Modeling &Control of Launch Vehicles

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Outline

- ❑ **ISRO Missions**
- ❑ **ISRO Launch Vehicles**
  - Structure Configuration (PSLV / GSLV / RLV)
  - Propulsion Configuration
  - Aerodynamics
  - Actuation Systems
  - Navigation systems
  - Trajectory Design – Guidance & Control
- ❑ **Digital Auto-Pilot (DAP)**
  - Inputs for design
  - Design problem
  - Design specification
  - Design methodology
  - Control Configuration
- ❑ **Launch Vehicle Modelling**
  - ❑ Input Data
  - ❑ Assumptions
  - ❑ Rigid Body rotational dynamics
  - ❑ Slosh
  - ❑ Flexibility

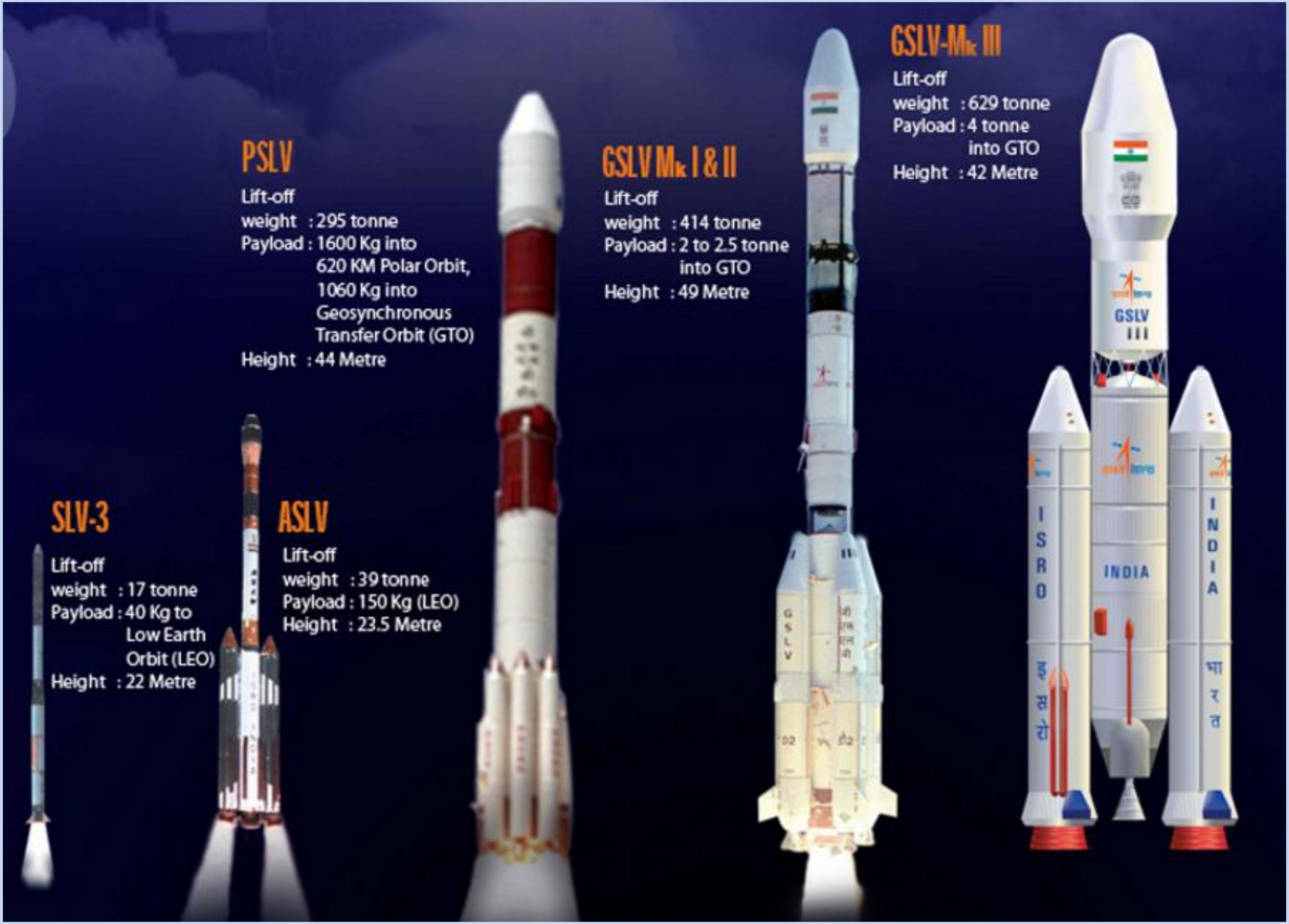
Outline

- **RLV-TD (HEX) Mission**
  - Mission profile
  - Different phase during descent
  - RLV-TD dynamics
- **Non-linear Control**
- **Design parameters**
- **Implementation aspect**
- **Control design & validation philosophy**
- **Post flight analysis**
- **Challenges in design**

ISRO Missions

- **Sun Synchronous Polar Orbit (SSPO)**
- **Eastward Missions – GTO**
  - Elliptical Orbits(Moon Mission/Mars Mission)
- **Space Capsule Recovery**
- **RLV – Technology Demonstrator**

ISRO Launch Vehicles



SLV-3

Lift-off
weight : 17 tonne
Payload : 40 Kg to
Low Earth
Orbit (LEO)
Height : 22 Metre

ASLV

Lift-off
weight : 39 tonne
Payload : 150 Kg (LEO)
Height : 23.5 Metre

PSLV

Lift-off
weight : 295 tonne
Payload : 1600 Kg into
620 KM Polar Orbit,
1060 Kg into
Geosynchronous
Transfer Orbit (GTO)
Height : 44 Metre

GSLV Mk I & II

Lift-off
weight : 414 tonne
Payload : 2 to 2.5 tonne
into GTO
Height : 49 Metre

GSLV-Mk III

Lift-off
weight : 629 tonne
Payload : 4 tonne
into GTO
Height : 42 Metre

PSLV Configuration

Heat Shield

Satellite

PS4 stage

PS3 Stage

PS2 Stage

PS1 stage

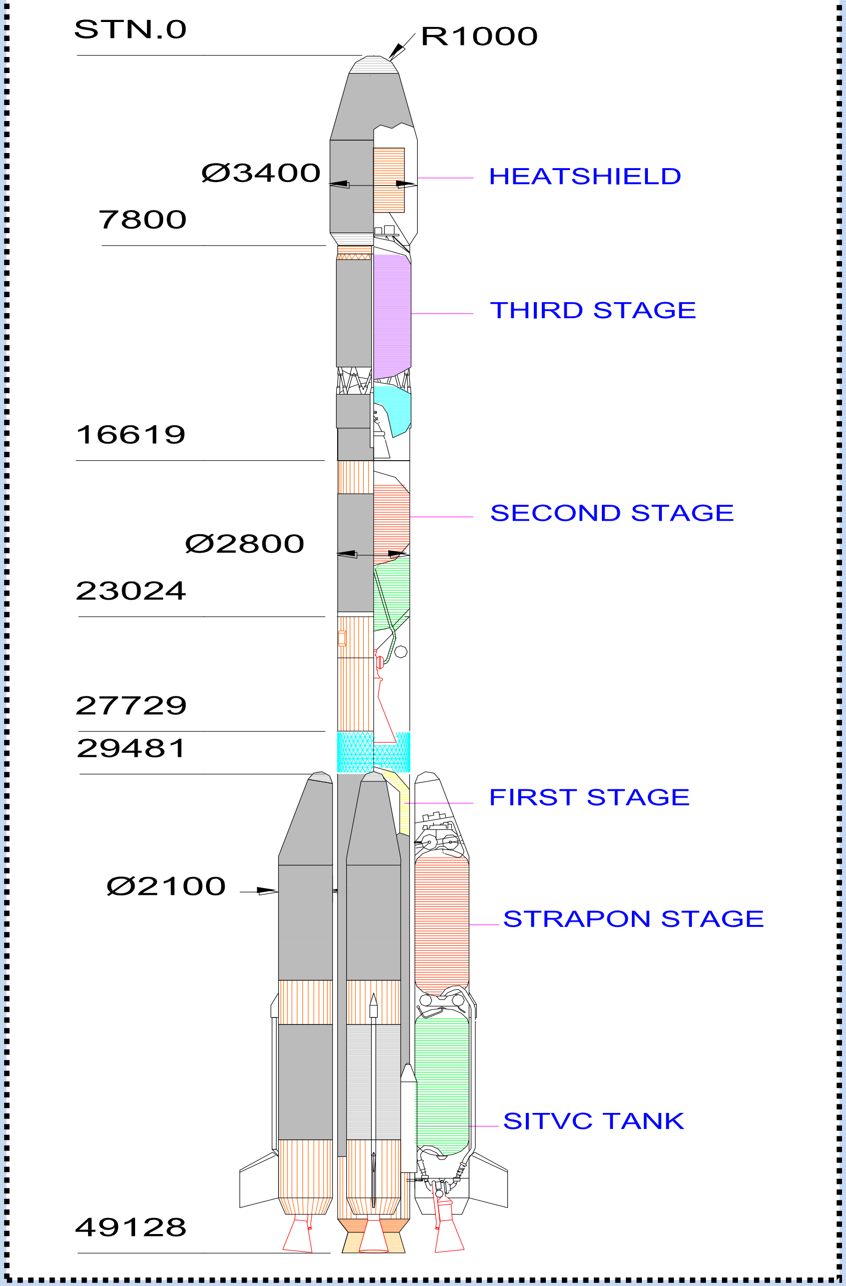
Strapons

SITVC tank

- ❖ Sensors
  - ➢ Inertial navigation system
  - ➢ Gyros(Attitude)
  - ➢ Accelerometers

- ❖ Actuators
  - ➢ SITVC
    (Secondary injection Thrust Vector Control)
  - ➢ Engine Gimbal Control
  - ➢ Flex Nozzle control

GSLV-MK2 Configuration



Definition
(4L40+S139)+L37.5+C12.5

Specification	
Overall length	**: 49.128 m**
Lift off Mass	**: 401.8 t**
GTO payload	**: 1600 kg**

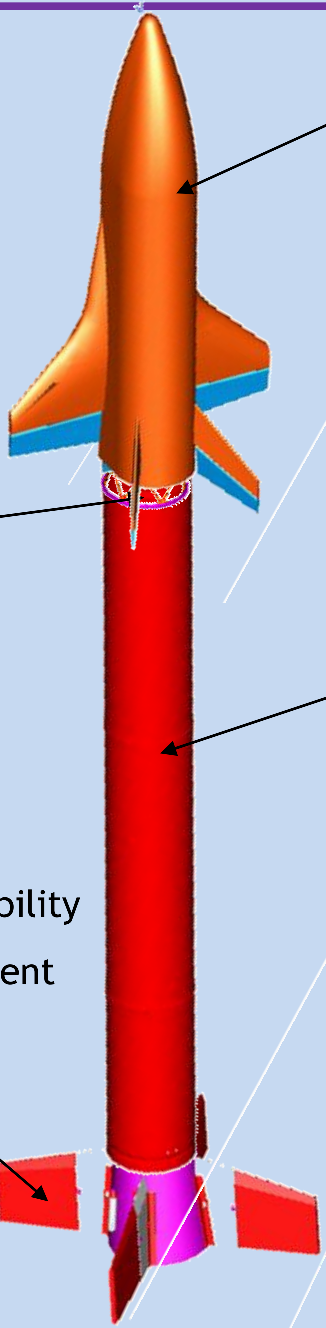
Sensors : RESINS at EB ,

RGP at ½ M

Actuators: EGC(L40)
EGC(L37.5),

CSCE, OSS

RLV-TD HEX-1 Vehicle Configuration



TDV

Experiment : 70 to 0

Mach No. : 6 to 0

Interstage to connect TDV with Booster

Booster to achieve required flight condition

HS9 Booster : 9T Propellant loading

Diameter : 1m

Base Shroud with Fins

To reduce aerodynamic instability

To provide control during ascent phase

Propulsion/Configuration

SLV-3: Core (S9) **+ 2nd stage solid + 3rd stage solid**

ASLV: Core (S9) **+ 2 Strapons (S9) + Solid Upper Stage**

PSLV: Core S139 (Solid) + 6 Strapons + PS2 (L37.5) + PS3 (Solid) + PS4 (L2.5)

GSLV: Core S139 (Solid) + 4 L40 + Cryo (C12)

Mk3: Core S200 (Solid) + 2 L110 + Cryo (C25)

RLV: Core + TDV (No Propulsion)

Aerodynamics

- **SLV-3:** **Core with Fins**
- **ASLV:** **Core with 2 Strapons in 1st stage**
- **PSLV:** **Core alone & (Core + 6 Strapons)**
- **GSLV:** **Core + 4 liquid Strapons**

Actuation Systems :Thrust Vector Control

- **SITVC (Secondary Injected Thrust Vector Control)**
- **Engine Gimbal Control**
- **Flex Nozzle Control**
- **Vernier Engine Control**
- **Reaction Control System (On-Off Control)**
- **Aerodynamic Surfaces**

Navigation System

- ❖ **RESINS:** Redundant Strap-down Inertial Navigation System
- ❖ **RGP:** Rate Gyro Package
- ❖ **LAP:** Lateral Accelerometer Package

Trajectory Design – Guidance & Control

Guidance : Point Mass Trajectory

- Maximizing the payload

  Atmospheric Phase Flight
- Dynamic Pressure Curve
- Structural Loads
- Heating Constraints
- Range Safety

Control:

Attitude Dynamics

Launch Vehicle (Pitch/Yaw/Roll) –

- Rigid Body
- Slosh
- Flexibility
- Engine dynamics (Actuator + Nozzle)

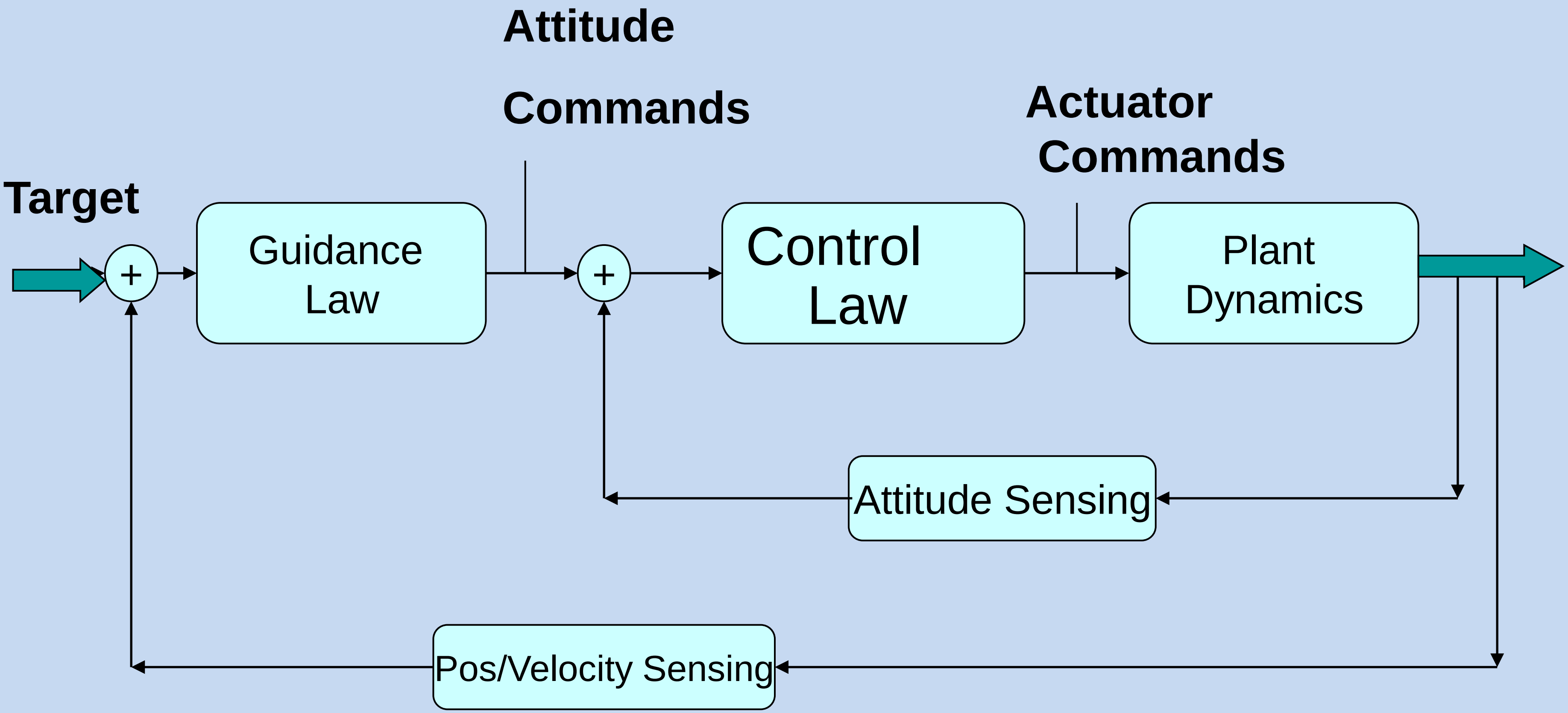
RLV-

- Longitudinal Dynamics
- Lateral/ Directional

Digital Auto-Pilot (DAP)

- Launch Vehicle Autopilot is an inner loop of the Navigation, Guidance and Control (NGC) subsystem.
- Controls the Attitude of the vehicle in Pitch, Yaw and Roll channels from lift-off till end of flight.
- It ensures the stabilisation of the attitude in the presence of disturbing forces and moments caused by various sources.
- Steers the vehicle along a desired trajectory, maintaining the structural integrity.

