Advanced Robust Control Design for the VEGA Launch Vehicle

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Layout

1. Motivation
2. VEGA mission & vehicle
3. Structured H-infinity synthesis
4. LPV (Linear Parameter Varying) synthesis
5. Conclusions

TASC Group:
Launcher activities in support of ESA

2014

esa — "Analytic Stochastic Time Varying Mu Analysis for the VEGA GNC (V&Vprob)" [2014-2017]

esa — Pedro Símplicio ESA traineeship [2014-2016]

→ **Robust Modeling & Analysis**

2015

esa — "Robust & Adaptable Launcher TVC Control Systems for the VEGA Evolution (VEGAdapt)" [2015-2018]

→ **Robust Control (Ascent)**
Diego Navarro-Tapia's PhD

2016

UK SPACE AGENCY — "Robust Nonlinear Guidance and Control for Landing on Small Bodies (NTSP2)" [2016-2017]

2017

esa — "Advanced Flight Control System Design with Active Load & Relief Capabilities (TAILOR)" [2017-2020]

→ **Robust Guidance & Control (Entry, Descent & landing)**

Reusable Launcher
Pedro Simplício's PhD

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VEGA mission and vehicle:
VEGA mission

VEGA (Vettore Europeo di Generazione Avanzata)

is the **new European Small Launch Vehicle**

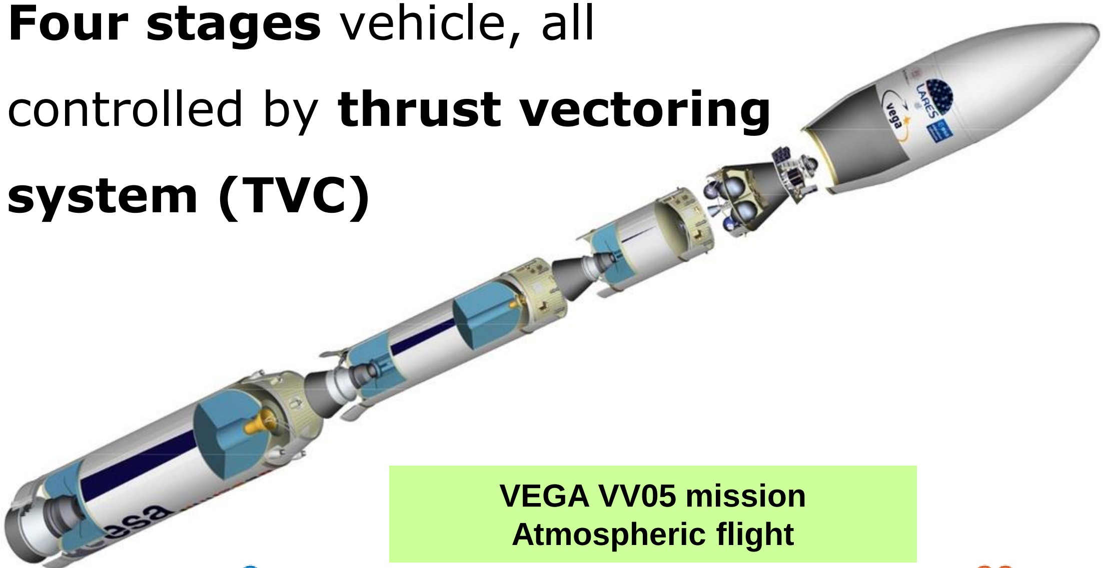
11 successful flights

- **1st flight** on 13th February 2012 (Multi payload)
- **2nd flight** on 7th May 2013 (Multi payload)
- **3rd flight** on 30th April 2014 (KazEOSAT-1)
- **4th flight** on 11th February 2015 (IXV)
- **5th flight** on 23rd June 2015 (Sentinel-2A)
- **6th flight** on 3rd December 2015 (LISA Pathfinder)
- **7th flight** on 16th September 2016 (Multi payload)
- **8th flight** on 5th December 2016 (Göktürk-1A)
- **9th flight** on 7th March 2017 (Sentinel 2B)
- **10th flight** on 1st August 2017 (Multi payload)
- **11th flight** on 8th November 2017 (Mohammed VI-A)

VEGA Soyuz Arianne 5 Saturn V

VEGA mission and vehicle:
Challenges – Vehicle, Environment and Dynamics

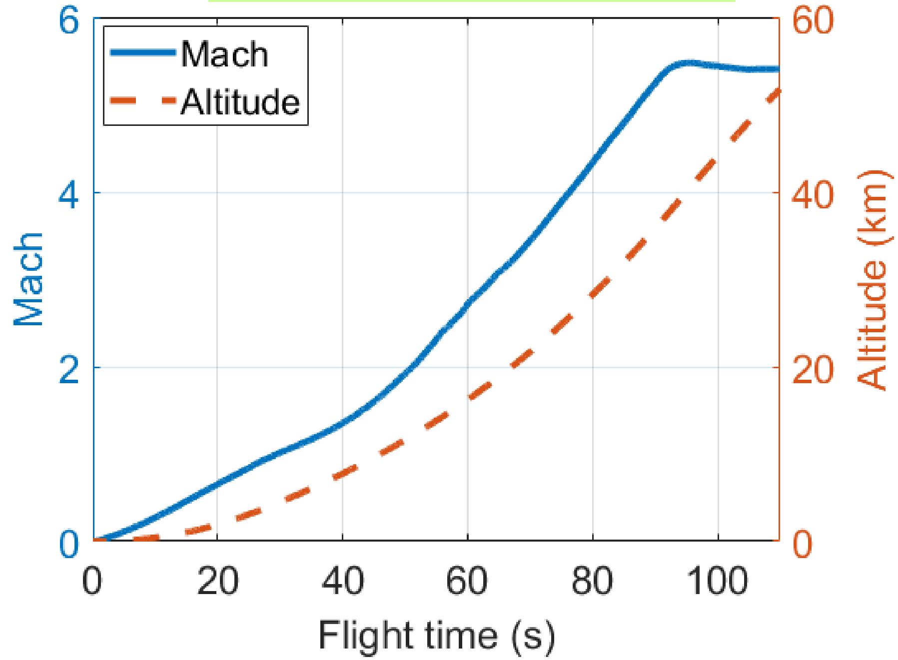
Four stages vehicle, all controlled by **thrust vectoring system (TVC)**



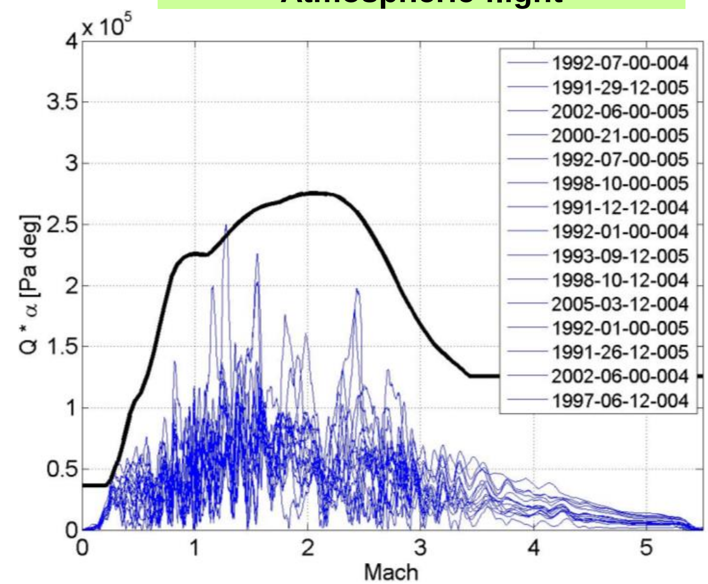
Atmospheric phase challenges

- ❑ **Launcher vehicle:**
  - Unstable
  - Flexible structure
- ❑ **High variation of flight parameters**
- ❑ **Challenging environment**:
  - Wind disturbances
  - Structural loads (Qalpha)

VEGA VV05 mission
Atmospheric flight



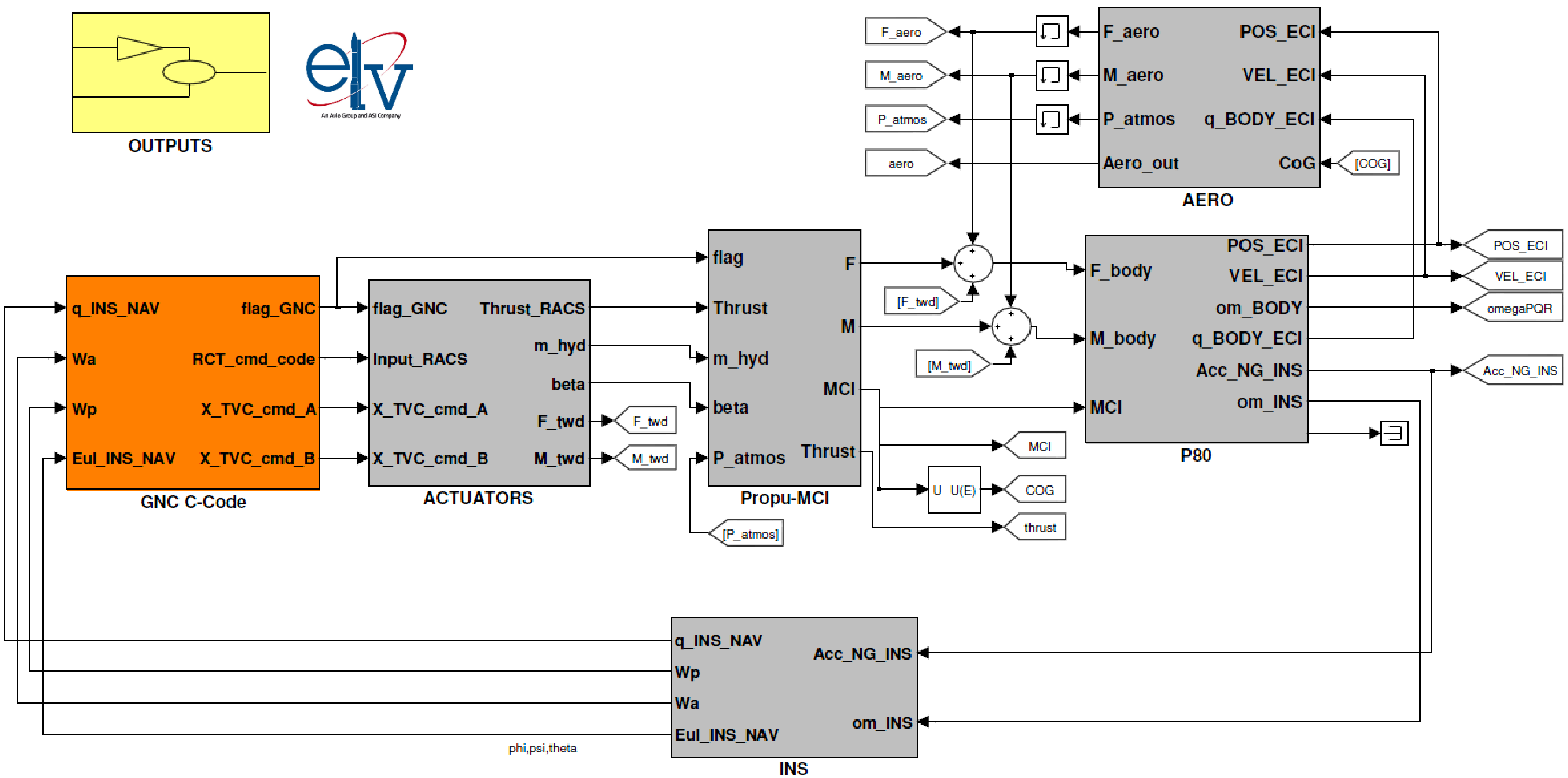
VEGA Q*alpha wind effect
Atmospheric flight



VEGA mission and vehicle:

High-fidelity, nonlinear, time-domain simulator

- The model used is a **6 degrees-of-freedom nonlinear simulator of the VEGA launcher** set up to perform simulations in the atmospheric flight phase P80, **VEGACONTROL**
- It is developed in Simulink with S-Function written in C-code and includes:



VEGA mission and vehicle:
VEGACONTROL simulator – Uncertainties

120 uncertain and dispersion parameters: MCI, bending modes characteristics …

Type	Flag	Description
AEROELASTICITY	Flag.aeroelastic	aero-elasticity effect (+10% on CN coefficient)
AERODYNAMICS	Flag.disp_CA	Dispersion on 1st Stage Axial Coefficient
	Flag.unc_CA	Uncertainty on 1st Stage Axial Coefficient
	Flag.disp_CN	Dispersion on 1st Stage Normal Coefficient
	Flag.unc_CN	Uncertainty on 1st Stage Normal Coefficient
	Flag.disp_Xcp	Dispersion on 1st Stage Xcp
	Flag.unc_Xcp	Uncertainty on 1st Stage Xcp
	Flag.aero_roll	To enable Roll motion
WIND	Flag.azimuth_wind_angle	Wind azimuth direction [rad]
	Flag.h_wind	Synthetic wind gust altitude [Km]
IRS	Flag.IRSmountingX	IRS Mounting Error wrt X Body Axis
	Flag.IRSmountingY	IRS Mounting Error wrt Y Body Axis
	Flag.IRSmountingZ	IRS Mounting Error wrt Z Body Axis
THRUST PARAMETERS SCATTERING	Flag.dISP	1st stage impulse scattering
	Flag.dTc	Scattering on time burn
	Flag.SRM_roll	Scattering on P80 Roll Torque
MCI	Flag.stagedM	Structural mass scattering
	Flag.stagedM_Prop	Scattering on propellant mass
	Flag.stagedJx	Scattering on Stage XX MOI
	Flag.stagedJy	Scattering on Stage YY MOI
	Flag.stagedJz	Scattering on Stage ZZ MOI
	Flag. stagedxCOG	Scattering on X CoG
	Flag. stagedyCOG	Scattering on Y CoG
	Flag. stagedzCOG	Scattering on Z CoG
	Flag. stagedJx_S	Scattering on structural Stage XX MOI
	Flag. stagedJy_S	Scattering on structural Stage YY MOI
	Flag. stagedJz_S	Scattering on structural Stage ZZ MOI
	Flag. stagedxCOG_S	Scattering on structural X CoG
	Flag. stagedyCOG_S	Scattering on Y structural CoG

MCI	Flag.PLdM	Scattering on PL Mass
	Flag.PLdJx	Scattering on PL XX MOI
	Flag.PldJy	Scattering on PL YY MOI
	Flag.PLdJz	Scattering on PL ZZ MOI
	Flag.PLdxCOG	Scattering on PL X CoG
	Flag.PLdyCOG	Scattering on PL Y CoG
	Flag.PLdzCOG	Scattering on PL Z CoG
THRUST OFFSET & MISALIGNMENT	Flag.TVC_SF_A	Scattering on TVC gain Lane A
	Flag.TVC_bias_A_disp	Scattering on TVC Lane A (Gaussian)
	Flag.TVC_bias_A_unc	Scattering on TVC Lane A (uniform)
	Flag.TVC_SF_B	Scattering on TVC gain Lane B
	Flag.TVC_bias_B_disp	Scattering on TVC Lane B (Gaussian)
	Flag.TVC_bias_B_unc	Scattering on TVC Lane B (uniform)
	Flag.Thrust_misA_disp	Scattering on thrust misalignment first lane (Gaussian)
	Flag.Thrust_misB_disp	Scattering on thrust misalignment second lane (Gaussian)
	Flag.Thrust_misA_unc	Scattering on thrust misalignment first lane (uniform)
	Flag.Thrust_misB_unc	Scattering on thrust misalignment second lane (uniform)
	Flag.PvP_offsetX	Scattering on thrust offset in X
	Flag.PvP_offsetY_disp	Scattering on thrust offset in Y (Gaussian)
	Flag.PvP_offsetZ_disp	Scattering on thrust offset in Z (Gaussian)
	Flag.PvP_offsetY_unc	Scattering on thrust offset in Y (uniform)
	Flag.PvP_offsetZ_unc	Scattering on thrust offset in Z (uniform)
ATMOSPHERE	Flag.air_density_scat	Atmospheric Density
SEPARATION DISTURB	Flag.sep_dist_yz	

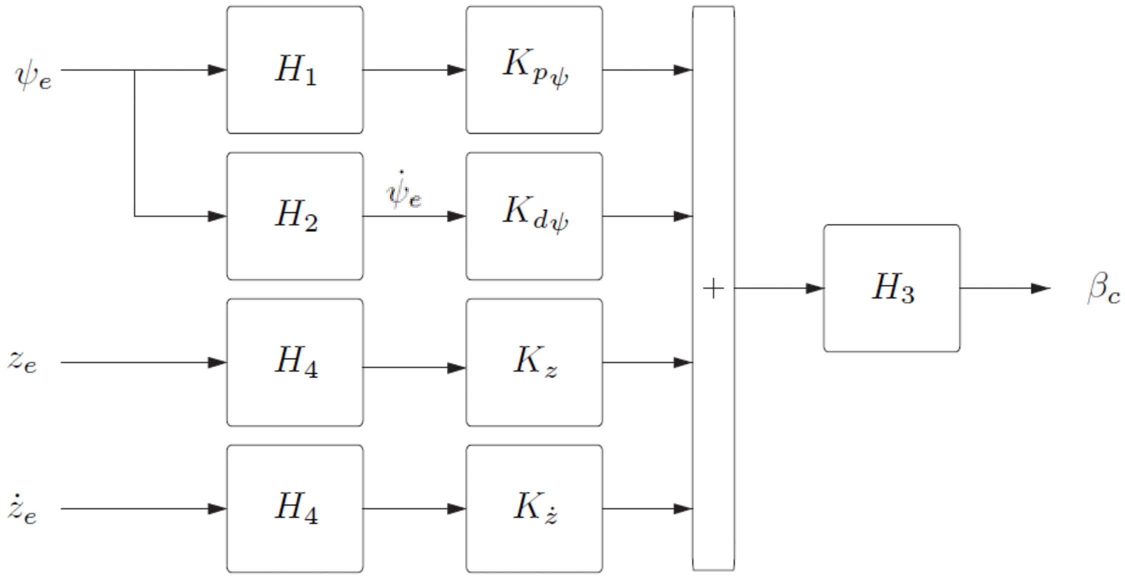
VEGA mission and vehicle:
Industrial state-of-the-practice for control design

