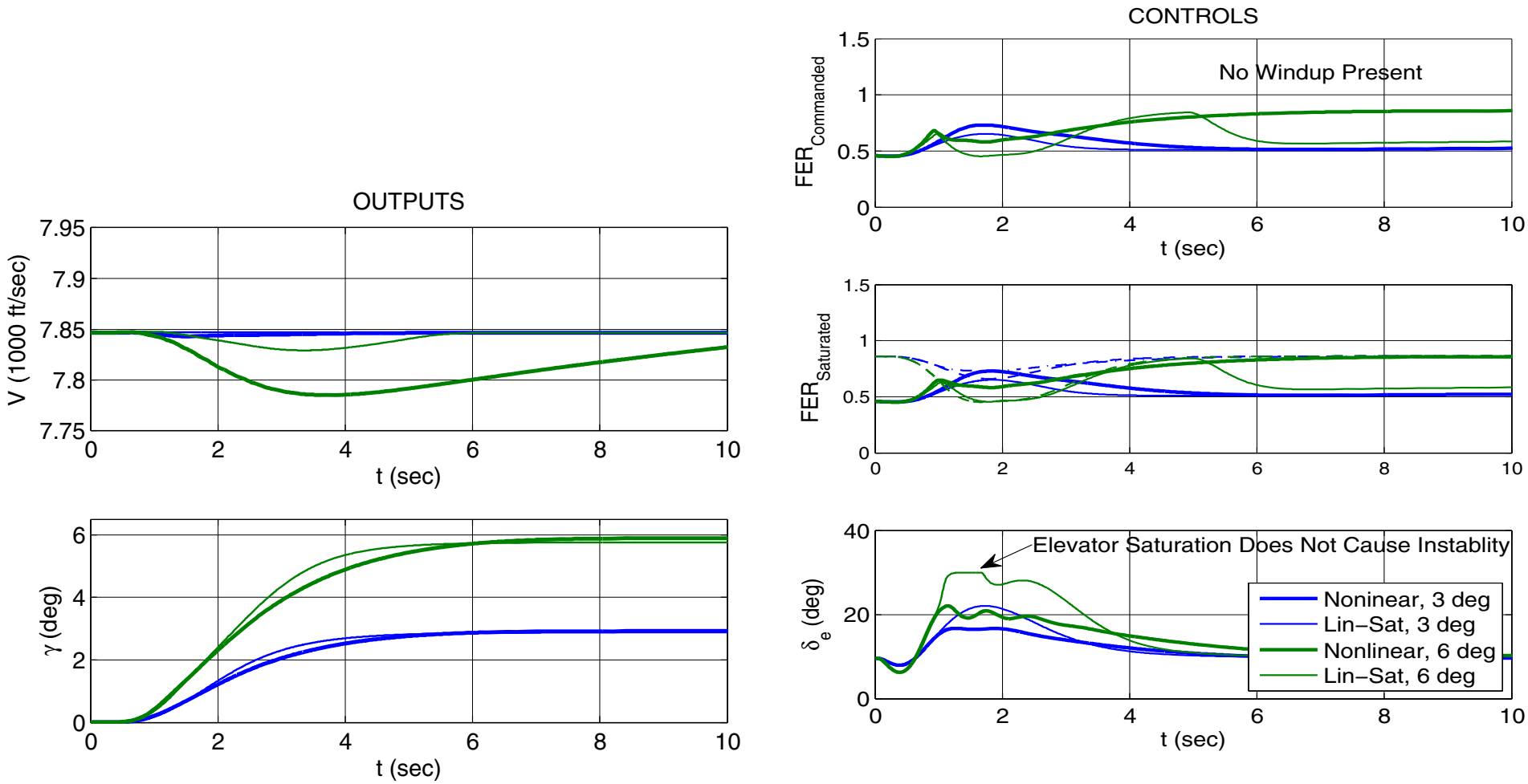


Figure 21: Nonlinear and Lin-Sat Responses to 3°, 6° FPA Commands - With Constraint Enforcement

- Nonlinear and lin-sat responses
- Constraint enforcement included
- Lin-sat response no longer unstable

