POLITECNICO DI MILANO

H-infinity helicopter attitude control design with rotor state feedback

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Motivation (1)

Future rotorcraft is expected to

- meet more and more stringent performance requirements (agility, manoeuvrability)
- reduce pilot workload (adverse weather conditions, DVE)

Motivation (2)

Rotorcraft is subject to:

- Instability
- Inter-axes coupling
- Model uncertainty
- High pilot workload (conversion)

Need for

- accurate dynamic model
- robustness to uncertainty
- simple FCS architecture
- compliance to standard requirements

Industrial practice…

Control design

- SISO
- No inter-axis coupling
- Non-robust

FCS tuning procedure:

- Non-systematic
- Iterative
- Manual
- Expensive

Extensive flight testing
"[…] UH-60 BlackHawk flight control development had accounted for about 37% of the overall flight test time" [Tischler et al, 2008]
Typical flight test cost **50k$/hr**

Objectives

Set-up of a rotorcraft attitude control design methodology

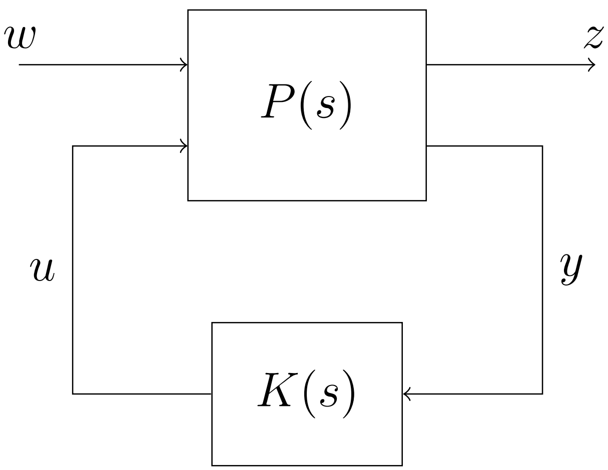
- Robustness wrt model uncertainty
- Requirements:
  - Standard (ADS-33)
  - Non-standard (from literature)
- Architecture consistent with industrial practice

Outline

- Problem formulation within the H_∞ framework
- Rotor state feedback
- Robustness to uncertainty

- Application: robust helicopter attitude control design

- u control inputs
- y measurable outputs
- w performance inputs (reference signals, disturbances, noise)
- z performance outputs (tracking errors, control inputs,…) to be minimized



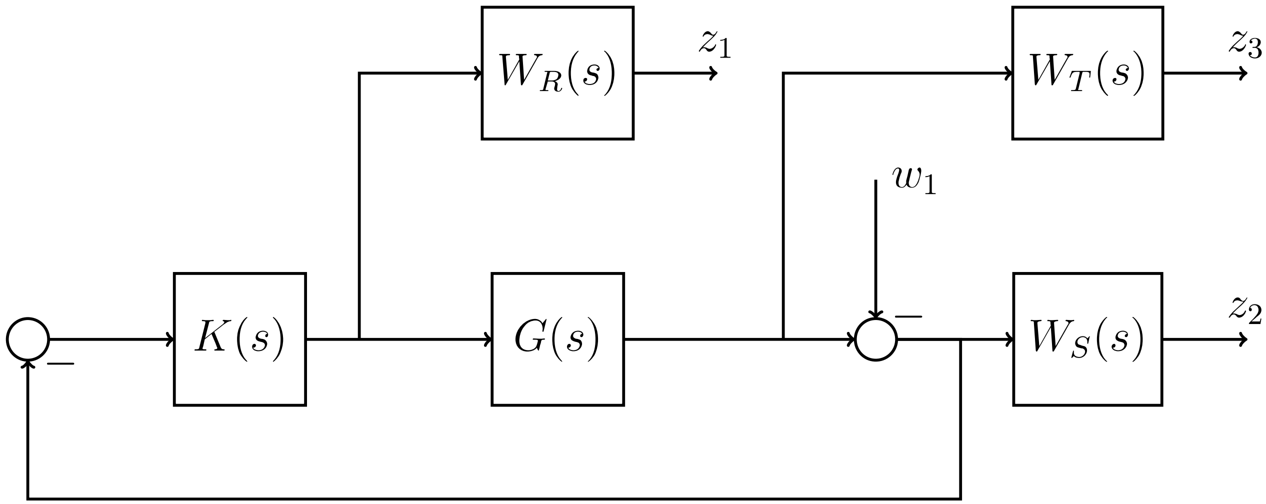
Optimal H_∞ problem

$$\begin{array}{rcl} \min\limits_{K} & & \gamma \\ \text{subject to} & & \\ \|T_{z,w}(s)\|_\infty & \leq & \gamma \\ K & \in & \mathcal{K} \end{array}$$

(Set of stabilizing controllers)

Control requirements → weights over the performance signals

Mixed-sensitivity H_∞ formulation



$G\ [p \times m]$

$z_1\ [m \times 1]$

$w_1\ [p \times 1]$

$z_2, z_3\ [p \times 1]$

$$\begin{bmatrix} z_1 \\ z_2 \\ z_3 \end{bmatrix} = \begin{bmatrix} W_R(s)\,R(s) \\ -W_S(s)\,S(s) \\ W_T(s)\,T(s) \end{bmatrix} w_1$$

- Square, diagonal weight matrices on the performance outputs
- w_1 can be interpreted both as a disturbance on the plant output or as the reference signal

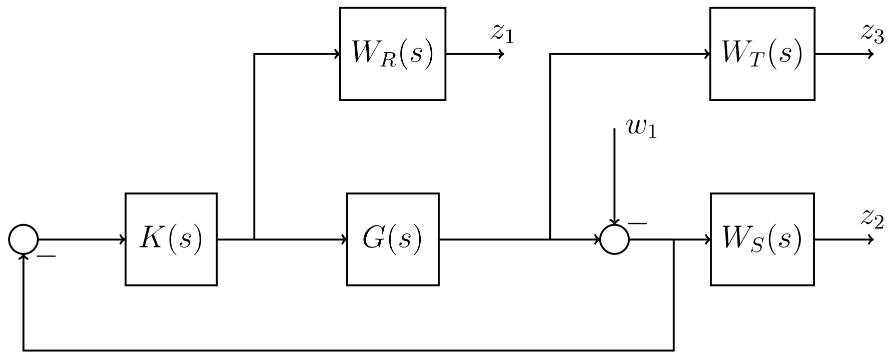
$$S(s) = (I + G(s)\,K(s))^{-1}$$

$$R(s) = K(s)\,(I + G(s)\,K(s))^{-1}$$

$$T(s) = G(s)\,K(s)\,(I + G(s)\,K(s))^{-1}$$

Frequency weights on the sensitivity functions!

Classical vs structured H_∞

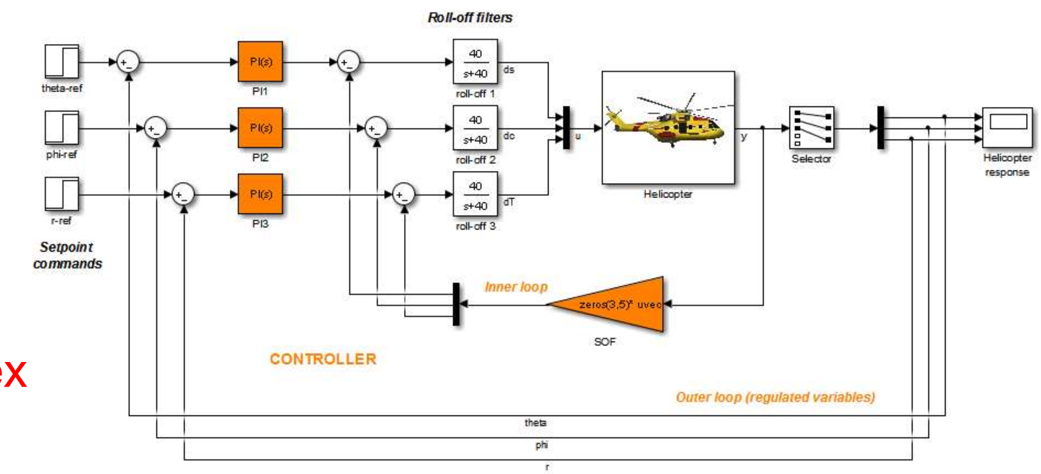


Structured H_∞:

- ✓ Define control system architecture w/tunable parameters→ adapt to existing FCS structure (e.g. retrofitting)
- ✓ Introduce optimization constraints which would not be available by means of classical H_∞ techniques
- ✓ Multiple system configurations
- ✗ Optimization problem is non-convex (local minima)
- ✗ Sub-optimal wrt classical H_∞

Classical H_∞:

- ✓ Suitable to MIMO systems
- ✓ Optimal regulator which satisfies the control requirements encoded as frequency weights
- ✓ Convex optimization problem (global optimum)
- ✗ Regulator is dynamic and high order (plant+weights)
- ✗ Full $[m \times p]$ transfer matrix



Matlab Robust Control Toolbox

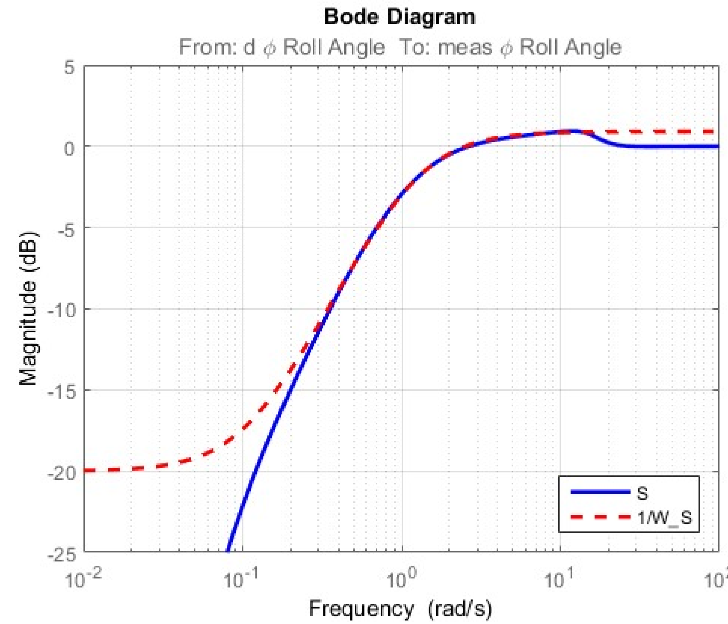
- Classical $\boldsymbol{H}_\infty$ synthesis: `hinfsyn()`
- Structured $\boldsymbol{H}_\infty$ synthesis: `systune()`

Read the documentation!

Translating requirements in the frequency domain

Requirements can be stated in the form of frequency weighting functions: $W(s)$

- Stable
- Minimum phase
- Proper



General guideline to choose (SISO) weights

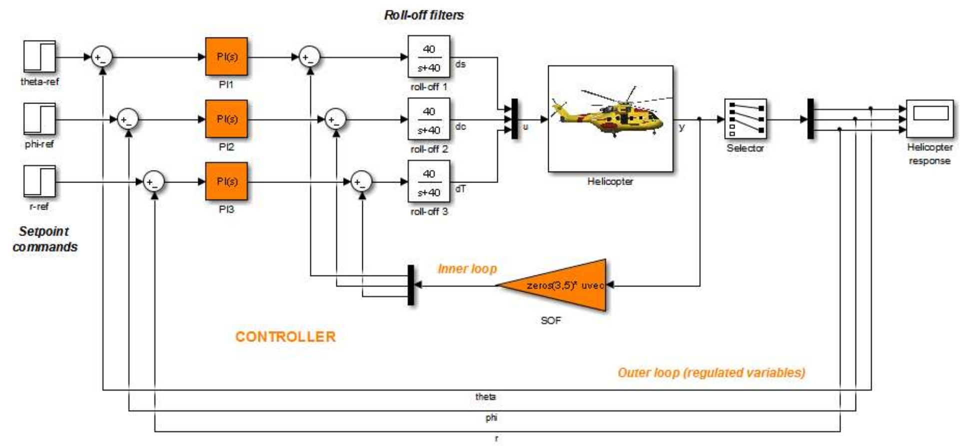
$$\|W(s)F(s)\|_\infty \le 1 \leftrightarrow |W(\jmath\omega)F(\jmath\omega)| \le 1 \ \forall\omega$$

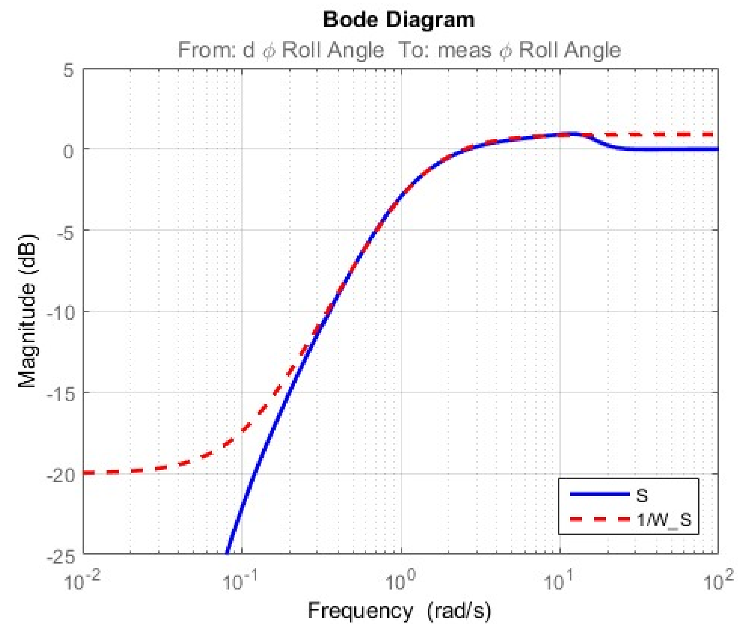
$$|F(\jmath\omega)| \le \frac{1}{|W(\jmath\omega)|}\forall\omega$$