Navigation Guidance and Control Loop



Attitude

Commands

Actuator

Commands

Target

+

Guidance Law

+

Control Law

Plant Dynamics

Attitude Sensing

Pos/Velocity Sensing

Inputs for the Design

- **Model of the System** to be controlled

  Plant : Rigid body, Flexibility, Slosh Dynamics
  Actuators : SITVC, EGS, FNC, RCS
  Sensors : RGP,RESINS, LAP

- **Disturbances**

  Thrust misalignment, CG offset, Differential Thrust, Winds

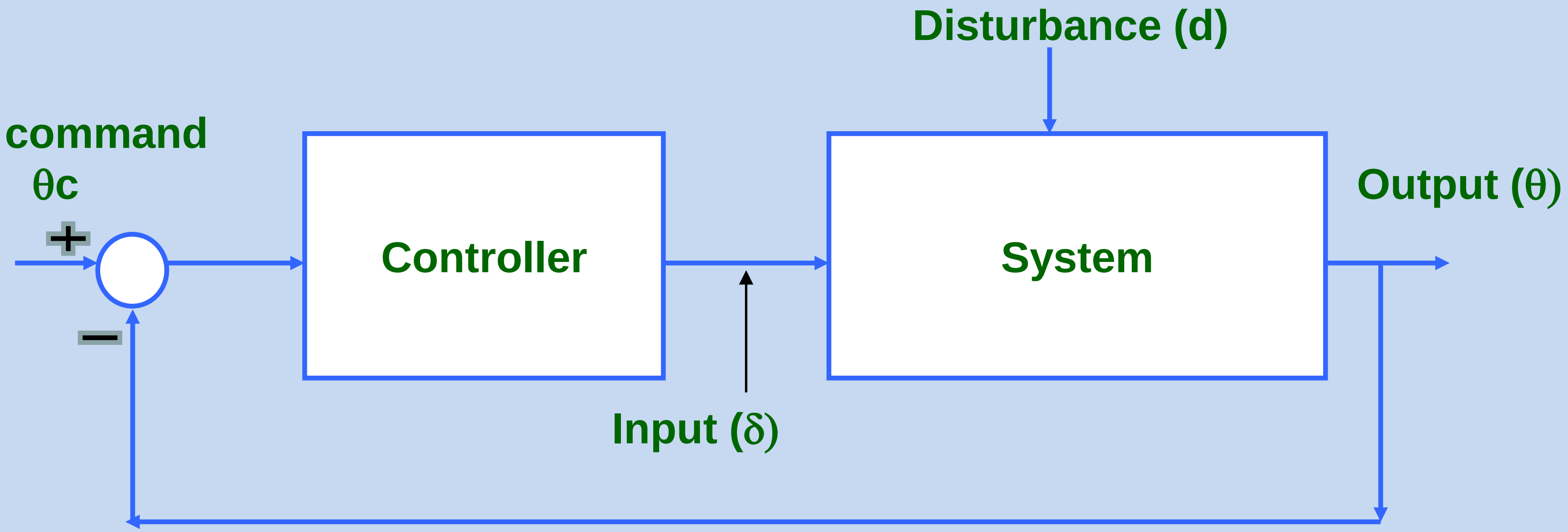
- **Tracking Commands**

  Generated by Guidance Law

- **Specifications**

Design Problem

- Behavior of the output in presence of the disturbance may not be satisfactory
- Controller has to ensure satisfactory response of the system rejecting the disturbance
- System will be modeled by using differential equations
- The controller will process the input signal to achieve satisfactory output.



Disturbance (d)

command

θc

+

−

Controller

Input (δ)

System

Output (θ)

Design Specifications

- **Primary Specification-**

  Tracing Error < 1 Degree

- **Robustness Specifications**

➢ **Rigid body**

Aero margin > 6 dB

Phase margin > 30 Degree

Gain margin > 6 dB

➢ **Bending modes**

Phase Margin > 40 Deg. : ***Phase Stabilisation***

Attend. margin > 6 dB : ***Gain Stabilisation***

➢ **Slosh modes**

Phase margin > 30 Degree

Design Methodology

- **Classical Design Technique**

  Tracking Error Specification -
  Bandwidth / Damping
  Gain Design- PID

- **Frequency Domain Design**

  Roll off, Notch, Lag-Lead filter

- **Analysis using –**

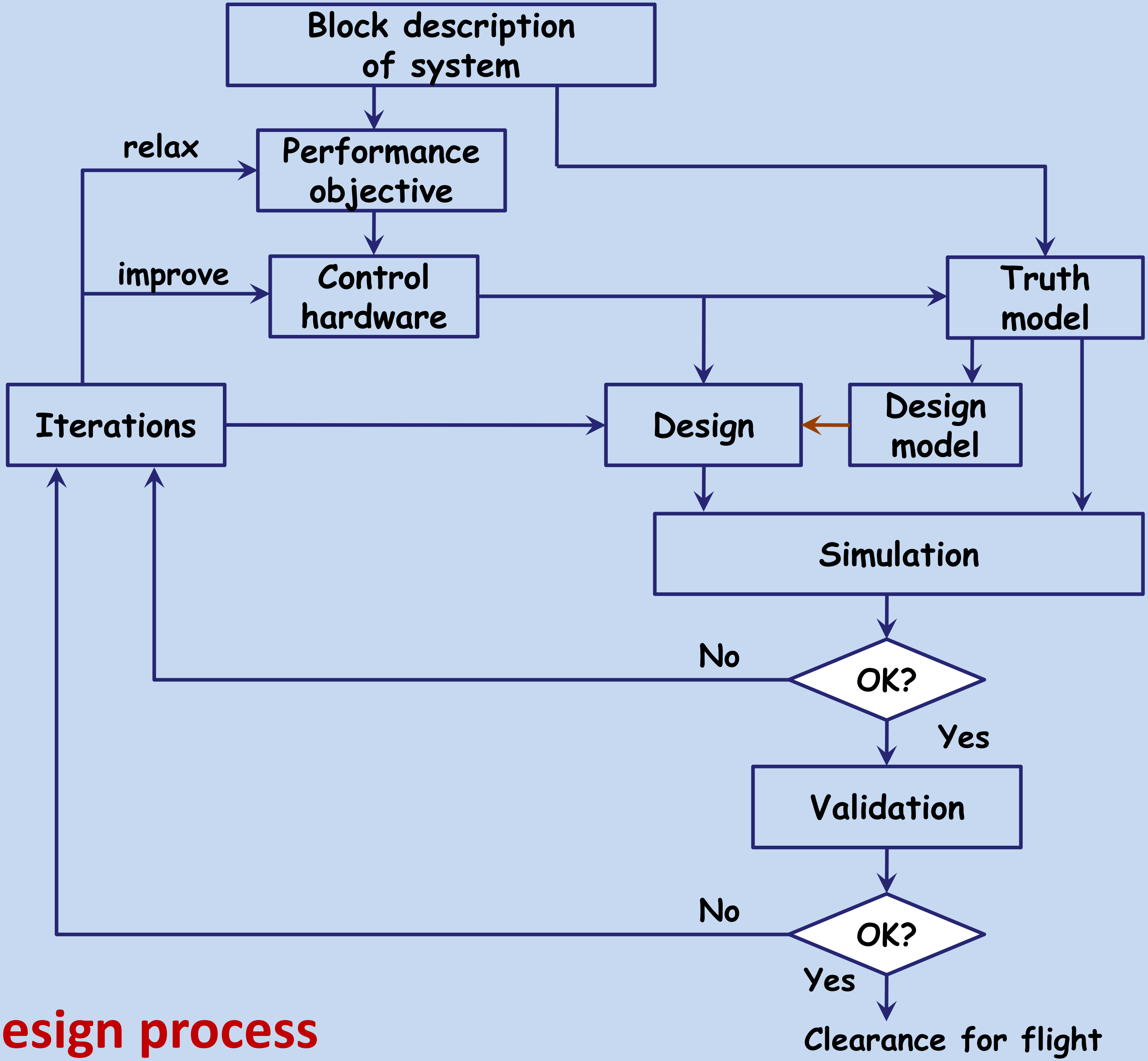
  Root Locus, Bode plot, Nyquist plot

Control Configuration

- **Control Power Plant**
  - Physical Location / Alignment
  - Control Force / Moment
  - Dynamics
- **Sensors**
  - Placement
  - Dynamics
- **Baffles**
  - Placement
  - Characteristics

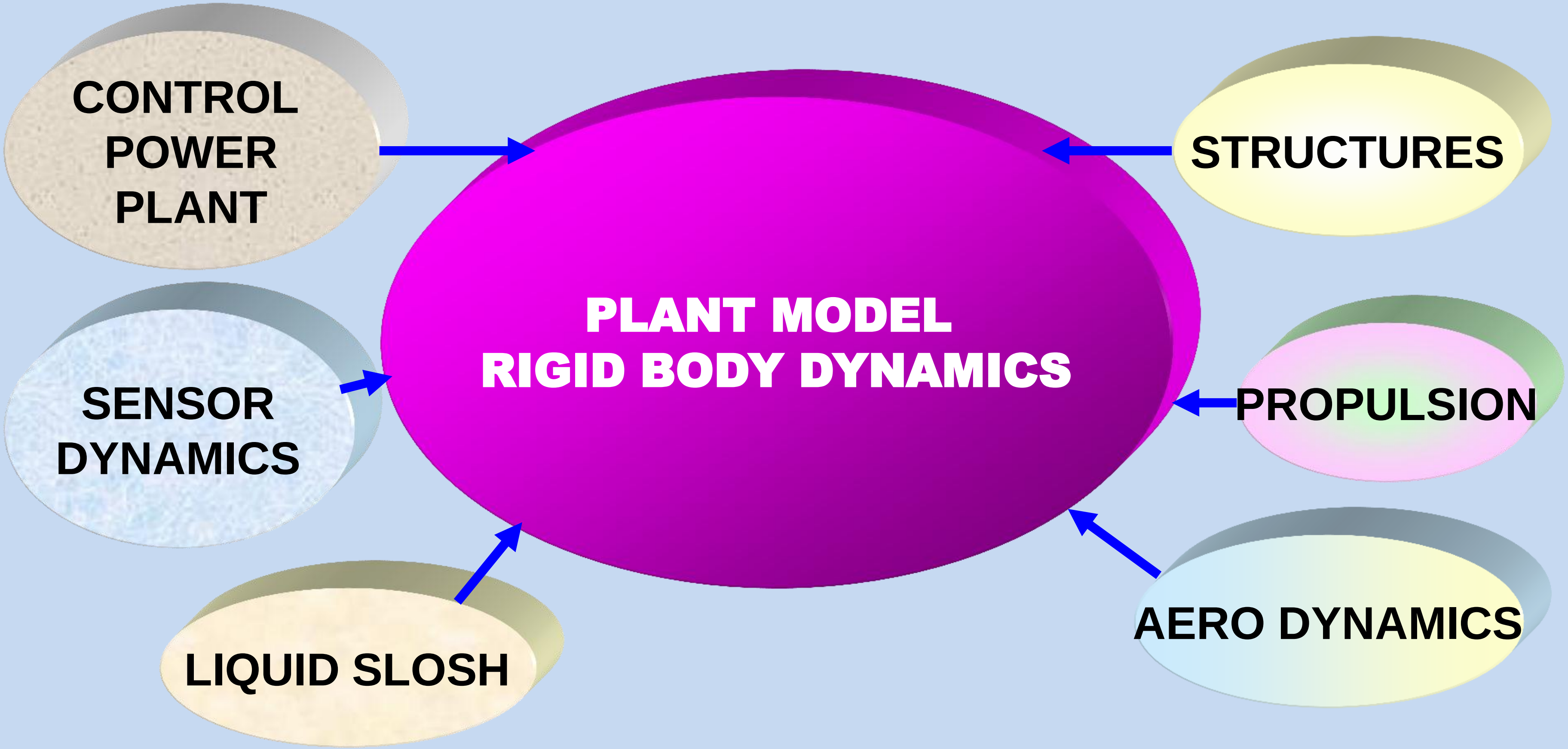
Design and development of Autopilot consists following important elements.

i). Mathematical model of vehicle dynamics
ii). Design to meet specifications
iii). On-board implementation of Autopilot Algorithm
iv). Validation



Control design process

LAUNCH VEHICLE MODELLING



PLANT MODEL
RIGID BODY DYNAMICS

CONTROL
POWER
PLANT

SENSOR
DYNAMICS

LIQUID SLOSH

STRUCTURES

PROPULSION

AERO DYNAMICS

Launch Vehicle Modelling

Input Data:

- **Plant Model** :Mass, Length, Diameter, CG, MI of vehicle
- **Control Power Plant** :Actuator model (transfer function), Nozzle mass, length, Inertia
- **Sensor Dynamics** :Attitude & body rate transfer functions
- **Liquid Slosh** :Pendulum Mass, Length, Distance of pendulum hinge point from CG, Un-damped natural frequency, Damping ratio
- **Structures** :Bending mode Frequency, Generalized mass, Mode shape, Mode slope, Damping ratio

Launch Vehicle Modelling

Input Data:

- **Propulsion** :Thrust
- **Aerodynamic** :Aerodynamic (Lateral/Side) force coefficients, Center of Pressure
- **Trajectory** :Altitude, Mach Number, Inertial velocity
- **Atmosphere** :Density
- **Dispersion level** :Specified Uncertainty bounds (example: Aero coefficients ±3%, Bending mode frequency ±10% etc.)

Launch Vehicle Modeling

Assumptions:

Time Slice Approach:

Time varying mass and inertia properties are frozen over a short period of time (Short Period Dynamics)

Small Angle Approximation:

Deviations from Reference trajectories are small so that trigonometric non-linearity, and higher order term's contributions are neglected.

Decoupling of Attitude Dynamics:

Due to axis symmetry of launch vehicles, Pitch/Yaw/Roll motions are assumed to be decoupled.

NOTE: There is significant amount of coupling in Yaw/Roll motion for aircraft.

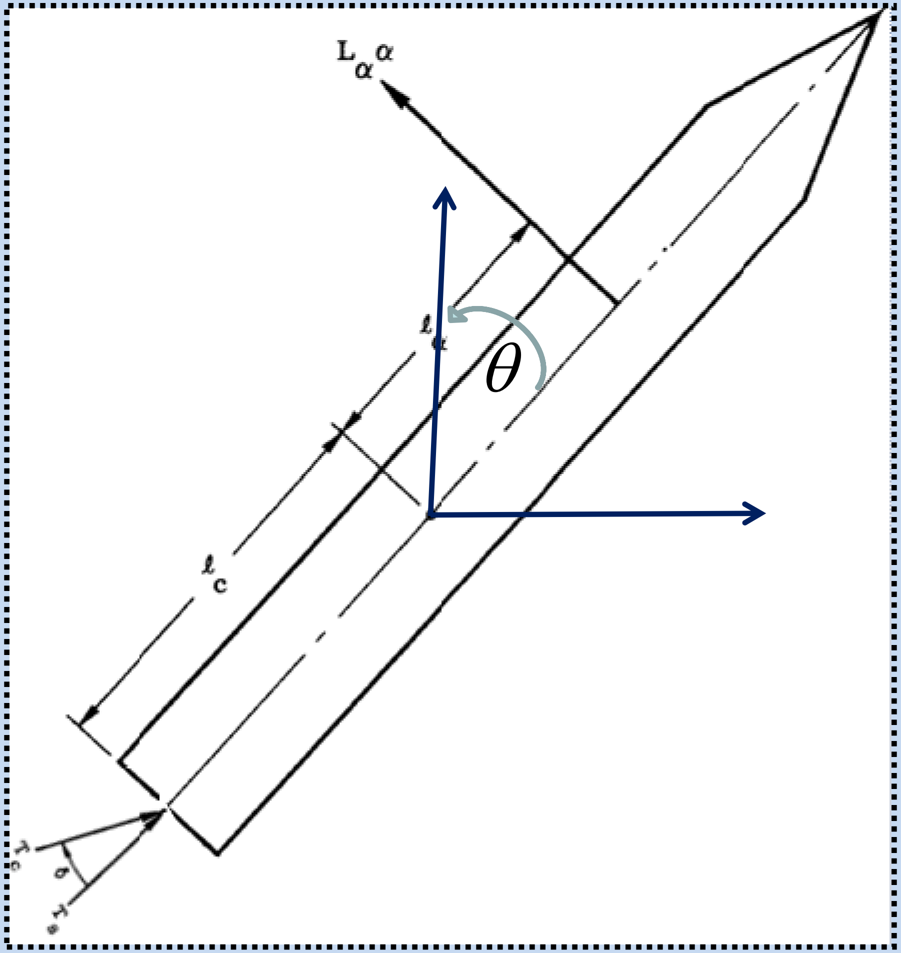
Linear Time Invariant :

Non-linearity of actuator/sensors (Dead-zone, slew rate etc.) are neglected at design phase.

(All above assumptions lead to LTI systems properties.)