1. Launcher **model linearized** at flight times = [10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110]secs

2. For each point, **independent design first & then joint tuning** of:
   - Rigid-body control design
   - Flexible bending filter design
   - Rigid- and flexible-body joint tuning

3. **Ad-hoc gain scheduling** based on some parameter (time, VNG)

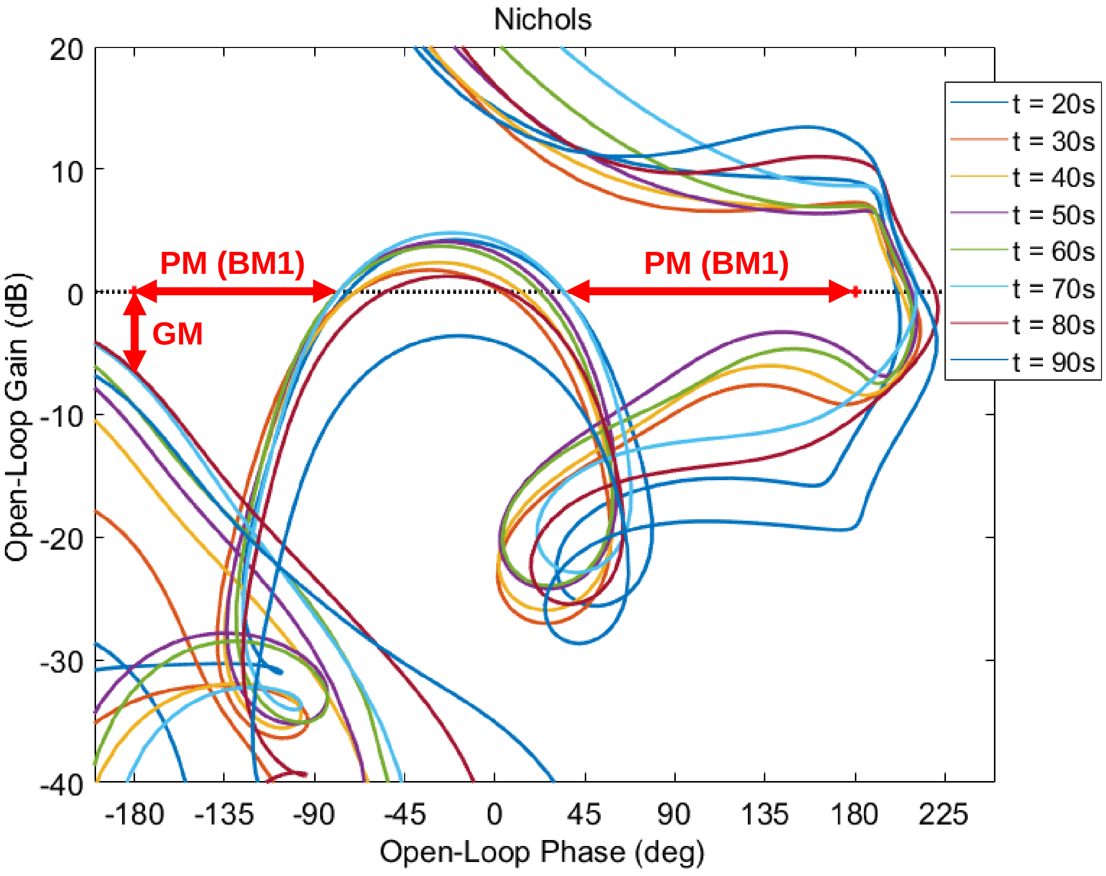
4. **Intensive V&V process** using high fidelity nonlinear simulation

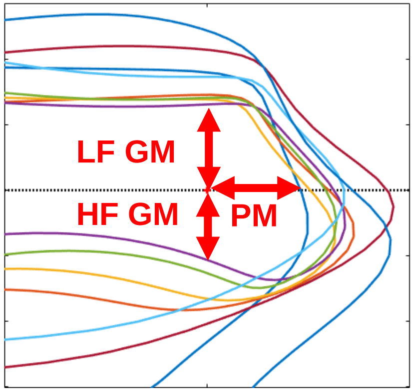


VEGA controller structure

- **PD in attitude**
- **Lateral control**
  (drift and drift-rate)
- **H filters (for Bending Modes)**

VEGA mission and vehicle:
Industrial state-of-the-practice for control design





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Structured H-infinity synthesis:

Why structured H_∞ control synthesis technique

Standard H∞ design **widely operational** but has several practical limitations:

- The designed controller is usually of **high-order** (and **sometimes unstable**)
- H-infinity generates controllers **without defined structure**

Structured H∞ design (**HINFSTRUCT & SYSTUNE**) allows to:

- Synthesize controllers with a **desired order and structure**
- Use the **same design framework as H∞**

  - But still, process to select weighting functions / objectives can be **tedious and unclear**

  - And it is **not deterministic** ➔ difficult to learnt from weight changing

It appeared only a few years ago but has had great impact on aerospace world

With already several examples of flown systems:

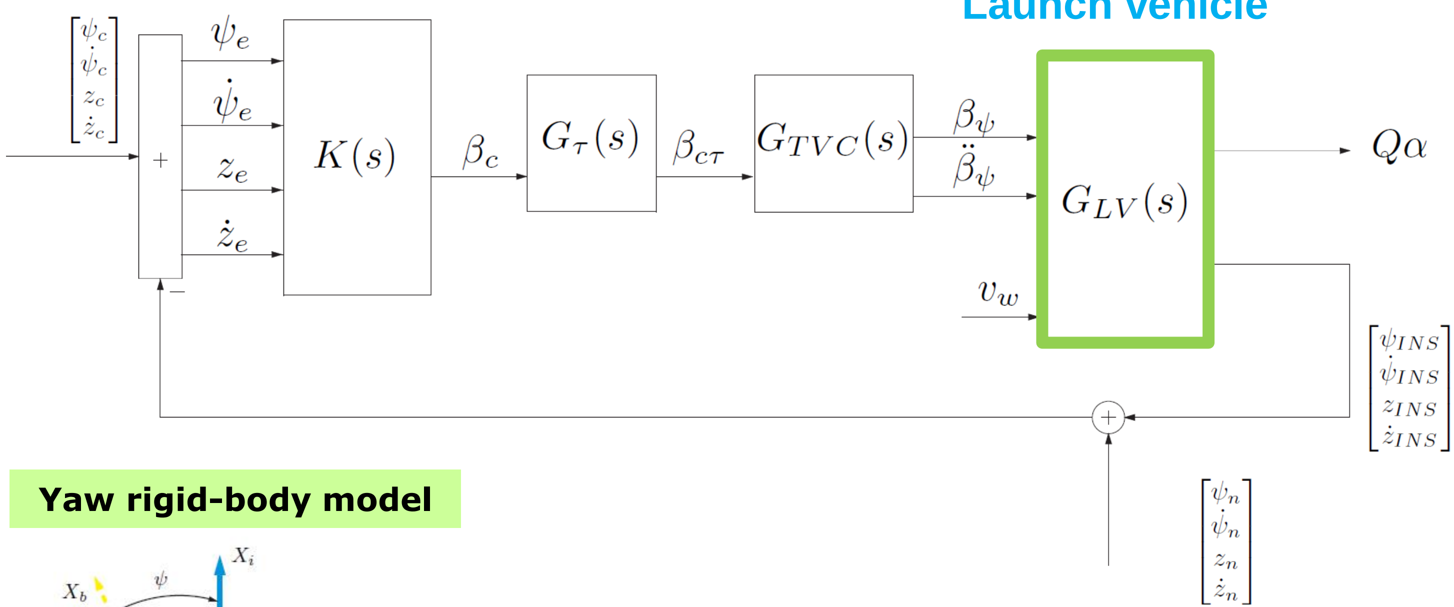
Airbus DS (Astrium SAS Toulouse) / ESA	*CNES (Toulouse)*	*University of Bristol TASC*
ROSETTA spacecraft	*MICROSCOPE satellite*	*JAXA MuPAL-α aircraft*

Structured H-infinity synthesis:
LEGACY RECOVERY - Design augmentation scheme

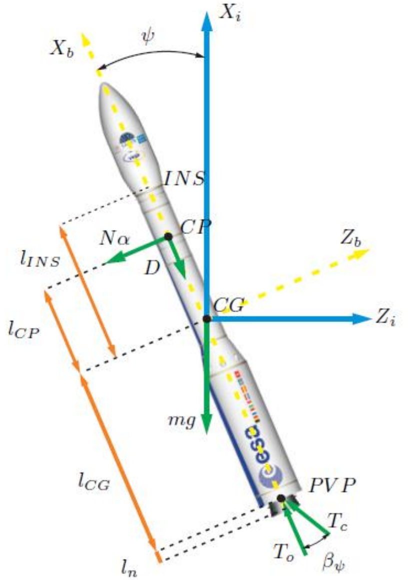
CLASSICAL CONTROL	STRUCTURED H-INFINITY
Nominal design	Nominal design

Main objective: recover the VEGA VV05 baseline rigid-body controller

Structured H-infinity synthesis:
LEGACY RECOVERY - Design interconnection



Yaw rigid-body model



The **launcher dynamics** described by:

Rotational motion (yaw ψ or pitch θ)

Translational motion (*y* or *z*)

Yaw and pitch planes are identical

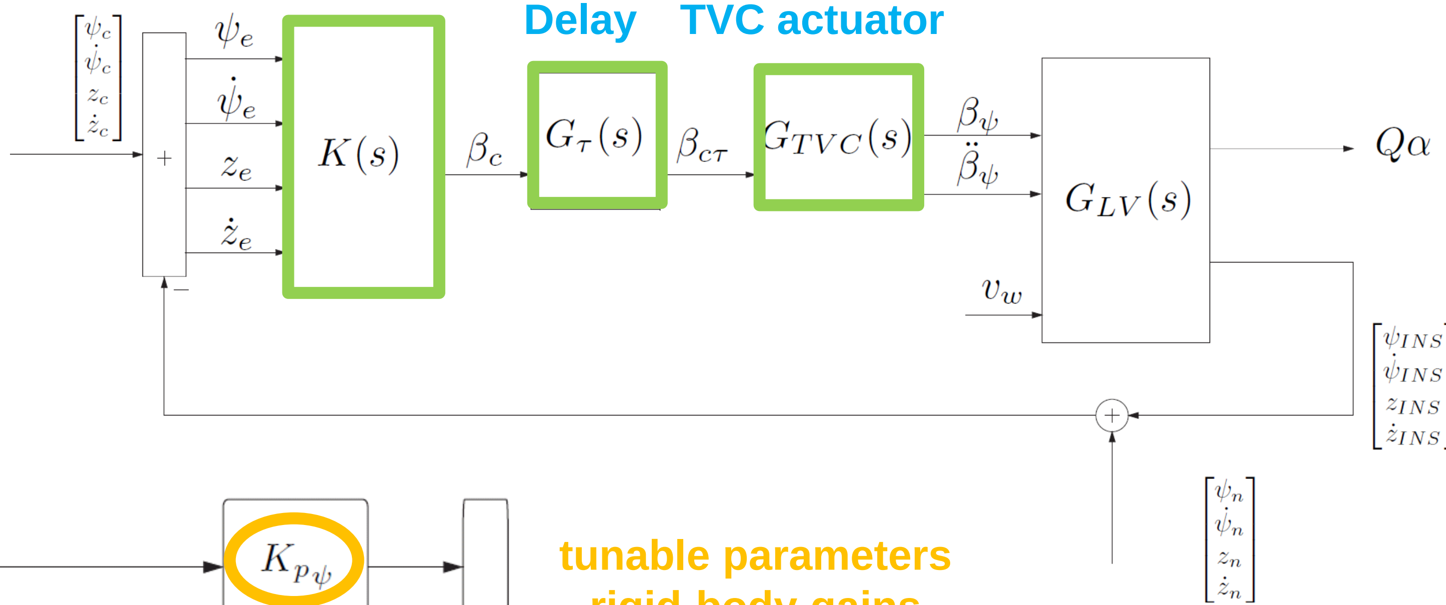
if the roll rate is considered negligible.

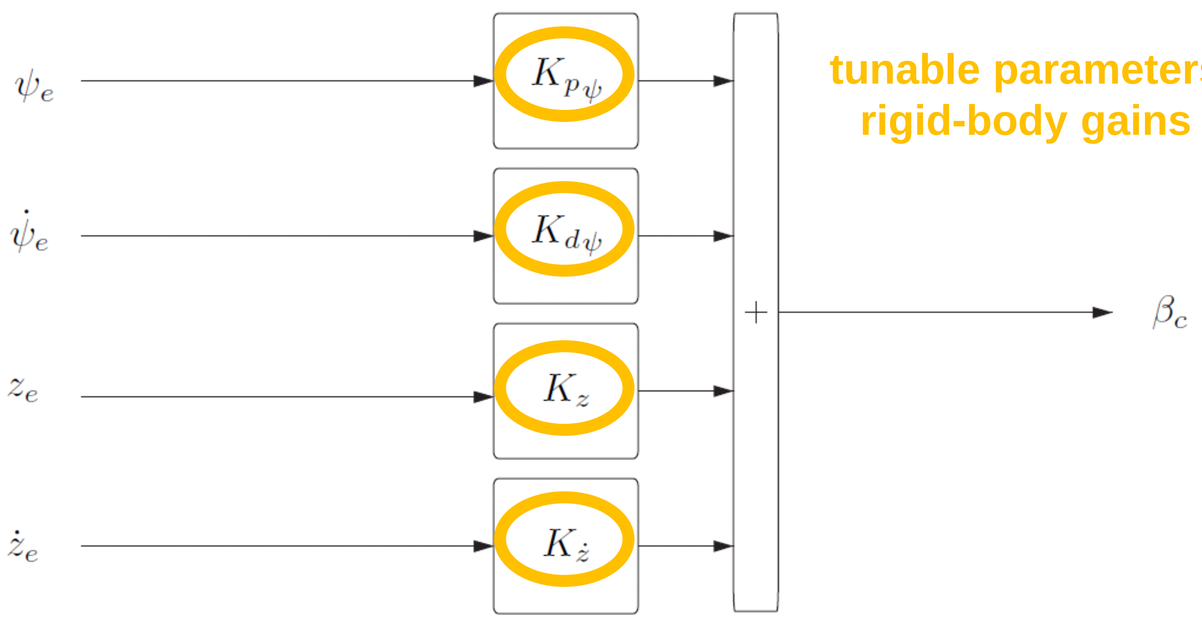
Structured H-infinity synthesis:
LEGACY RECOVERY - Design interconnection

Controller

Delay

TVC actuator





tunable parameters
rigid-body gains

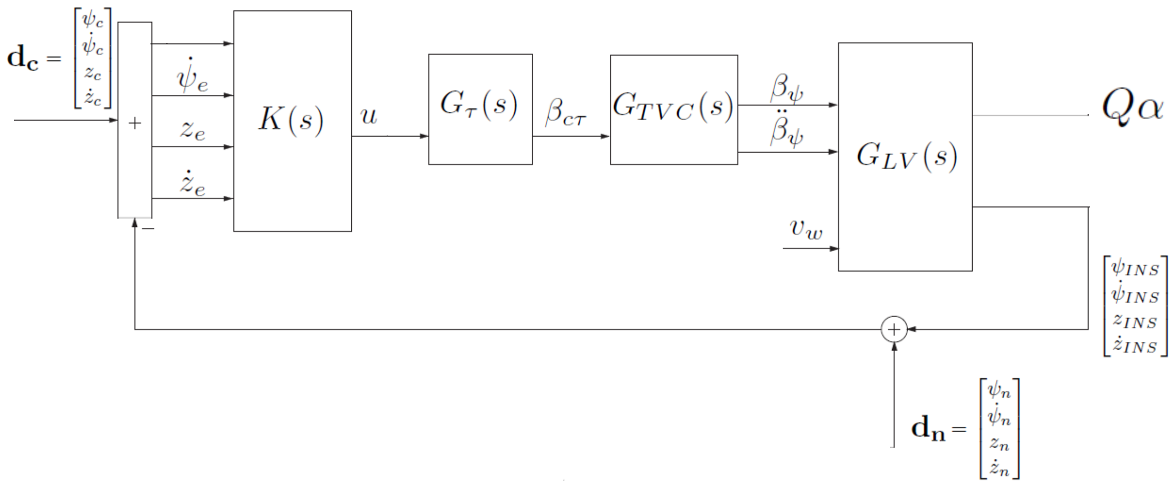
Rigid-body design

VEGA controller structure

- **PD in attitude**
- **Lateral control**
  (drift and drift-rate)
- **H filters**