Shaping function

Approach: H-infinity optimization-based control law synthesis methodology

- **Structured control law synthesis**:
  - impose the *structure* of control law *a priori*
  - tune the control law parameters
- **Control requirements:**
  - frequency dependent weighting functions
  - multi-objective
- Mixed-sensitivity H-infinity: (closed loop) **frequency weighted** sensitivity functions
- **Robustness**: uncertainty description is introduced in the control law synthesis stage





Formulation of the attitude control problem in the H_∞ framework

Requirements are encoded as frequency weights and imposed on proper closed-loop transfer functions (mixed-sensitivity):

- Stabilization (default)
- Performance → sensitivity function
- Control action moderation → control sensitivity function
- Robustness → complementary sensitivity function

$$S(s) = (I + G(s)K(s))^{-1}$$ Sensitivity

$$R(s) = K(s)(I + G(s)K(s))^{-1}$$ Control sensitivity

$$T(s) = G(s)K(s)(I + G(s)K(s))^{-1}$$ Complementary sensitivity

Optimization problem set-up

Structured control law $K(\rho)$

Tunable parameters $\rho \in \mathbb{R}^{n_\rho}$

(e.g. upper and lower bounds) $\underline{\rho}_l \leq \rho_l \leq \bar{\rho}_l \qquad l = 1..n_\rho$

Closed-loop transfer function

weight

Scalar requirements $J_i(\rho) = \|W_i(s) S_i(s,\rho)\|_\infty \qquad i = 1..n$

Scalarized cost function $J(\rho) = \max_{i=1..n} J_i(\rho)$

Unconstrained H_∞ multi-objective optimization problem

$$\begin{aligned}
\min_{\rho} J(\rho) \quad &= \quad \min_{\rho} \max_{i=1..n} J_i(\rho) \\
\text{subject to} & \\
\underline{\rho}_l \leq \rho_l \quad &\leq \quad \bar{\rho}_l \qquad l = 1..n_\rho \\
\\
J_i(\rho) \quad &= \quad \|W_i(s) S_i(s,\rho)\|_\infty \qquad i = 1..n
\end{aligned}$$

Constrained H_∞ multi-objective optimization problem

Define additional constraints (i.e., higher priority requirements):

$$H_j(\rho) = \|W_j(s)S_j(s,\rho)\|_\infty \qquad j = 1..c \qquad\qquad H(\rho) = \max_{j=1..c} H_j(\rho)$$

$$\begin{aligned}
\min_\rho J(\rho) &= \min_\rho \max_{i=1..n} J_i(\rho) \\
\text{subject to} & \\
\max_{j=1..c} H_j(\rho) &\le 1 \\
\underline{\rho}_l \le \rho_l &\le \bar{\rho}_l \qquad l = 1..n_\rho
\end{aligned}$$

«soft» requirements

«hard» requirements

$$\begin{aligned}
J_i(\rho) &= \|W_i(s)S_i(s,\rho)\|_\infty \qquad i = 1..n \\
H_j(\rho) &= \|W_j(s)S_j(s,\rho)\|_\infty \qquad j = 1..c
\end{aligned}$$

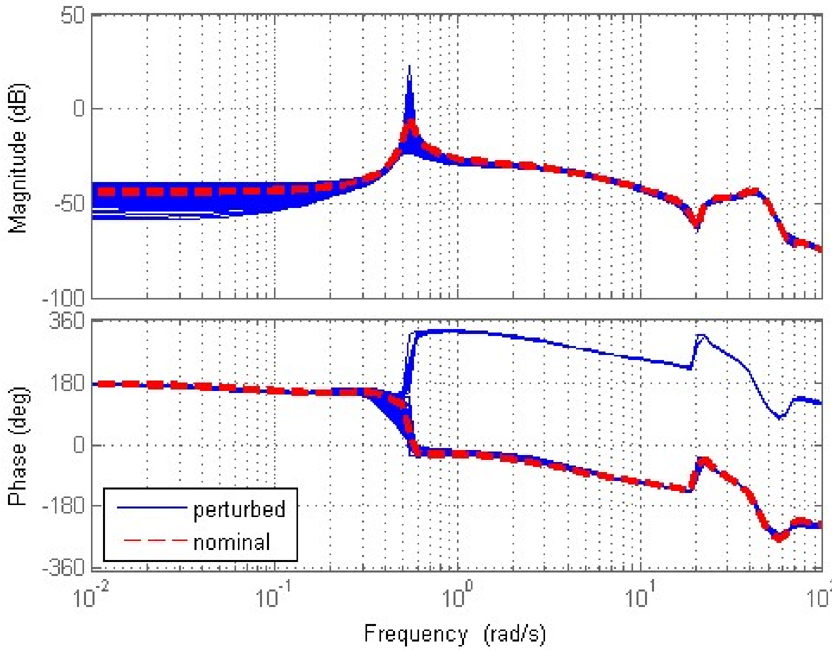
Uncertainty description in the frequency domain (1)

Idea: to represent model uncertainty by

- A nominal LTI model (with no uncertainty) $G(s)$
- A set of perturbed models Π
- The generic perturbed model in the set $G_p(s) \in \Pi$

A particular model in the set of perturbed models can be obtained by the combination of

- A nominal branch
- An uncertain branch



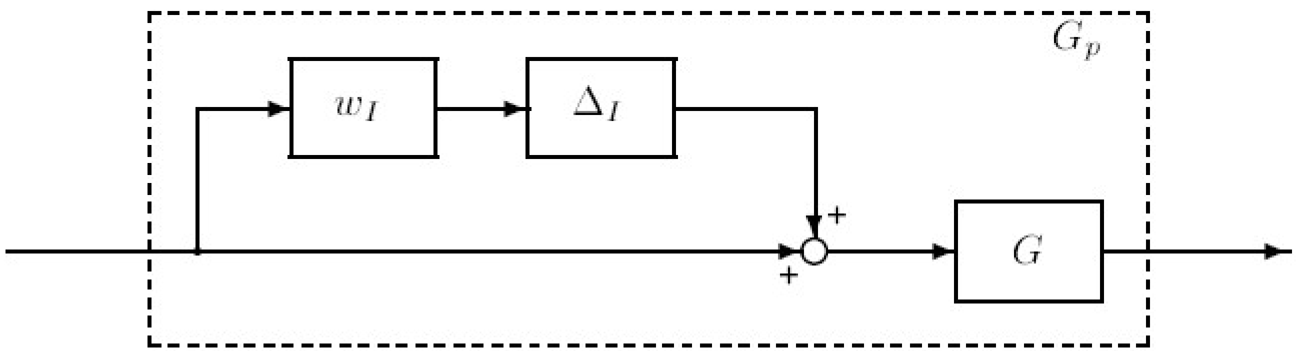
Uncertainty description in the frequency domain (2)

The uncertain branch is made up of

- An uncertain, stable transfer function bounded in magnitude $\Delta(s)$
- A stable transfer function

$$W(s)$$

which can be interpreted as a weight which determines the amount of uncertainty as a function of frequency (namely, the uncertainty description)



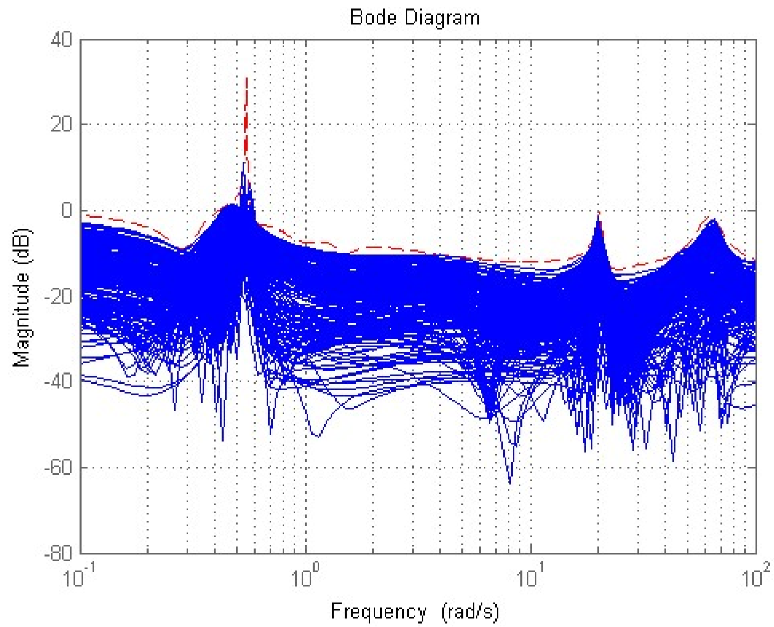
Choice of the uncertainty description: SISO case

In the multiplicative uncertainty case, the uncertainty description can be computed as follows:

- For each of the perturbed models, compute

$$\frac{G_p(s)-G(s)}{G(s)}$$

- Get the magnitude upper envelope



$$l(\omega)=\max_{G_p\in\Pi}\left|\frac{G_p(\jmath\omega)-G(\jmath\omega)}{G(\jmath\omega)}\right|$$

- Find a rational transfer function which approximates the upper envelope

$$|W(\jmath\omega)|\geq l(\omega),\forall\omega$$

Robust stability (RS)

The closed loop system is stable for any perturbed system in the set

$$L(s) = G(s)K(s)$$

Loop transfer function

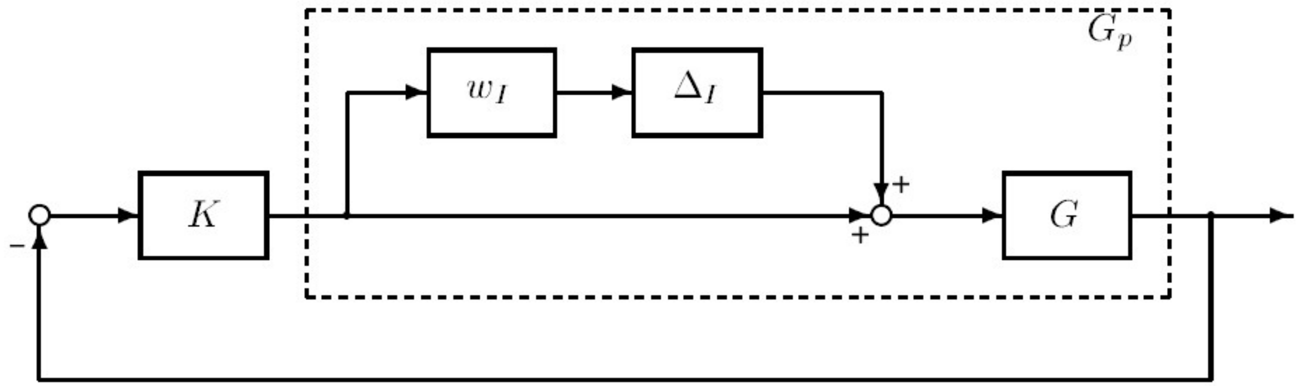
$$T(s) = L(s)\left(I + L(s)\right)^{-1}$$

Complementary sensitivity function

$$T(s) = \frac{L(s)}{1+L(s)}$$

Complementary sensitivity function (SISO)

$$\|T(s)W(s)\|_\infty < 1 \Leftrightarrow |T(j\omega)W(j\omega)| < 1, \forall \omega \qquad \text{(SISO)}$$



Application

HELICOPTER ATTITUDE CONTROL DESIGN WITH ROTOR STATE FEEDBACK

Command style

- AC: attitude command
- RC: rate command
- TRC: translational rate command
- …

Feed-forward, response to pilot command

Hold capability

- AH: attitude hold
- DH: direction hold
- PH: position hold
- HH: height hold
- …

Feedback, disturbance rejection (e.g. **Attitude hold**: “the attitude angle shall return to its initial value as a response to external disturbance” - from standard specification ADS-33)