Rigid Body Rotational Dynamics

θ : Attitude
δ : Control variable
α : Angle of attack
L_α : ($QSC_{N\alpha}$)
l_C : Control moment arm
I : Moment of inertia
l_α : Aerodynamic moment arm
Q : Dynamic Pressure, S – Reference area
$C_{N\alpha}$: Aerodynamic Normal Force Coefficient, **T_C** : Controlling Thrust



$$I\ddot{\theta} = L_\alpha l_\alpha \alpha + T_C l_C \sin(\delta)$$

Assumptions:

$$\alpha \approx \theta \quad \& \quad \sin(\delta) = \delta$$

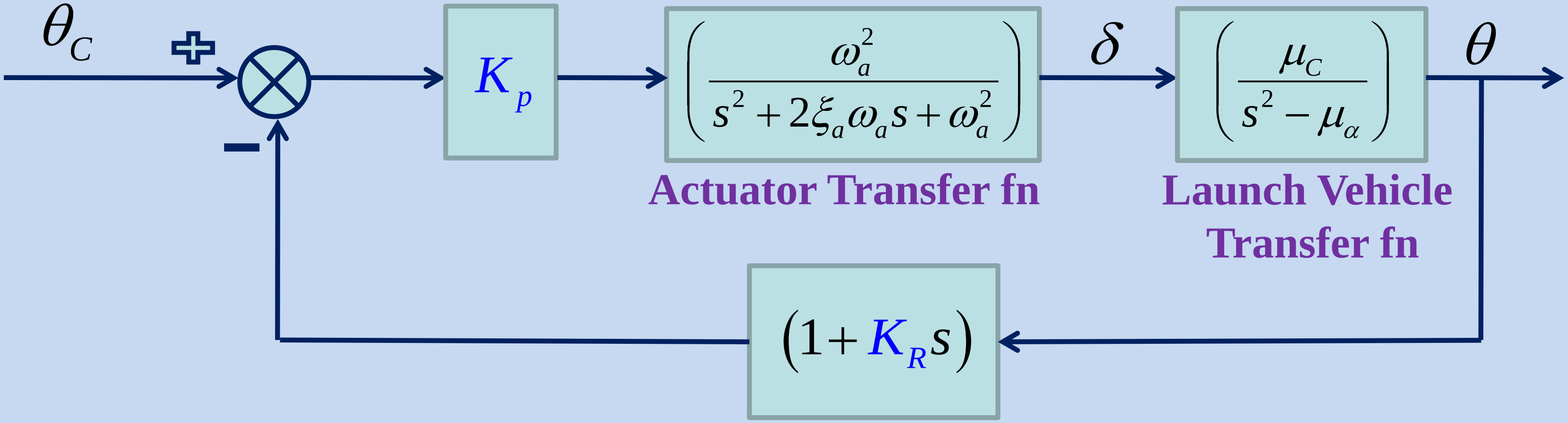
$$I\ddot{\theta} = L_\alpha l_\alpha \theta + T_C l_C \delta$$

$$\frac{\theta(s)}{\delta(s)} = \left(\frac{\mu_C}{s^2 - \mu_\alpha}\right)$$

where,

$$\mu_C = \left(\frac{T_C l_C}{I}\right), \qquad \mu_\alpha = \left(\frac{L_\alpha l_\alpha}{I}\right)$$

Rigid Body : Close loop system

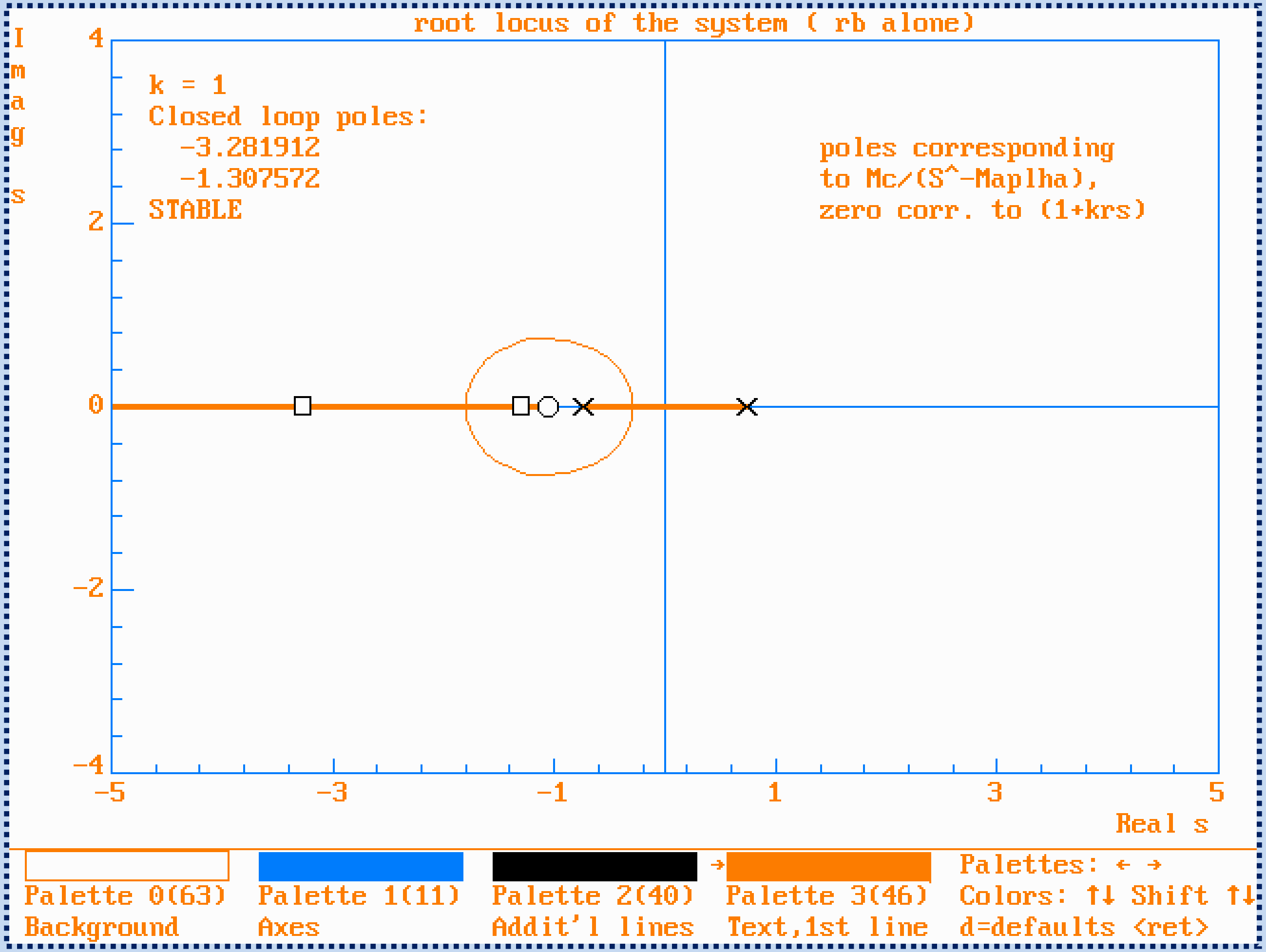


Actuator Transfer fn

Launch Vehicle Transfer fn

Block Diagram: Close loop system (Rigid Body Only)

Root locus analysis



root locus of the system (rb alone)

```
k = 1
Closed loop poles:
  -3.281912
  -1.307572
STABLE
```

poles corresponding
to Mc/(S^-Maplha),
zero corr. to (1+krs)

```
☐ Palette 0(63)   🟦 Palette 1(11)   ⬛ Palette 2(40)  → 🟧 Palette 3(46)   Palettes: ← →
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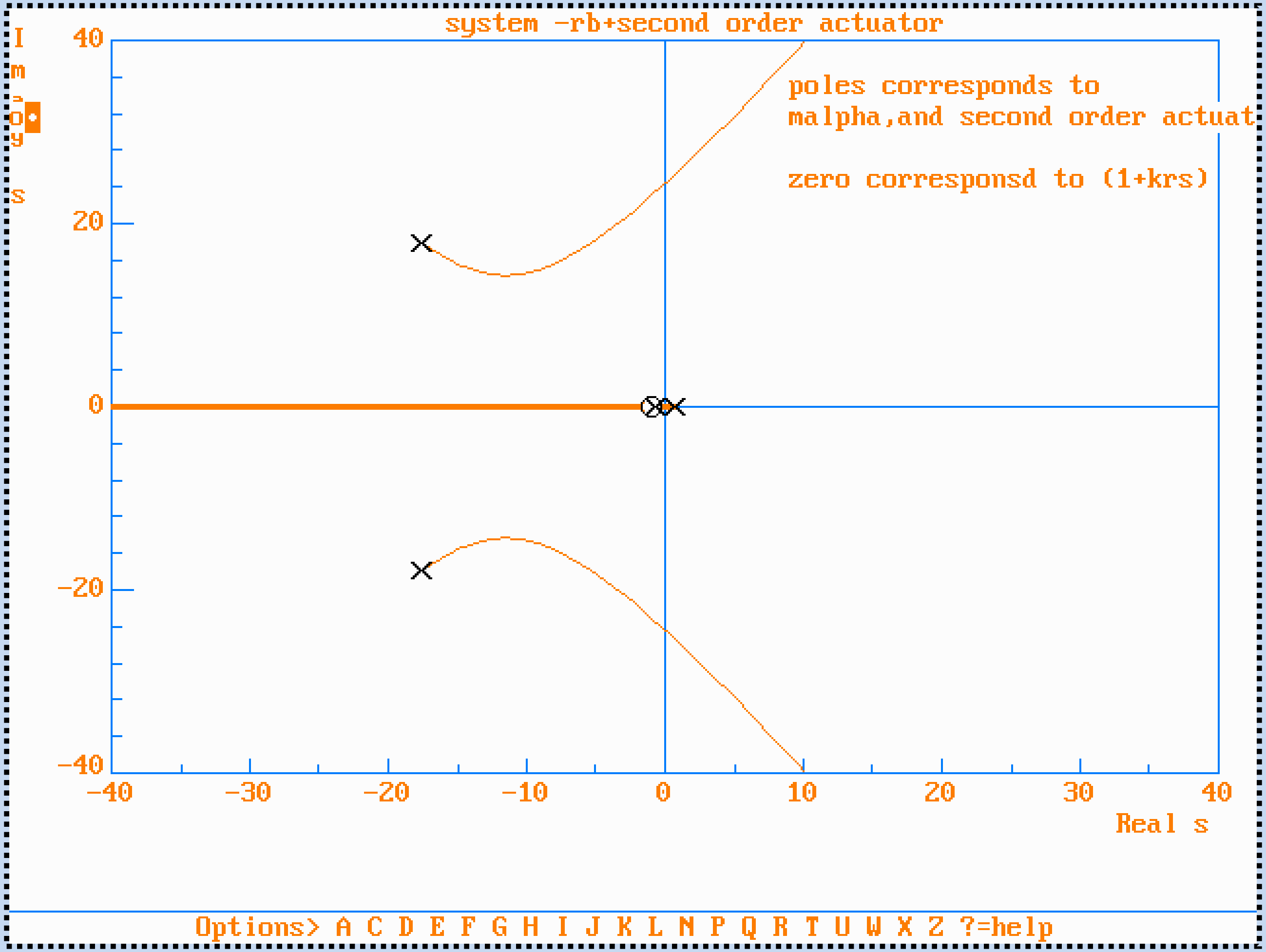
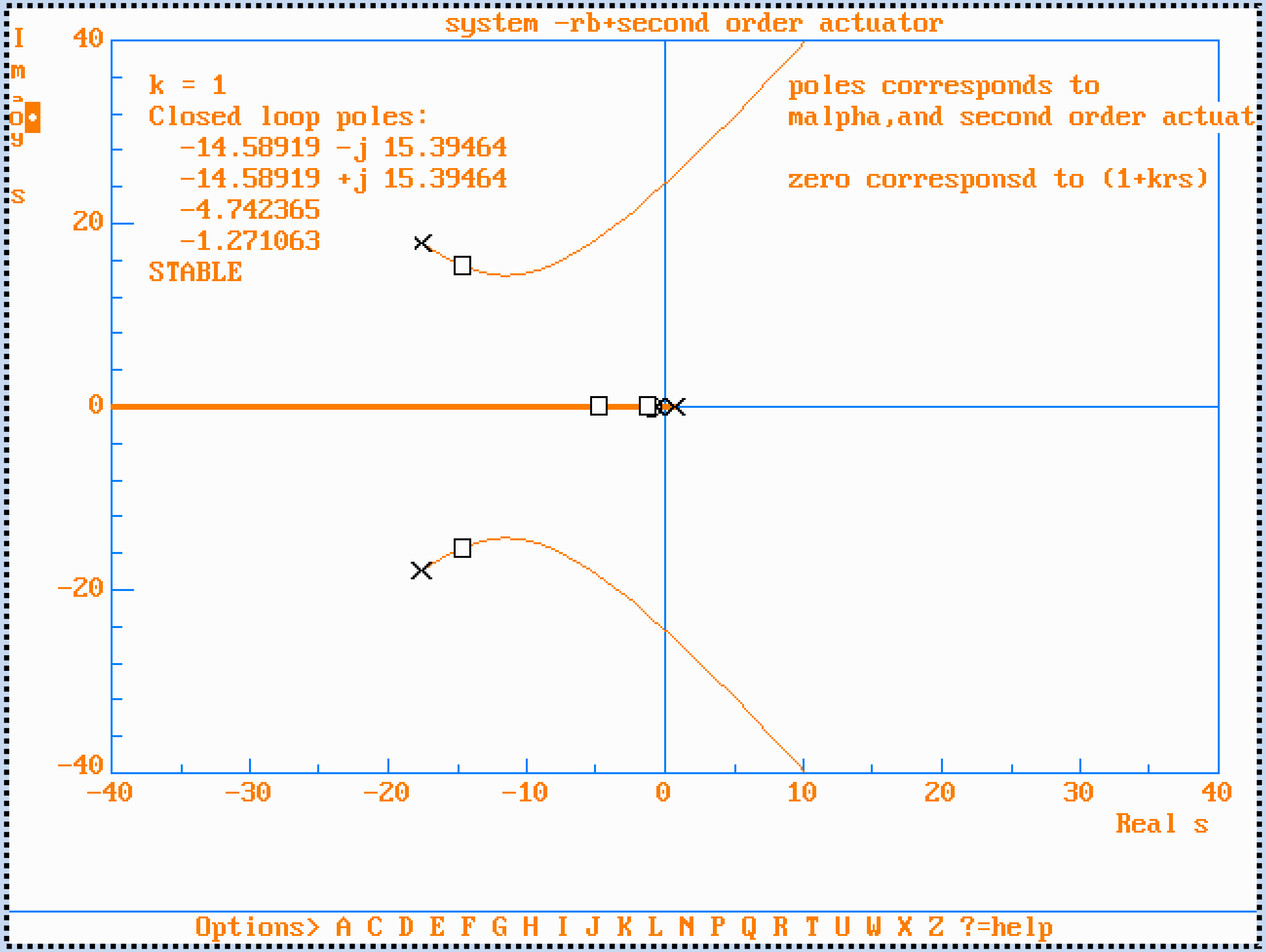


system -rb+second order actuator

poles corresponds to
malpha,and second order actuat

zero corresponsd to (1+krs)



system -rb+second order actuator