Structured H-infinity synthesis:
LEGACY RECOVERY - Requirements formulation

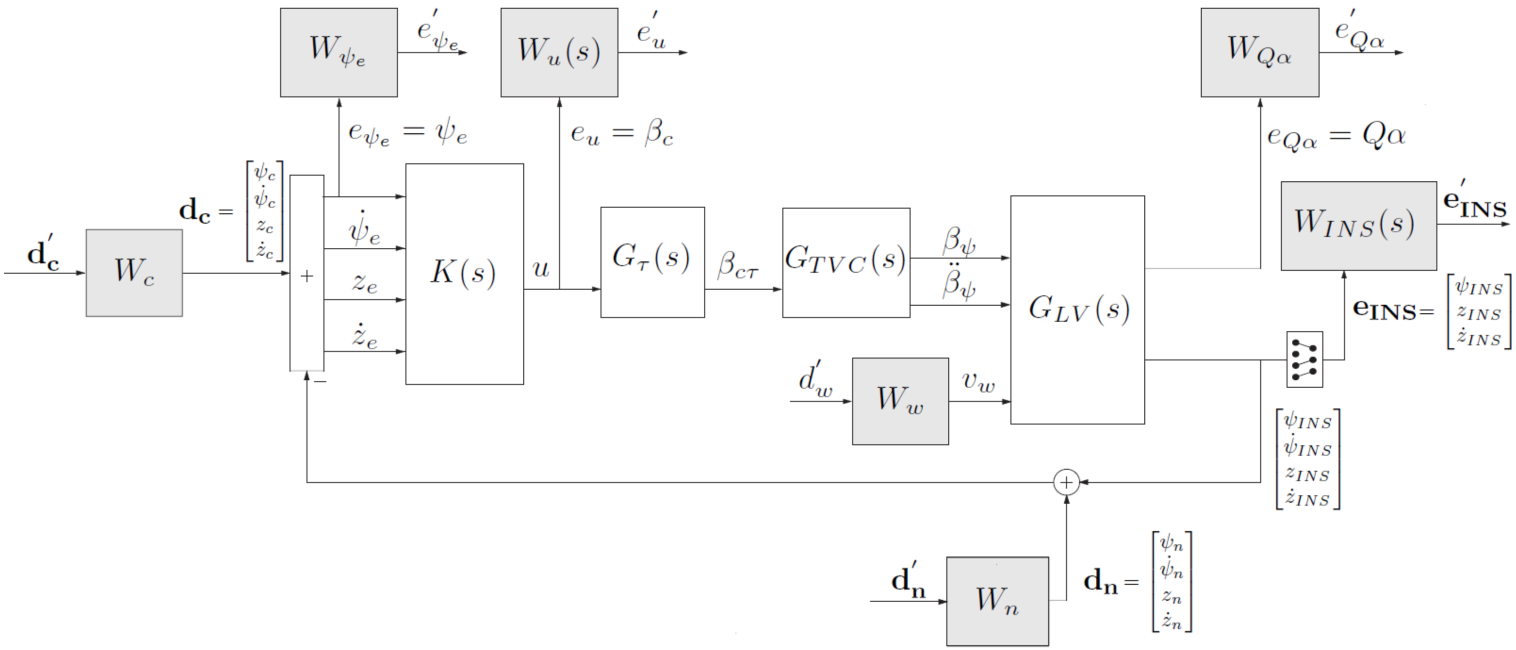
Requirements expressed as input/output weighting functions



Structured H-infinity synthesis:

LEGACY RECOVERY - Requirements formulation

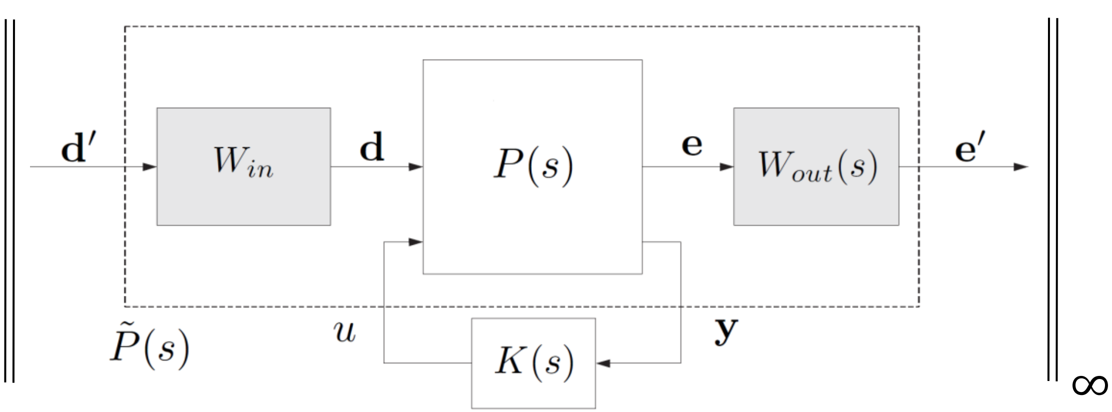
Requirements expressed as input/output weighting functions



Standard H_∞ interconnection

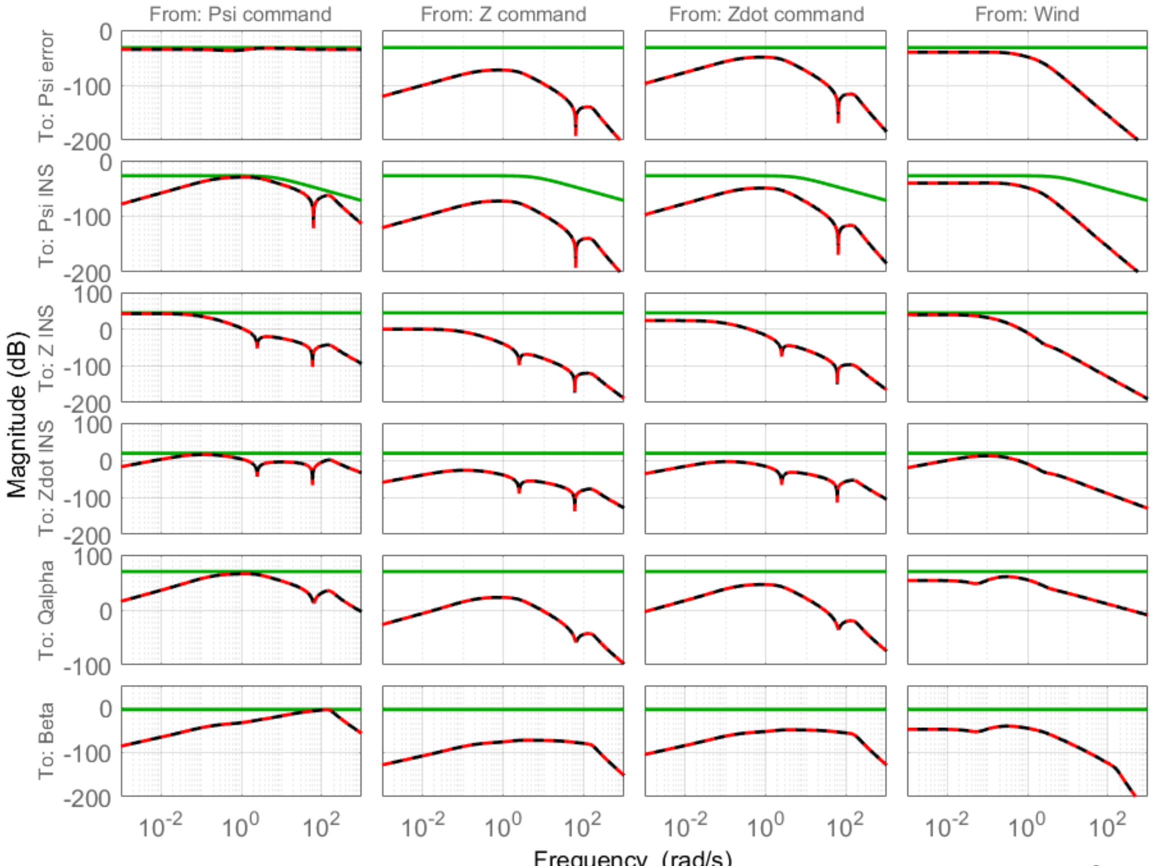
Structured H-infinity Control problem

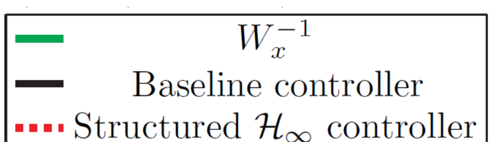
$$\min_{K(s)} ||\mathcal{F}_l(\tilde{P}(s), K(s))||_\infty$$



Structured H-infinity synthesis:

LEGACY RECOVERY - VEGA legacy recovery





$$\frac{z_{INS}}{\psi_c}(s) = K_p \frac{s^2[a_p + l_{INS}k_1] + s[a_2k_1 - a_5a_p + l_{INS}(a_4a_p - a_1k_1)] + [a_3k_1 - a_6a_p]}{\Delta_c}$$

$$\frac{z_{INS}}{\dot{\psi}_c}(s) = K_d s \frac{s^2[a_p + l_{INS}k_1] + s[a_2k_1 - a_5a_p + l_{INS}(a_4a_p - a_1k_1)] + [a_3k_1 - a_6a_p]}{\Delta_c}$$

$$\frac{\psi_{INS}}{v_w}(s) = -\frac{s^2[a_4] + s[K_{\dot{z}}(a_4a_p - a_1k_1)] + [K_z(a_4a_p - a_1k_1)]}{\Delta_c}$$

$$\frac{z_{INS}}{v_w}(s) = -\frac{s^2[a_1 + l_{INS}a_4] - s[K_d(a_4a_p - a_1k_1)] + [K_p(a_4a_p - a_1k_1) + a_1a_6 - a_3a_4]}{\Delta_c}$$

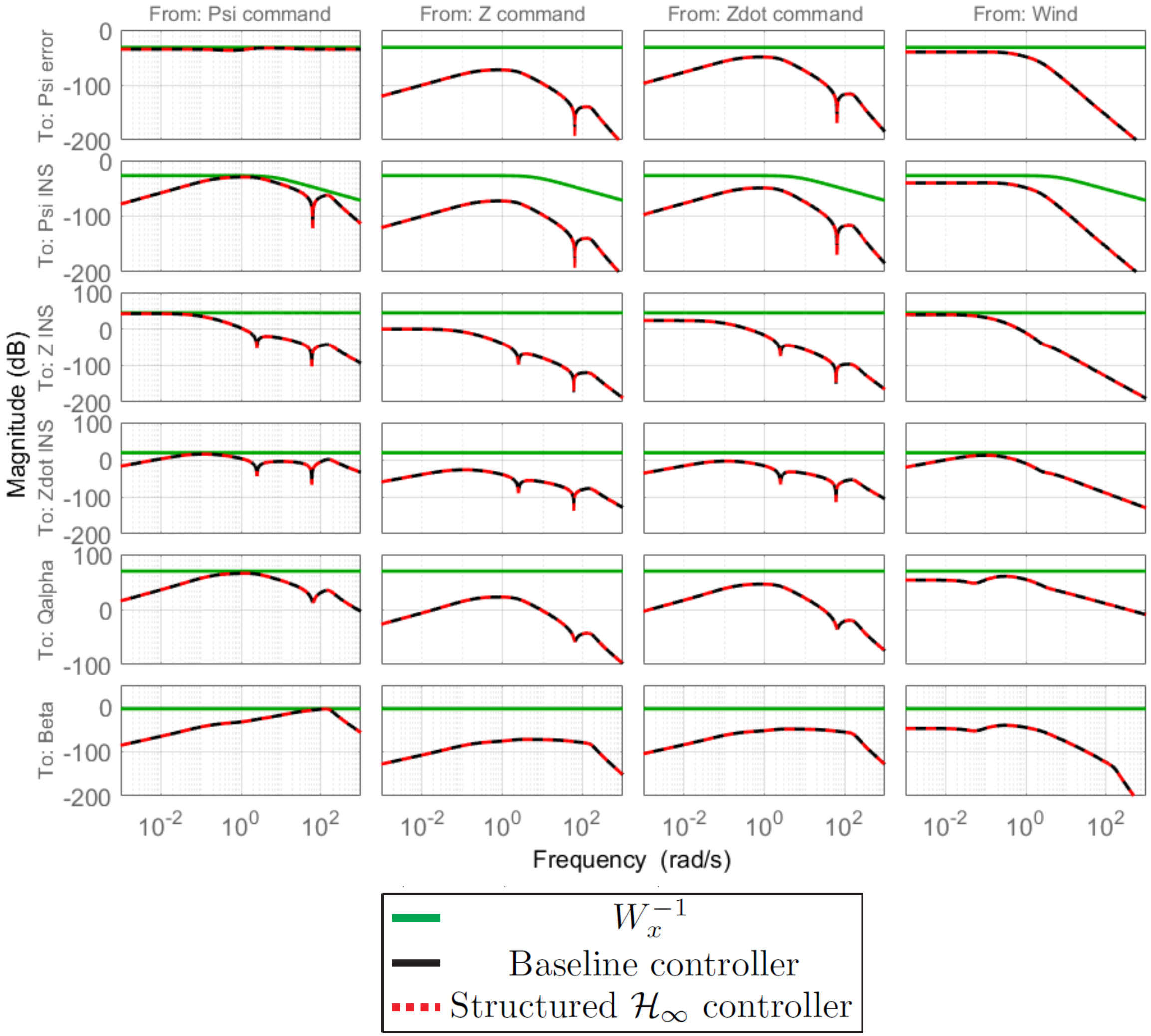
Baseline controller frequency response successfully recovered at all flight instances

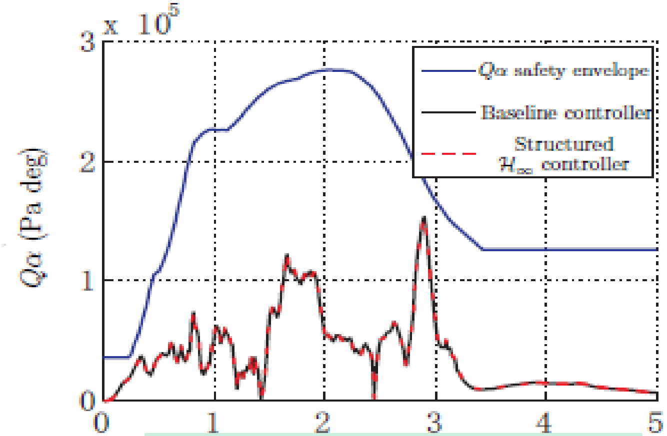
rol T

Structured H-infinity synthesis:

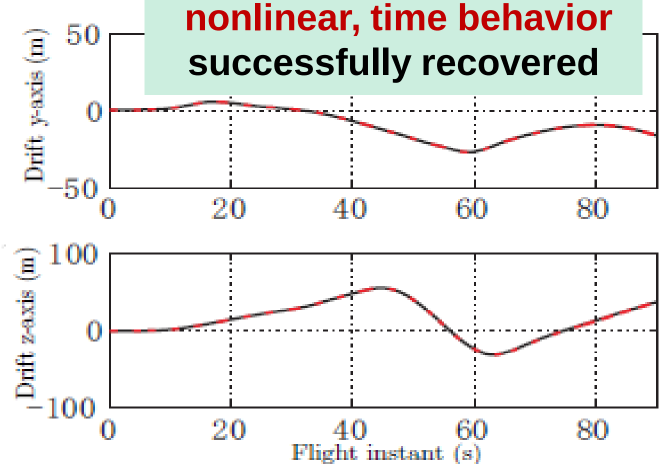
LEGACY RECOVERY - VEGA legacy recovery

VEGACONTROL verification





Baseline controller nonlinear, time behavior successfully recovered

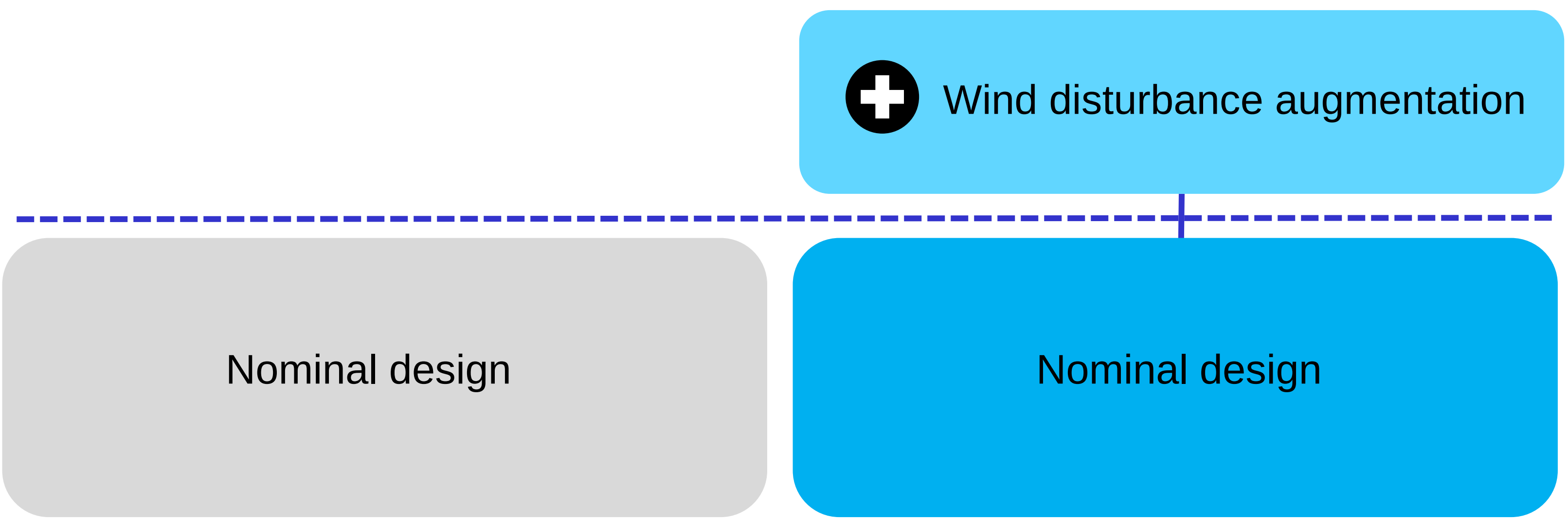


(c) Drift

Baseline controller frequency response successfully recovered at all flight instances

D. Navarro-Tapia, A. Marcos, S. Bennani and C. Roux, "**Structured H-infinity Control Design for the VEGA Launch Vehicle: Recovery of the Legacy Control Behaviour**", in Proceedings of the 10th International ESA Conference on Guidance, Navigation and Control Systems, May 2017.