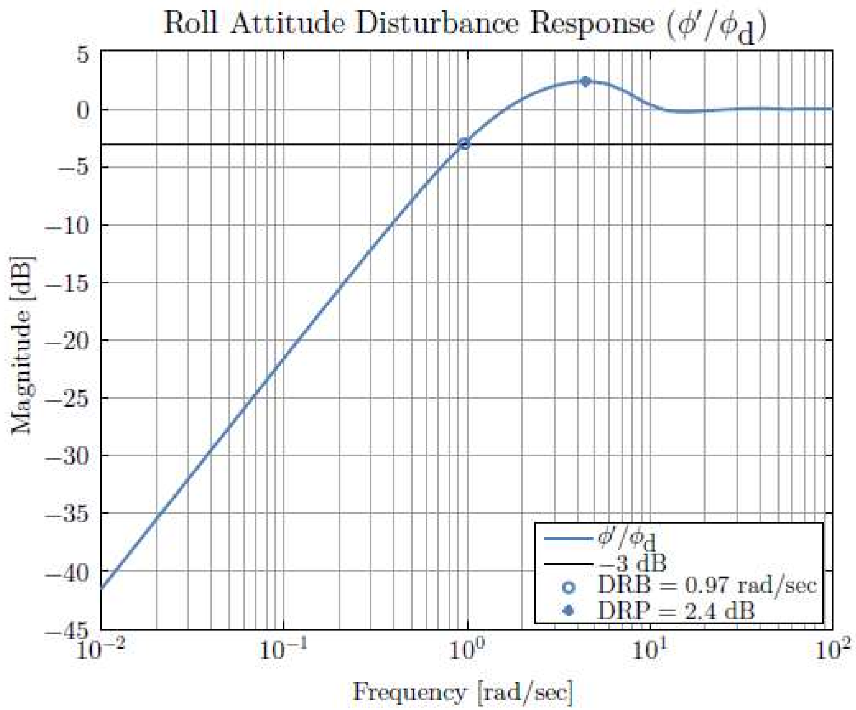
$$\begin{bmatrix} p \\ \varphi \end{bmatrix} = G(s)\theta_{1c}$$

Closed-loop performance is characterized by the *hold variable* sensitivity function:

- Disturbance rejection bandwidth (DRB)
- Disturbance rejection peak (DRP) → damping ratio

$$S(s) = (I + G(s)K)^{-1} \quad \text{(MIMO)}$$

$$S\varphi(s) = \frac{\varphi}{d_\varphi} \quad \text{(SISO)}$$



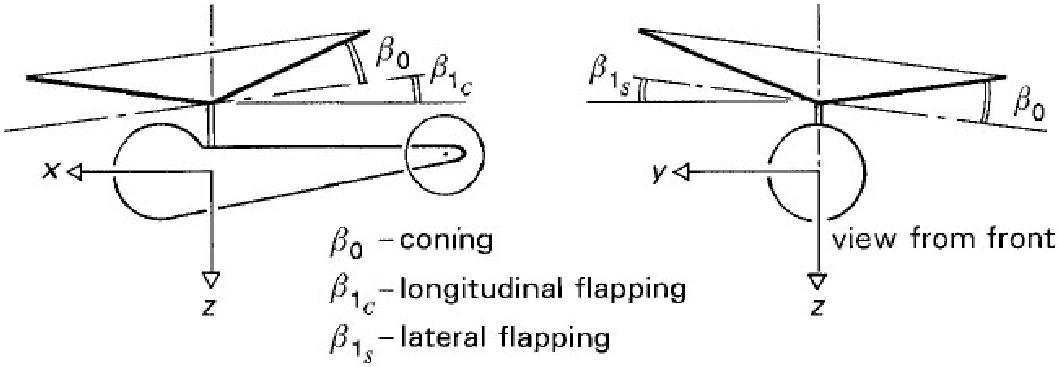
T. Berger, C. Ivler, M. Berrios, M.B. Tischler and D. Miller. «Disturbance rejection handling qualities criteria for rotorcraft». *72nd Annual Forum of the American Helicopter Society, West Palm Beach, USA,* 2016

MBC transformation

Objective: to represent the rotor blades motion as a whole
Rotor DOFs transformation: coordinate change

- From the frame rotating with the hub…
- … to the frame fixed in the fuselage

$$\begin{cases} \beta_0 &= \frac{1}{N_B} \sum_{i=1}^{N_B} \beta_i \\ \beta_{nc} &= \frac{2}{N_B} \sum_{i=1}^{N_B} \beta_i \cos(n\psi_i) \\ \beta_{ns} &= \frac{2}{N_B} \sum_{i=1}^{N_B} \beta_i \sin(n\psi_i) \\ \beta_{N/2} &= \frac{1}{N_B} \sum_{i=1}^{N_B} \beta_i (-1)^i \end{cases}$$



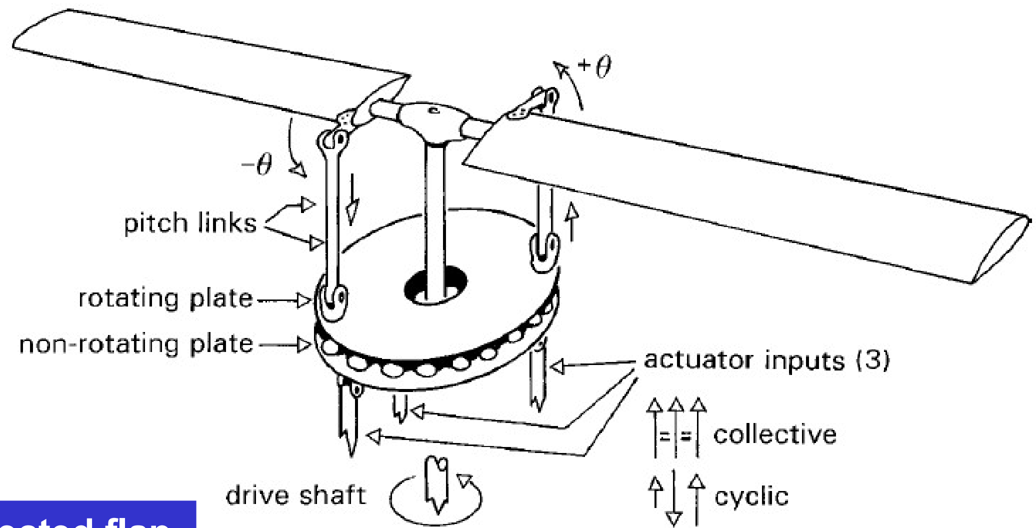
New DOFs (expressed in body axes frame):

- β_0 coning angle
- β_{1c} cone axis tilt angle in forward direction
- β_{1s} lateral tilt
- …other reactionless DOFs

Tip path plane (TPP)

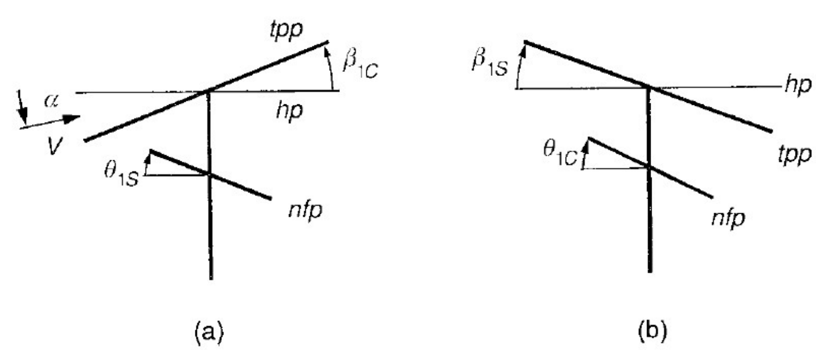
Swashplate

How to tilt the rotor disc?
•Tilting the rotor shaft (small helicopters)
✓Varying the blade pitch (swashplate)



Command	Symbol	Effect	Affected flap variable
Collective	θ_0	Increase all blades' pitch	β_0
Longitudinal cyclic	θ_{1s}	Periodic (Ω) pitch change	β_{1c}
Lateral cyclic	θ_{1c}	Periodic (Ω) pitch change	β_{1s}
Tail rotor collective	$\theta_{0,tail}$	Increase tail rotor blades' pitch	$\beta_{0,tail}$

$$\theta(\psi) = \theta_0 + \theta_{1c}\cos(\psi) + \theta_{1s}\sin(\psi)$$



ψ = 90° (view from left) ψ = 0° (view from front)

Role of rotor dynamics in control-oriented attitude models

- Rotor and fuselage are dynamically coupled in the attitude control frequency range (pitch/roll moments depend on longitudinal/lateral flap angle)
- Rotor dynamics introduce phase lag in the loop
- High gain control (with classical attitude control laws) results in poor stability margin → bandwidth of the attitude loop is limited

Low order equivalent system are used in attitude control design
Modeling complexity depends on bandwidth of the attitude loop:

- Low-bandwidth: rotor can be interpreted as an actuator and its (fast) dynamics can be simplified
- High-bandwidth: rotor dynamics should be accounted for in the model used in attitude control design

Low bandwidth:

quasi-steady rotor

$$\frac{p}{\theta_{1c}} = \frac{K}{s+L} e^{-\tau s}$$

High bandwidth:

coupled fuselage-rotor

$$\frac{p}{\theta_{1c}} = \frac{K(s+z)}{s^2+a_1 s+a_2} e^{-\tau s}$$

Roll axis

φ^0

ACAH (attitude command, attitude hold)

Static output feedback

- Baseline:

$K = [K_p, K_\varphi]$

$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p\right)$$

- Rotor state feedback (RSF):

$K = \left[\begin{array}{ccc} K_{\beta_{1s}} & K_p & K_\varphi \end{array}\right]$

$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p + K_{\beta_{1s}}\beta_{1s}\right)$$

fuselage measurements

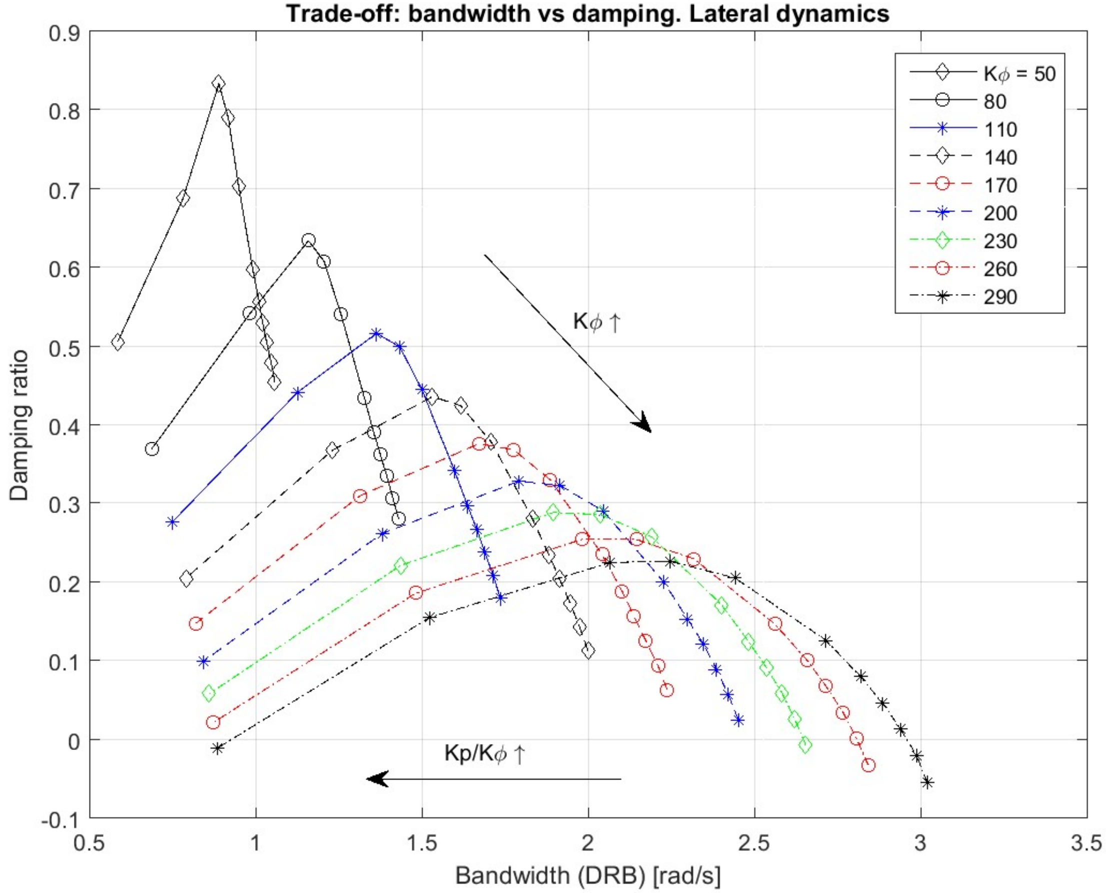
RSF

Bandwidth vs damping trade-off: helicopter roll attitude control law

$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p\right)$$

$$K_\varphi \left[\frac{\%}{rad}\right]$$

$$K_p \left[\frac{\%}{rad/s}\right]$$

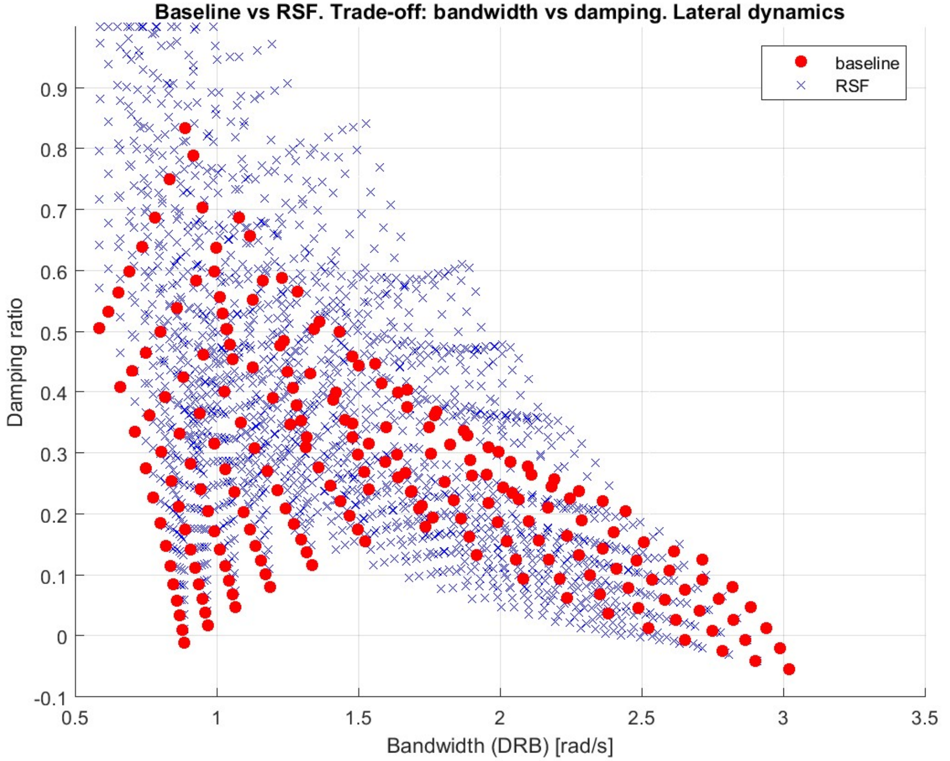


$$\frac{K_p}{K_\varphi} = \begin{bmatrix} 0.02 \\ 0.04 \\ 0.06 \\ 0.08 \\ 0.1 \\ 0.13 \\ 0.2 \\ 0.25 \\ 0.3 \\ 0.5 \\ 1 \end{bmatrix}$$