```
k = 1
Closed loop poles:
  -14.58919 -j 15.39464
  -14.58919 +j 15.39464
  -4.742365
  -1.271063
STABLE
```

poles corresponds to
malpha,and second order actuat

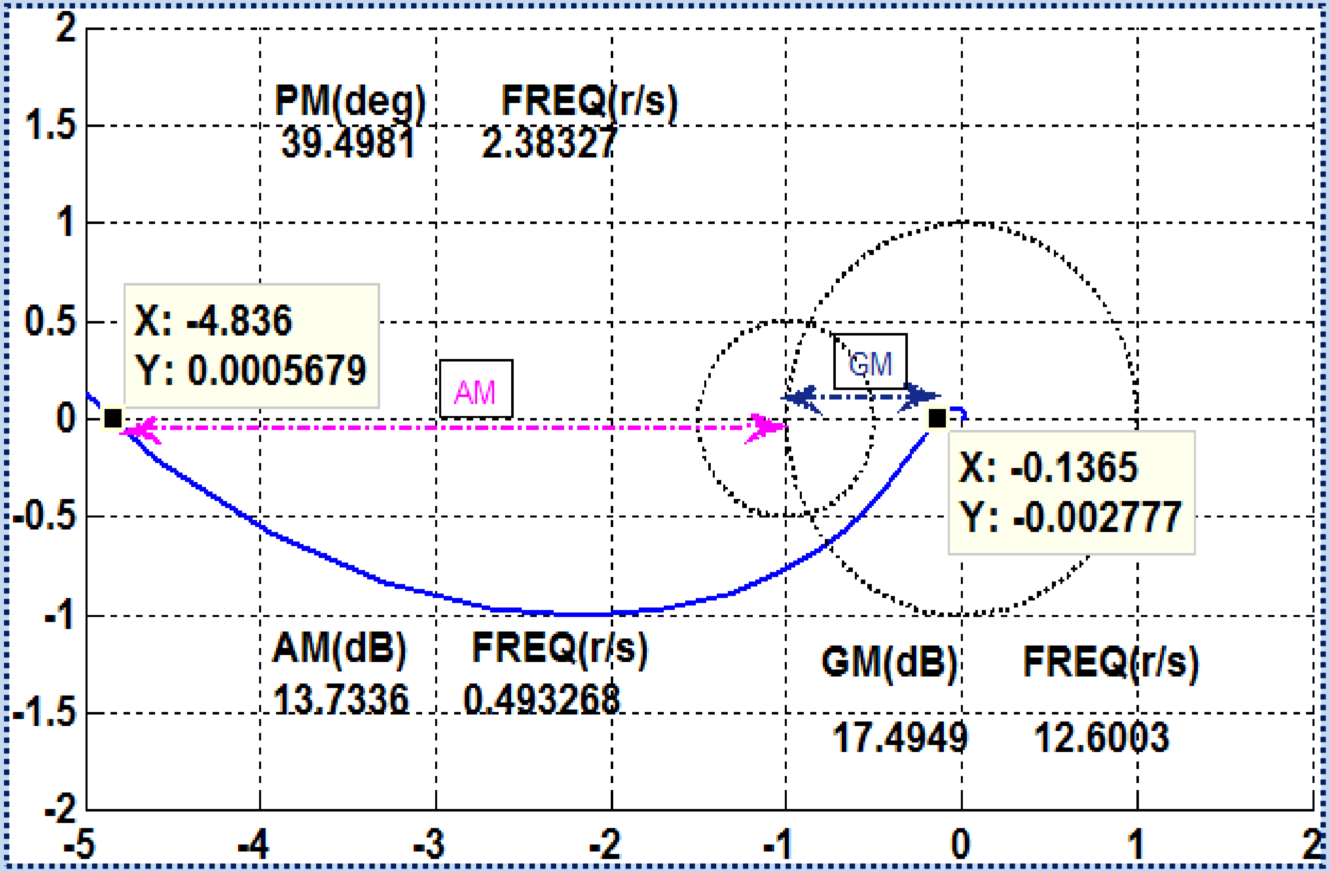
zero corresponsd to (1+krs)

Options> A C D E F G H I J K L N P Q R T U W X Z ?=help

Nyquist Plot @Ign. + T sec

No. of open loop poles in RHP : P = 1
 # counter-clockwise encirclement : N =1

Z = P – N = 0
(STABLE)



Gain Design Method-1:

Characteristic equation: $1+K_P\left(\frac{\omega_a^2}{s^2+2\xi_a\omega_a s+\omega_a^2}\right)\left(\frac{\mu_C}{s^2-\mu_\alpha}\right)(1+K_R s)=0$

Reference equation : $(s^2+2\xi_n\omega_n s+\omega_n^2)(s^2+as+b)=0$

Known variables : $\xi_a,\ \omega_a,\ \mu_C,\ \mu_\alpha,\ \xi_n,\ \omega_n$

Unknown variables : $\mathrm{K_p},\ \mathrm{K_R},\ \mathrm{a},\ \mathrm{b}$

degree of ch. polynomial : 4

Rigid Body gain : $\mathrm{K_P}$ & $\mathrm{K_R}$

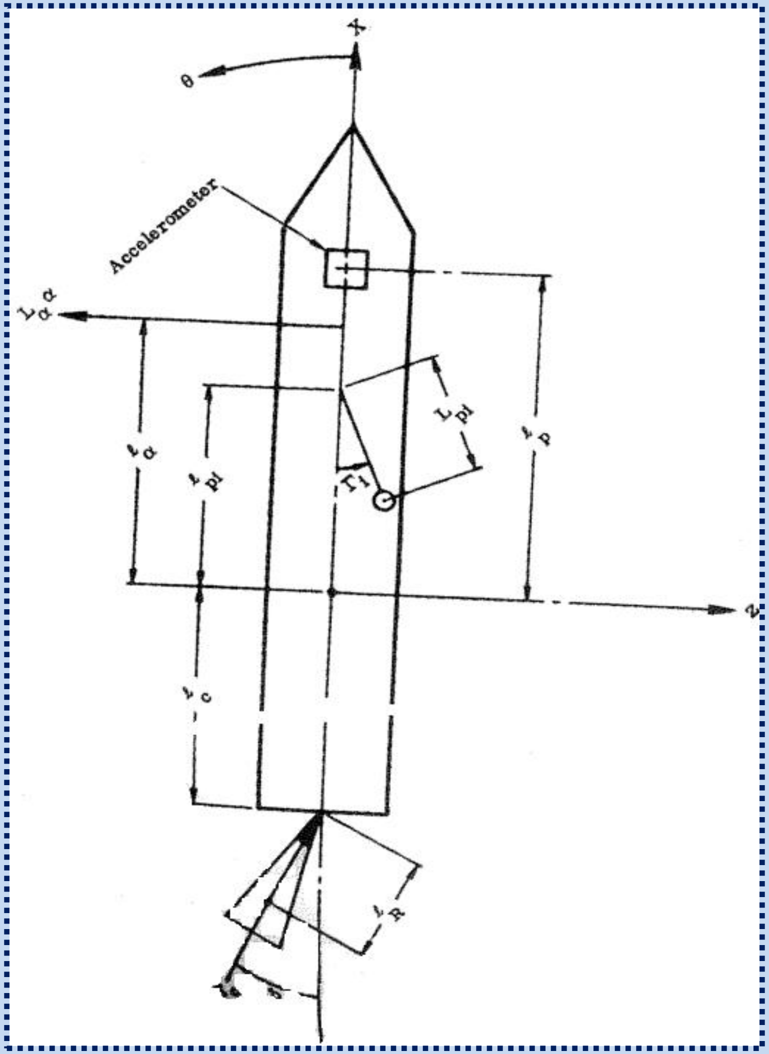
a, b : information of rest poles locations

Slosh

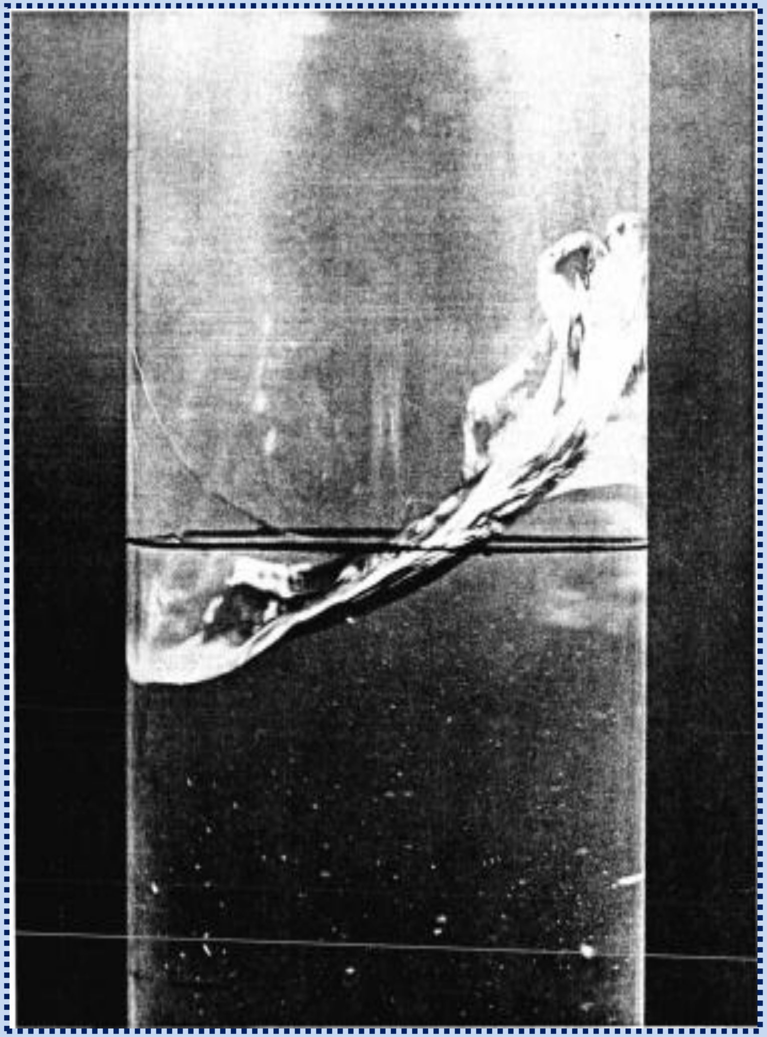
- Lateral oscillations of liquids in tank is slosh
- Modelled by replacing liquid mass with rigid mass and a harmonic oscillator such as spring or pendulum
- Pendulum parameters are function of tank shape and liquid level

Modeling Liquid Slosh

The Force & Moments produced by sloshing of the liquid fuel is analyzed by an equivalent Mass and Pendulum Or an equivalent Spring Mass Analogy.



Ref: Elements of Control Theory by A. L. Greensite



Ref: NASA SP-106

Slosh Dynamics

$$L_{pi}(s^2 + 2\zeta_{pi}\omega_{pi}s + \omega_{pi}^2)\Gamma_i = -(\dot{w} - U_0\dot{\theta}) + (\ell_{pi} - L_{pi})\ddot{\theta}$$

where,

L_{pi} : *Length* of i$^{\text{th}}$ pendulum

ℓ_{pi} : distance of i$^{\text{th}}$ pendulum hinge point from body cg

ζ_{pi} : damping of i$^{\text{th}}$ Pendulum

ω_{pi} : Undamped natural Frequency of i$^{\text{th}}$ Pendulum

Γ_i : Pendulum angle

$\dot{w}$: Lateral acceleration

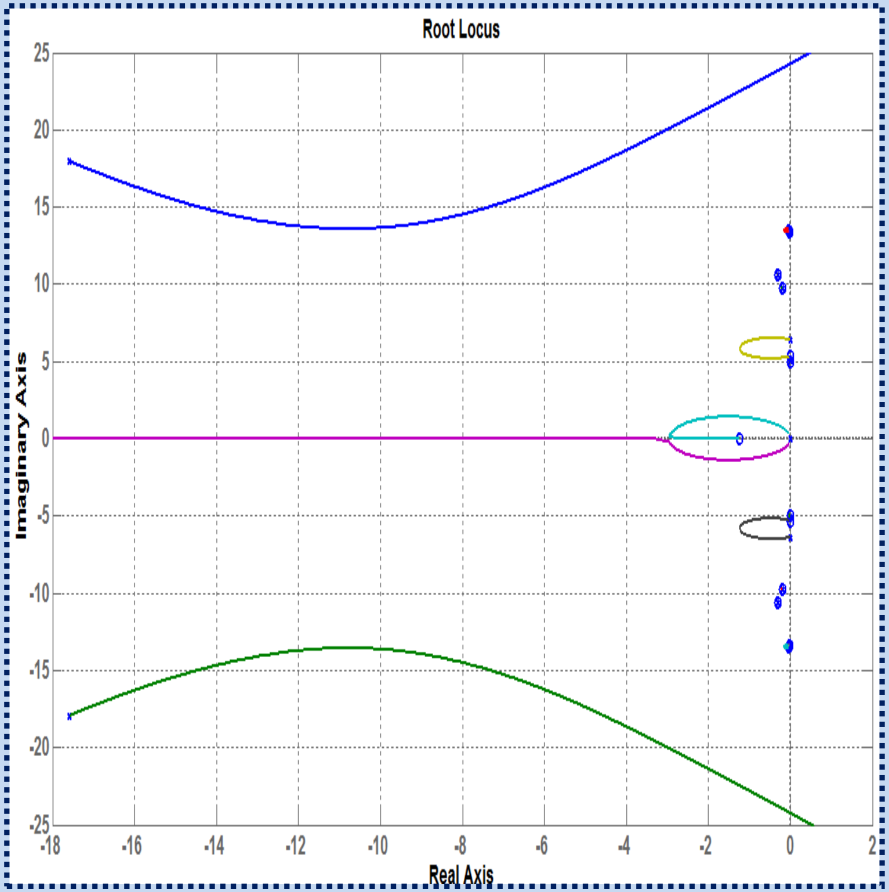
U_0 : Forward inertial velocity

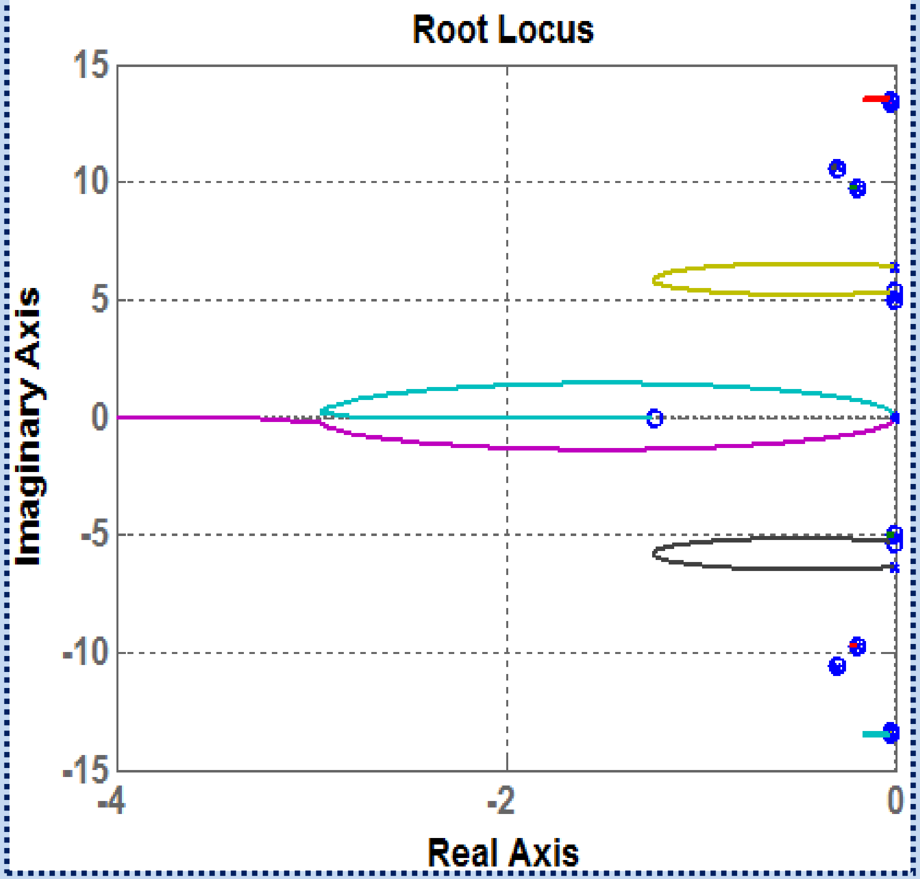
$\dot{\theta}$: attitude rate

NOTE: Complex Pole-zero pair is introduced in Rigid body dynamics by each Slosh mode.

Root Locus (Rigid Body + Slosh)

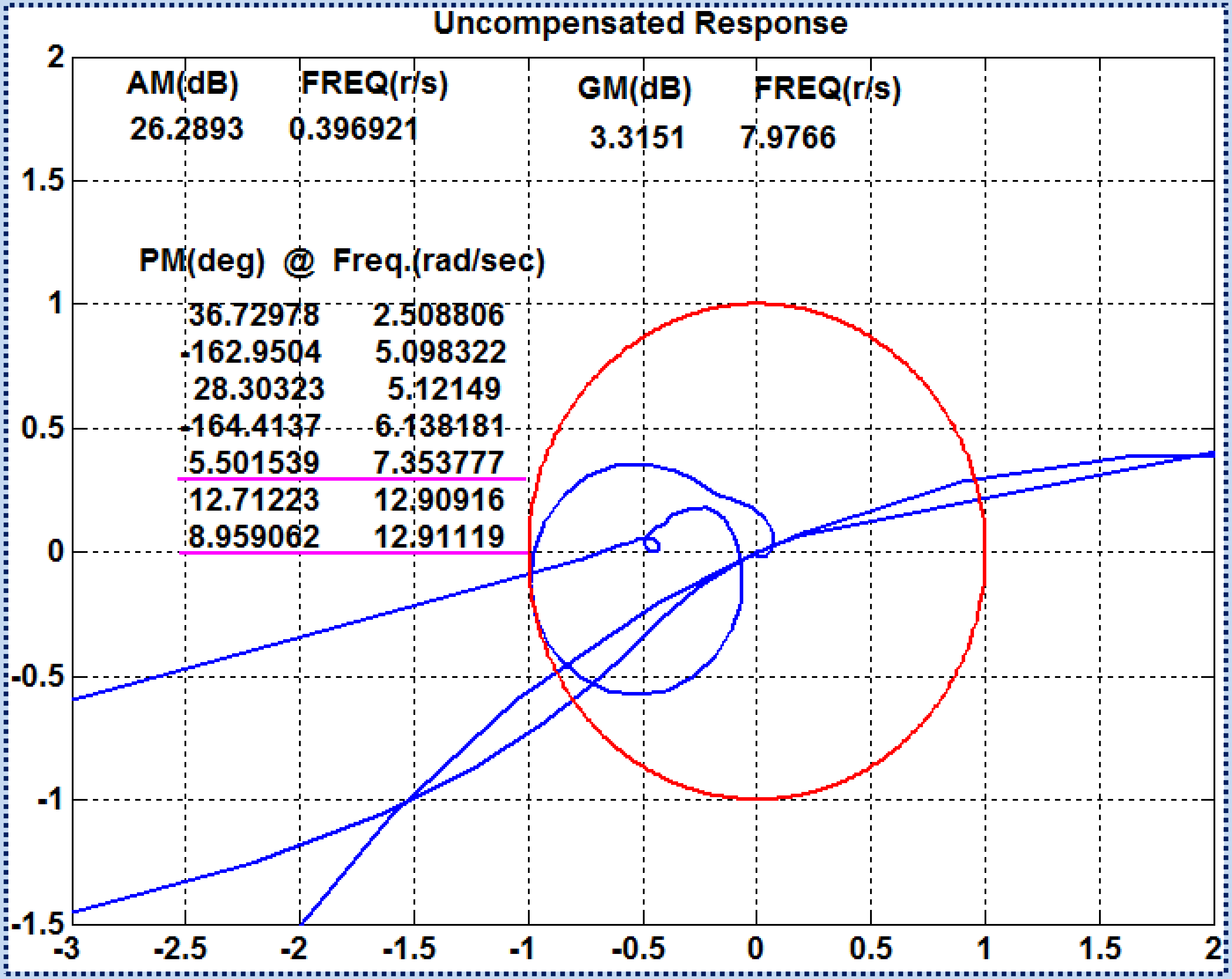
Rigid Body poles: Two poles at origin [K/s^2]
Actuator : Second order system [$w^2/s^2+2*z*w*s+w^2$]
Slosh : 6 slosh mode (complex pole zeros pair per slosh mode)