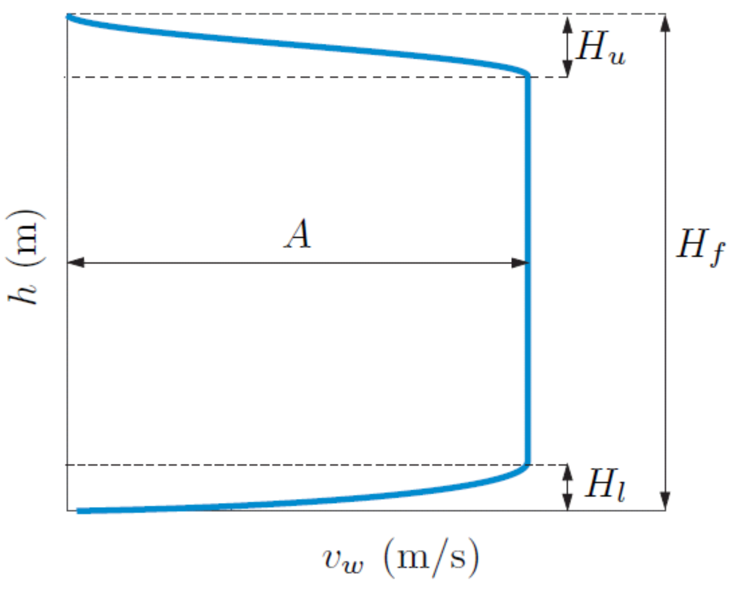
CLASSICAL CONTROL | **STRUCTURED H-INFINITY**



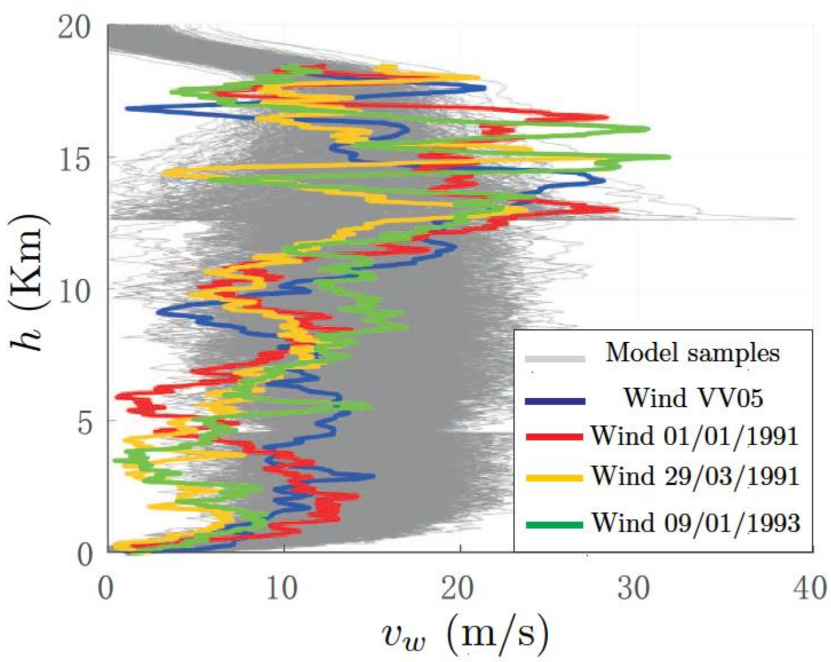
Structured H-infinity synthesis:
WIND MODEL augmentation - Wind generator

Wind model defined by a **Dryden filter** for [light, moderate, severe] turbulence

$$G_{wind}(s,h) = \frac{v_w}{n_w}(s,h) = \frac{\sqrt{\frac{2}{\pi}\frac{V(h)-v_{wp}(h)}{L(h)}\sigma^2(h)}}{s + \frac{V(h)-v_{wp}(h)}{L(h)}}$$

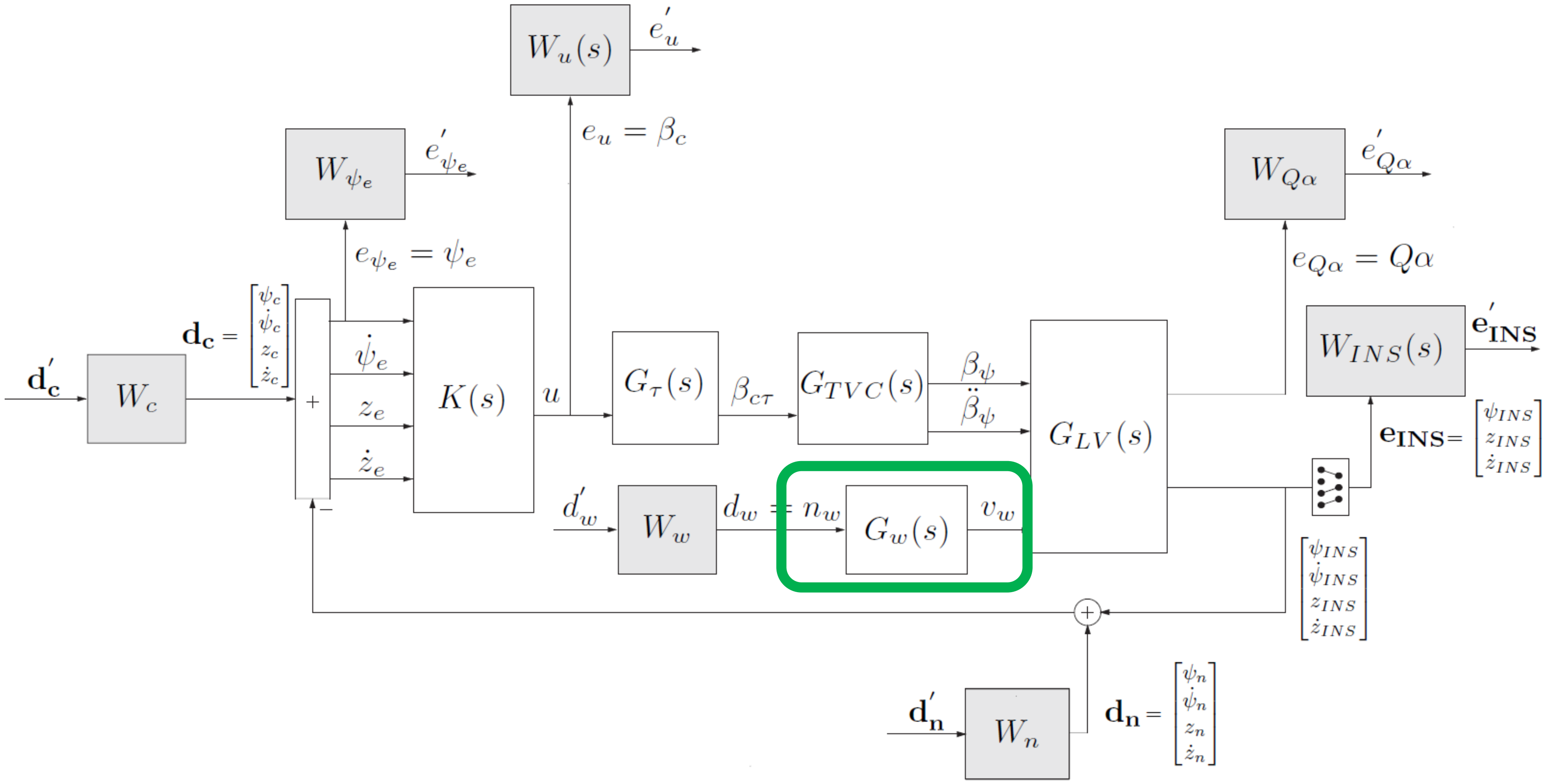


$$v_{wp}(h) = \begin{cases} 10A[(\frac{h}{H_l})^{0.9} - 0.9\frac{h}{H_l}] & \text{for} \quad 0 \leq h < H_l \\ A & \text{for} \quad H_l \leq h \leq H_f - H_u \\ \frac{A}{2}[1 - cos(\frac{\pi}{H_u}(h - H_f))] & \text{for} \quad H_f - H_u < h \leq H_f \end{cases}$$



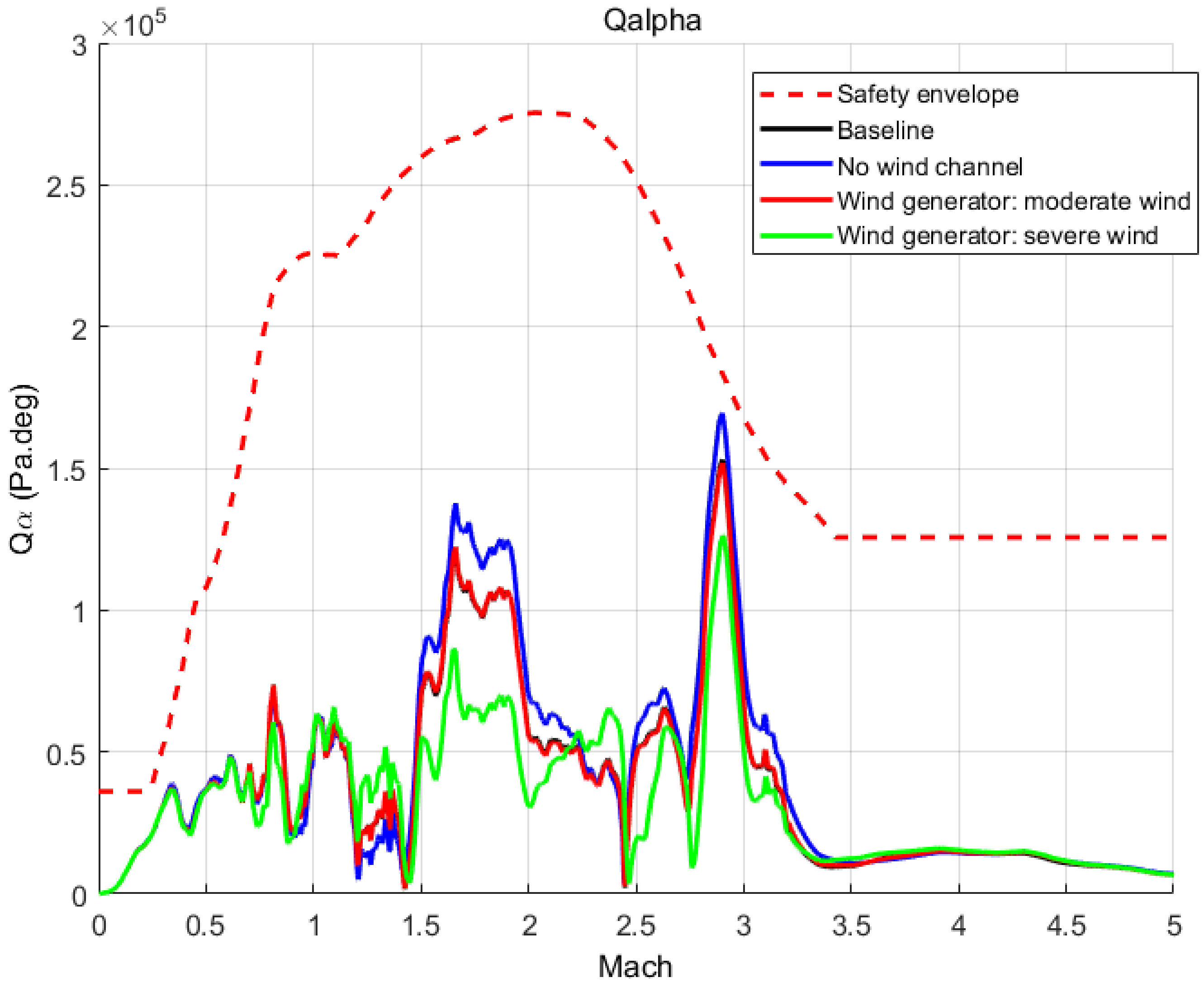
P. Simplício, S. Bennani, A. Marcos, C. Roux , X. Lefort, "**Structured Singular-Value Analysis of the Vega Launcher in Atmospheric Flight**", in Journal of Guidance, Control and Dynamics, Vol. 39, No. 6, June 2016

Structured H-infinity synthesis:
WIND MODEL augmentation - Design interconnection



Structured H-infinity synthesis:
WIND MODEL augmentation - Qalpha benchmark

Wind VV05: '07_2015_23_12_005.wind'



Controller [K1]

No wind channel in the design

Controller [K2]

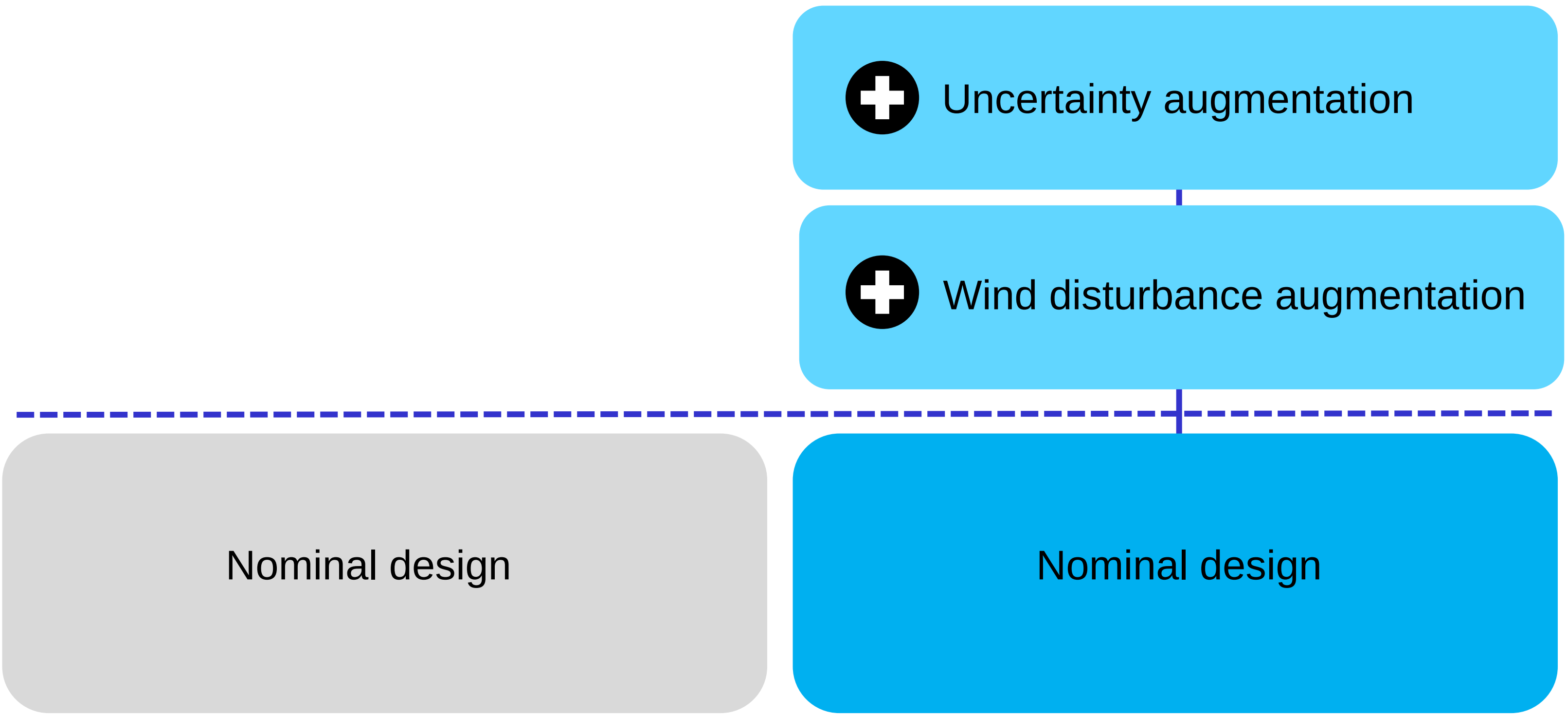
Wind generator: moderate wind

Controller [K3]

Wind generator: severe wind

Structured H-infinity synthesis:
UNCERTAINTY augmentation - Design augmentation scheme