$$S\varphi(s) = \frac{\varphi}{d_\varphi}$$

Performance trade-off: Baseline vs RSF

- Feedback from rotor states introduces phase lead in the loop
- RSF allows to increase bandwidth while maintaining adequate stability margin
- Overcome the trade-off between bandwidth/damping ratio



$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p + K_{\beta_{1s}}\beta_{1s}\right)$$

$$K_{\beta_{1s}} = \begin{bmatrix} 0 & 30 & 60 & 90 & 120 & 150 & 180 & 210 & 240 \end{bmatrix} \left[\frac{\%}{rad}\right]$$

Rotor state feedback: safety

Rotor flapping is related to cyclic (1/rev) yoke chord bending loads, both in helicopter and airplane modes [Manimala et al., 2004; King et al, 1993]

Enforce safety constraints: reduce amount of flapping

- reduce fatigue on structural components
- avoid contact between blade and wing

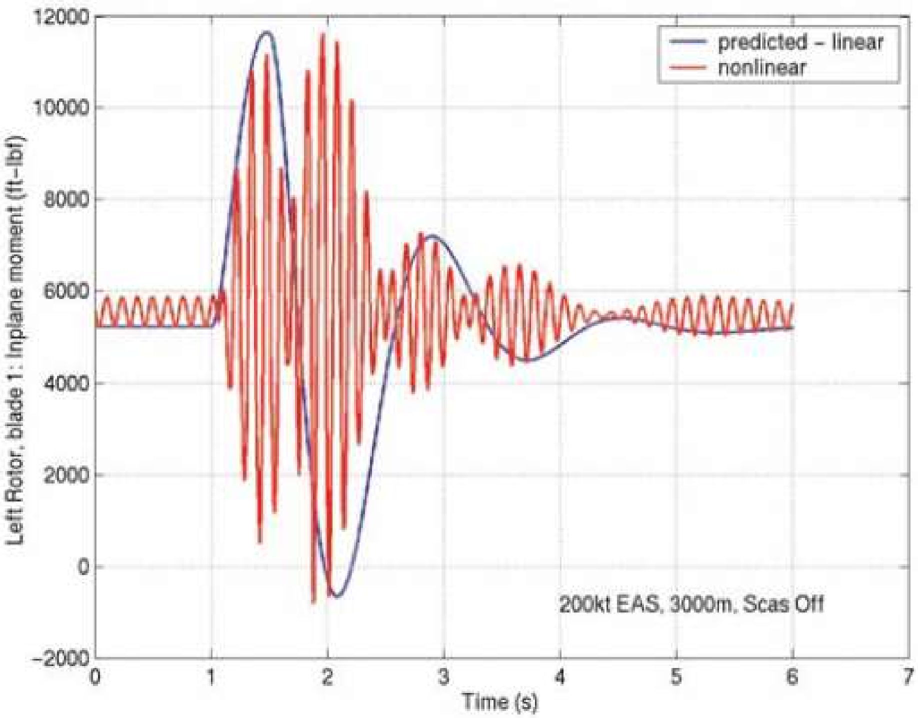


Figure 13. In-plane bending moment in a 2·5g pull-up manoeuvre (200kt, 3,000m): FXV-15.

Manimala et al. (2004) Load alleviation in tilt rotor aircraft through active control; modelling and control concepts. The Aeronautical Journal, 108, 169-184.

Helicopter model

FLIGHTLAB (http://www.flightlab.com)

- 58 states
- linearized in hover
- parameters: forward speed, mass, altitude, CG position, …
- Fully-coupled

Leonardo AW139 helicopter

Component	Frequency range	States
Fuselage	Low-medium	• Translational velocity (u, v, w) (low frequency) • Attitude angles (φ, θ, ψ) and rates (p, q, r) (medium frequency)
Main rotor	Medium-high	• MBC flap+lag (+ derivatives) → LTI model • Inflow+wake
Tail rotor	High	• Collective flap • Inflow

Helicopter model (58 states - eigenvalues)

Low frequency translational dynamics

Medium frequency coupled attitude (**lateral** and **longitudinal**) + rotor dynamics

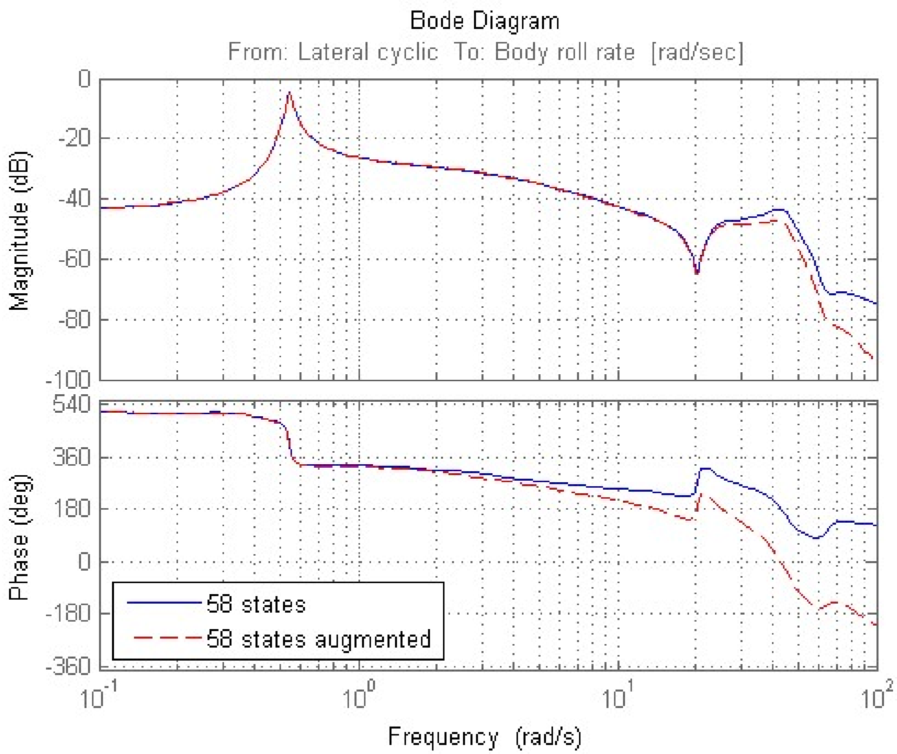
High frequency rotor dynamics

Response mode	Eigenvalue	$\omega[rad/s]$	ξ
Heave+yaw	$-0.228 \pm 0.019\imath$	0.229	0.996
Longitudinal phugoid	$0.160 \pm 0.450\imath$	0.477	-0.334
Lateral oscillation	$-0.014 \pm 0.543\imath$	0.543	0.026
Pitch subsidence	-0.964	0.964	1.000
Regressive flap(1)	-3.790	3.790	1.000
Regressive flap(2)	-5.512	5.512	1.000
Roll subsidence	-7.473	7.473	1.000
Collective lag	$-5.025 \pm 7.718\imath$	9.210	0.546
Collective inflow	-17.015	17.015	1.000
Regressive lag	$-3.750 \pm 21.738\imath$	22.059	0.170
Collective flap	$-12.846 \pm 27.240\imath$	30.117	0.427
Cyclic inflow	$-33.600 \pm 2.685\imath$	33.707	0.997
Progressive lag	$-5.297 \pm 43.703\imath$	44.022	0.120
Progressive flap	$-15.564 \pm 58.459\imath$	60.496	0.257

Actuators & sensors

- Actuators: 3rd order model (1st order dominant dynamics, bandwidth $\omega \sim 50\,rad/s$)
- Sensors (roll/pitch rate): 2nd order model
  - bandwidth $\omega \sim 50\,rad/s$
  - damping ratio $\xi \sim 0.7$
- Pure time delay (10[ms] due to ZOH + 10[ms] due to signal processing)

Overall augmented system: +10 states, 20[ms] time delay

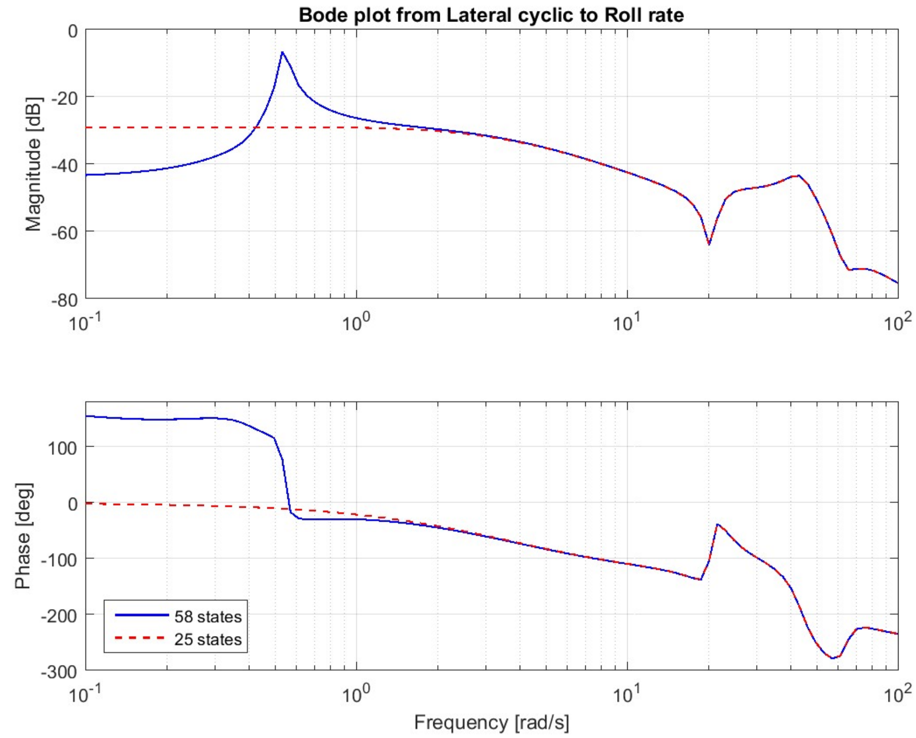


Model reduction (25 states)

Focus on the pitch/roll attitude dynamics: reduced-order model

25 states (+10 due to actuator&sensor)

Obtained by truncation: neglect translational velocities (u, v, w), and the yaw/heave dynamics