Nyquist plot at maximum slosh sensitivity instant :

- Rigid Body with Slosh , Actuator, Sensor & delay
- Slosh margin 5.5 degree & 8.9 degree



AM(dB)	FREQ(r/s)
26.2893	0.396921

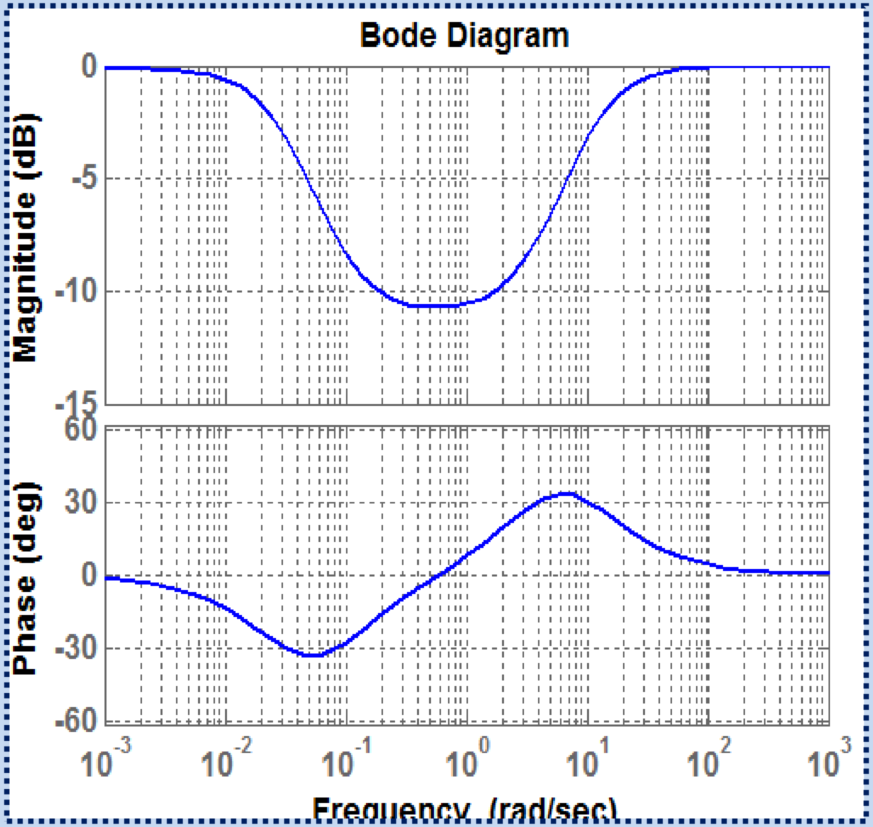
GM(dB)	FREQ(r/s)
3.3151	7.9766

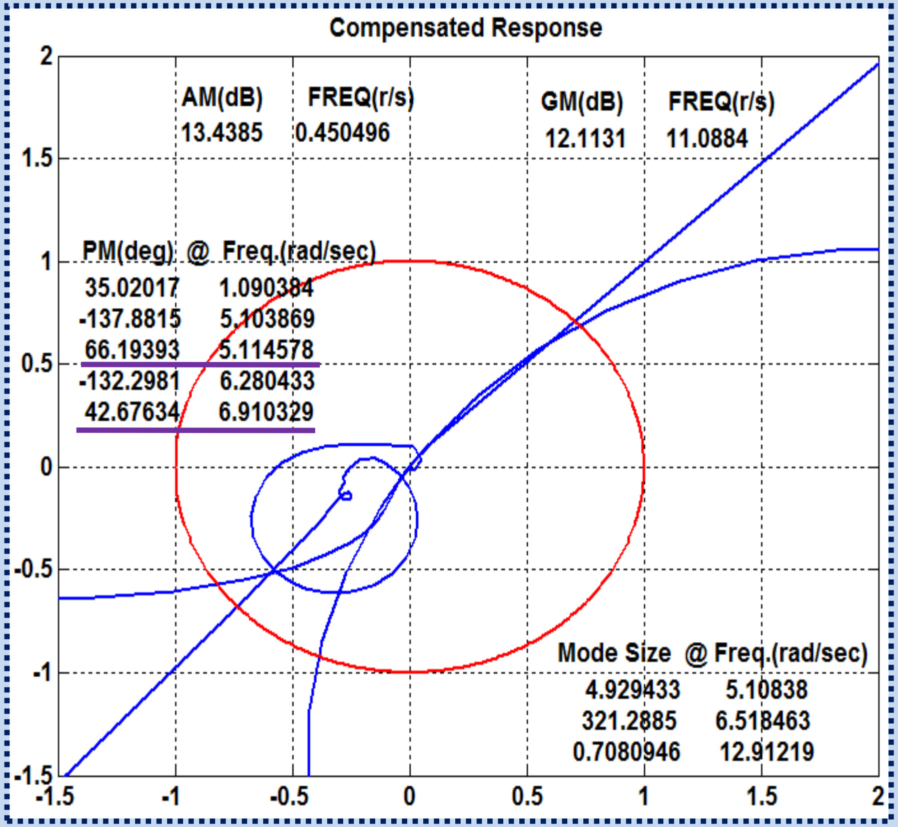
PM(deg) @	Freq.(rad/sec)
36.72978	2.508806
-162.9504	5.098322
28.30323	5.12149
-164.4137	6.138181
5.501539	7.353777
12.71223	12.90916
8.959062	12.91119

Lag-lead compensator

(phase margin improvement)

Lag-Lead Compensator Bode plot



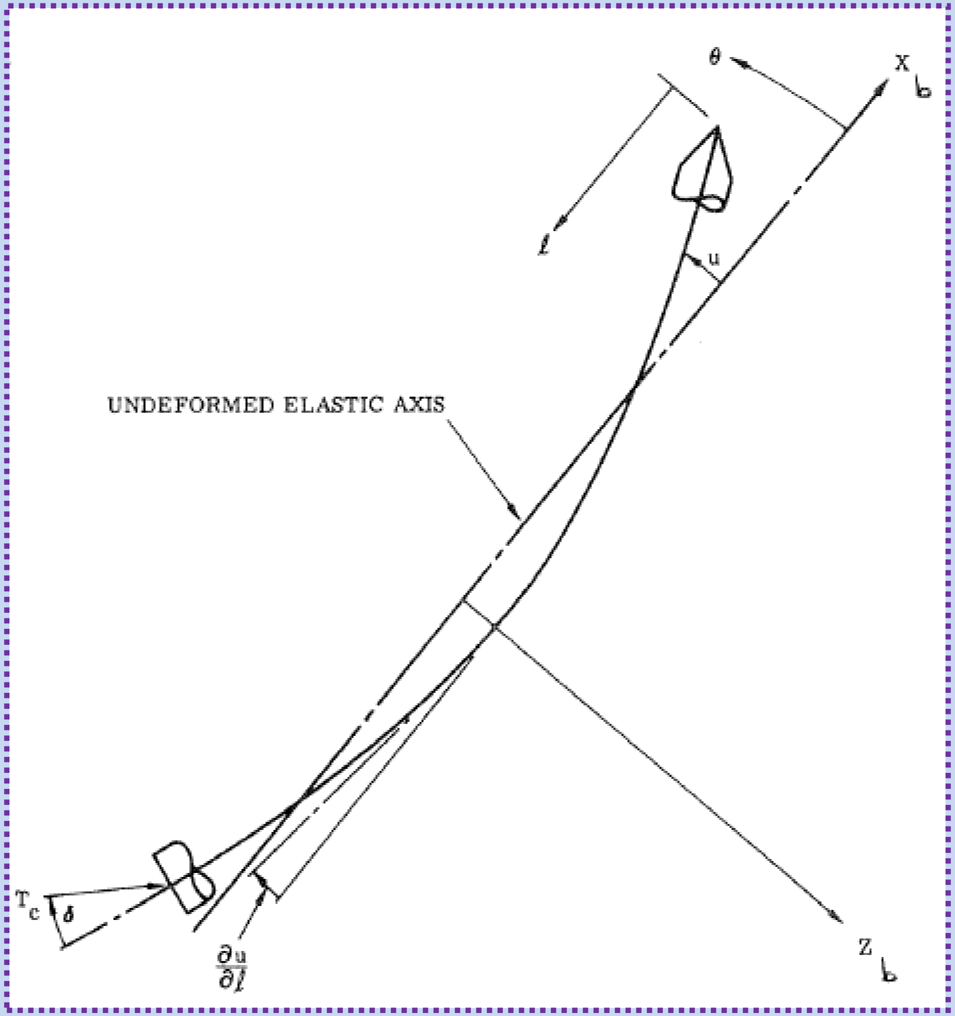


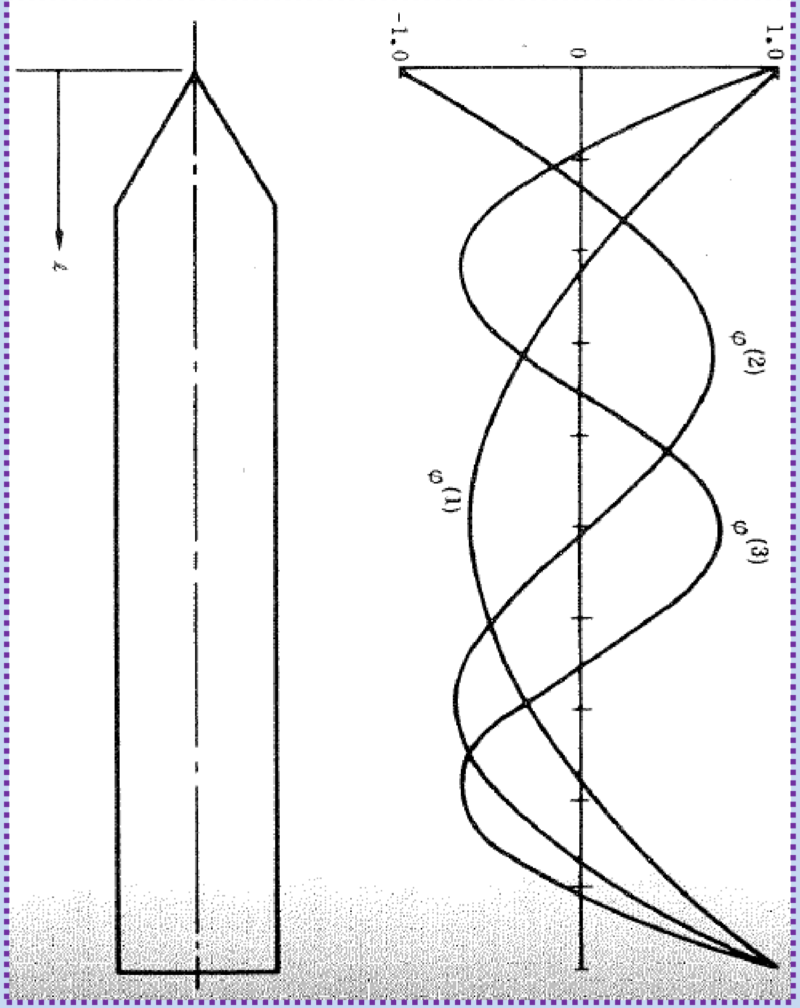
Modeling Flexibility Dynamics

Bending Mode displacement: $u = \sum_i \varphi^{(i)}(\ell) q^{(i)}(t)$

Where, $\varphi^{(i)}(\ell)$:Generalized Mode Shape of ith Bending mode

$q^{(i)}(t)$:Generalized Co-ordinate of ith Bending mode





Ref: Elements of Control Theory by A. L. Greensite

Flexibility Dynamics

1. Generalized mode shape is a function of vehicle length and mass distribution etc. Since mass of vehicle is rapidly decreasing, Mode shape is changing w.r.t. time. (Predicted with uncertainty bounds)

2. Generalized Co-ordinate dynamics is represented by second order differential equation.

$$(s^2 + 2\zeta^{(i)}\omega^{(i)}s + [\omega^{(i)}]^2)q^{(i)} = -\frac{T_c}{M^{(i)}}\delta, \quad i = 1, 2, 3...$$

3. Flexibility deflection is picked-up by attitude sensor & Flexible-deflection rate is picked-up by rate sensor.

$$\dot{\theta} = \dot{\theta}_R + \sum_i \sigma_{RG}{}^{(i)}\dot{q}(i)$$

$$\theta = \theta_R + \sum_i \sigma_{PG}{}^{(i)}q(i)$$

where, $\sigma^{(i)} = -\frac{\partial\varphi^{(i)}}{\partial\ell}$

4. Complex Pole-zero pair is introduced in Rigid body dynamics by each Generalized Co-ordinate.

Bending Mode Stabilization

Gain Stabilization:

Attenuate control loop gain at desired frequency, to ensure stability regardless of control loop phase uncertainty.

(Second/Higher BM are usually Gain stabilized)

Phase Stabilization:

Provide proper phase characteristics at desired frequency to obtain a close loop damping, that is greater than the passive damping.

(First/Second BM are usually Gain stabilized)

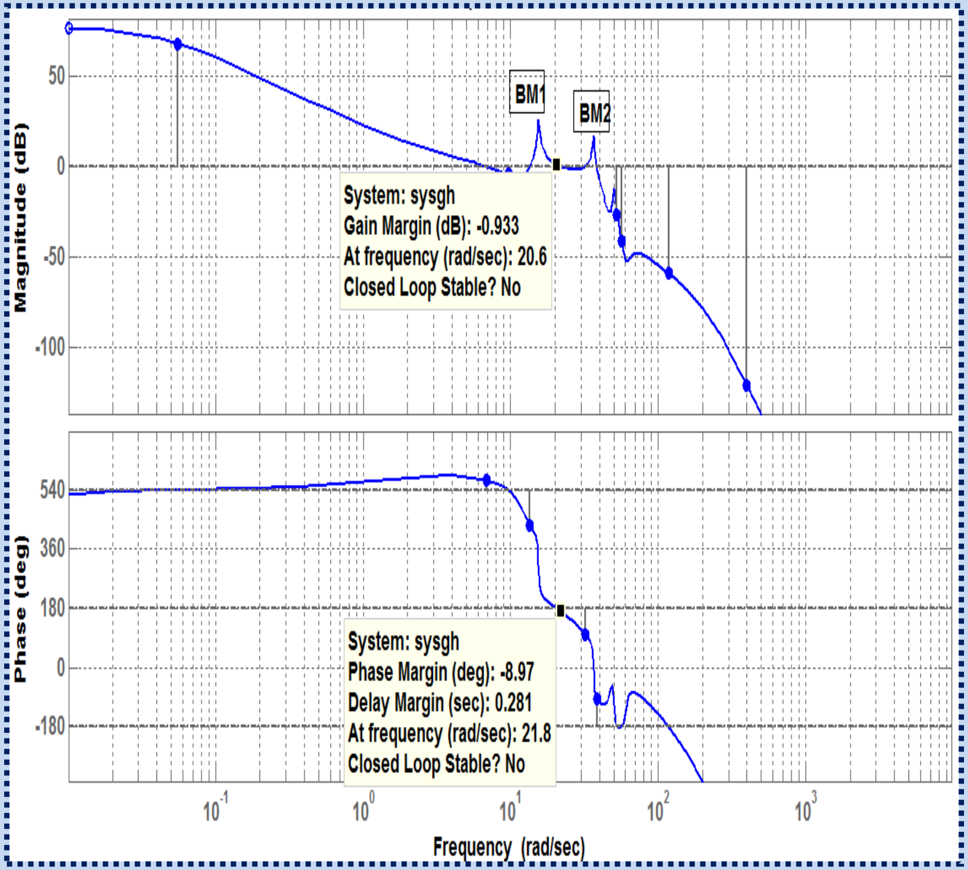
Gain-Phase Stabilization:

A Rigid body/Flexible mode is said to be gain-phase stabilize if it is close loop stable with finite gain and phase margin.

Rigid Body + Flexibility