CLASSICAL CONTROL | **STRUCTURED H-INFINITY**

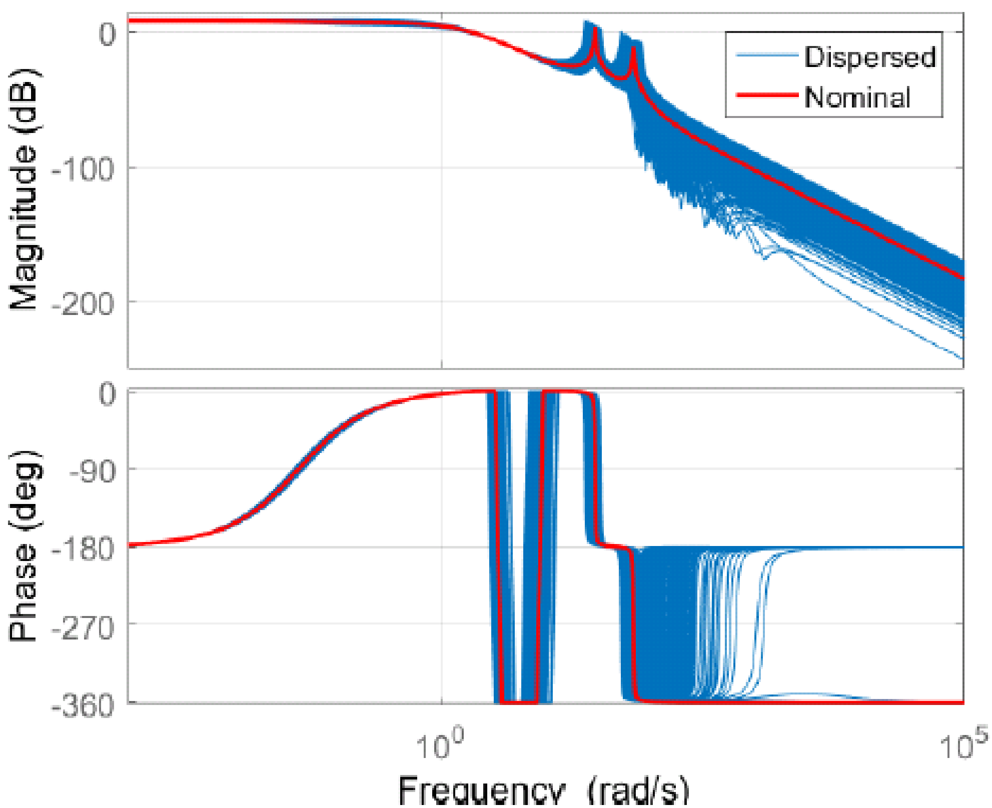


Structured H-infinity synthesis:
UNCERTAINTY augmentation - LFT models

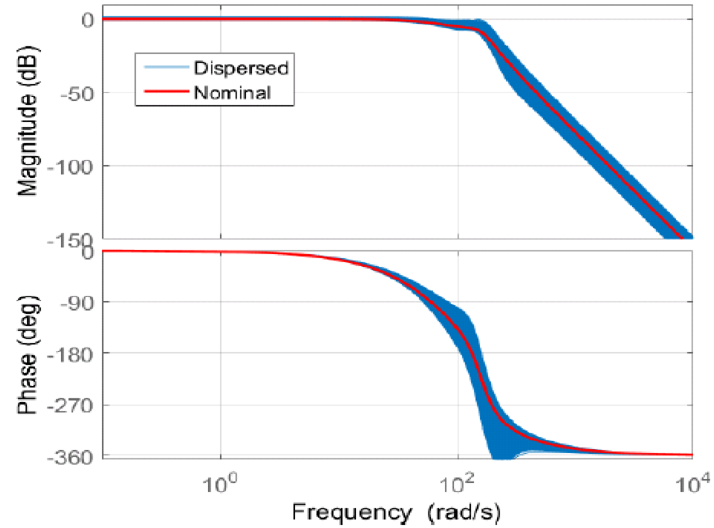
Parametric uncertainties modeled using

Linear Fractional Transformation (**LFT**) representations

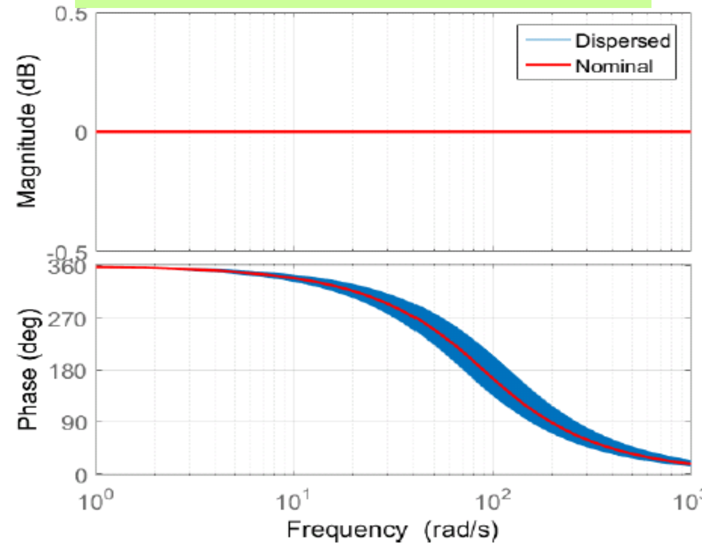
VEGA LFT model at t=50s



TVC actuator LFT model

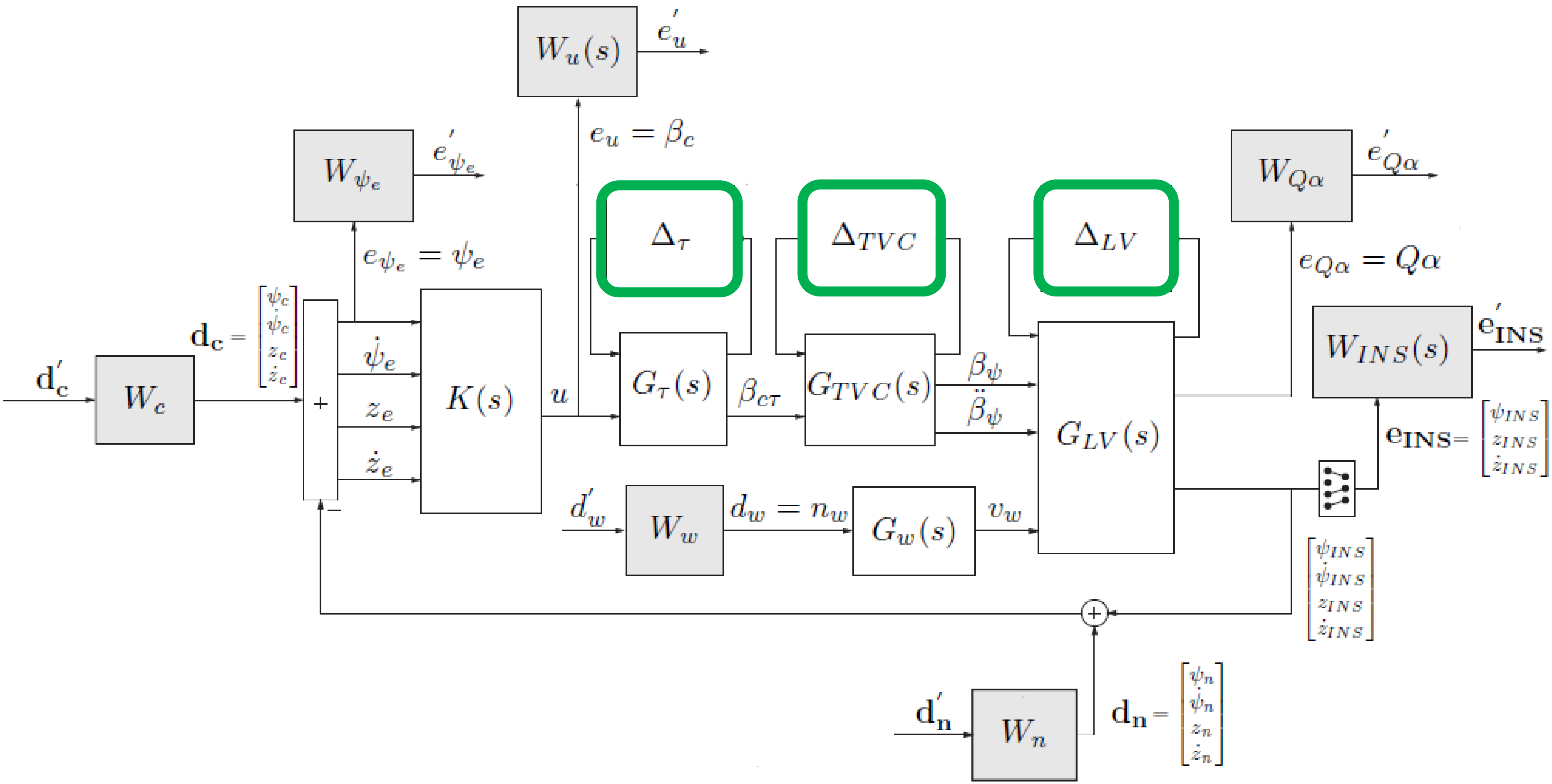


Delay LFT model



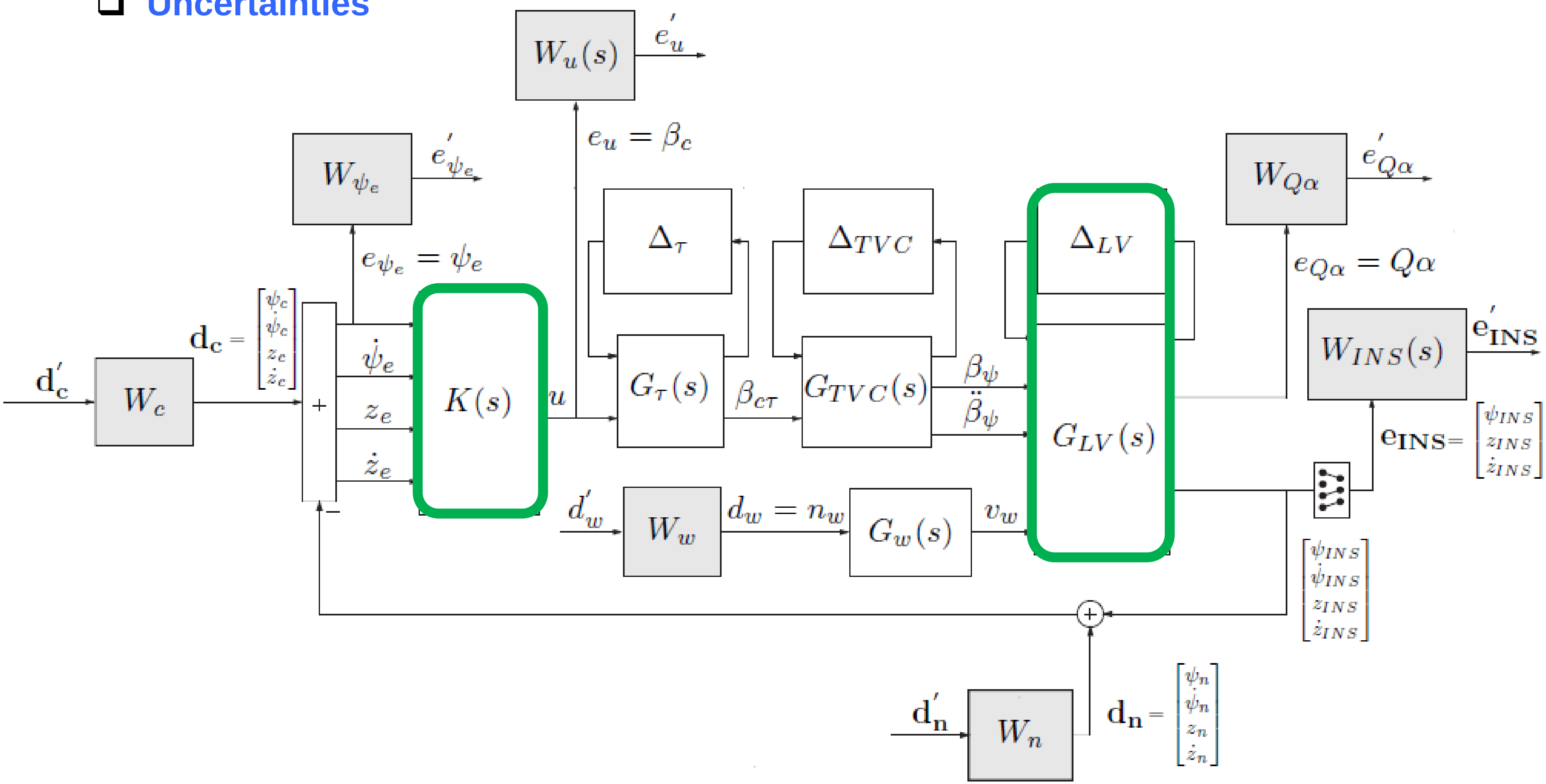
Structured H-infinity synthesis:
UNCERTAINTY augmentation - Design interconnection

Using **LFT** models in design interconnection allows augmentation to robust design



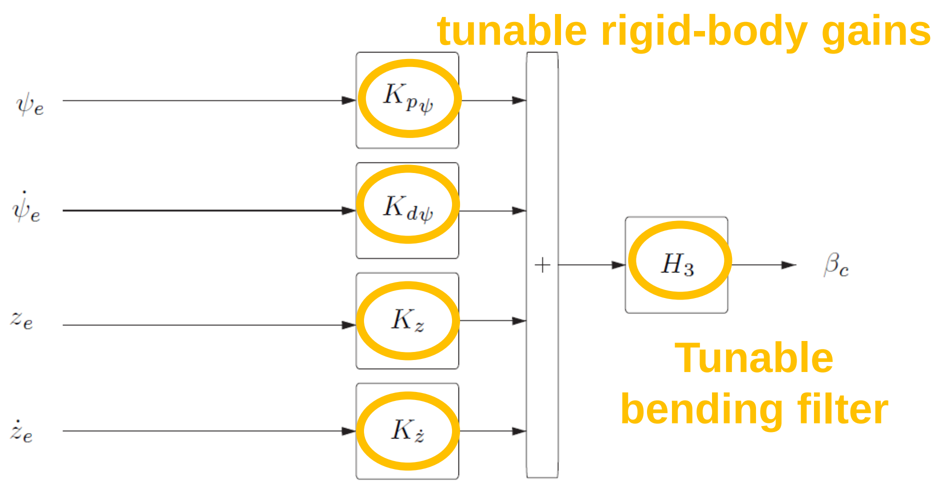
CLASSICAL CONTROL	STRUCTURED H-INFINITY
	➕ Joint design rigid-body controller and bending filters
	➕ Uncertainty augmentation
	➕ Wind disturbance augmentation
Nominal design	Nominal design

- Rigid-body and flexible-body dynamics (1st bending mode)
- Wind disturbance model
- Uncertainties



Structured H-infinity synthesis:
Robust RIGID+FLEXIBLE - Controller structure

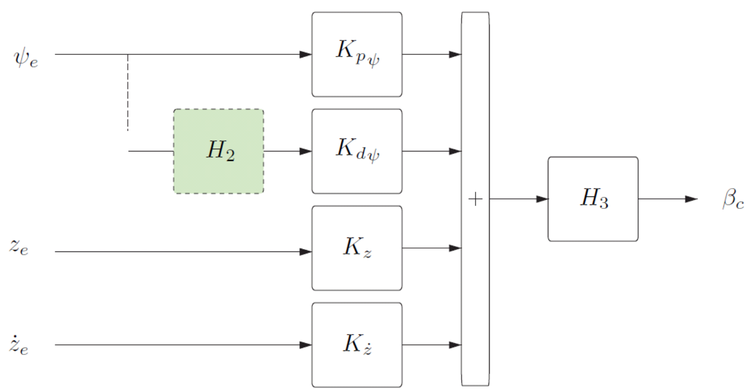
Simplified TVC structure for design



VEGACONTROL implementation

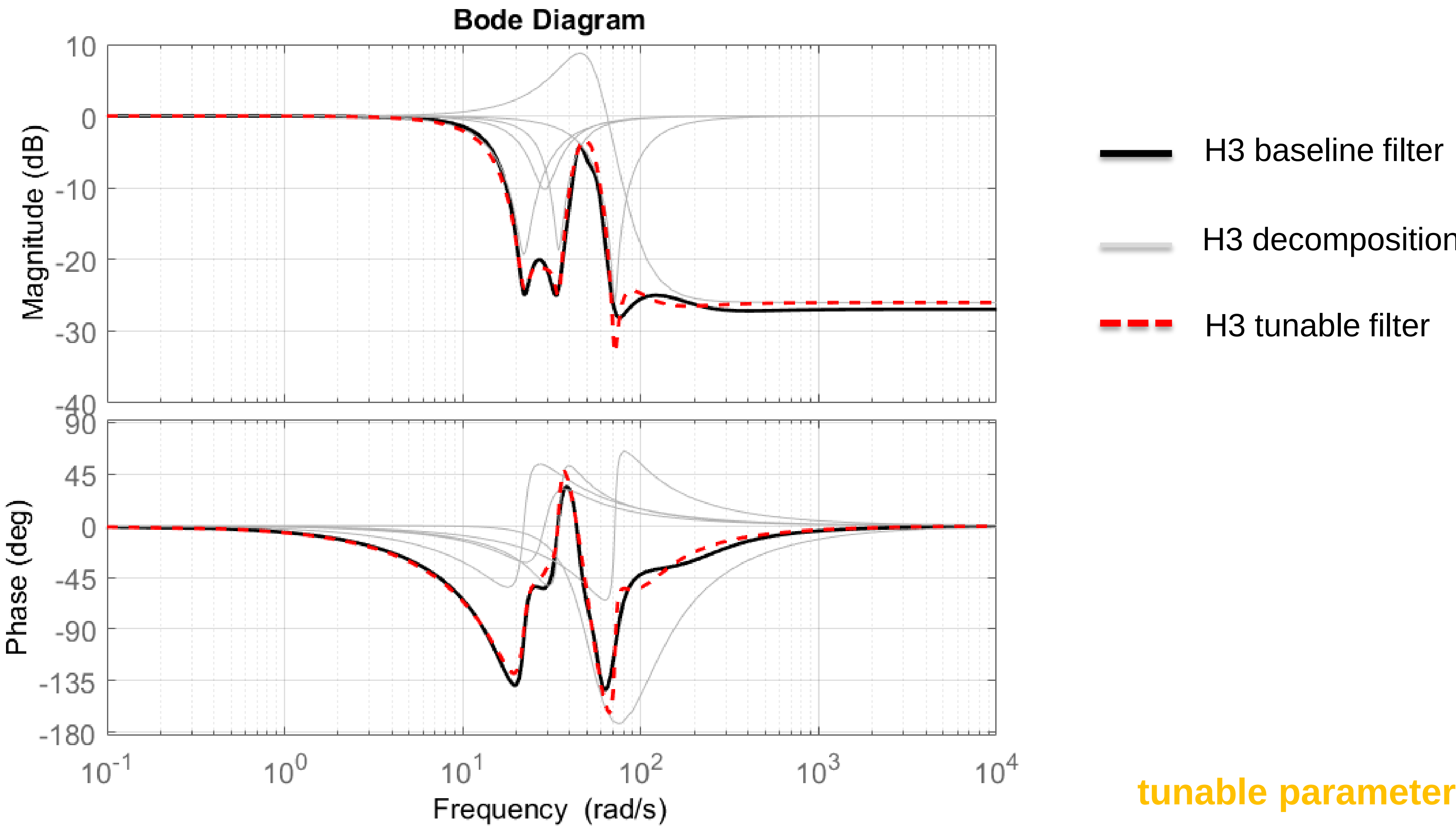
H2 filter is also simplified as a first order pseudo-derivative filter

$$H_2 = \frac{s}{\sigma s + 1}$$



Structured H-infinity synthesis:

Robust RIGID+FLEXIBLE - Bending filter parametrization

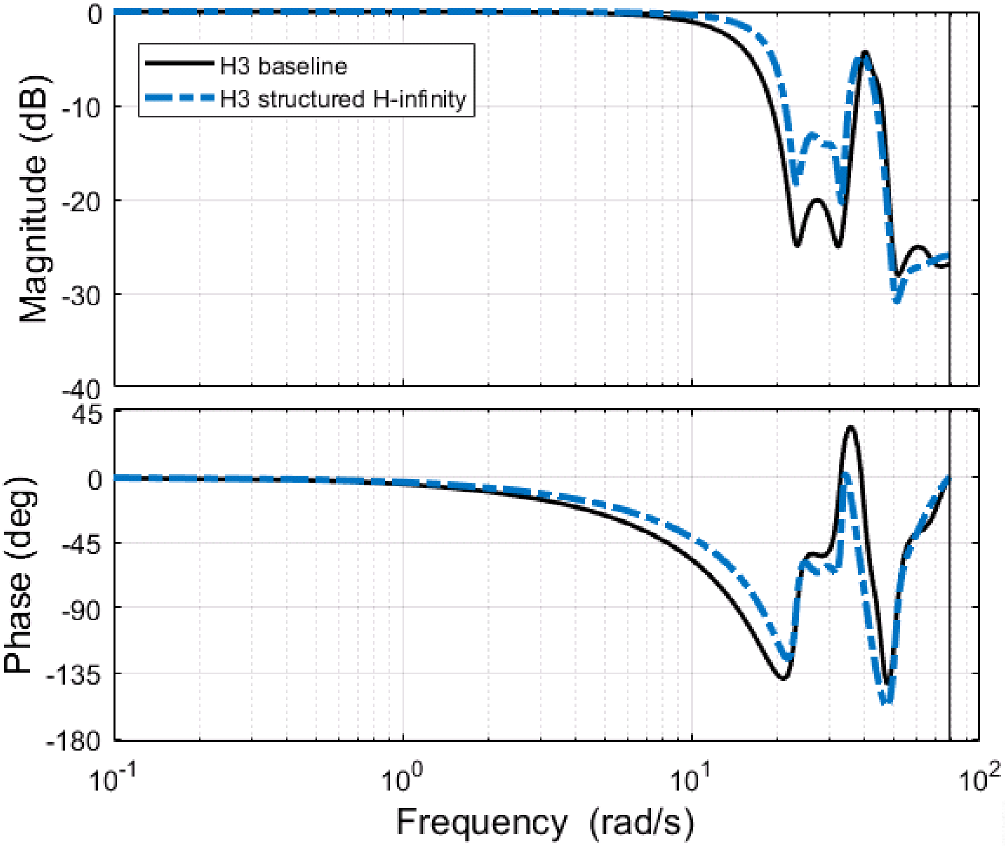


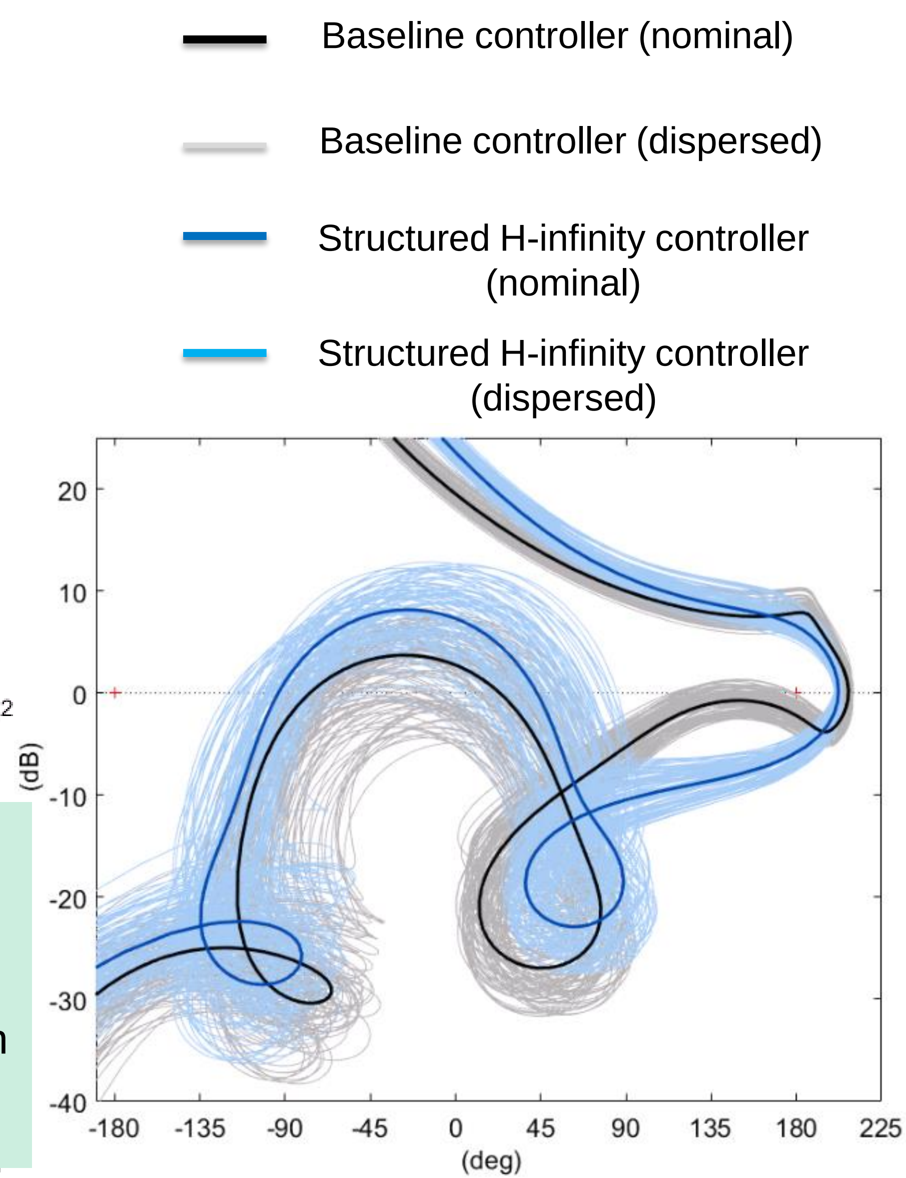
tunable parameters

$$H_3(s) = \underbrace{\frac{s^2 + \epsilon_1 s + (\underline{\omega_{q1}})^2}{s^2 + \eta_1 s + (\underline{\omega_{q1}})^2}}_{\text{Notch 1}} \underbrace{\frac{s^2 + \epsilon_2 s + (\underline{\omega_{q1}})^2}{s^2 + \eta_2 s + (\underline{\omega_{q1}})^2}}_{\text{Notch 2}} \underbrace{\frac{s^2 + \epsilon_3 s + (\overline{\omega_{q1}})^2}{s^2 + \eta_3 s + (\overline{\omega_{q1}})^2}}_{\text{Notch 3}} \underbrace{\frac{s^2 + \epsilon_4 s + (\underline{\omega_{q2}})^2}{s^2 + \eta_4 s + (\underline{\omega_{q2}})^2}}_{\text{Notch 4}} \underbrace{\frac{Att\, s^2 + \epsilon_5 s + (0.6\,\underline{\omega_{q2}})^2}{s^2 + \eta_5 s + (0.6\,\underline{\omega_{q2}})^2}}_{\text{Low-pass Notch 5}}$$

Structured H-infinity synthesis:

Robust RIGID+FLEXIBLE - Results at t=50sec

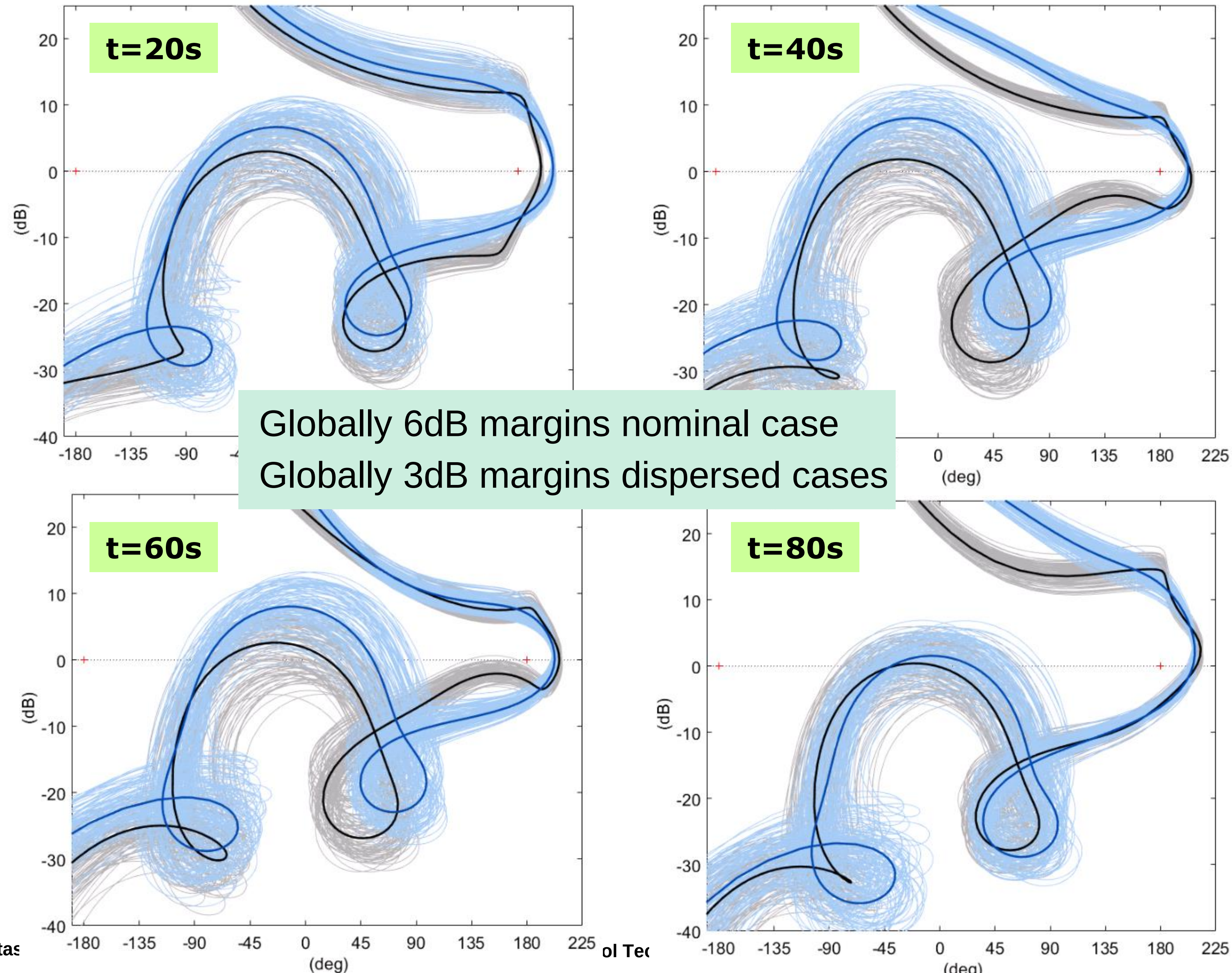




- ❑ 1st bending **phase stabilized**
- ❑ Upper bending modes **gain stabilized**
- ❑ **Trade-off** between 1st bending mode attenuation and rigid-body stability margins

Structured H-infinity synthesis:

ANALYSIS - Classical stability margins assessment

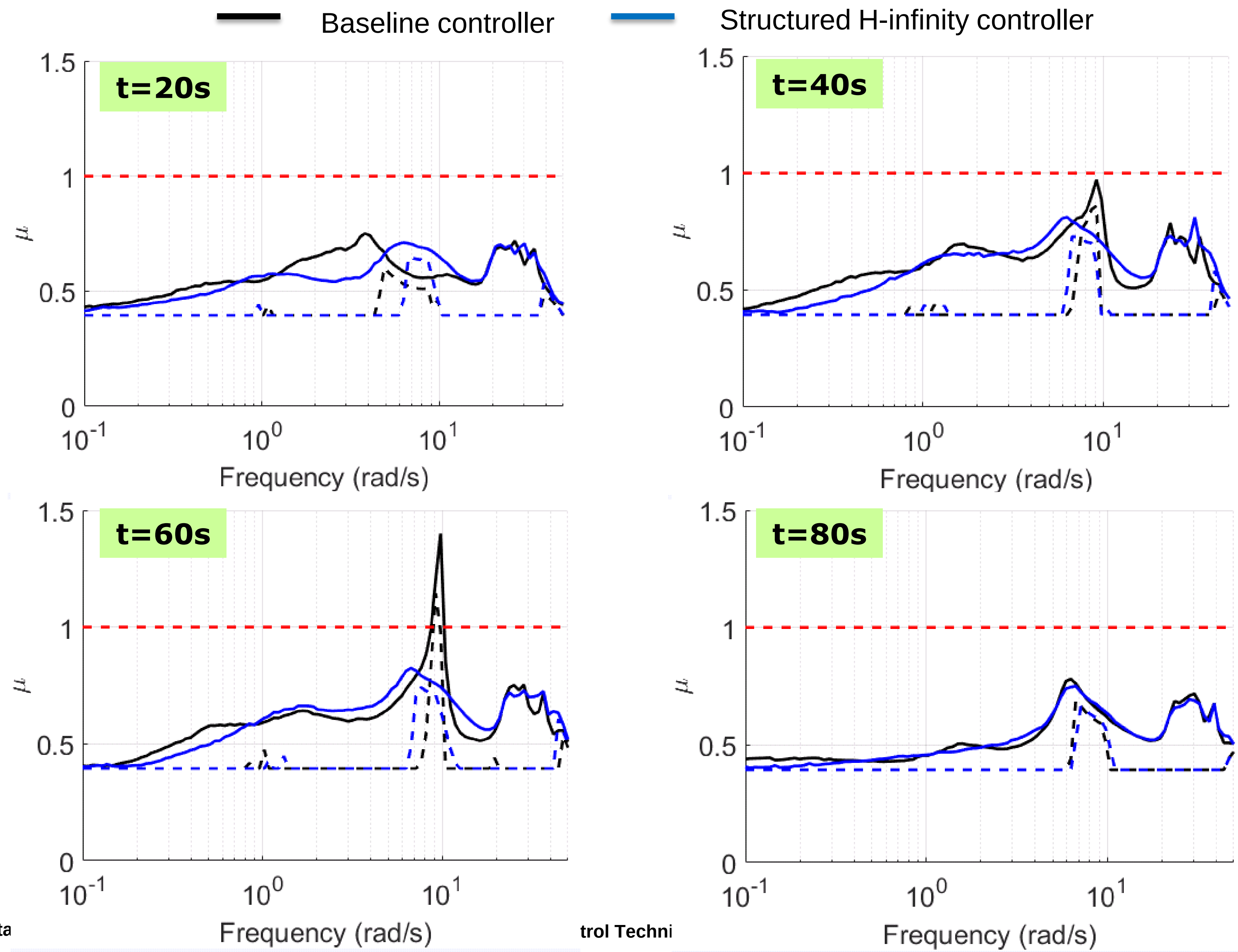


Globally 6dB margins nominal case

Globally 3dB margins dispersed cases

Structured H-infinity synthesis:

ANALYSIS - Singular structured value analysis



Structured H-infinity synthesis:
ANALYSIS – Monte Carlo assessment

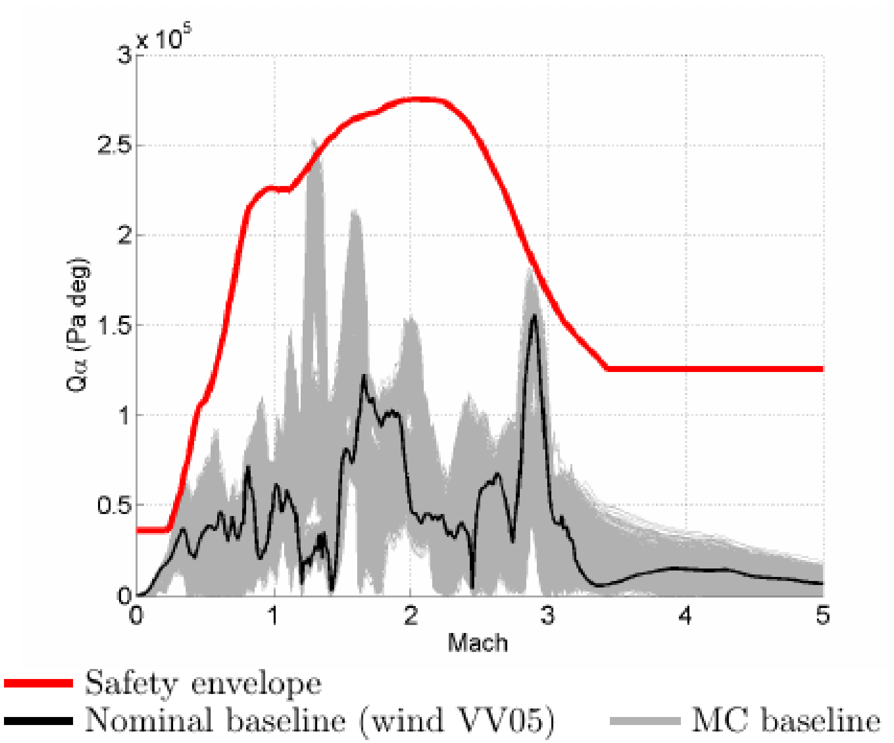
Non linear analysis

The same **4 MC campaigns of 500 runs each** are applied to two controllers:

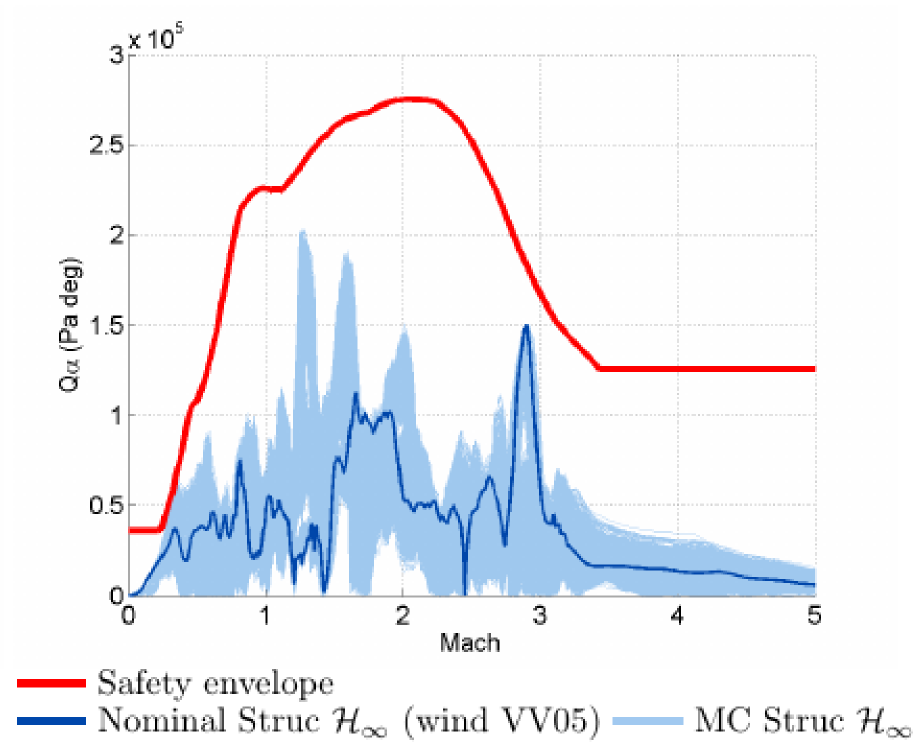
VEGA VV05 baseline controller and **Structured H-infinity controller**

Each MC campaign uses the **same 500 scattering flags** but a **different wind profile**

Baseline controller



Structured H-infinity controller



Baseline — ∞-norm Structured $\mathcal{H}_\infty$ — 2-norm Structured $\mathcal{H}_\infty$

Drift rate
z-axis

$\mathrm{Q}\alpha$

Drift rate
y-axis

Actuation
Lane A

Drift
z-axis

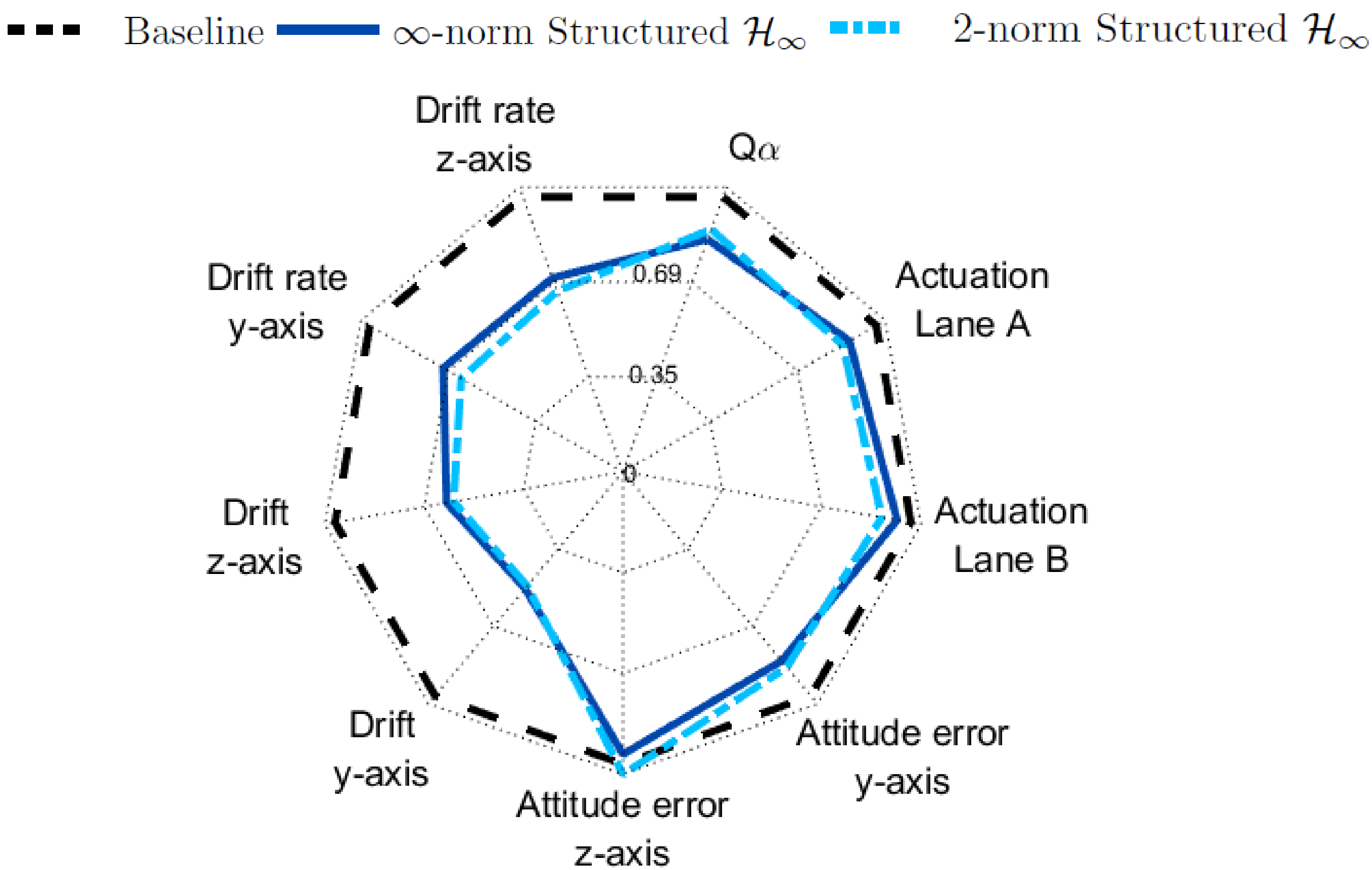
Actuation
Lane B

Drift
y-axis

Attitude error
z-axis

Attitude error
y-axis

Structured H-infinity synthesis:
ANALYSIS – Monte Carlo assessment



Layout

Linear Parameter Varying (LPV) systems are continuous functions of a measurable set of time-varying parameters $\boldsymbol{\theta}(\boldsymbol{t})$ (i.e. time, VNG)

$$\dot{x}(t) = A[\theta(t)]x(t) + B[\theta(t)]u_{LV}(t)$$
$$y_{LV}(t) = C[\theta(t)]x(t) + D[\theta(t)]u_{LV}(t)$$

$$\theta \in \Omega$$
$$\underline{v} \leq \dot{\theta} \leq \overline{v}$$

Main features

- ❑ **Controller design and gain-scheduling** are incorporated into a **single design step**

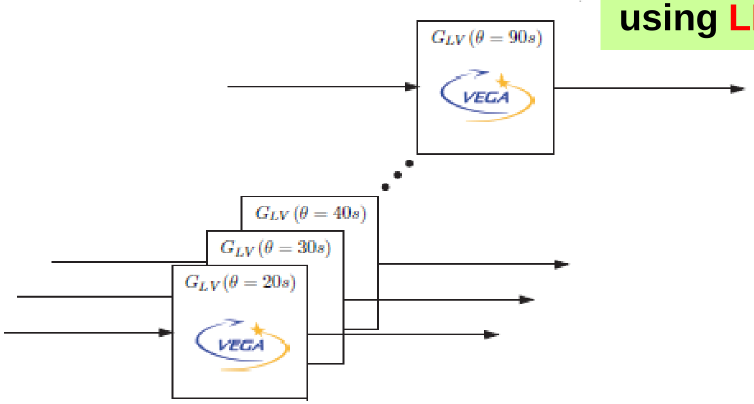
  This feature may reduce the tuning and design effort prior to each mission
- ❑ **Performance and robustness are guaranteed** along the flight envelope
- ❑ It uses the same **design framework** as H-infinity

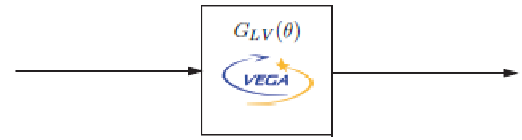
LPV synthesis:
LPV modeling

Family LTI models

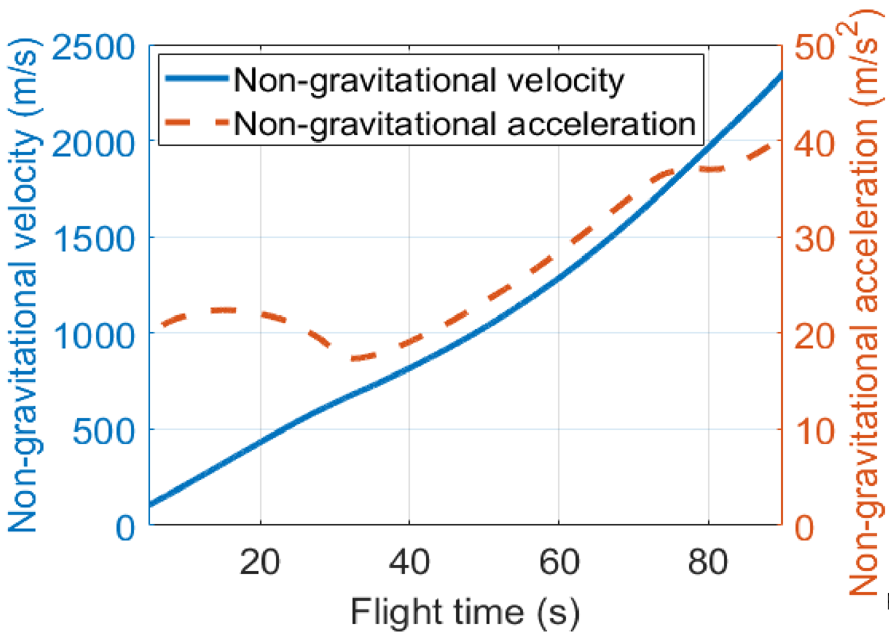
LPV modelling and design using LPVToolsv1.0 from UMN

LPV model

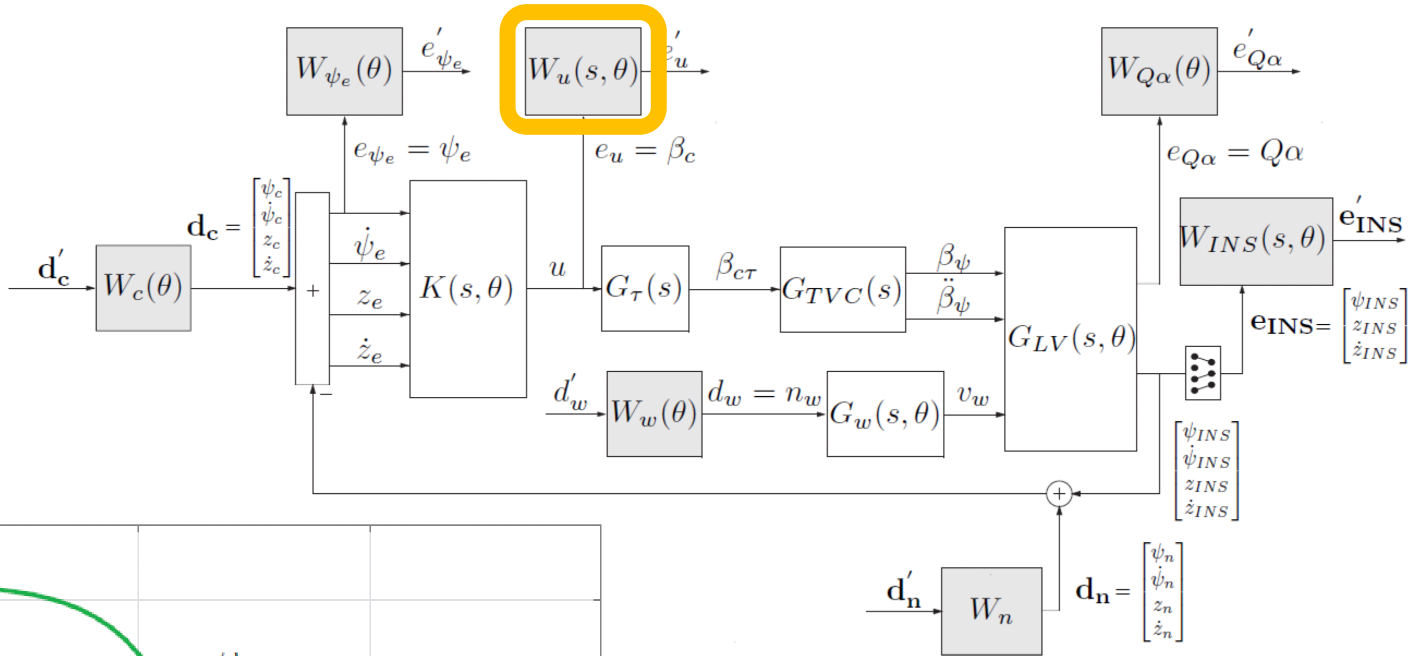


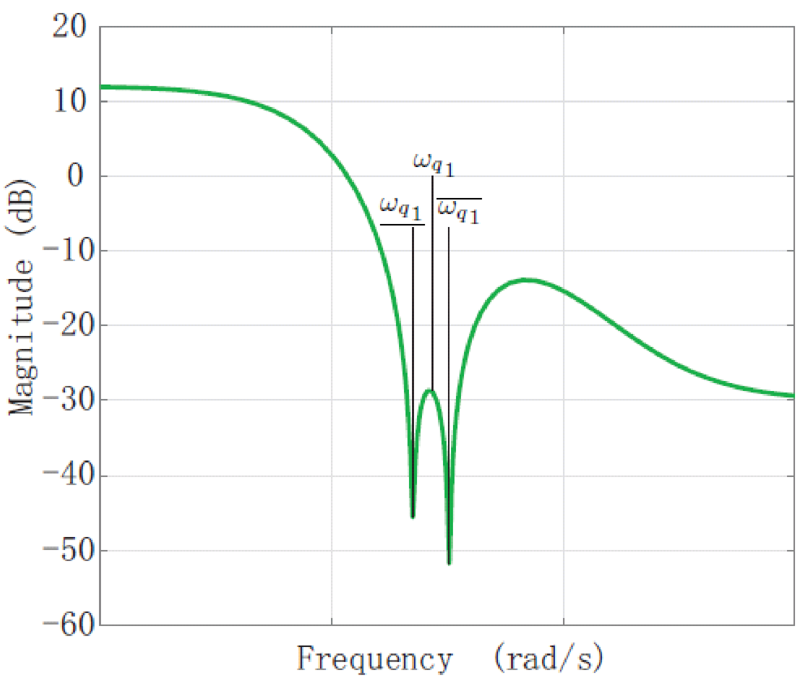


Time-varying parameter: non-gravitational velocity



Integrated design of rigid-body controller and bending filters



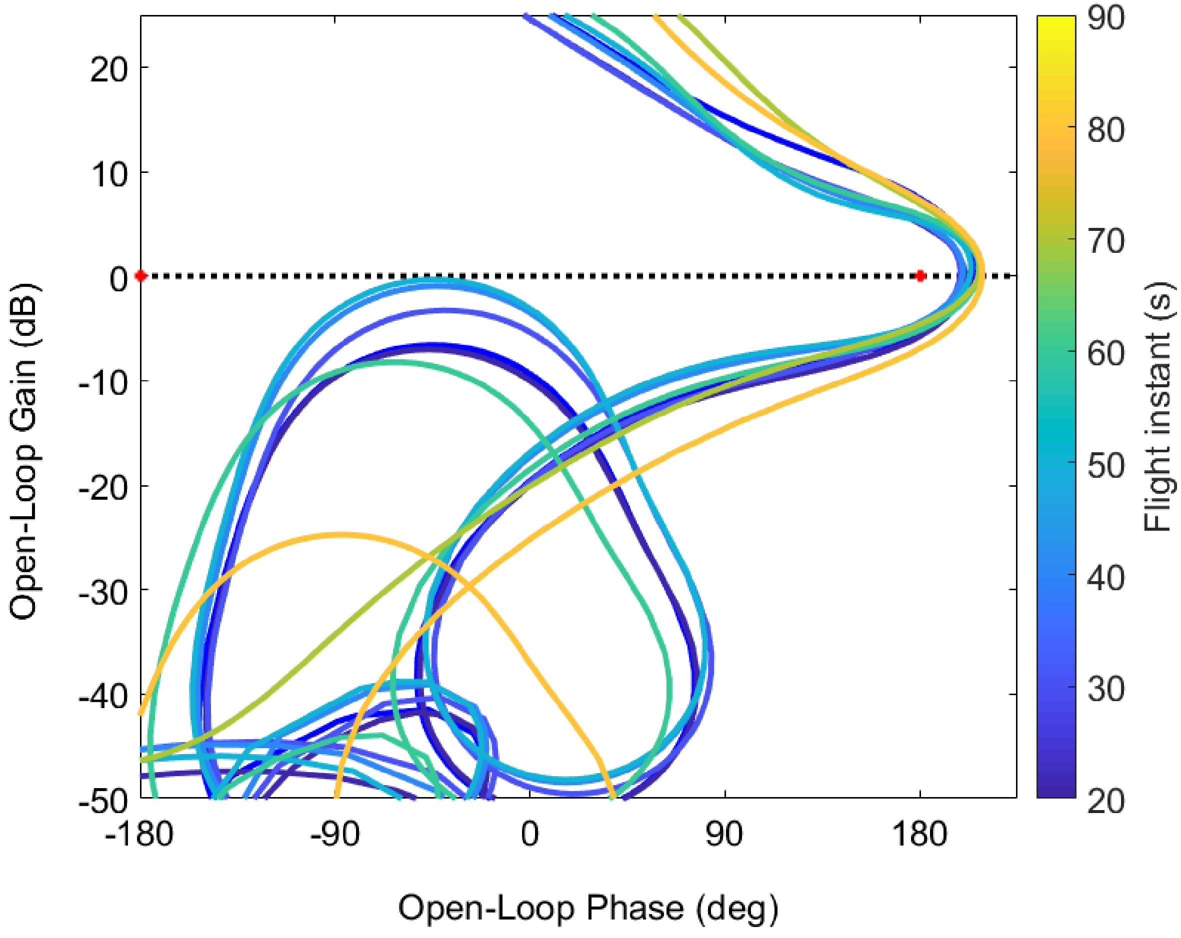


Actuation weighting function

$$W_u^{-1}(s,\theta) = \underbrace{\frac{s^2 + 0.5s + (\underline{\omega_{q_1}}(\theta))^2}{s^2 + 70s + (\underline{\omega_{q_1}}(\theta))^2}}_{\text{Notch 1}} \underbrace{\frac{s^2 + 0.5s + (\overline{\omega_{q_1}}(\theta))^2}{s^2 + 70s + (\overline{\omega_{q_1}}(\theta))^2}}_{\text{Notch 2}} \underbrace{F(s,\theta)}_{\text{Low-pass filter}}$$