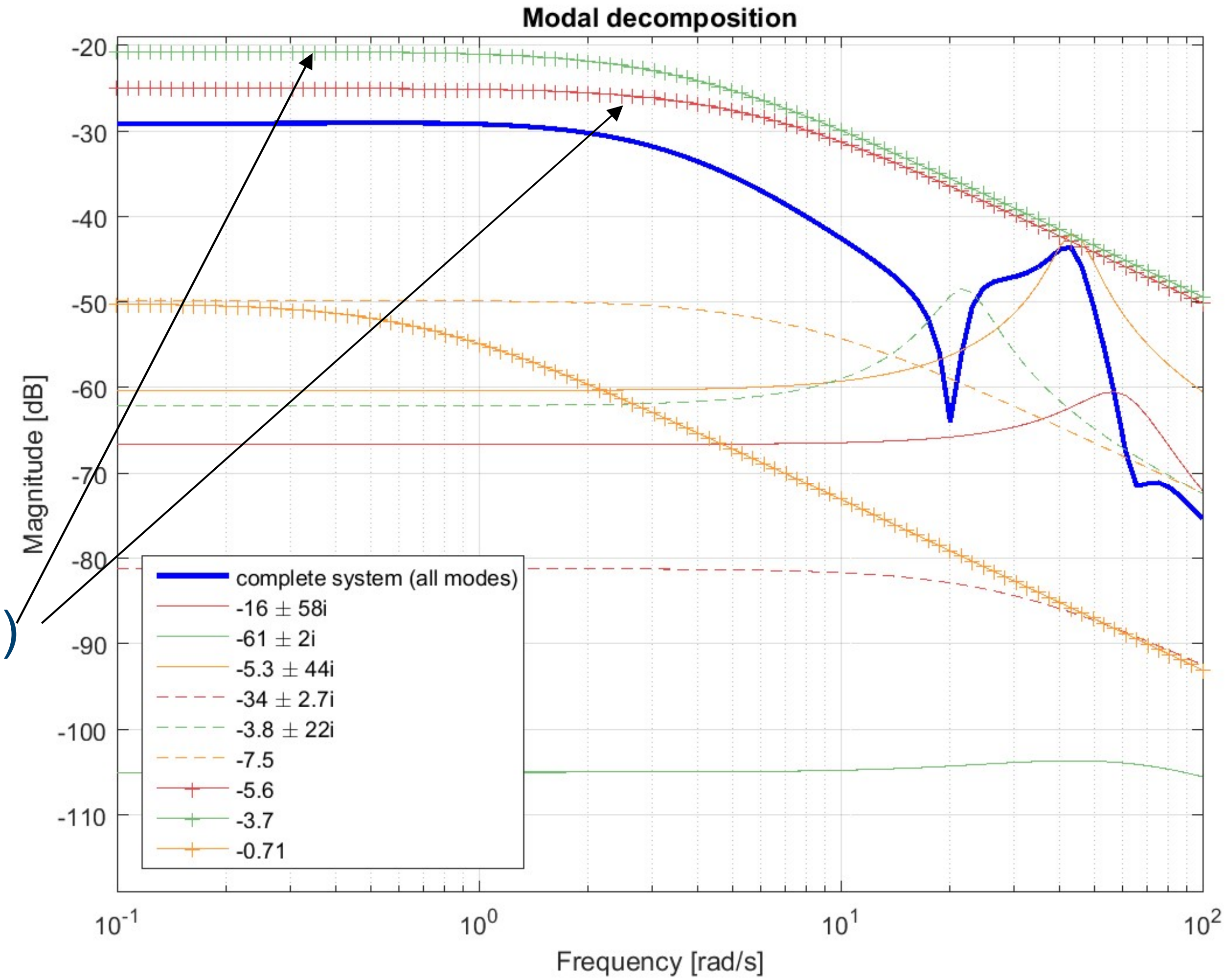
Retain fuselage attitude + rotor dynamics ([1-10]rad/s)

Modal decomposition: lateral attitude (magnitude)

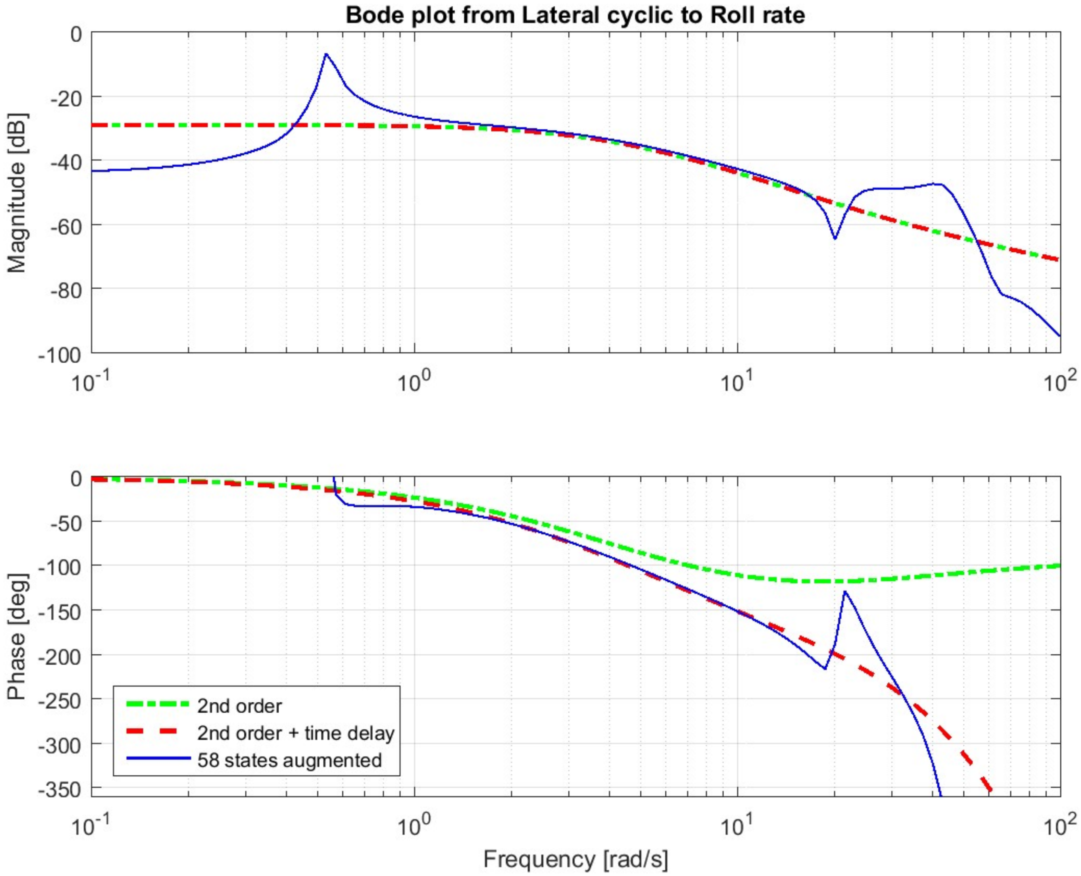
Reduce order 25 model to 2nd order model (approximate lateral attitude dynamics)

Regressive flap (1&2)

Rotor-fuselage coupling



- Lateral attitude dynamics can be approximated by regressive flap
- Equivalent pure time delay 71[ms] @ 10[rad/s] (In order to keep into account the phase lag due to actuators&sensors)



$$\tau_{eq} = \frac{\Delta\phi}{\bar{\omega}}$$

$$\bar{\omega} = 10\,\mathrm{rad/s}$$

$$G_{eq}(s) = G_{bare}(s)e^{-\tau_{eq}s}$$

$$\Delta\phi = \angle G_{bare}(\jmath\bar{\omega}) - \angle G_{augm}(\jmath\bar{\omega})$$

Why is delay so important in feedback control systems?

https://youtu.be/_fNp37zFn9Q

Roll axis

φ^0

ACAH (attitude command, attitude hold)

Static output feedback

- Baseline:

$$K = [K_p, K_\varphi]$$

$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p\right)$$

- Rotor state feedback (RSF):

$$K = \left[\begin{array}{ccc} K_{\beta_{1s}} & K_p & K_\varphi \end{array}\right]$$

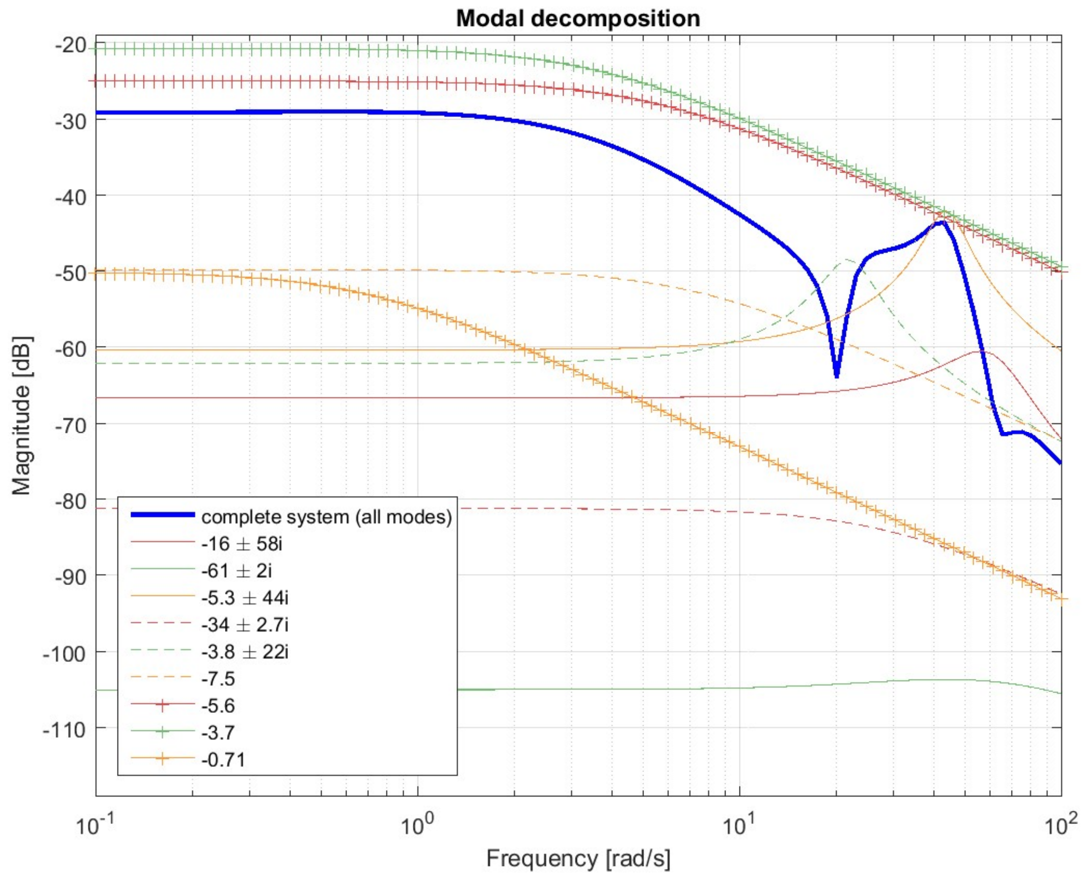
$$\theta_{1c} = -\left(K_\varphi(\varphi - \varphi^0) + K_p p + K_{\beta_{1s}}\beta_{1s}\right)$$

fuselage measurements

RSF

Rotor state feedback: motivation

- Low bandwidth attitude control: fuselage dynamics model, quasi-steady rotor
- To achieve high bandwidth implies incurring into a frequency range in which fuselage and rotor are dynamically coupled
- Using rotor state measurements in the feedback control law (RSF) gives access to rotor dynamics
- MBC measurements of flap (β_{1s}, β_{1c})



Set-up of synthesis problem

	Performance	Control moderation
Closed-loop TF	Roll attitude angle sensitivity $S\varphi(s) = \frac{\varphi}{d_\varphi}$	Control sensitivity $R(s) = K(I + G(s)K)^{-1}$
Weighting function	$W_{S\varphi}(s)$	$W_R(s)$
Cost function	$J_S = \|S_\varphi(s)W_{S\varphi}(s)\|_\infty$	$J_R = \|W_R(s)R(s)\|_\infty$