Rigid Body poles : Two poles at origin [$K/(s^2 - a)$]
Actuator : Second order system [$w^2/s^2+2*z*w*s+w^2$]
Slosh : 3 bending mode (complex pole zeros pair per bending mode)

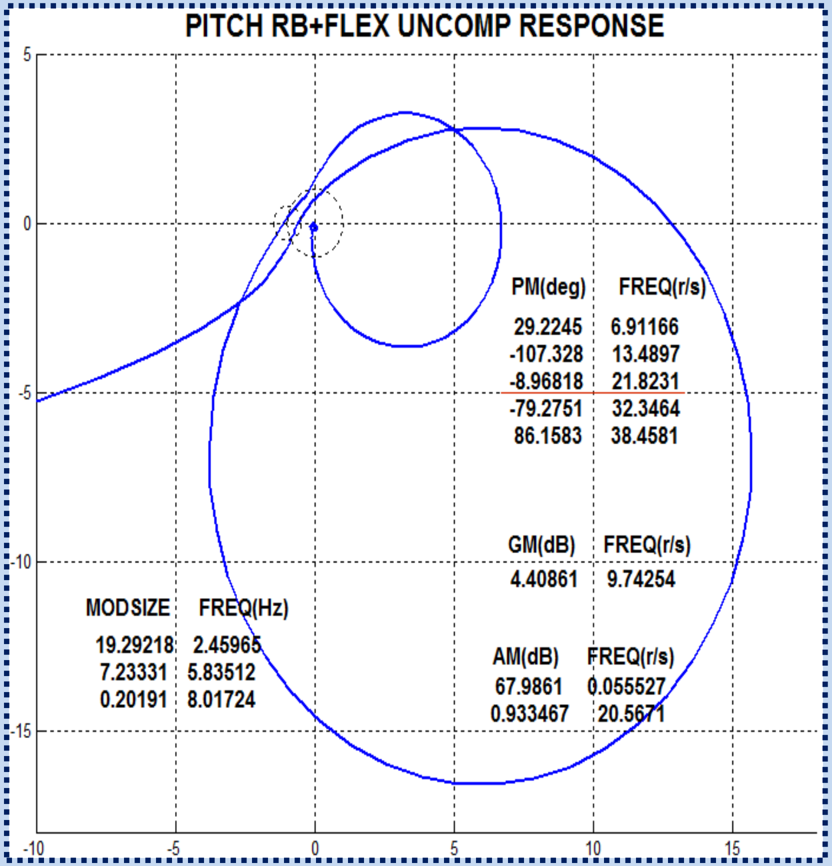
Uncompensated Bode plot



System: sysgh
Gain Margin (dB): -0.933
At frequency (rad/sec): 20.6
Closed Loop Stable? No

System: sysgh
Phase Margin (deg): -8.97
Delay Margin (sec): 0.281
At frequency (rad/sec): 21.8
Closed Loop Stable? No

Uncompensated Nyquist plot



PM(deg)	FREQ(r/s)
29.2245	6.91166
-107.328	13.4897
-8.96818	21.8231
-79.2751	32.3464
86.1583	38.4581

GM(dB)	FREQ(r/s)
4.40861	9.74254

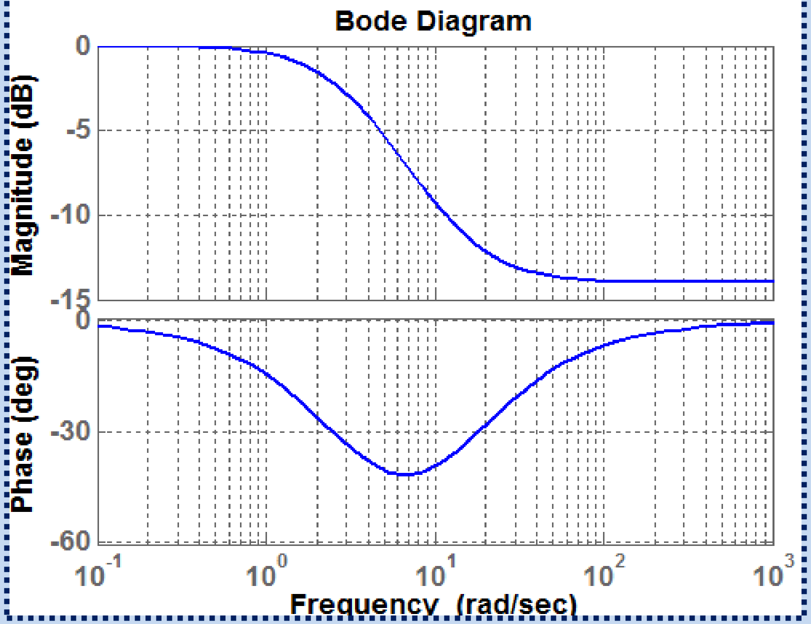
MODSIZE	FREQ(Hz)
19.29218	2.45965
7.23331	5.83512
0.20191	8.01724

AM(dB)	FREQ(r/s)
67.9861	0.055527
0.933467	20.5671

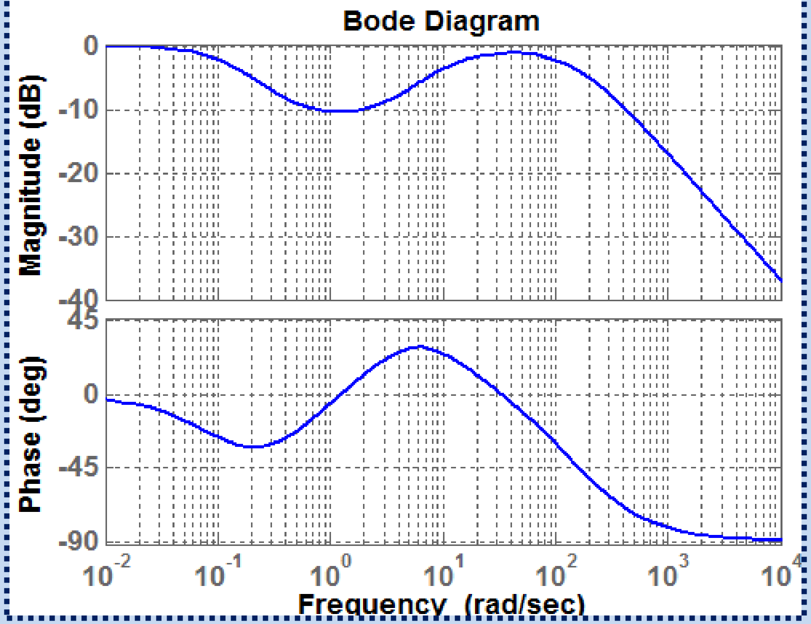
Compensated Nyquist Plot

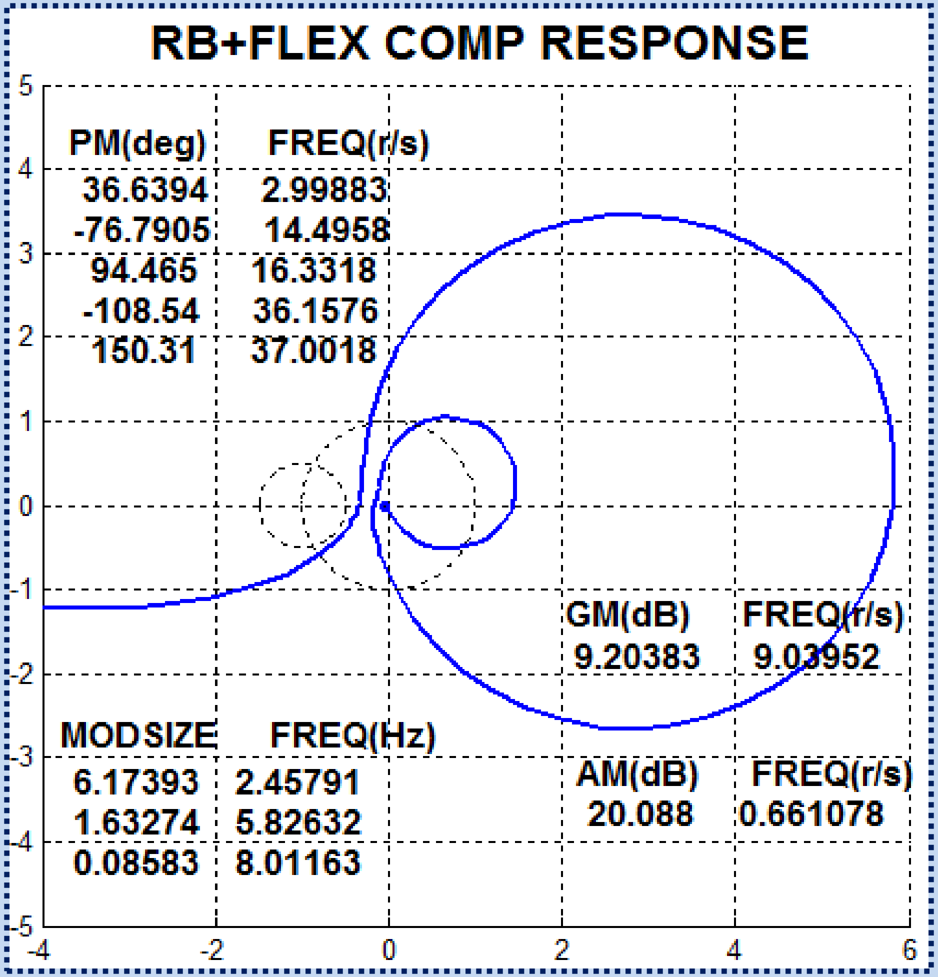
- ☐ **BM1, BM2** are **Phase stabilized**
- ☐ **BM3 Gain stabilized**

Lag Compensator in Rate path



Lag-lead & Roll off filter in forward path





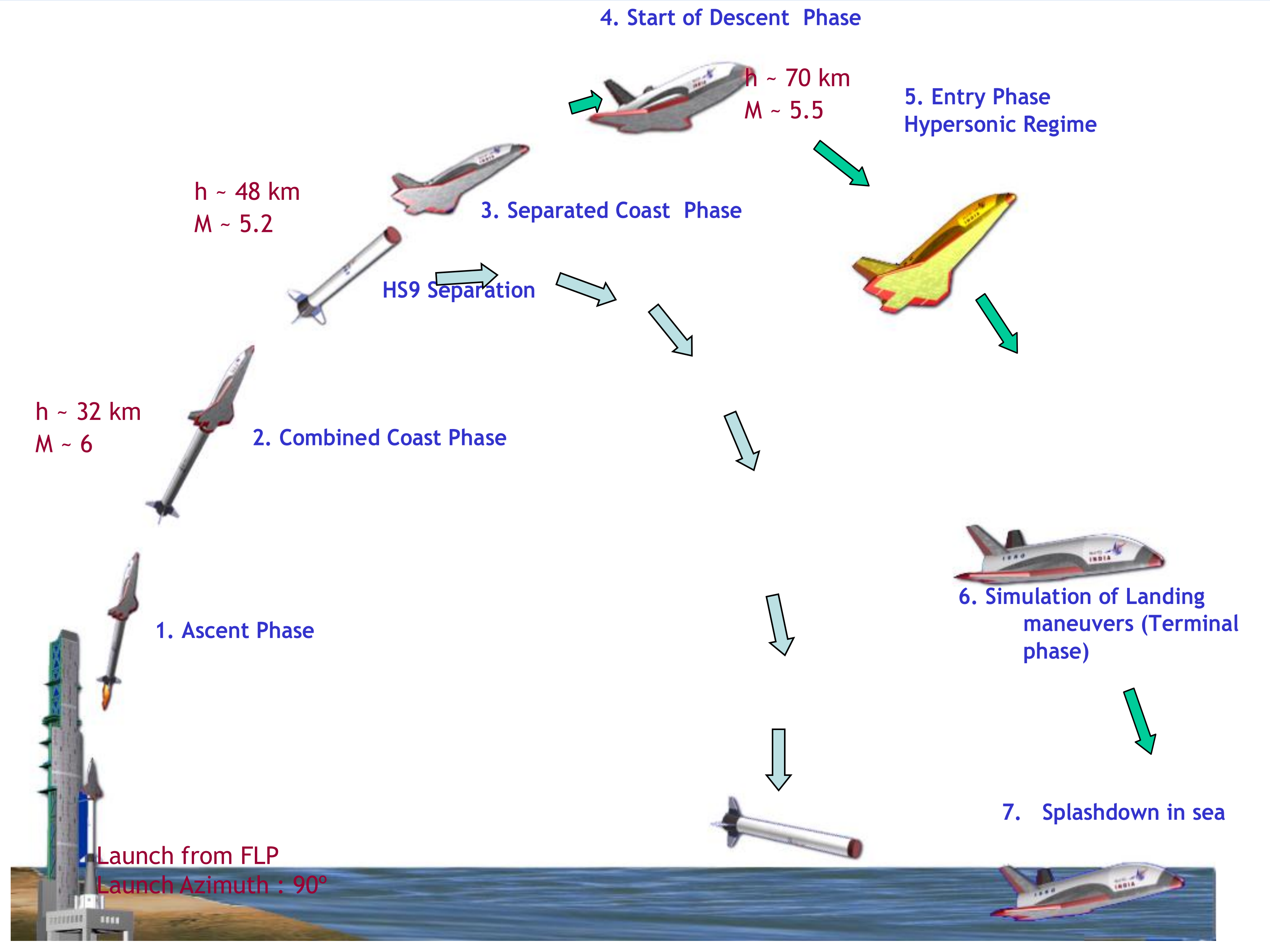
PM(deg)	FREQ(r/s)
36.6394	2.99883
-76.7905	14.4958
94.465	16.3318
-108.54	36.1576
150.31	37.0018

GM(dB)	FREQ(r/s)
9.20383	9.03952

MODSIZE	FREQ(Hz)
6.17393	2.45791
1.63274	5.82632
0.08583	8.01163

AM(dB)	FREQ(r/s)
20.088	0.661078

HEX-1 MISSION PROFILE



4. Start of Descent Phase

h ~ 70 km
M ~ 5.5

5. Entry Phase
Hypersonic Regime

h ~ 48 km
M ~ 5.2

3. Separated Coast Phase

HS9 Separation

h ~ 32 km
M ~ 6

2. Combined Coast Phase

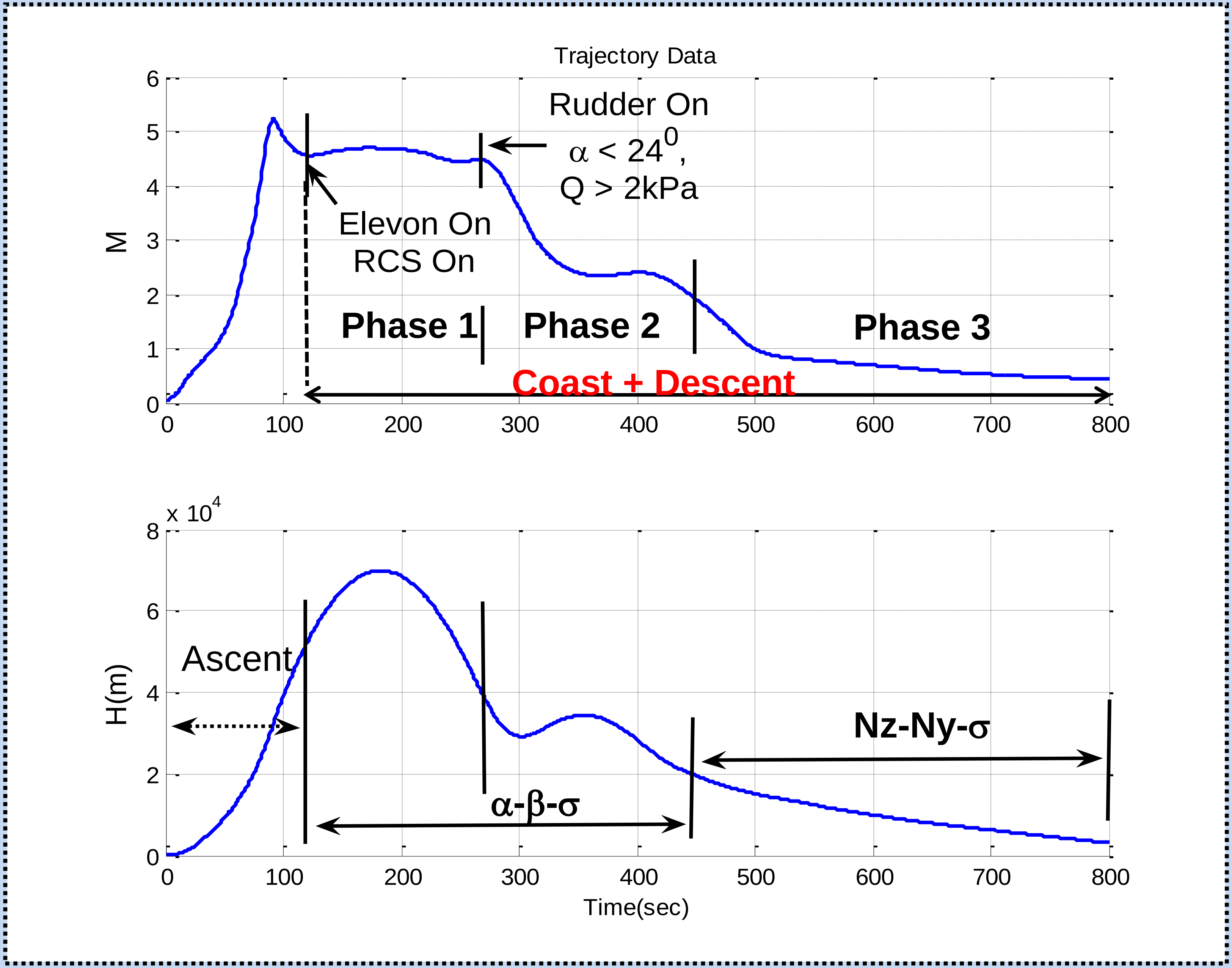
6. Simulation of Landing
maneuvers (Terminal
phase)

1. Ascent Phase

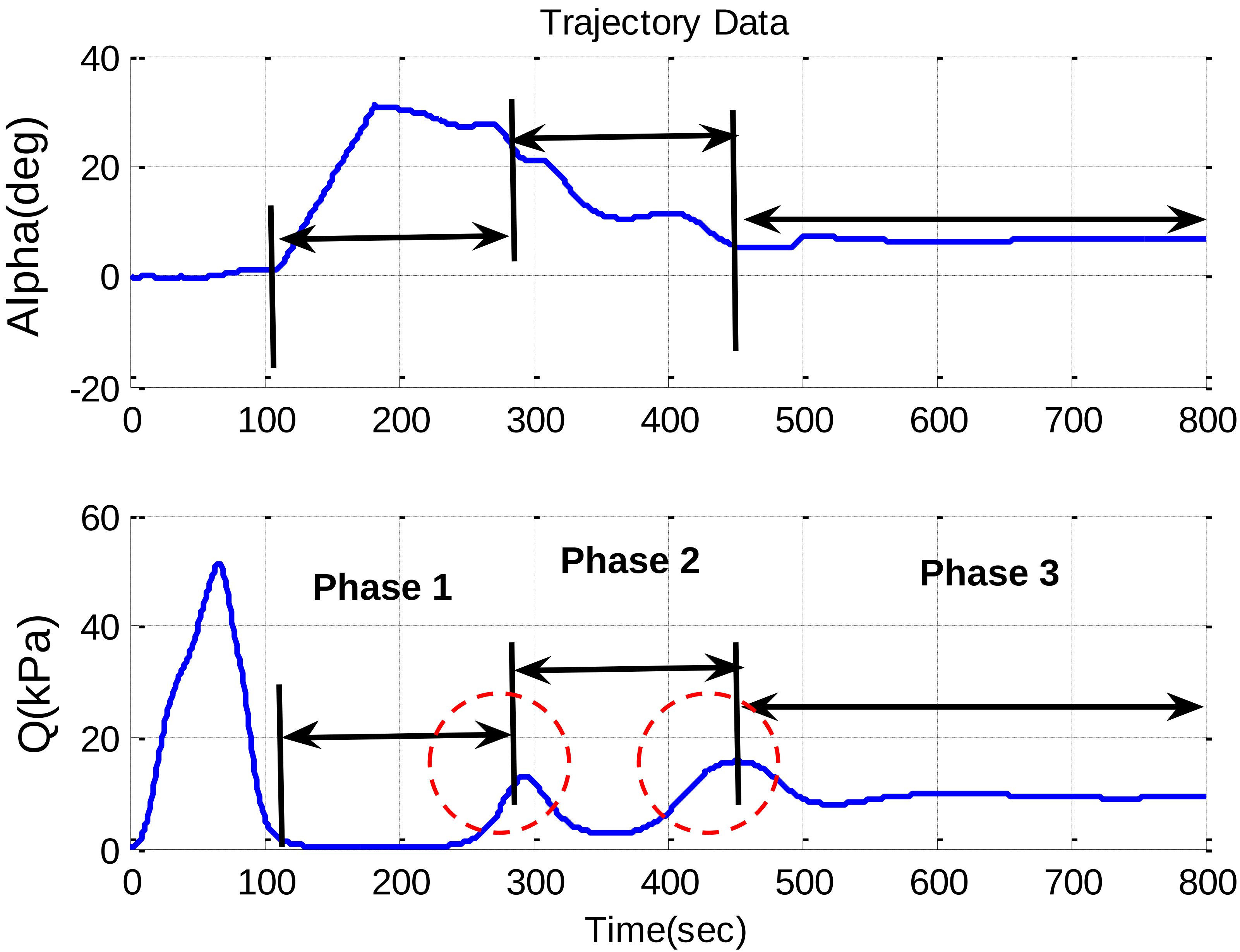
7. Splashdown in sea

Launch from FLP
Launch Azimuth : 90°

Different Phases of RLV during TDV alone Flight



Critical Regions of Flight during TDV alone Phase

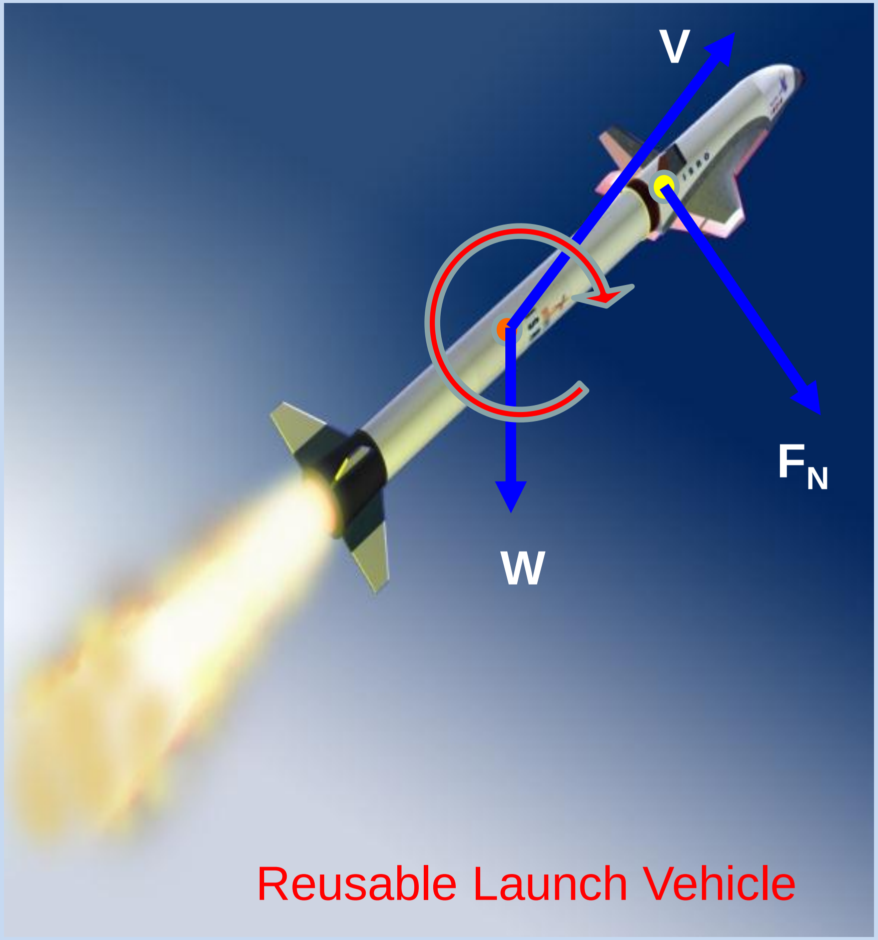


Aerodynamic instability and Control requirement

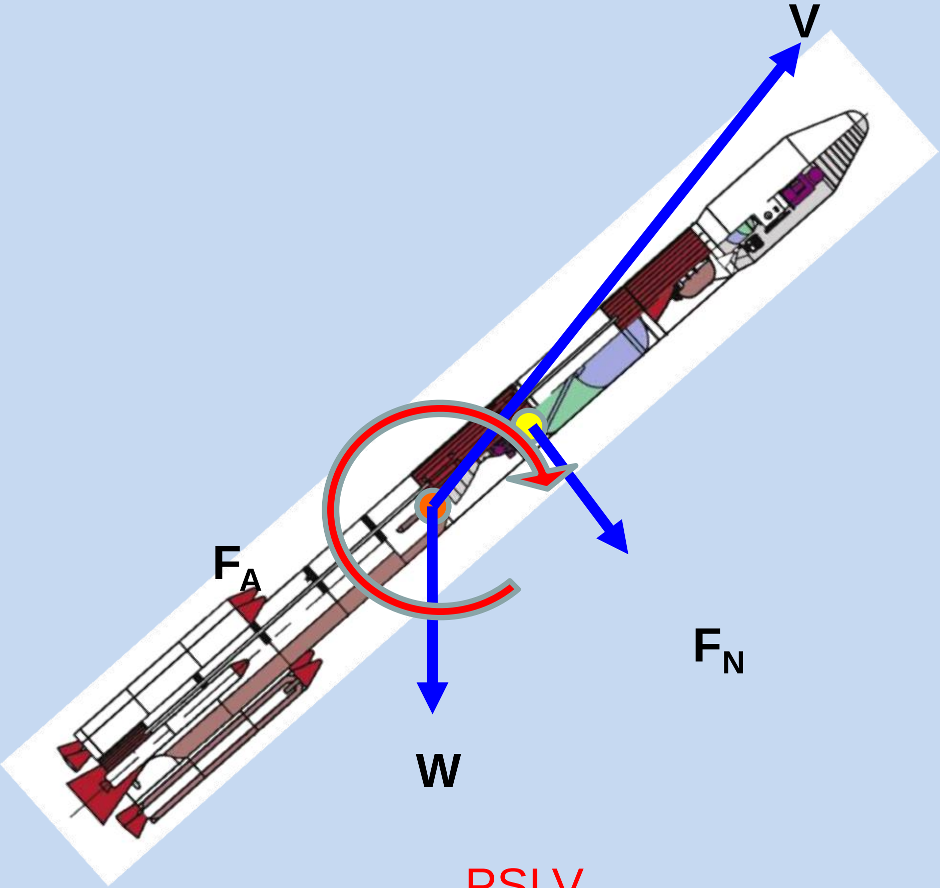
Higher the aerodynamic instability
faster is the divergence:
requires quicker Control

$$\mu_\alpha = 16, T_d = 0.33\,\mathrm{s}$$

$$\mu_\alpha = 0.75, T_d = 1.52\,\mathrm{s}$$

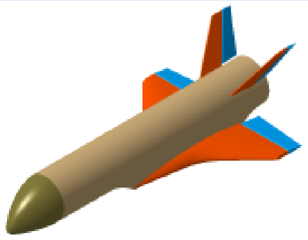


Reusable Launch Vehicle



PSLV

Rigid body and Actuator Bandwidth requirements for various launch vehicles



Vehicle	μ_α	Time to double	Rigid body BW (ω_c)	Actuator BW ($6\omega_c$)
