Max-Planck-Institut
für biologische Kybernetik

TU Delft

Delft University of Technology

Robust Stability Analysis: a Tool to Assess the Impact of Biodynamic Feedthrough on Rotorcraft

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Outline

- Aeroelastic Rotorcraft/Pilot Couplings
- Robust Stability Analysis
- Biodynamic Feedthrough
- Robust Stability of Aeroelastic Rotorcraft-Pilot Couplings
- Conclusions and Future Work

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Aeroelastic A/RPC

Aircraft/Rotorcraft-Pilot Couplings are

“unintentional (inadvertent) sustained or uncontrollable vehicle oscillation characterized by a mismatch between the pilot’s mental model of the vehicle dynamics and the actual vehicle dynamics.” (Mc Ruer)

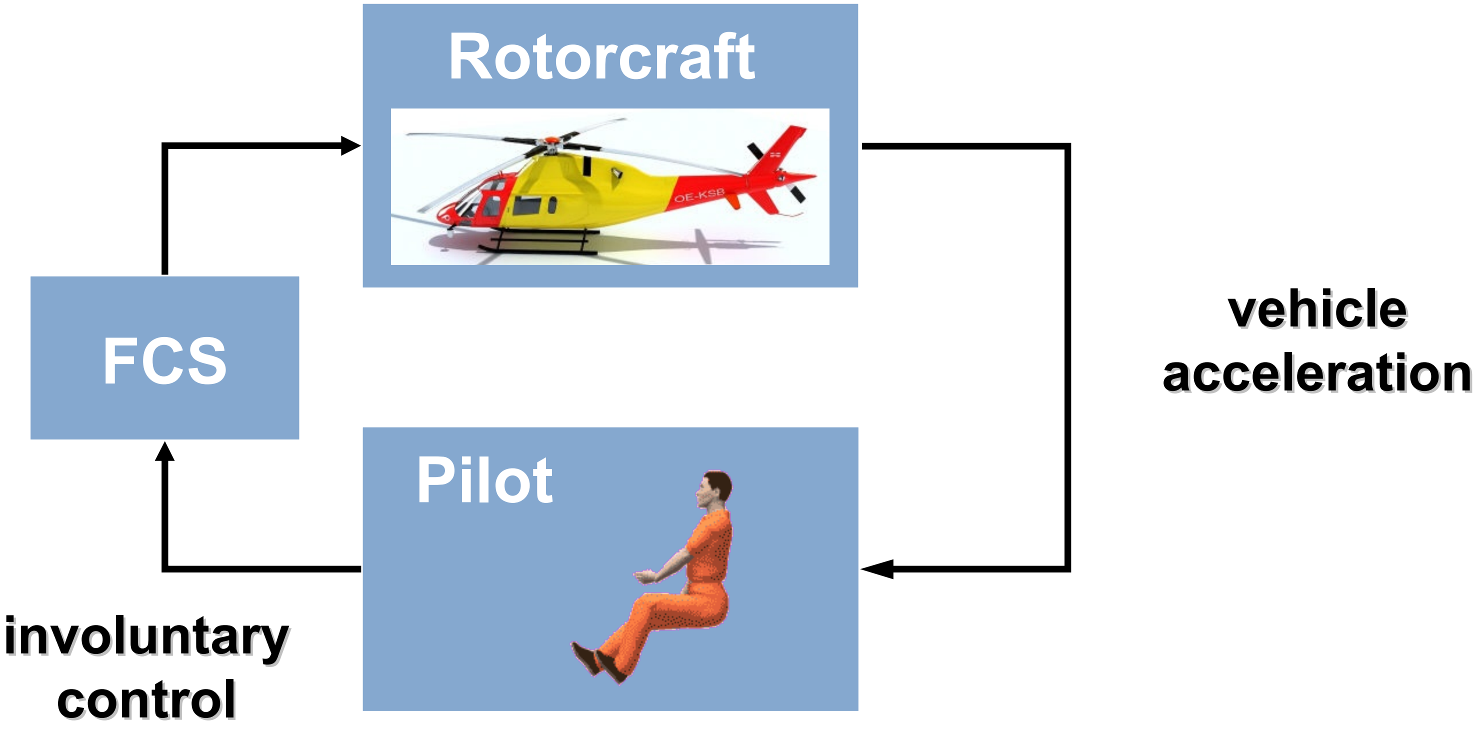
ARISTOTEL: research project sponsored by EC 7th FP led by TUDelft

Aircraft and Rotorcraft Pilot Couplings Tools
and Techniques for Alleviation and Detection
http://www.aristotelproject.eu/

This presentation is related to research on aeroelastic RPC resulting from involuntary control inputs generated by the pilot as a consequence of vibrations of the vehicle