$$\min_{\rho} J$$

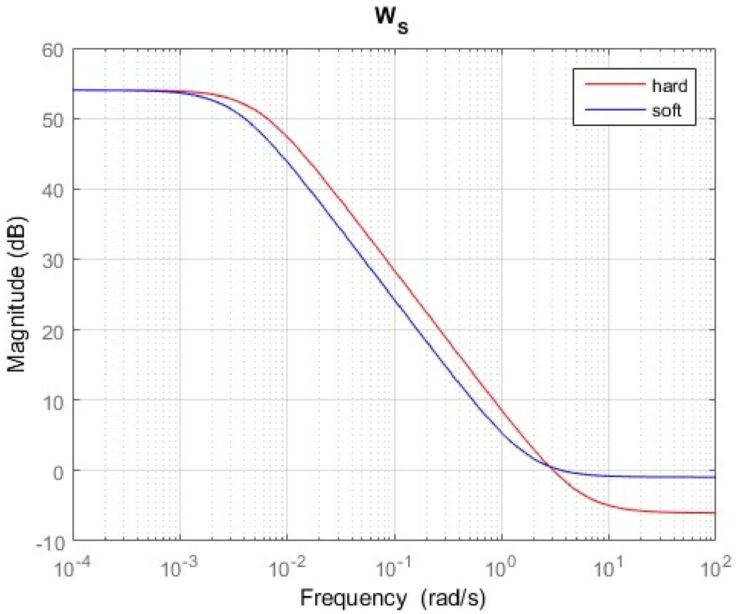
$$\text{subject to}$$

$$J = \max\{J_S, J_R\}$$

$$J_S = \|S_\varphi(s)W_{S\varphi}(s)\|_\infty$$

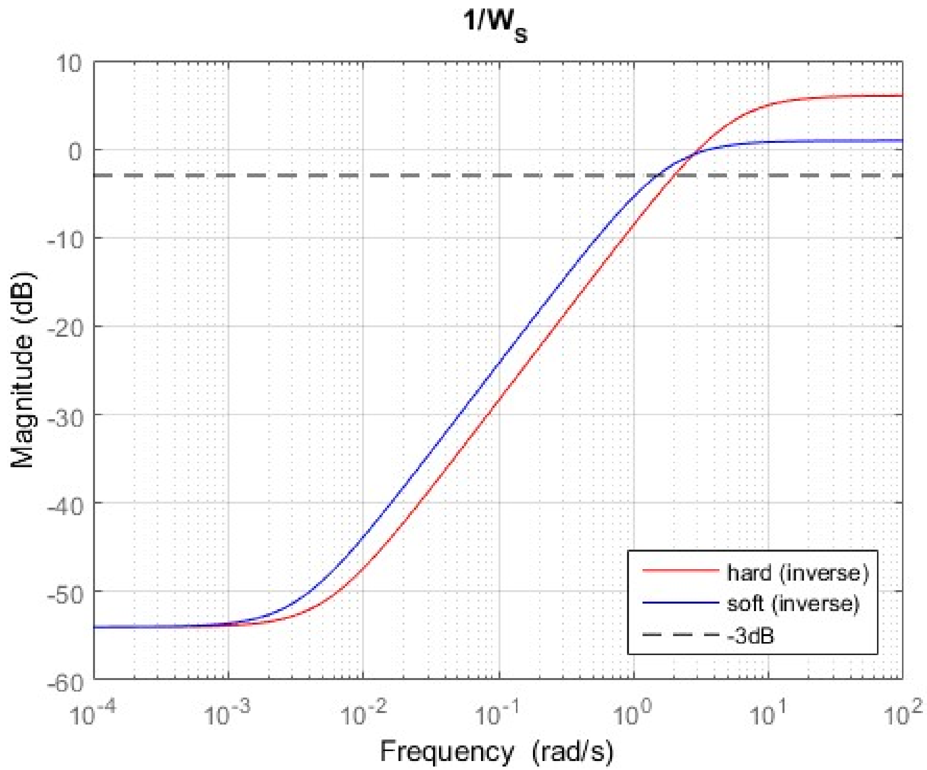
$$J_R = \|W_R(s)R(s)\|_\infty$$

H_∞ choice of weighting functions: sensitivity



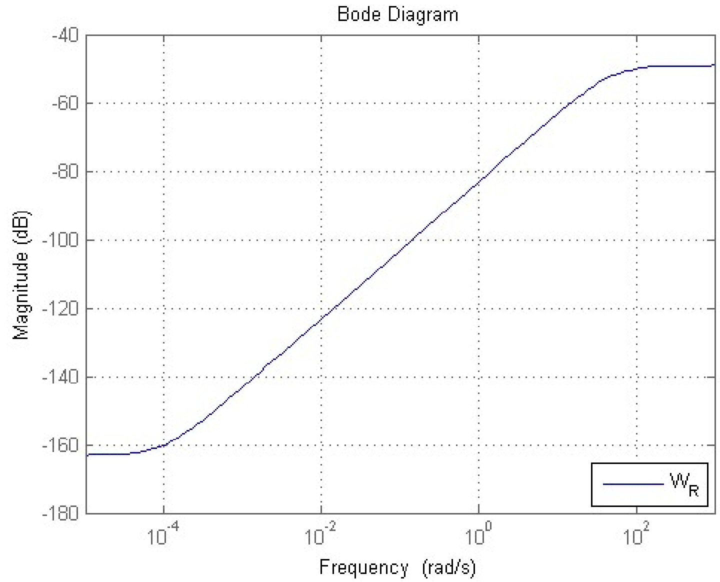
$$W_{S\varphi}(s) = K_{HF}\frac{s+z}{s+p}$$

$W_{S\phi}$ parameters	Soft	Hard
Desired bandwidth [rad/s]	1.5	2
DC gain	500	500
High frequency gain	0.9	0.5



H_∞ choice of weighting functions: control sensitivity

- Control sensitivity weight is necessary in order to limit control action (actuator range is bounded)
- Limit control action outside actuator bandwidth
- Control sensitivity can be interpreted as the tf from measurement noise to control action: it is important to bound control action as a response to high frequency noise
- Small gain at low frequency to avoid interferences with sensitivity



W_R parameters	Soft	Hard
High frequency gain	$3.5E-3$	$12E-3$
Pole frequency [rad/s]	50	50
Ratio high/low frequency gains	$5E5$	$5E5$

Fault robustness

Robustness to loss of measurement of β_{1s} $(i.e., \beta_{1s} = 0)$

- Nominal configuration → nominal performance
- Faulty configuration → degraded performance

Stability shall be guaranteed in face of faults

Different requirements can be imposed according to the condition (nominal/faulty)

Approach: multi-model synthesis

$G^N(s)$ Nominal open-loop system

$G^F(s)$ Faulty open-loop system

$K(\rho)$

Nominal closed-loop	Faulty closed-loop
$S_\varphi^N(s)$	$S_\varphi^F(s)$
$R^N(s)$	$R^F(s)$

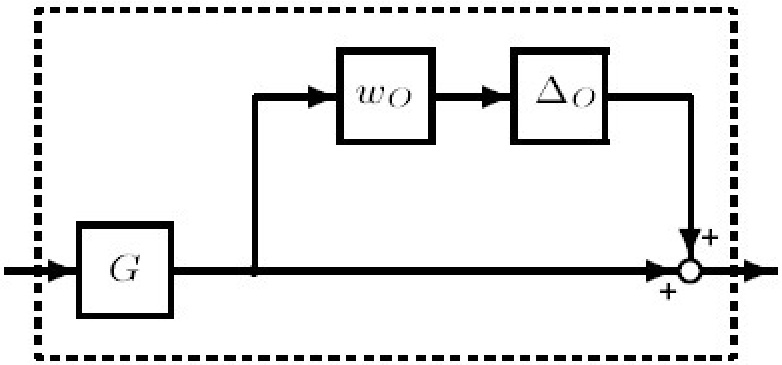
$$\min_{\rho} \max \left\{ J_S^N, J_R^N, J_S^F, J_R^F \right\}$$

subject to

$$J_S^N = \left\| S_\varphi^N(s) W_{S\varphi}^N(s) \right\|_\infty$$
$$J_R^N = \left\| W_R^N(s) R^N(s) \right\|_\infty$$
$$J_S^F = \left\| S_\varphi^F(s) W_{S\varphi}^F(s) \right\|_\infty$$
$$J_R^F = \left\| W_R^F(s) R^F(s) \right\|_\infty$$

H_∞ choice of weighting functions: complementary sensitivity

Complementary sensitivity weight may be interpreted as a multiplicative uncertainty description $W_O(s)$



Robust stability condition (w/respect to multiplicative uncertainty)

$$\|W_O(s)T(s)\|_\infty \leq 1 \qquad \|\Delta_O\|_\infty \leq 1$$

… however, in this example no weight was imposed on complementary sensitivity in control law synthesis

H_∞ control requirements formulation

	Hard performance	Soft performance
Hard control moderation		RSF soft
Soft control moderation	RSF hard RSF fault robust (nominal)	Baseline RSF fault robust (fault)

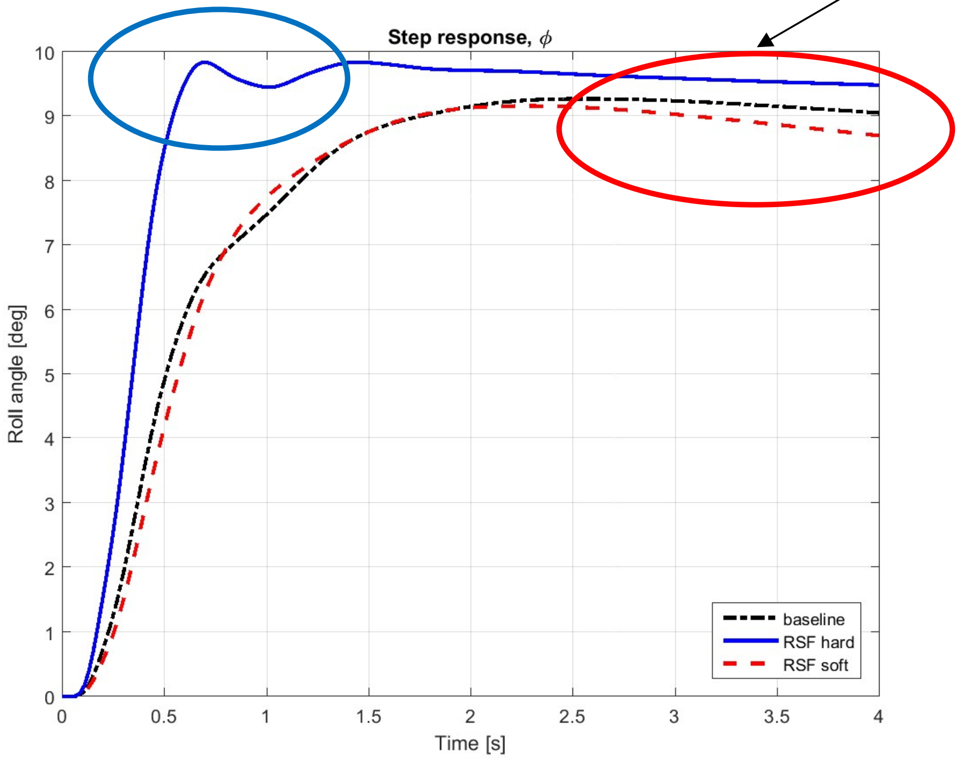
	$K_{\beta_{1s}} \frac{[\%]}{[rad]}$	$K_p \frac{[\%]}{[rad/s]}$	$K_\varphi \frac{[\%]}{[rad]}$
RSF_H	88	76	259
RSF_S	12	45	91
RSF_FR	231	63	158
Baseline	0	65	119