PSLV	0.75	1.52	2.96 rad/s (0.47 hz)	2.8 hz (6.5 hz)
GSLV	0.7	1.57	1.92 rad/s (0.31 hz)	1.86 hz (4 hz)
MK III	3.6	0.694	3.18 rad/s (0.51 hz)	3.06 (4 hz)
RLV	30.8	stable	11.1 rad/s (1.76 hz)	10.56 hz (6.5hz)
TSTO Orbiter	5.2	0.5775	4.56 rad/s (0.7247 hz)	4.34 hz (> 4 hz)
Shuttle	3.4	0.7142	3.68 rad/s (0.5869 hz)	3.52 hz (6.5 hz)

RLV-TD Pitch Dynamics

$$\begin{bmatrix} \dot{v} \\ \dot{\alpha} \\ \dot{q} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} -\frac{2QsC_{Do}}{mV_o} & g\cos\gamma_o - \frac{QsC_{D\alpha}}{m} & 0 & g\cos\gamma_o \\ -\frac{2QsC_{Lo}}{mV_o^2} - \frac{\dot{\gamma}_0}{V_0} & \frac{mg\sin\gamma_o - QsC_{L\alpha}}{mV_o} & 1 & -\frac{g\sin\gamma_o}{V_o} \\ \frac{2QscC_{mo}}{V_o Iyy} & \frac{QscC_{m\alpha}}{Iyy} & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} v \\ \alpha \\ q \\ \theta \end{bmatrix} + \begin{bmatrix} -\frac{QsC_{D\delta e}}{m} \\ -\frac{QsC_{L\delta e}}{mV_o} \\ \frac{QscC_{m\delta e}}{Iyy} \\ 0 \end{bmatrix} \delta_e$$

Longitudinal Dynamics characteristic equations

$$\Delta(s) = (s^2 + 2\varsigma_s \omega_s s + \omega_s^2)(s^2 + 2\varsigma_p \omega_p s + \omega_p^2) = 0$$

RLV-TD Yaw-Roll Dynamics

- State space model:
- **States:** p (roll rate), r (yaw rate), β (side-slip angle) and σ (bank angle)
- **Outputs:** σ' (bank rate), β' (side-slip rate), β (side-slip angle) and σ (bank angle)
- **Inputs:** Differential deflection of elevons (δ_e) and symmetric deflection of rudders (δ_r)

State equations

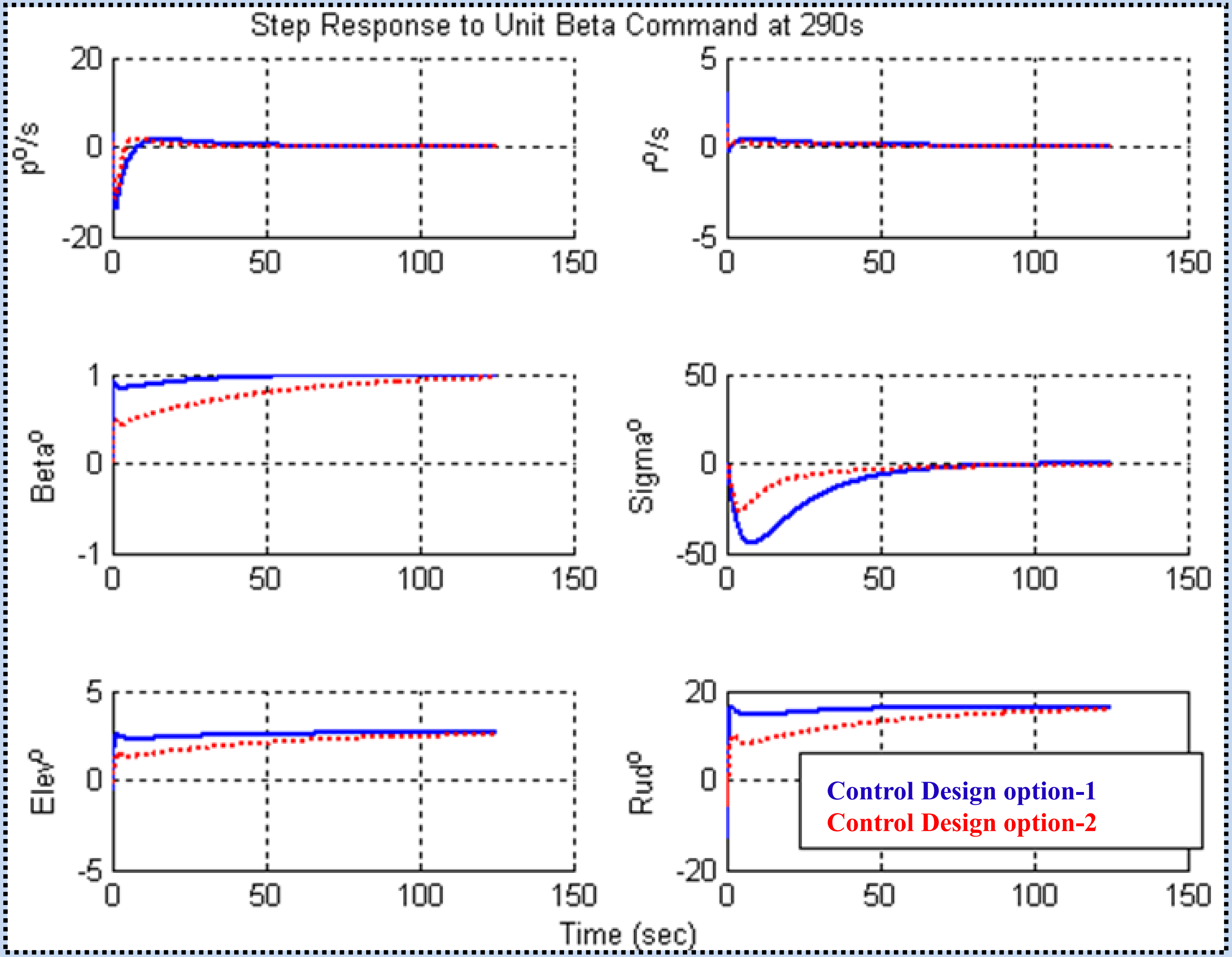
$$\begin{bmatrix}\dot{p}\\ \dot{r}\\ \dot{\beta}\\ \dot{\sigma}\end{bmatrix} = \begin{bmatrix} L_p & L_r & L_\beta & L_\sigma \\ N_p & N_r & N_\beta & N_\sigma \\ \sin(\alpha_{trim}) + Y_p & -\cos(\alpha_{trim}) + Y_r & Y_\beta & Y_\sigma \\ \cos(\alpha_{trim}) & \sin(\alpha_{trim}) & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \sigma \end{bmatrix} + \begin{bmatrix} L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & Y_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_r \end{bmatrix}$$

Output equations

$$\begin{bmatrix}\dot{\sigma}\\ \dot{\beta}\\ \beta\\ \sigma\end{bmatrix} = \begin{bmatrix} \cos(\alpha_{trim}) & \sin(\alpha_{trim}) & 0 & 0 \\ \sin(\alpha_{trim}) & -\cos(\alpha_{trim}) & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \sigma \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_r \end{bmatrix}$$

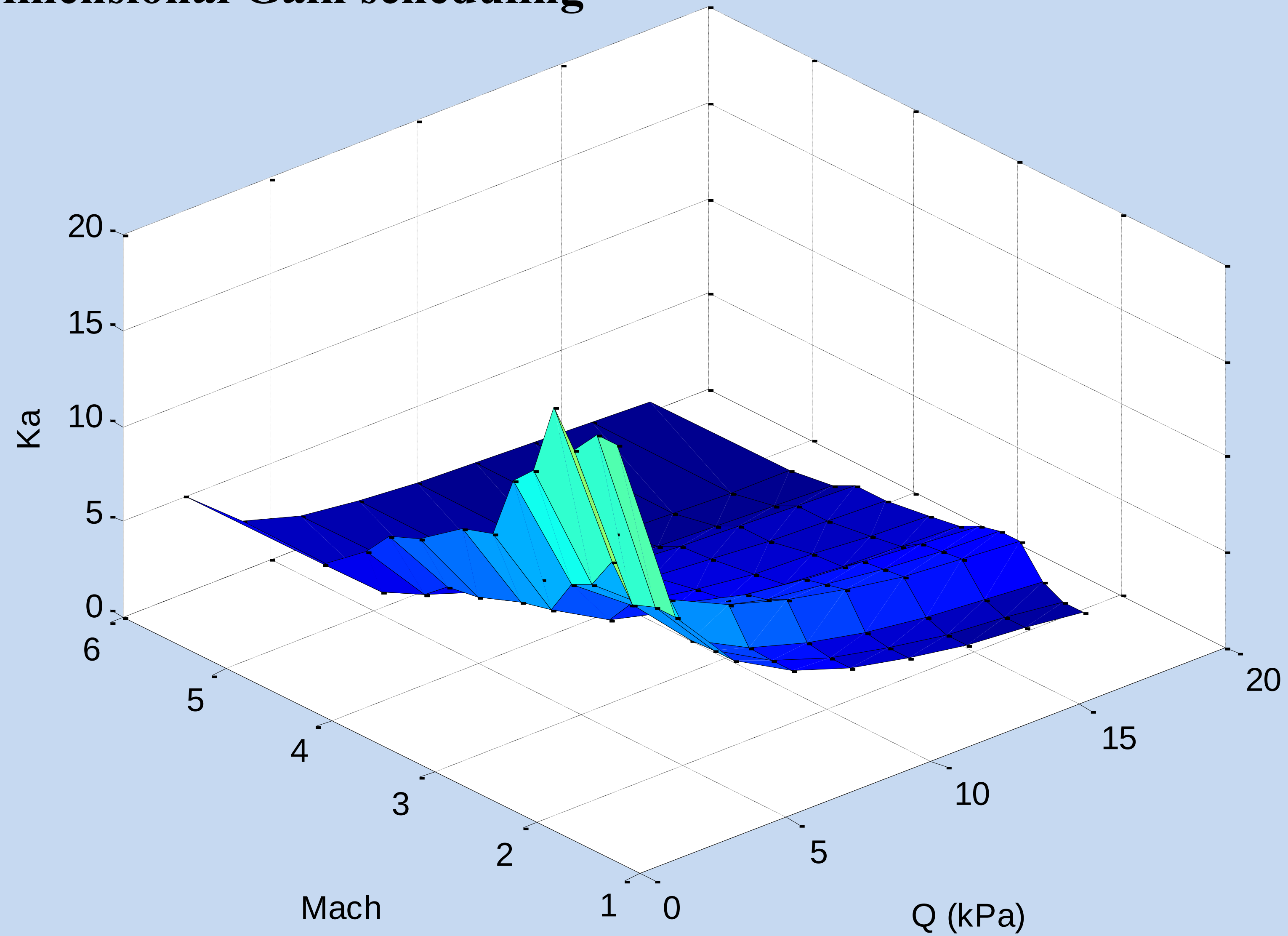