GPC Time Response

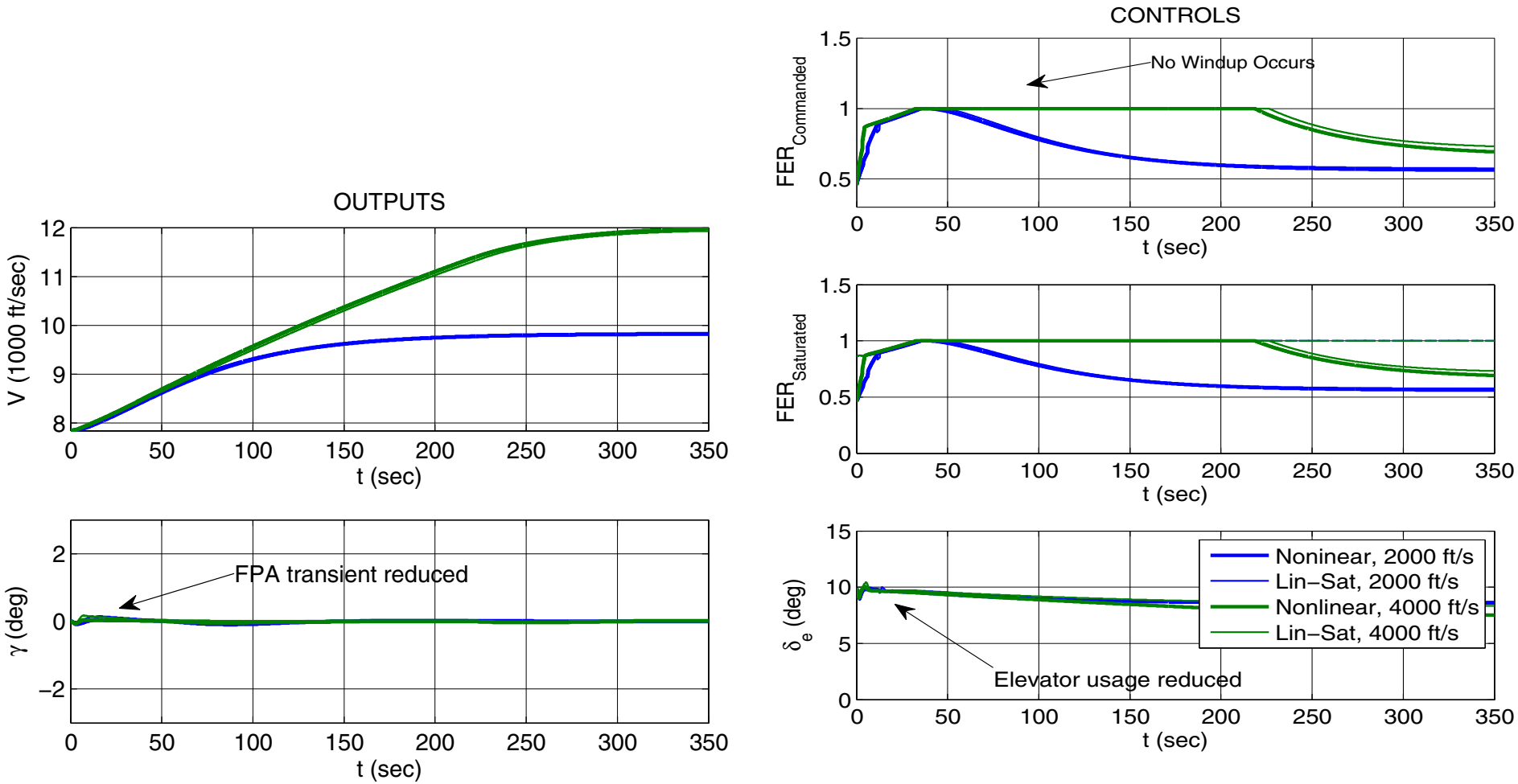


Figure 22: Nonlinear and Lin-Sat Responses to 2000, 4000 ft/s Velocity Commands - With Constraint Enforcement

- Nonlinear and lin-sat responses
- Constraint enforcement included
- FER is observed to hit and stay at the rails - resulting in maximum acceleration.

Summary and Conclusion

Trim (Static) Properties

- Trimmable Region: ∼Mach 5-12, 70-115 kft
- Show importance of FER Margin and how it depends on mach, altitude, flow turning angle (AOA+forebody deflection).
  $FERM_{TC}$ decreases with decreasing Mach, increasing altitude, increasing FTA (AOA+forebody deflection).
  $FERM_{unity}$ decreases with increasing Mach, increasing altitude (independent FTA).

Dynamic Properties

- More unstable at lower altitudes and higher Machs
- Instability (and poles) invariant along constant dynamic pressure profiles

Control Design Tradeoffs (LQR)

- While state feedback can be used to eliminate minimum BW constraint at error, acceptable command following and disturbance attenuation requirements require a minimum BW (at error); also, still require minimum BW at controls
- FPA BW limited by RHP zero (inverse response) effects and flexible dynamics
  - Elevator+FER allows for decrease in FPA settling time by 3% (5.15 sec to 5.0 sec)
  - Elevator+canard (no FER) allows for 23% decrease (5.15 sec to 3.97 sec)...but canard may burn off!
- FPA robustness with respect to uncertainty in flexibility
  - Elevator alone allows for 11.2% decrease in flexility (EI) before instability
  - Elevator+FER allows for 17.1% decrease in flexibility (52% improvement)
  - Elevator+FER+canard allows for 19.5% decrease of flexibility

Nonlinear Issues

- FER Margin limits controller BW and/or reference command magnitudes (mainly velocity; FPA to much lesser extant)
- Elevator saturation can induce instability for large controller BW/reference FPA command magnitudes
  - constraint enforcement methodologies needed to ensure stability and best possible tracking