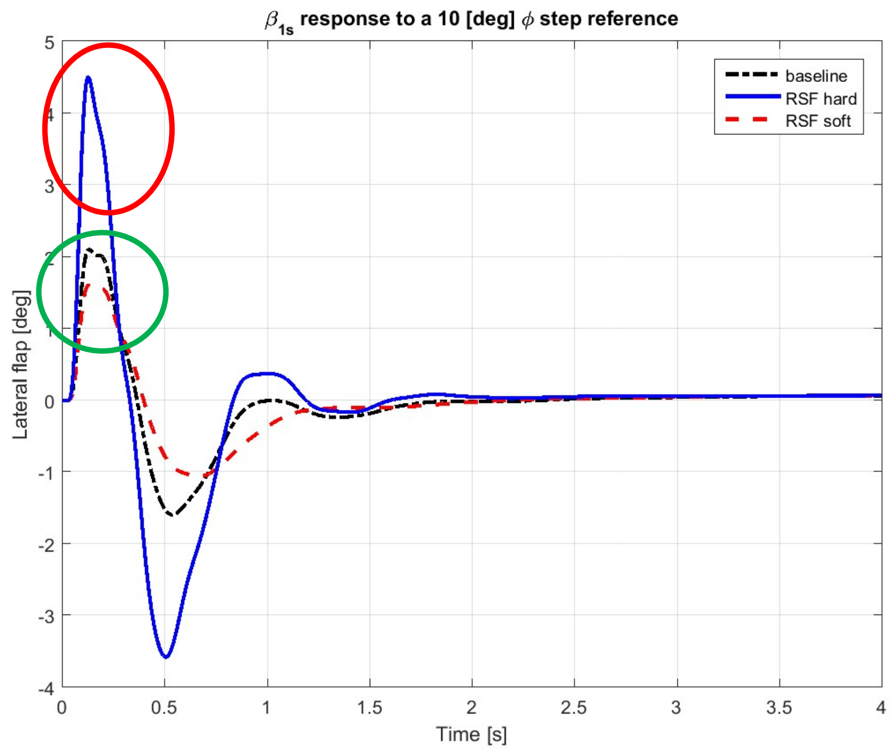
Controllers comparison: step responses

Faster response, oscillations

Drift – unstable low frequency modes

Large flapping

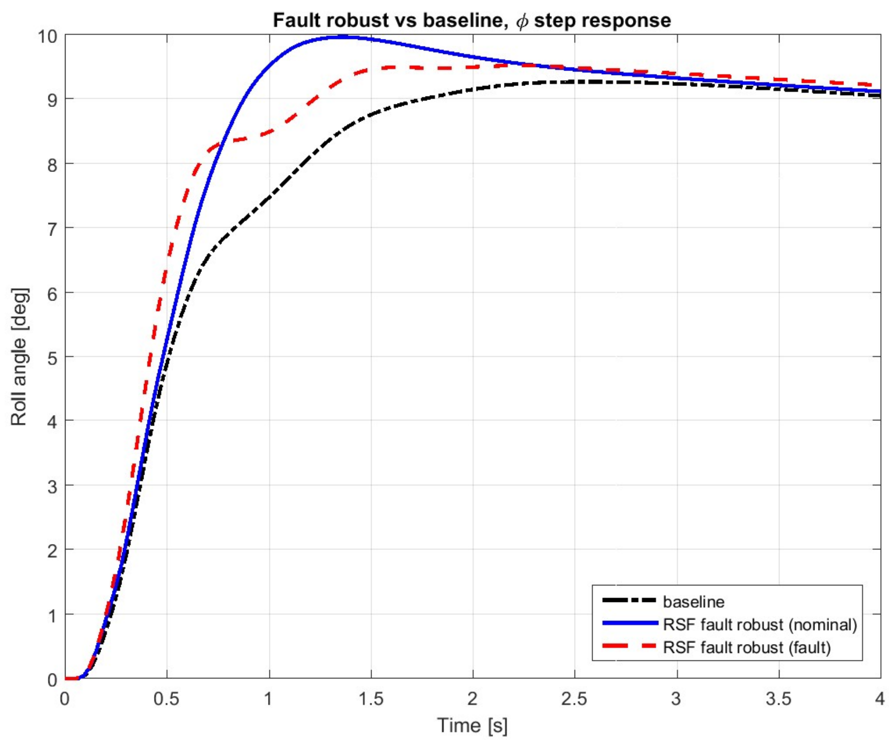


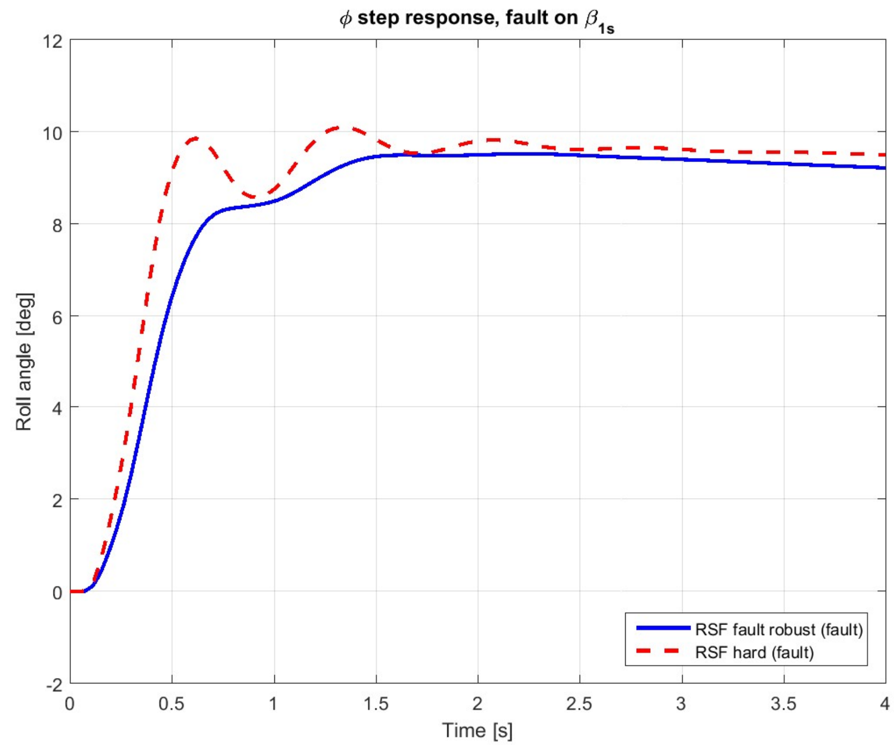


10deg step reference φ^0

RSF_S features less flapping than B

Controllers comparison: fault robustness





Degradation in performance is limited (nominal→fault)
Response is still faster than baseline

RSF_FR yields better performance in the faulty case than RSF_H (but the opposite is true in the nominal case)

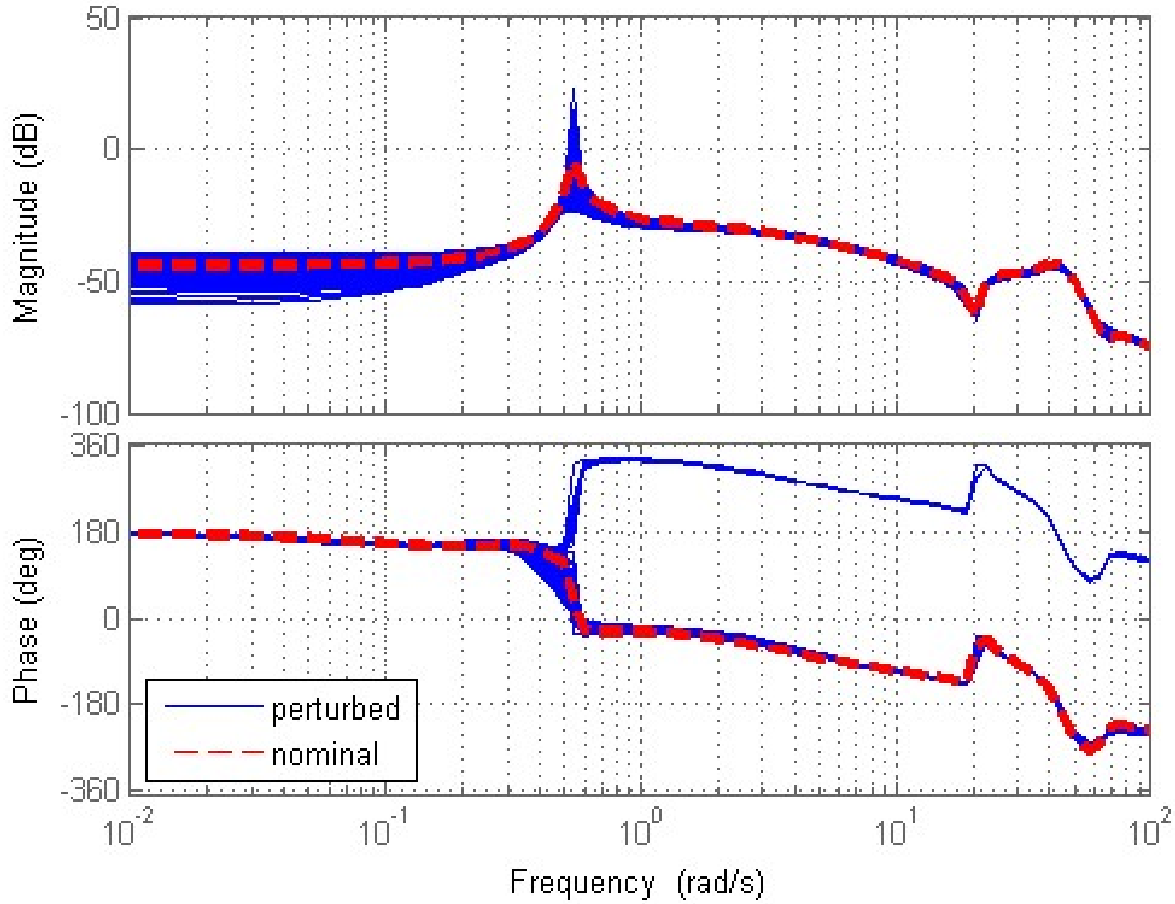
Parameters perturbations

- n models were generated ($n \sim 300$) by perturbing the parameter (mass, altitude, CG offset) values about the nominal value, in different combinations
- A multiplicative uncertainty description was then obtained, based on the nominal model
- Robustness analysis (a posteriori)

	Min	Max	Pace	Nominal
Mass [kg]	4400	6700	100	6000
Altitude [ft]	0	10000	5000	0
CG_X [m]	5	5.5	0.1	5.3
CG_Y [m]	-0.02	0.08	0.1	-0.02
CG_Z [m]	2.072	2.372	0.1	2.172

$$V = \{0, 50, 90\}[kts]$$

Nominal vs perturbed models (lat cyclic to roll rate, hover)



SISO multiplicative uncertainty description

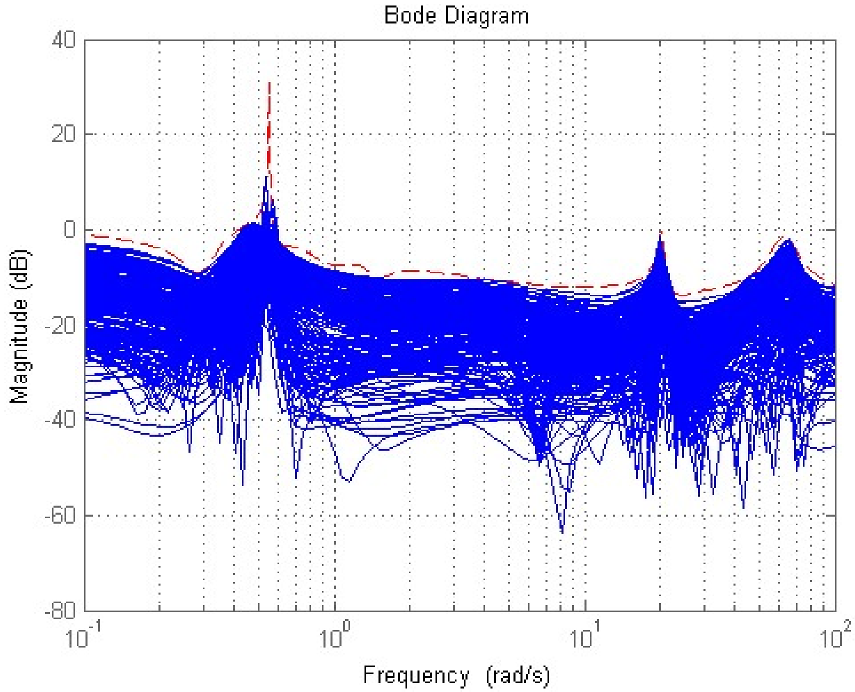
1 input, 3 outputs: $u = \theta_{1c}$ $y = \begin{bmatrix} \beta_{1s} \\ p \\ \varphi \end{bmatrix}$ $n_p = 3$

SISO uncertainty description (one-channel at a time)

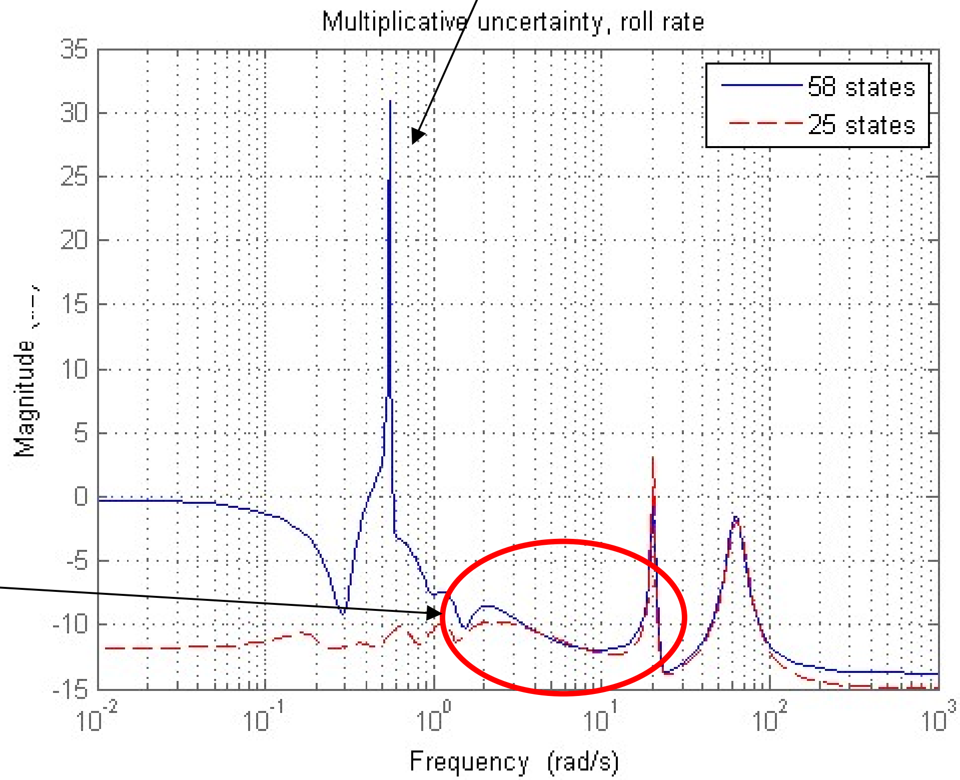
$$\tilde{G}_i = (1 + W_{O,i}(s)\Delta_i(s))G_i(s) \qquad i = 1..n_p$$

$$\|\Delta_i(s)\|_\infty \leq 1$$

SISO uncertainty description, hover



High peak at low frequency, due to lateral oscillation mode



Low uncertainty (and good agreement) in the attitude dynamics frequency range

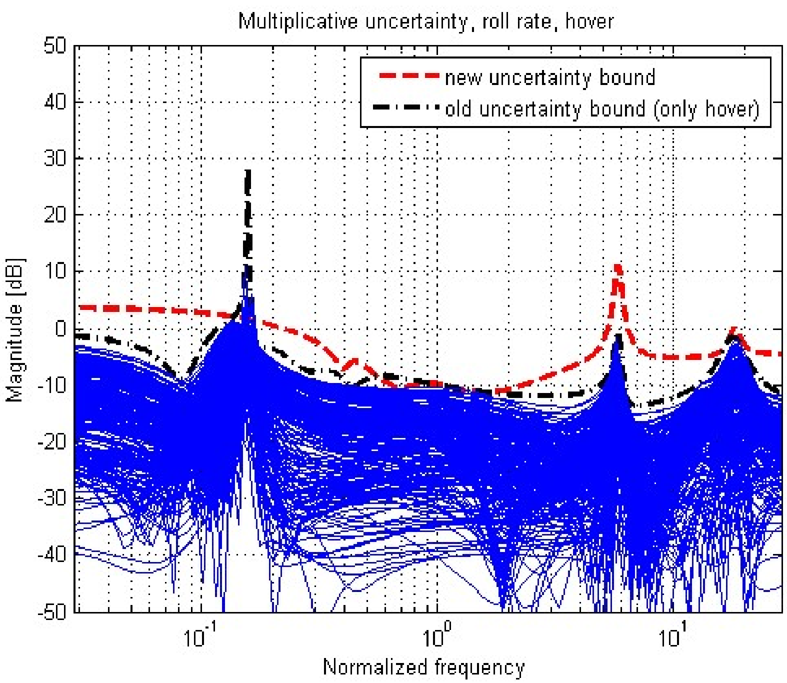
Uncertainty description, hover+forward flight