$$\begin{bmatrix} \dot{p} \\ \dot{r} \\ \dot{\beta} \\ \dot{\sigma} \end{bmatrix} = \begin{bmatrix} L_p & L_r & \underset{\downarrow\,-74.5}{L_\beta} & L_\sigma \\ N_p & N_r & N_\beta & N_\sigma \\ \sin(\alpha_{trim}) + Y_p & -\cos(\alpha_{trim}) + Y_r & Y_\beta & Y_\sigma \\ \cos(\alpha_{trim}) & \sin(\alpha_{trim}) & 0 & 0 \end{bmatrix} \begin{bmatrix} p \\ r \\ \beta \\ \sigma \end{bmatrix} + \begin{bmatrix} \underset{\downarrow\,139.8}{L_{\delta_a}} & \underset{\downarrow\,8.9}{L_{\delta_r}} \\ \underset{\downarrow\,15}{N_{\delta_a}} & N_{\delta_r} \\ 0 & Y_{\delta_r} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_e \\ \delta_r \end{bmatrix}$$

Yaw Roll Dynamics coupling



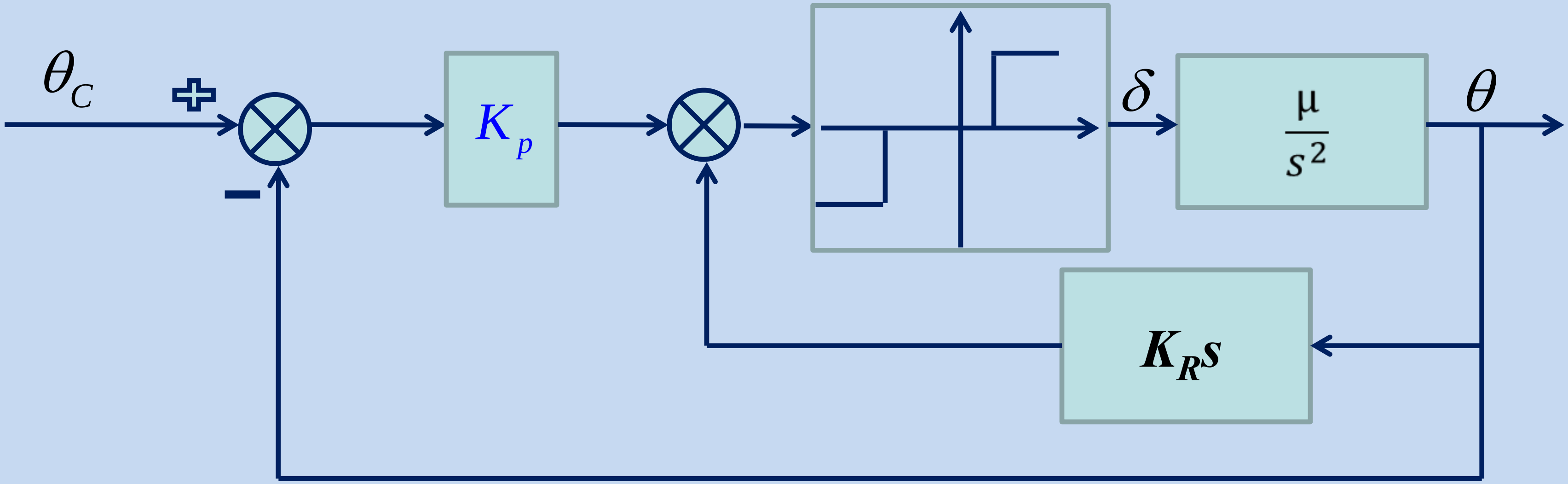
Forward Path Gain

2-Dimensional Gain scheduling



Non-Linear Control

- Integrator limit
- Rate Control Limit
- Dead-zone



Block Diagram : ON-OFF Control with Dead-zone

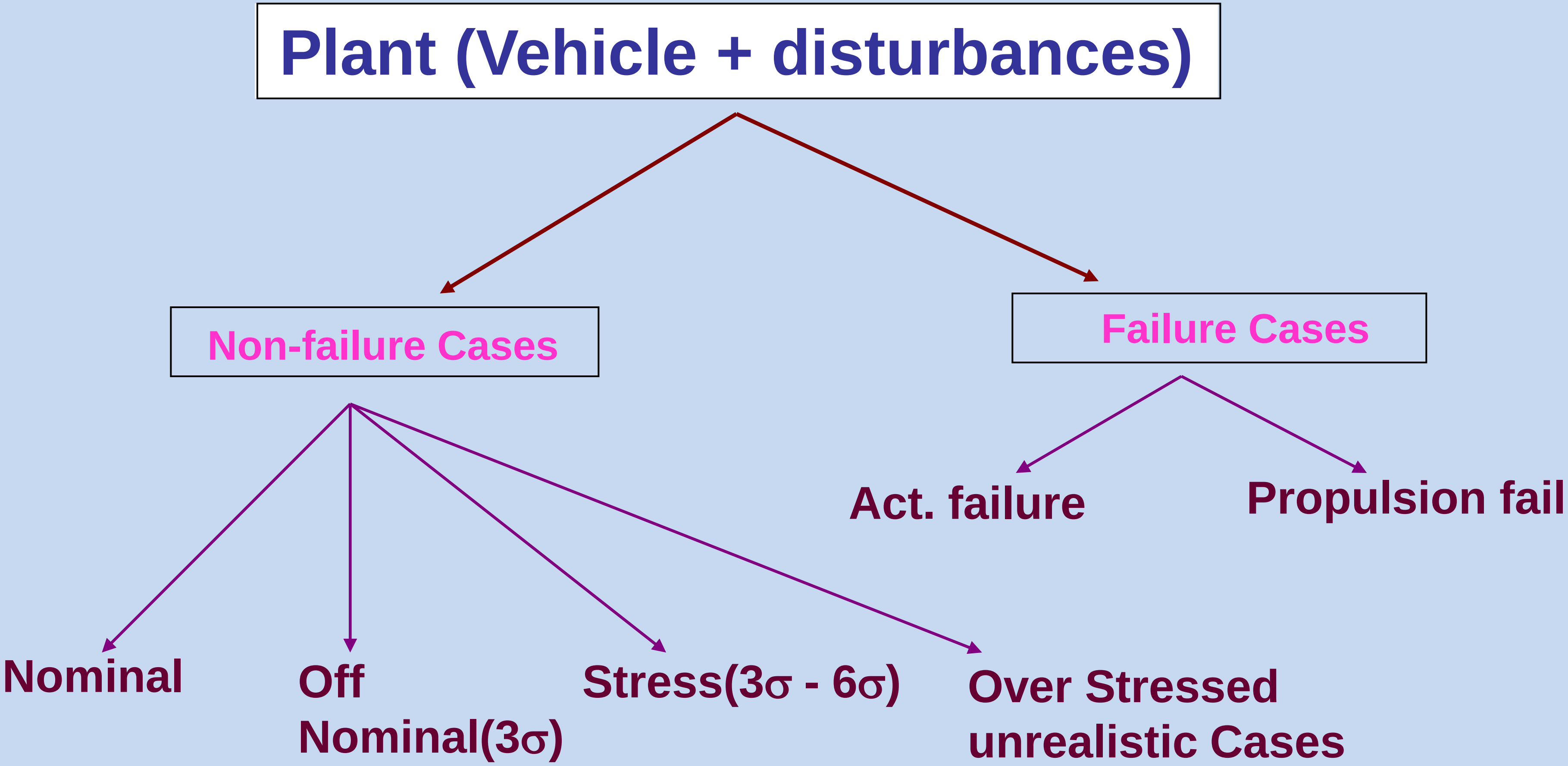
Design parameters

- Control Law- Error computation
- Gain Schedule
- Filters
- Integrator
- Nonlinear control Logics

Implementation Aspects

- Finite Word length Machine
- Memory and Execution Time
- Fixed point representation
- Accuracy and Scaling
- Overflow problems
- Transportation and computational delays

Control Design & Validation Philosophy



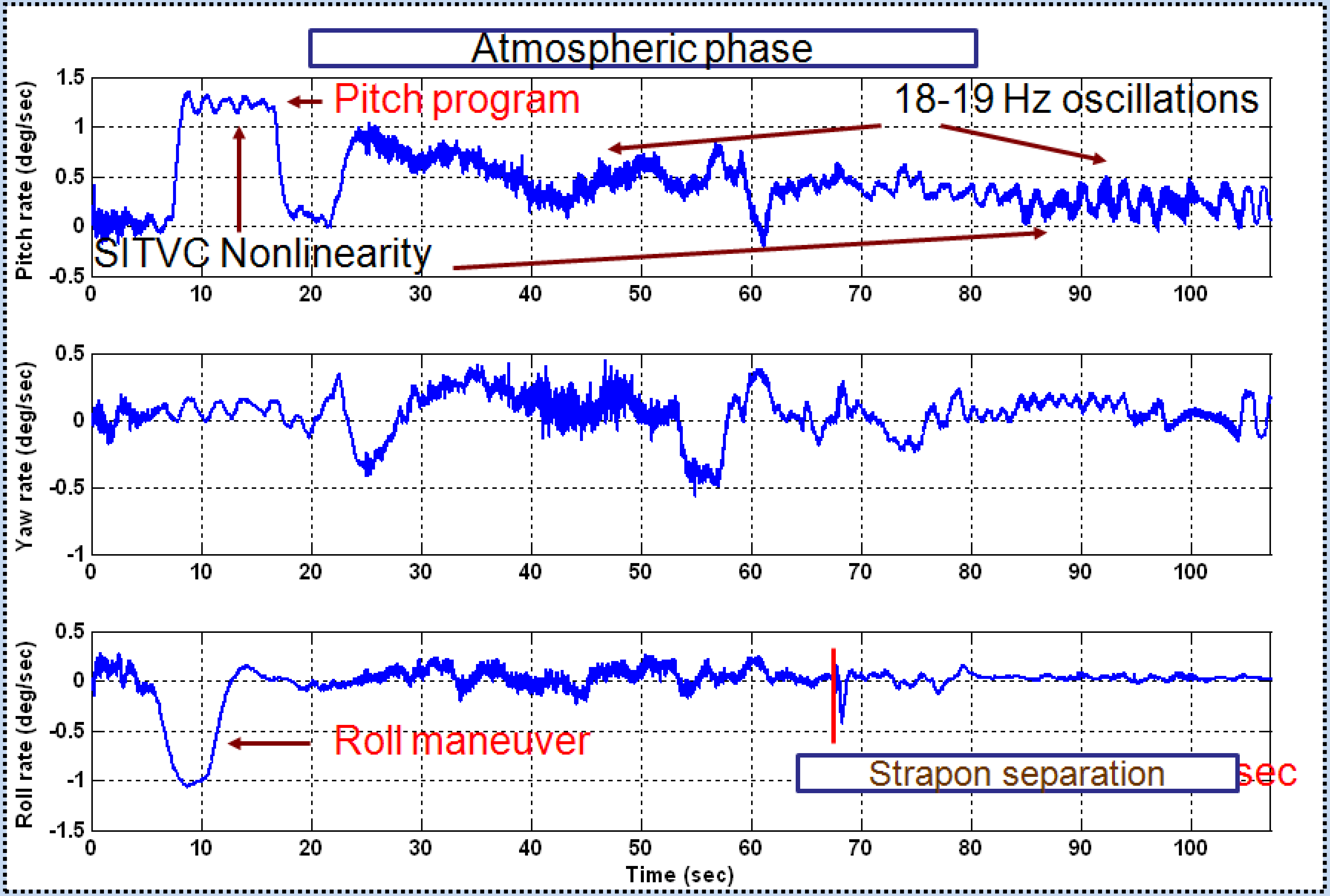
Plant (Vehicle + disturbances)

- Non-failure Cases
  - Nominal
  - Off Nominal(3σ)
  - Stress(3σ - 6σ)
  - Over Stressed unrealistic Cases
- Failure Cases
  - Act. failure
  - Propulsion fail

Validation

- Simulated Input Profile (SIP)
- OBC In Loop Simulation (OILS)
- Hardware In Loop Simulation (HLS)
- Actuator In Loop Simulation (ALS)
- Flight Test
- Post flight analysis – Disturbance calculation- model matching
- Model Update / Design Update

Post Flight Analysis



Atmospheric phase

Pitch program

18-19 Hz oscillations

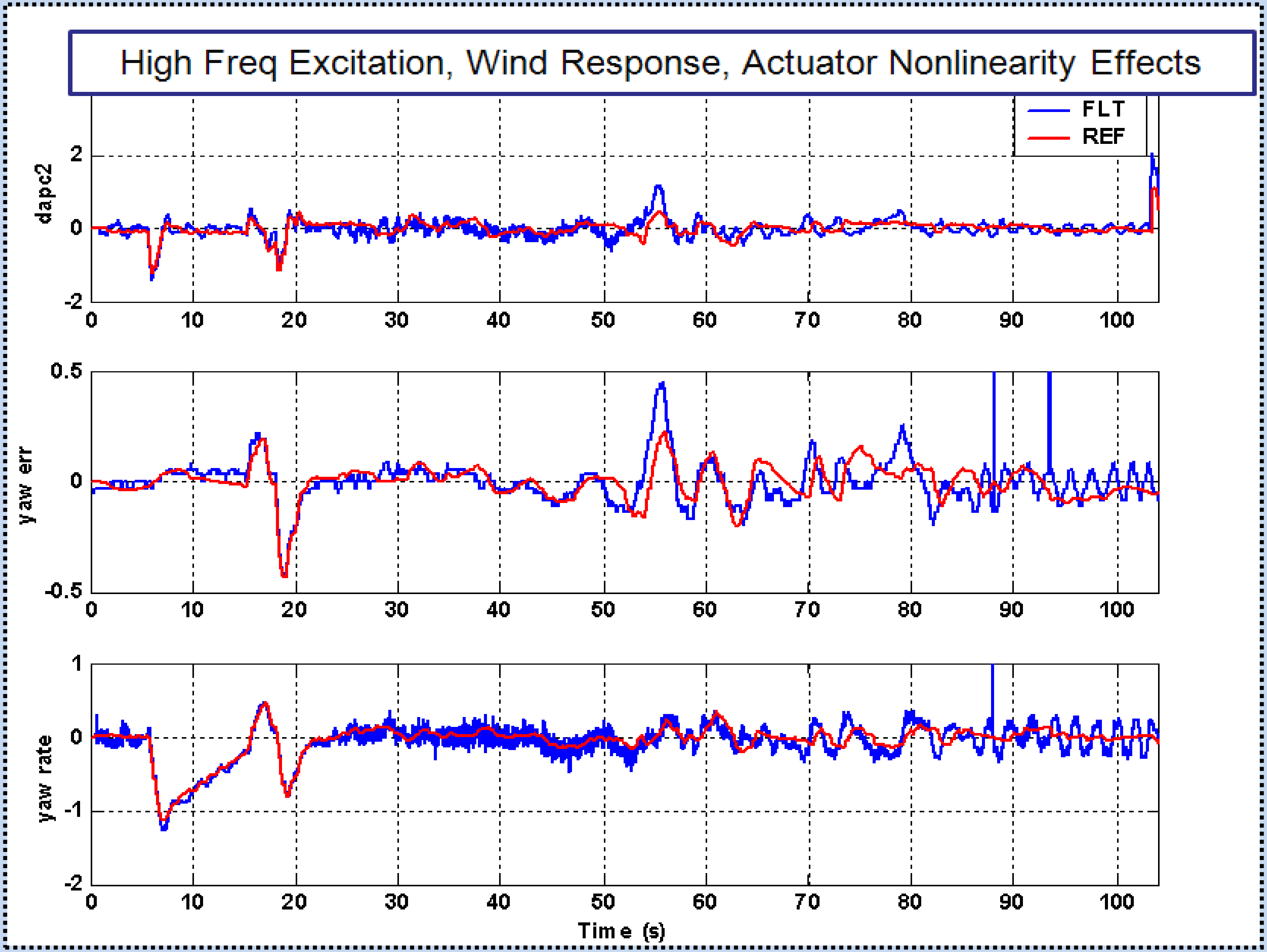
SITVC Nonlinearity

Roll maneuver

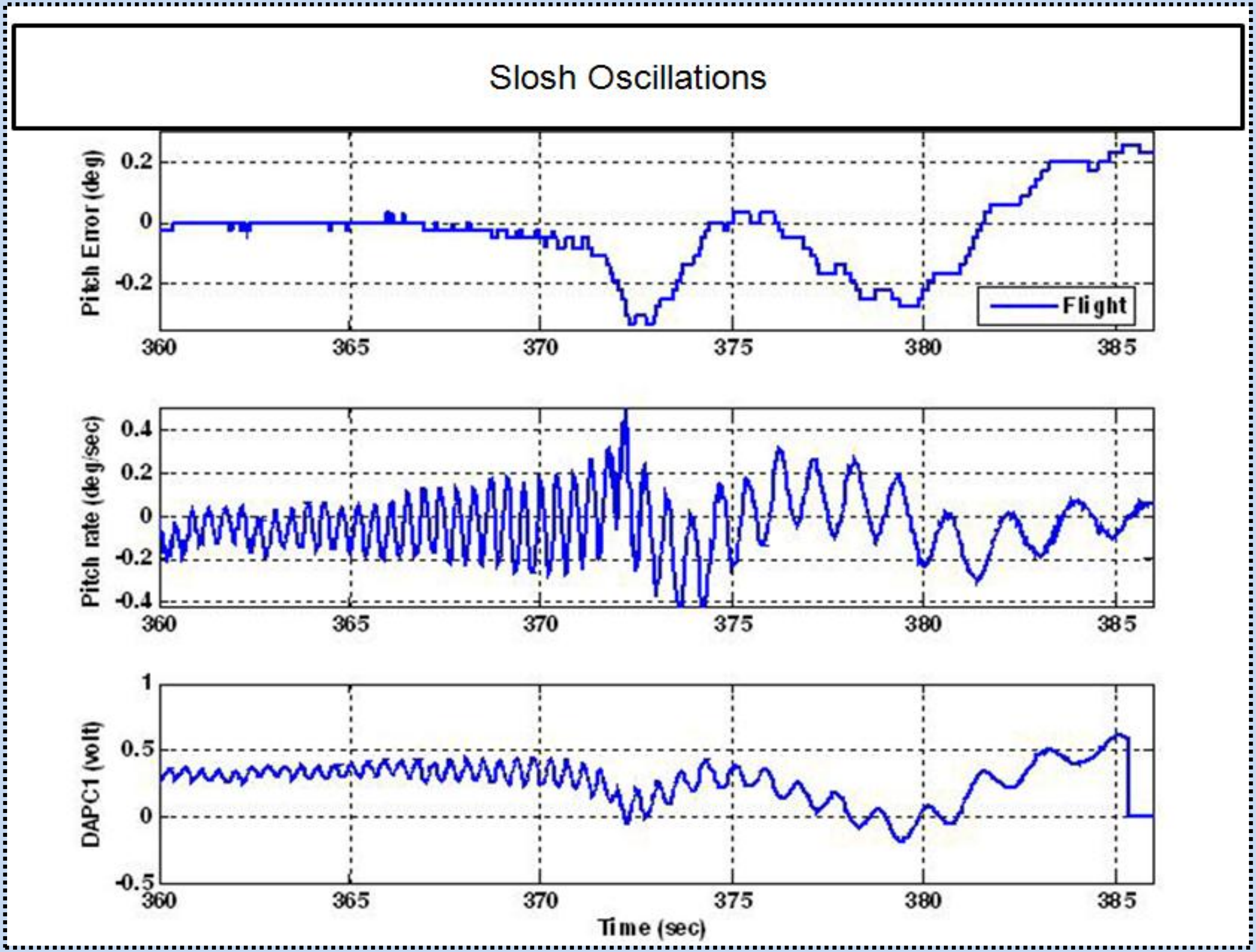
Strapon separation

sec

Post Flight Analysis



Post Flight Analysis



Challenges in Design

- Complexity of the model
- Robust Design Requirement
- Fault tolerance
- SISO to MIMO
- Unified Design Approach
- Design Automation
- Code Automation

- **Acknowledgement**

  I would like to acknowledge my colleagues from Control Design division, CGDG, VSSC for their support in preparation of this course material.

Thank You