Aeroelastic A/RPC

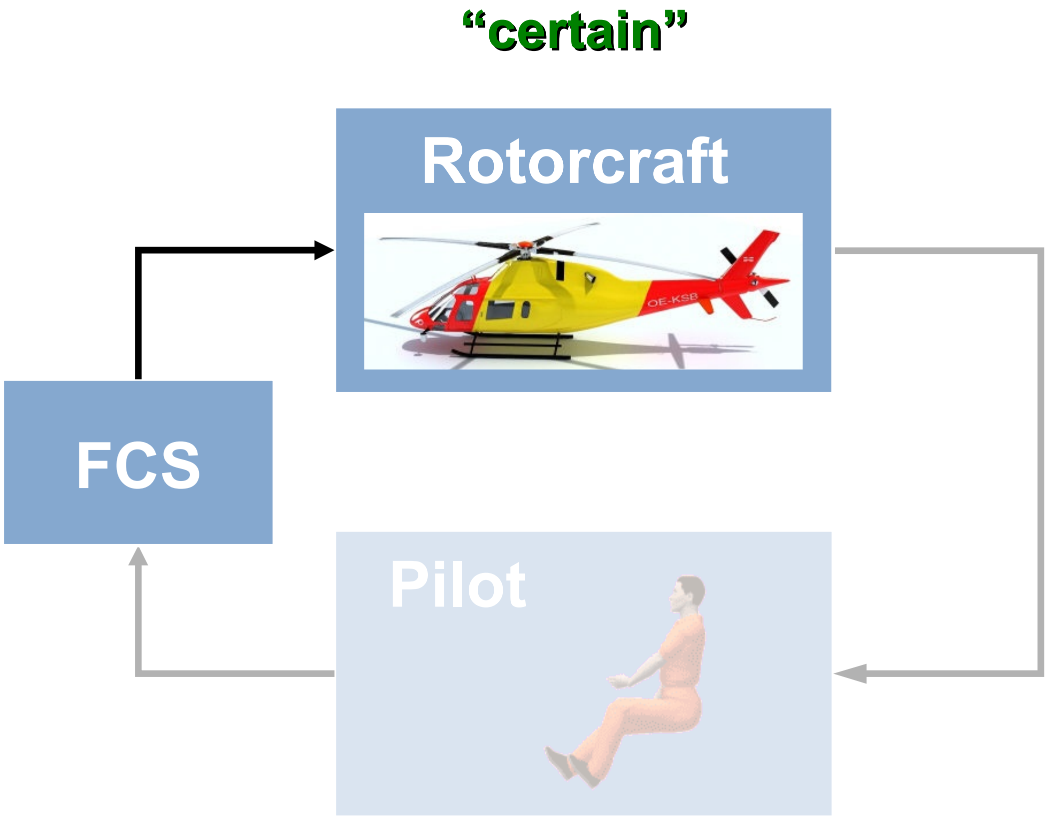
- Voluntary interaction (PIO) "active" pilot
- <u>Involuntary interaction</u> (PAO) "passive" pilot (Biodynamic Feedthrough)



Aeroelastic A/RPC

Vehicle:

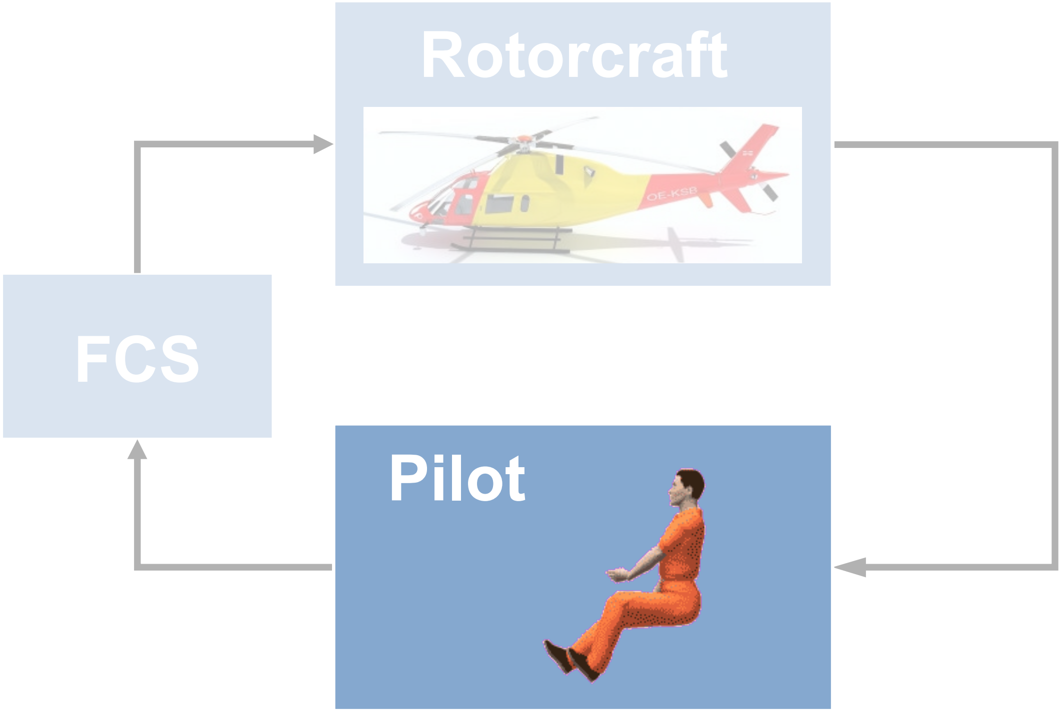
- Certain (deterministic): models available
- Assumed <u>asymptotically stable</u> (stabilized if needed)