LPV synthesis:

ANALYSIS - Classical stability margins assessment

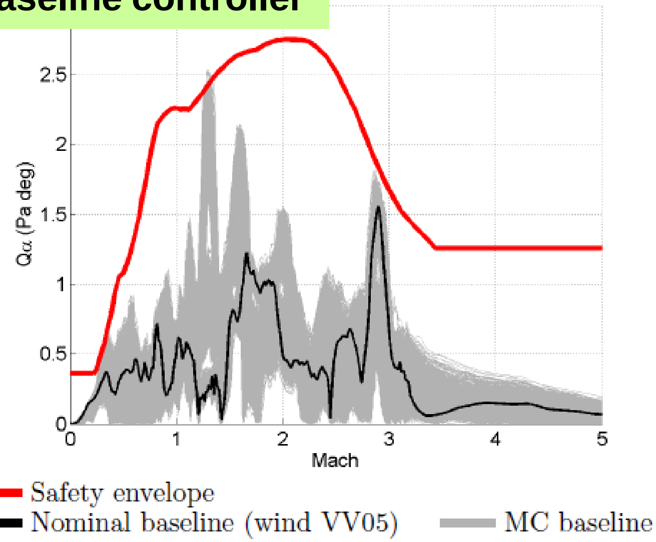


- Good rigid-body margins
- All bending modes are gain stabilized

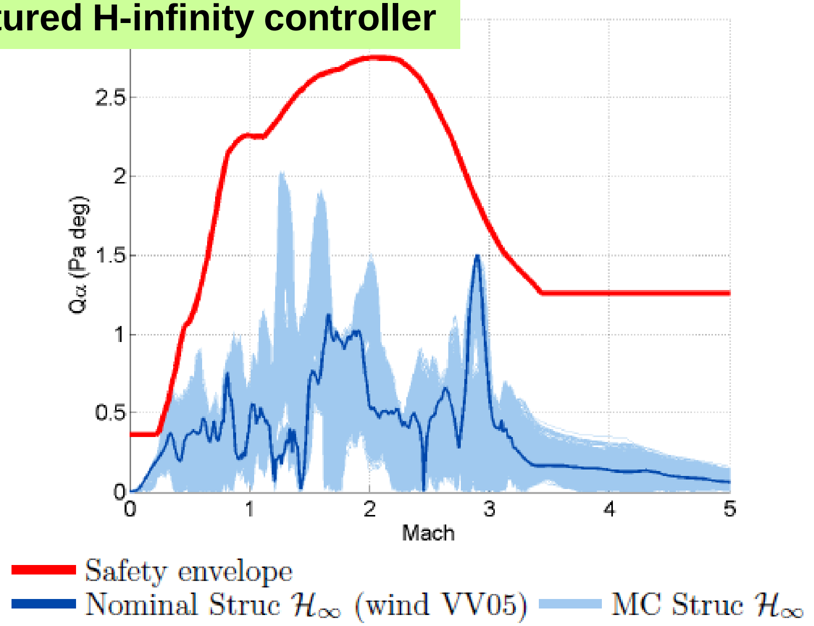
LPV synthesis:
ANALYSIS – Monte Carlo assessment

Same MC campaign as before

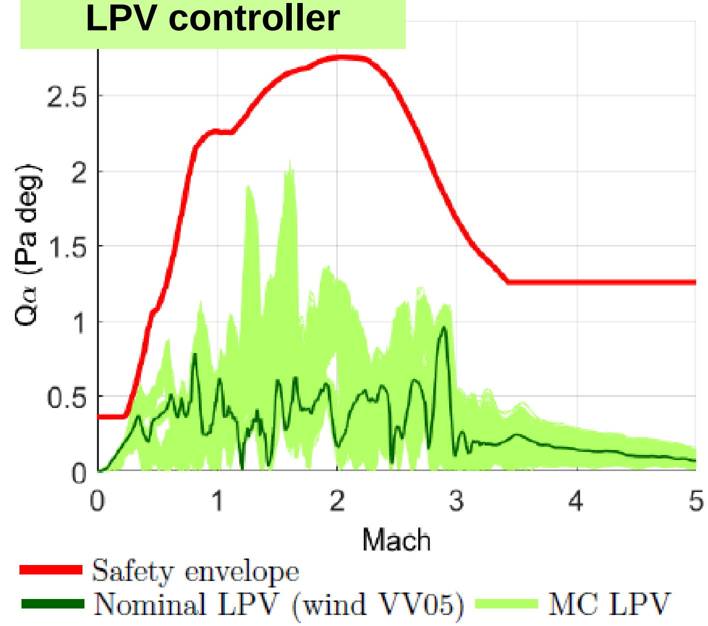
Baseline controller



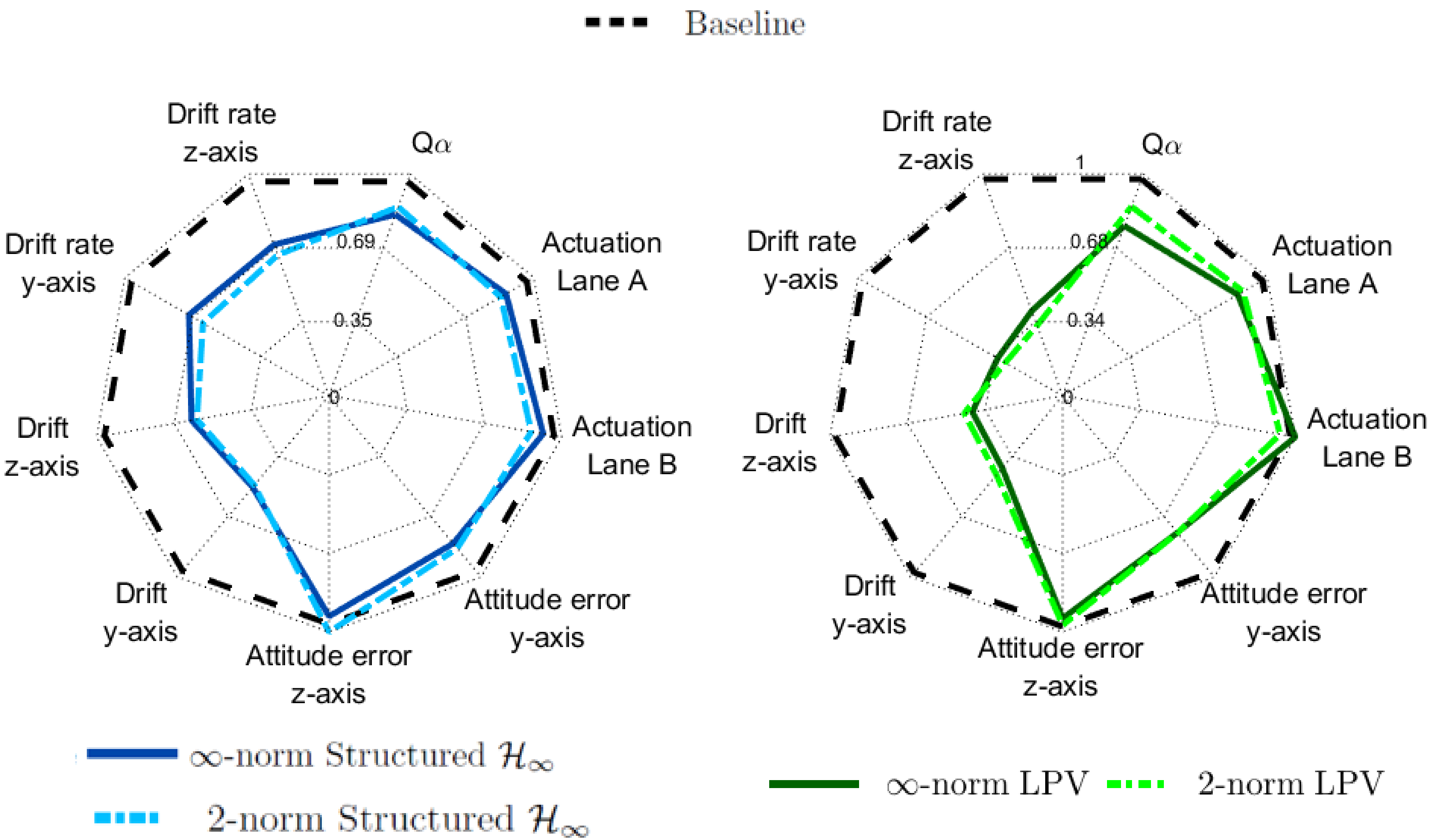
Structured H-infinity controller



LPV controller



LPV synthesis:
ANALYSIS – Monte Carlo assessment



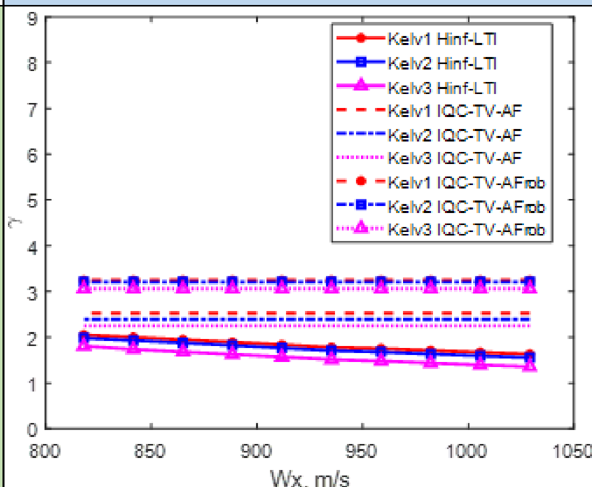
LPV synthesis:
ANALYSIS – Effect of Plant Time Variations & Uncertainty

Frozen H-infinity norm (Hinf-LTI) **IQC Linear Time Varying Arbitrarily Fast (IQC-TV-AF)** **IQC Linear Time Varying Robust Arbitrarily Fast (IQC-TV-AFrob)**

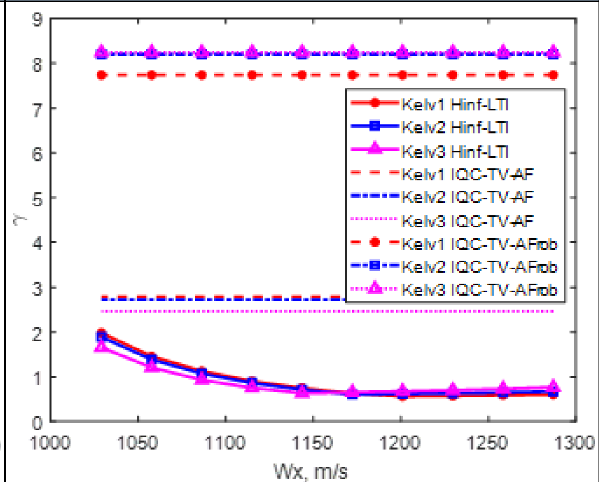
RG4: $G_{LPV} \in [40, 50]$ secs | RG5: $G_{LPV} \in [50, 60]$ secs | RG6: $G_{LPV} \in [60, 70]$ secs

Kelv

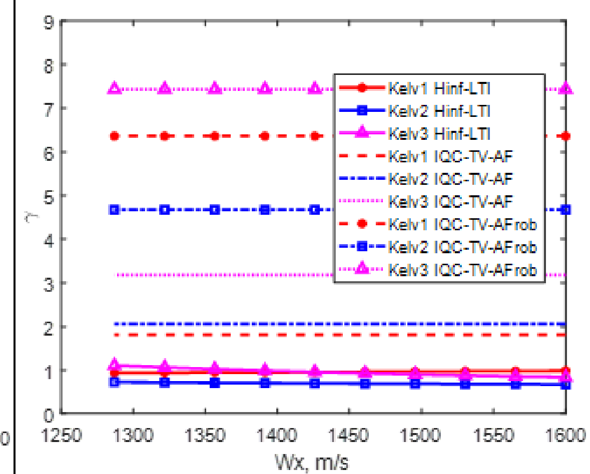
Region RG4, controllers at [40, 50, 60]



Region RG5, controllers at [40, 50, 60]

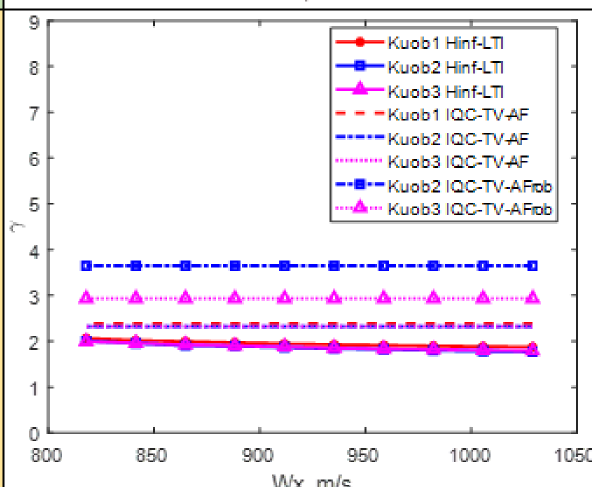


Region RG6, controllers at [50, 60, 70]

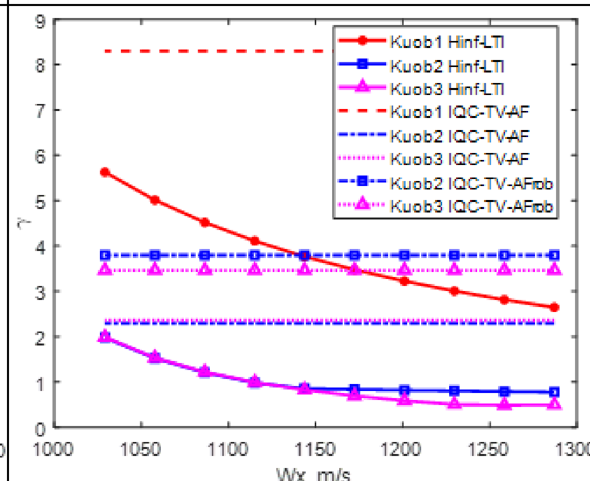


Klpv

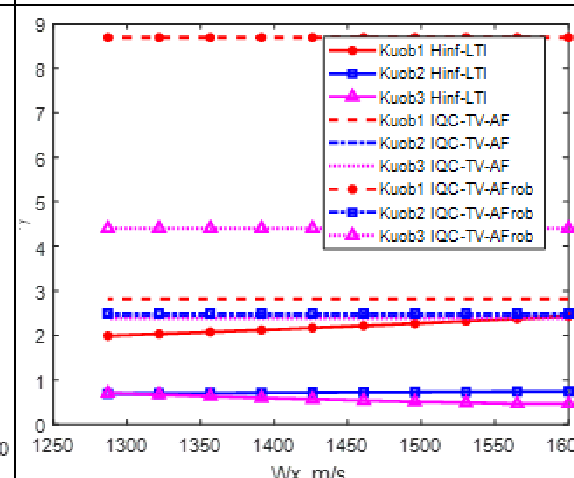
Region RG4, controllers at [40, 50, 60]



Region RG5, controllers at [40, 50, 60]



Region RG6, controllers at [50, 60, 70]



1. Motivation
2. VEGA mission & vehicle
3. Structured H-infinity synthesis
4. LPV (Linear Parameter Varying) synthesis
5. Conclusions

Conclusions

- The atmospheric phase **VEGA launcher control problem** has been presented.

- **Classical control** has a rich heritage but several limitations are recognized.

- **Two robust control design techniques have been presented**:
  - **Structured** H_∞ infinity synthesis
  - **LPV** synthesis

Project showed that a <u>robust control design and analysis</u> framework:

- More suitable for multivariable control problems
- Can incorporate wind disturbance estimation in the design
- Guarantees robustness and performance by design
- Allows performing RS/RP, WC and TV/NL analyses

Thank you for your attention