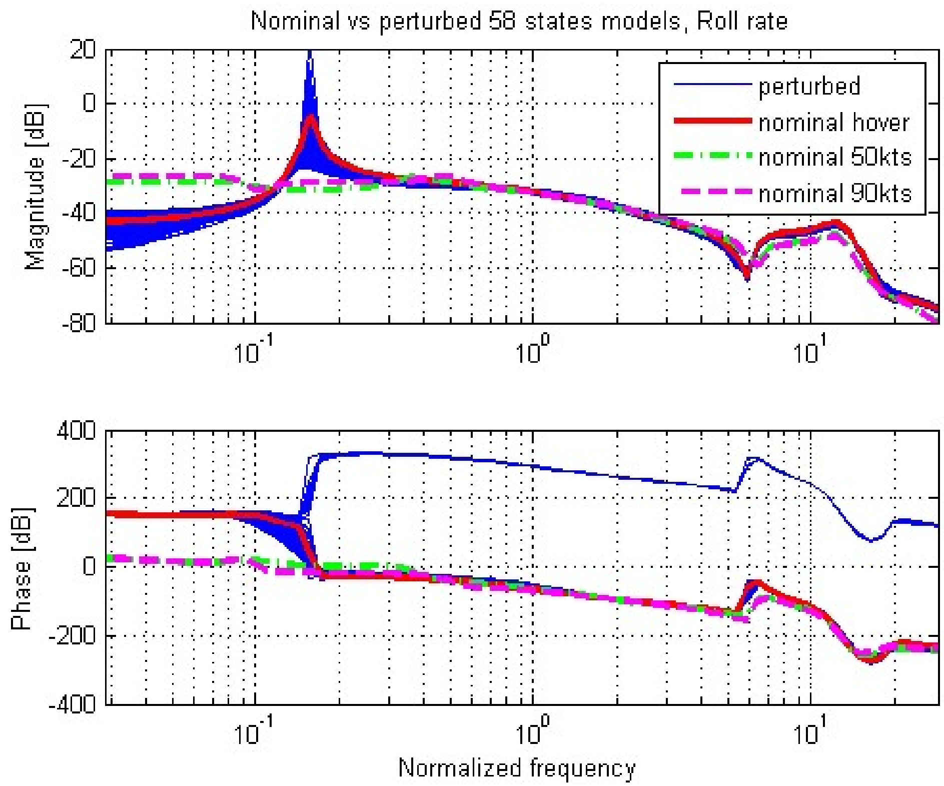
$$V = \{0, 50, 90\}[kts]$$

Analysis was extended to the case of forward flight

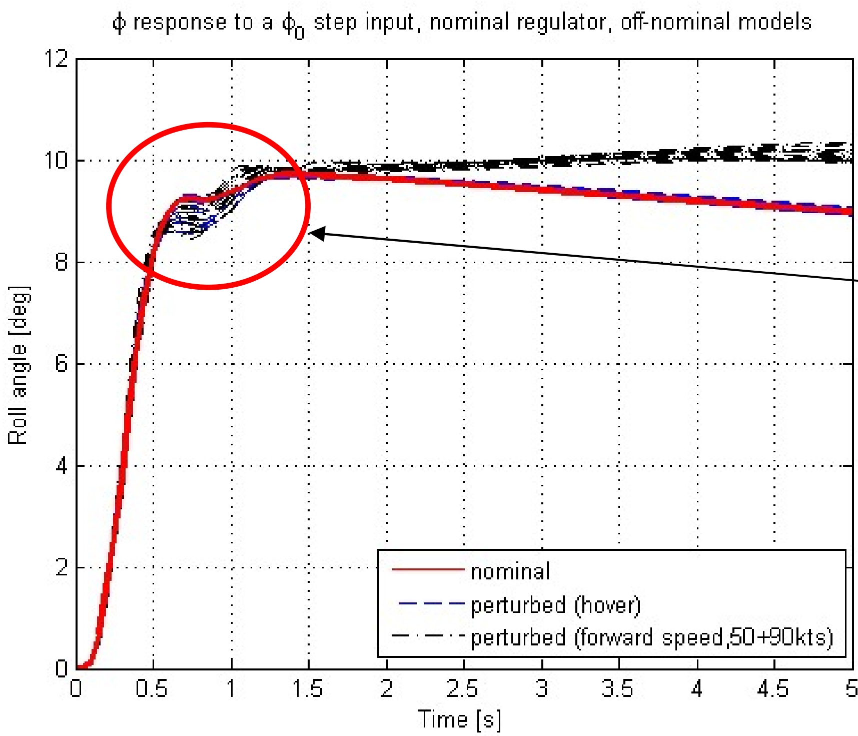
Uncertainty is larger (being the set of perturbed models larger)

No robustness issues were detected as for the attitude control loop



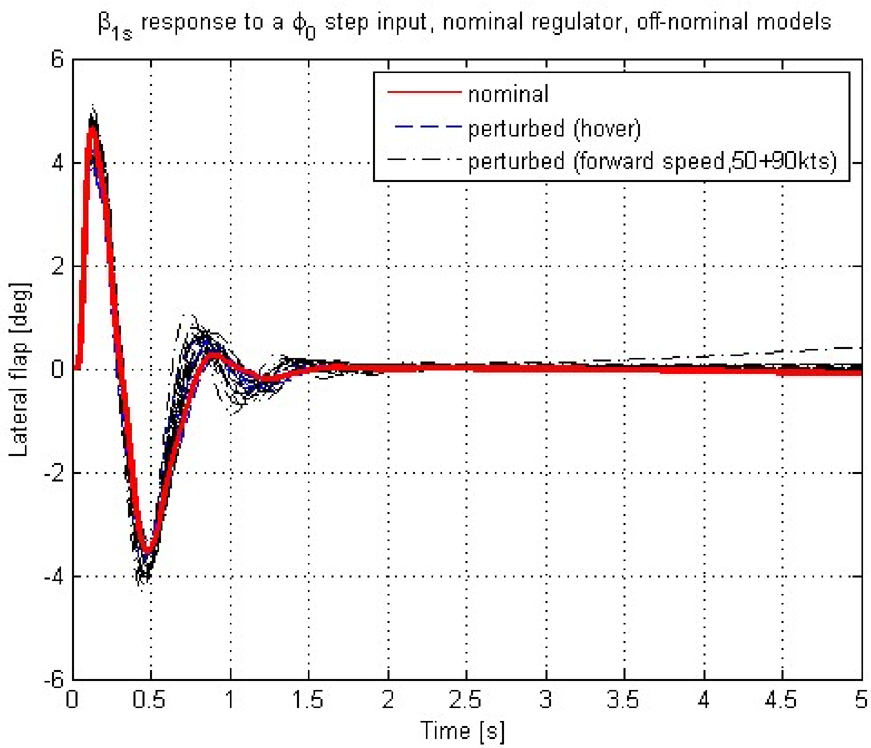


A posteriori robustness analysis: time domain (hover + forward flight)



Step response, roll angle (RSF hard, hover)

Variability in time response due to mass perturbations



Step response, lateral flap (RSF hard, hover)

Acknowledgements

This work was developed in the framework of project MANOEUVRES

MANOEUVRES "Manoeuvring Noise Evaluation Using Validated Rotor State Estimation Systems" is a project funded by the Clean Sky Joint Undertaking within the framework of Green Rotorcraft of the Clean Sky JTI

http://www.manoeuvres.eu

Conclusions (1)

Optimization-based methodology for the tuning of rotorcraft attitude control laws

- Multivariable
- Structured
- Based on $\boldsymbol{H}_\infty$ framework
- Multiple requirements → multi-objective optimization problem
  - Performance (bandwidth)
  - Control action moderation
  - Safety
  - Robustness to uncertainty

Choice of frequency weights can be time-consuming…

Conclusions (2)

RSF allows to address requirements of:

- Safety
- Performance

- A trade-off shows up between performance vs safety
- Overcome intrinsic trade-off of classical control laws (bandwidth vs damping ratio)

Practical issues: a flap sensor is to be mounted on each of the blades (to compute MBC transformation)

- Heavy
- Expensive
- Space in the rotor head is limited…

THANK YOU

FOR YOUR ATTENTION

References (1)

ADS-33E-PRF, Aeronautical Design Standard, Performance Specification. Handling Qualities Requirements for Military Rotorcraft, US Army Aviation and Missile Command. 2000

M.B. Tischler et al. Handling-qualities optimization and trade-offs in rotorcraft flight control design. AHS Specialists Meeting on Rotorcraft Handling-Qualities, Liverpool, UK, 2008.

T. Berger et al. Disturbance rejection handling qualities criteria for rotorcraft. *72nd Annual Forum of the American Helicopter Society, West Palm Beach, USA,* 2016.

Manimala et al. Load alleviation in tilt rotor aircraft through active control; modelling and control concepts. The Aeronautical Journal, 108, 169-184. 2004.

D.W. King, et al. V-22 load limiting control law development, 49th AHS annual forum, 1993

References (2)

S. Panza and M. Lovera. Rotor state feedback in helicopter flight control: robustness and fault tolerance. In IEEE Multi-Conference on Systems and Control, Antibes-Nice, France. 2014

S. Panza and M. Lovera. Rotor state feedback in the design of rotorcraft attitude control laws. In 3rd CEAS Specialist Conference on Guidance, Navigation and Control, Toulouse, France. (also available as book chapter) 2015

S. Panza, M. Bergamasco, L. Viganò and M. Lovera. Rotor state feedback in rotorcraft attitude control. In 41st European Rotorcraft Forum ERF 2015, Munich, Germany. 2015

Rotor state feedback: safety (2)

Load limiting control laws were developed to alleviate V-22 structural issues

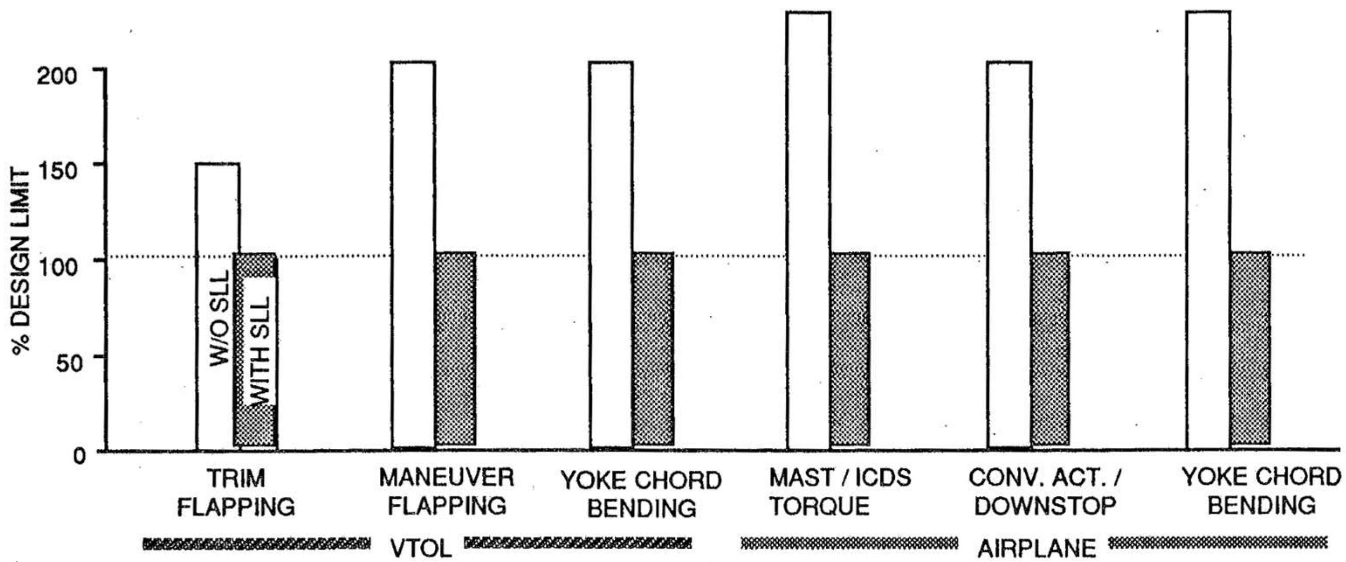


Fig. 21 V-22 Critical component loads for worst-case maneuvers

D.W. King, C. Dabundo, R.L Kisor and A. Agnihotri. V-22 load limiting control law development, 49th AHS annual forum, 1993