Aeroelastic A/RPC

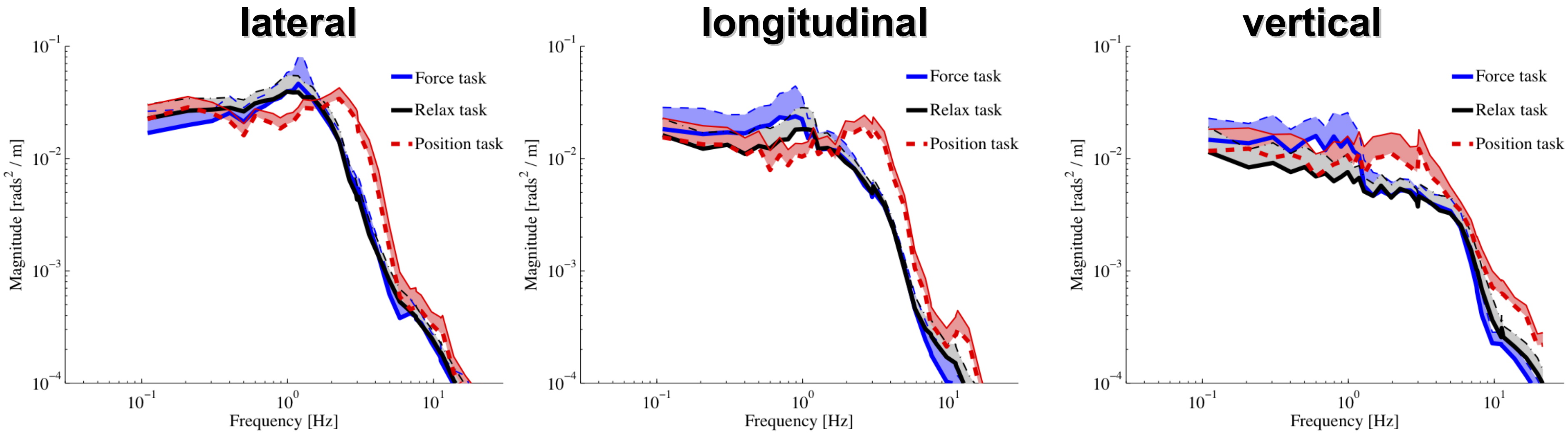
Pilot:

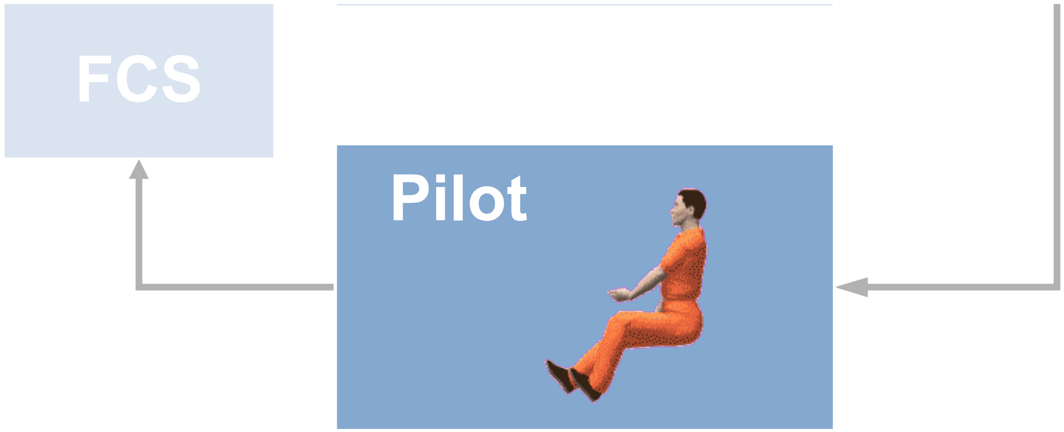
- Intrinsically uncertain
- Models often unavailable or unreliable
- Assumed intrinsically <u>asymptotically stable</u>



“uncertain”

Biodynamic Feedthrough (BDFT)





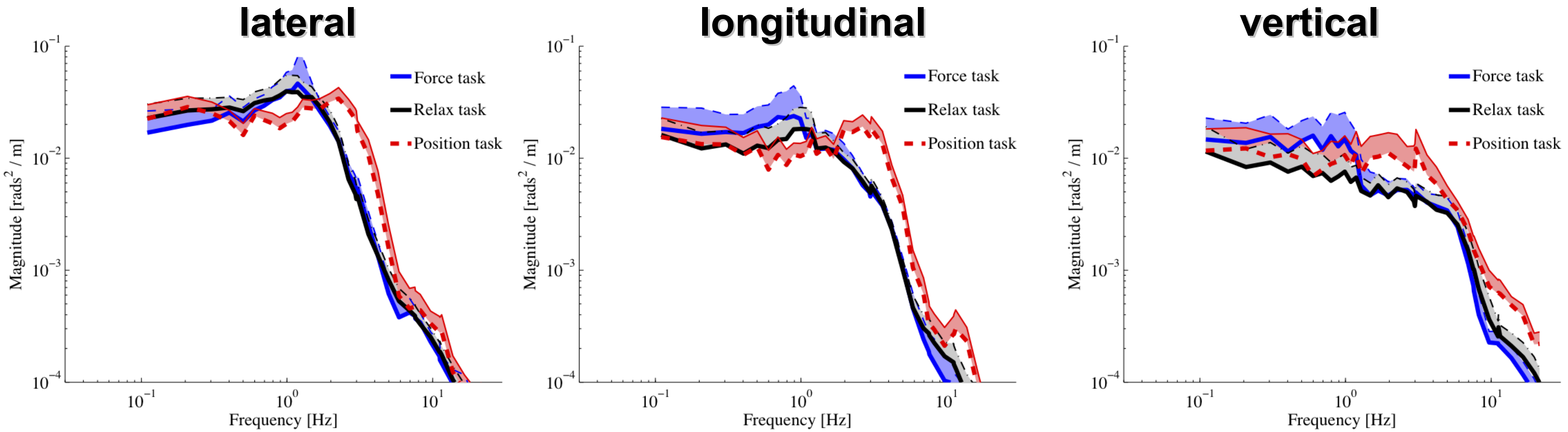
FCS

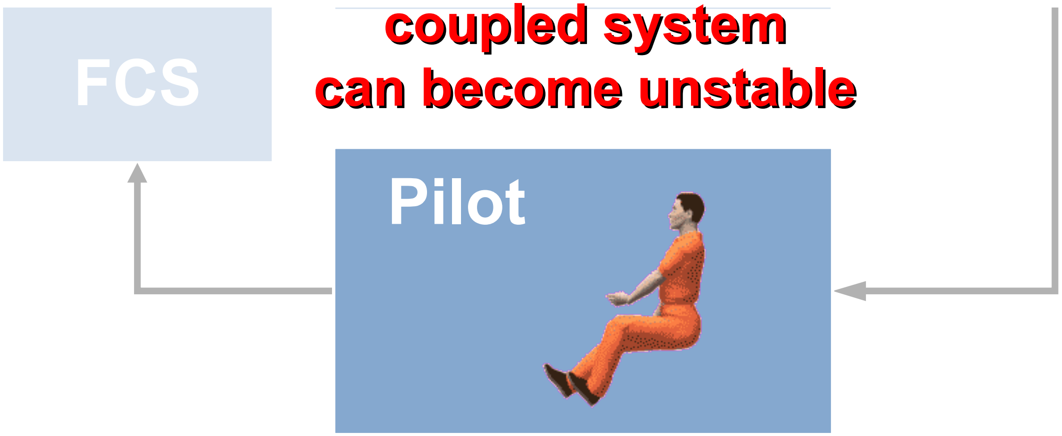
Pilot

- Cockpit vibration excites the pilot
- Pilot exerts involuntary controls
- BDFT is (device and) task dependent [1]

[1] Venrooij, J., Abbink, D. A., Mulder, M., van Paassen, M. M., and Mulder, M., “Biodynamic feedthrough is task dependent,” 2010

Biodynamic Feedthrough (BDFT)





FCS

coupled system can become unstable

Pilot

- Cockpit vibration excites the pilot
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[1] Venrooij, J., Abbink, D. A., Mulder, M., van Paassen, M. M., and Mulder, M., “Biodynamic feedthrough is task dependent,” 2010

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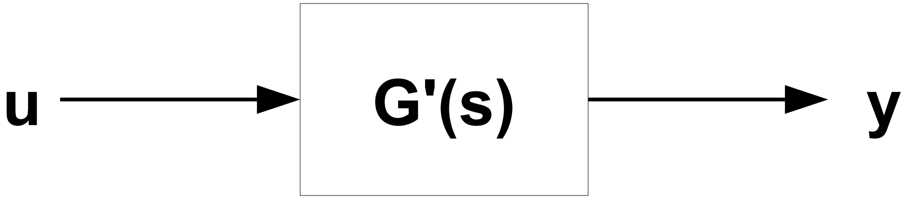
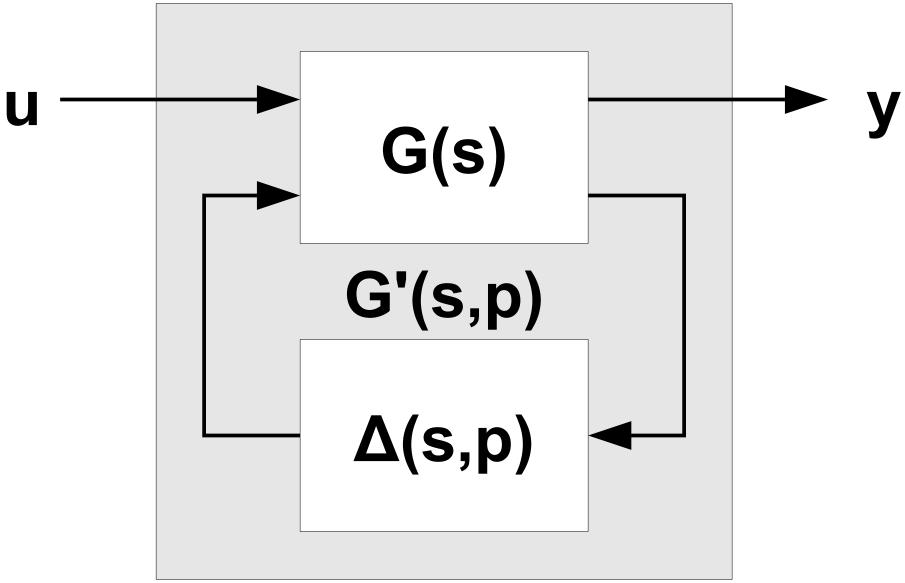
Robust Stability Analysis

Vehicle: linear time invariant (LTI), asymptotically stable system



Can be modified using Linear Fractional Transformation (LFT)



G'(s): vehicle (+ pilot)
G(s): vehicle
Δ(s, p): pilot
y: acceleration
u: control input
p: uncertain parameters (within bounds)

Robust Stability Analysis

Assumptions:

- The baseline system is stable (either the possibly augmented vehicle alone is stable, or a baseline pilot model stabilizes it)
- The nominal pilot transfer function is stable for allowable values of the uncertain parameters

$$\begin{Bmatrix} y \\ \eta \end{Bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{Bmatrix} u \\ \zeta \end{Bmatrix} \qquad \zeta = -\Delta\eta$$

The coupled system

$$y = \left(G_{11} - G_{12}\Delta\left(I + G_{22}\Delta \right)^{-1} G_{21} \right) u$$

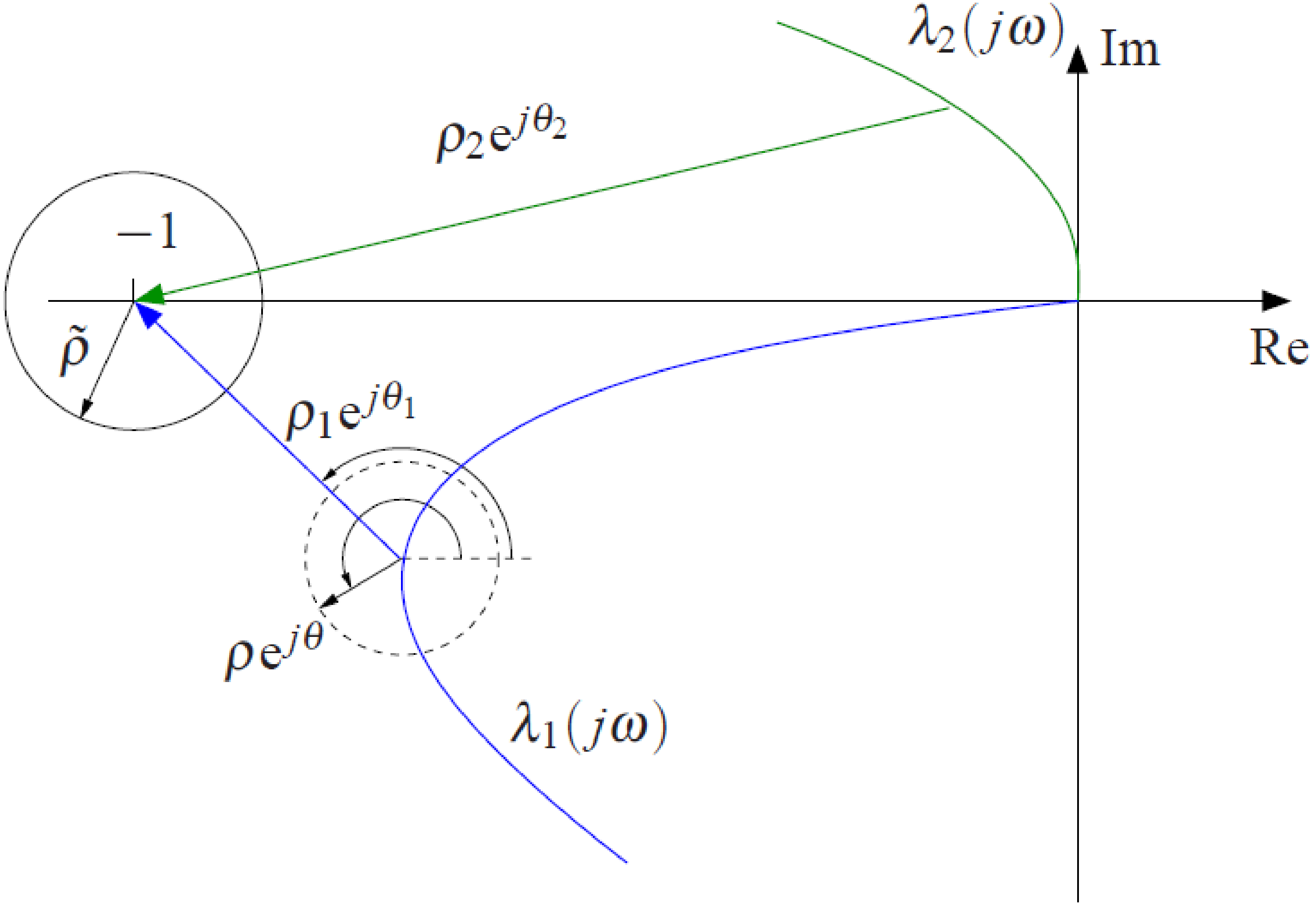
is stable when the loop transfer matrix

$$H(s,p) = G_{22}(s)\Delta(s,p)$$

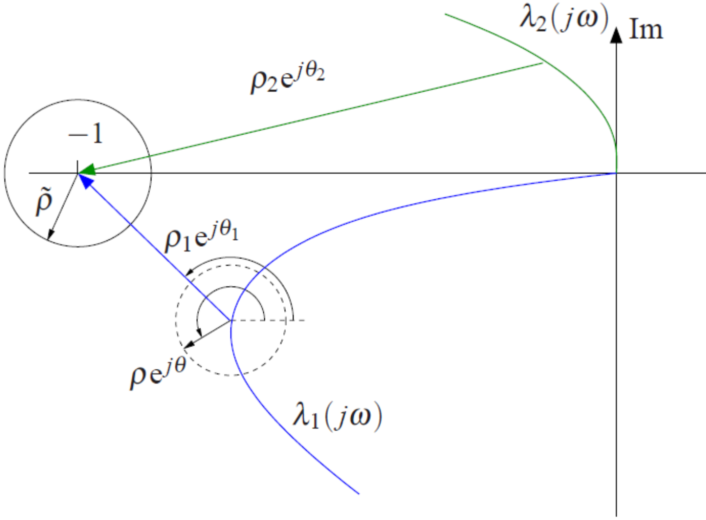
is stable (Generalized Nyquist Criterion, GNC: Nyquist criterion applied to eigenvalues of *H*).

Robust Stability Analysis

Nyquist eigenloci: distance of eigenvalues of nominal $H = G_{22}\Delta$ from point (-1, j*0) determines stability margin



Robust Stability Analysis



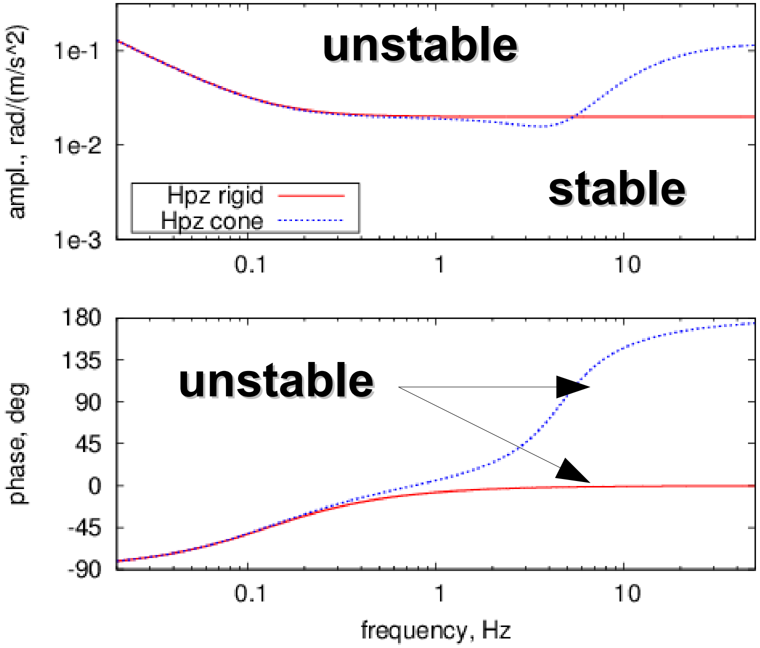
Distance of eigenvalues of $H = G_{22}\Delta$ from (-1, j*0):

- **Magnitude: generalized gain margin**
- **Direction: generalized phase margin**

Determine stability limits;

can be mapped on value of uncertain parameters *p*

- **When magnitude resulting from uncertain params envelope is below limit amplitude, instability is not possible**
- **Otherwise, instability occurs when phase matches direction towards (-1, j*0)**



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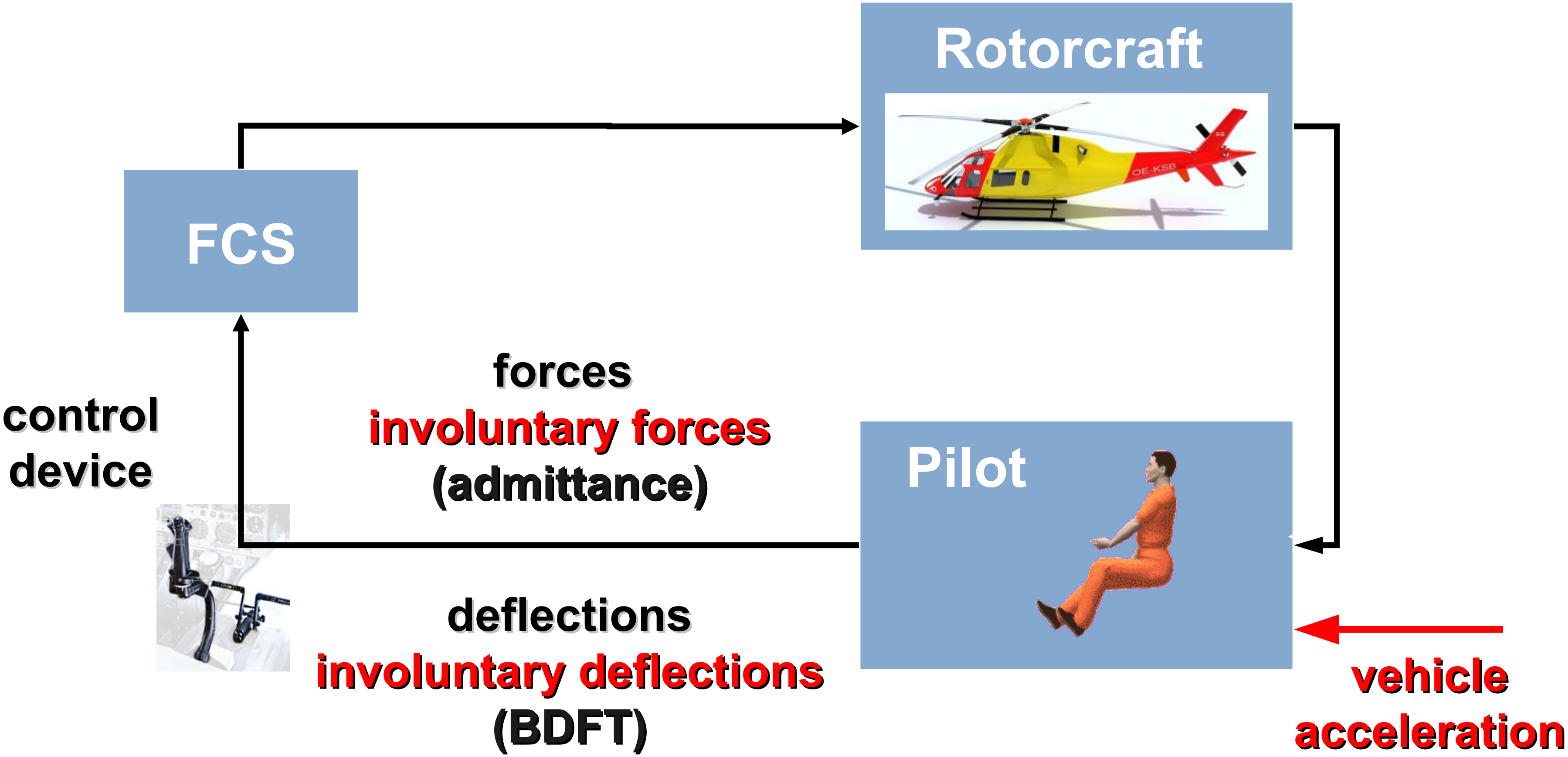
Biodynamic Feedthrough

- Voluntary interaction (PIO)
- Involuntary interaction (PAO)



Rotorcraft

FCS

Pilot

control device

forces
involuntary forces
(admittance)

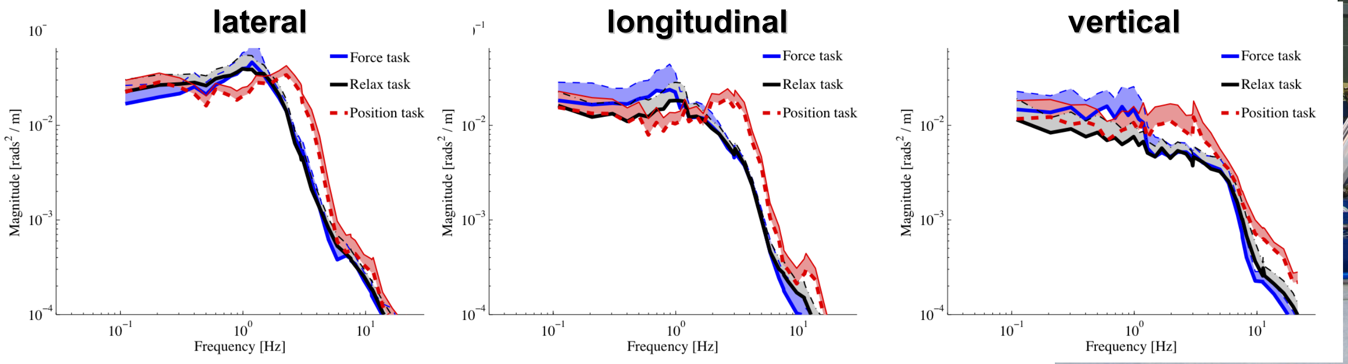
deflections
involuntary deflections
(BDFT)

vehicle acceleration

Biodynamic Feedthrough

SIMONA research simulator

- Control devices:
    - Electrically actuated coll. & cyclic
- Input signals:
    - Motion dist. (on sim): BDFT
    - Force dist. (on stick): admittance
- Results [1]:
    - Admittance estimate
    - BDFT estimate



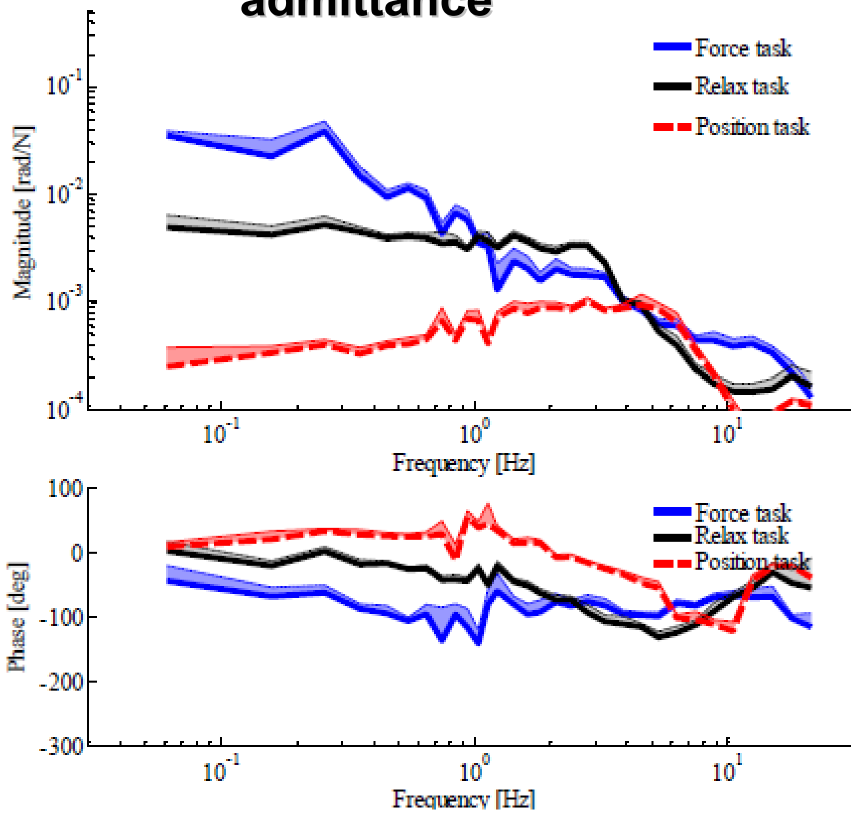
[1] Venrooij, Yilmaz, D., Pavel, M. D., Quaranta, G., Jump, M., and Mulder, M., “Measuring Biodynamic Feedthrough in Helicopters,” 37th European Rotorcraft Forum, 2011

Biodynamic Feedthrough

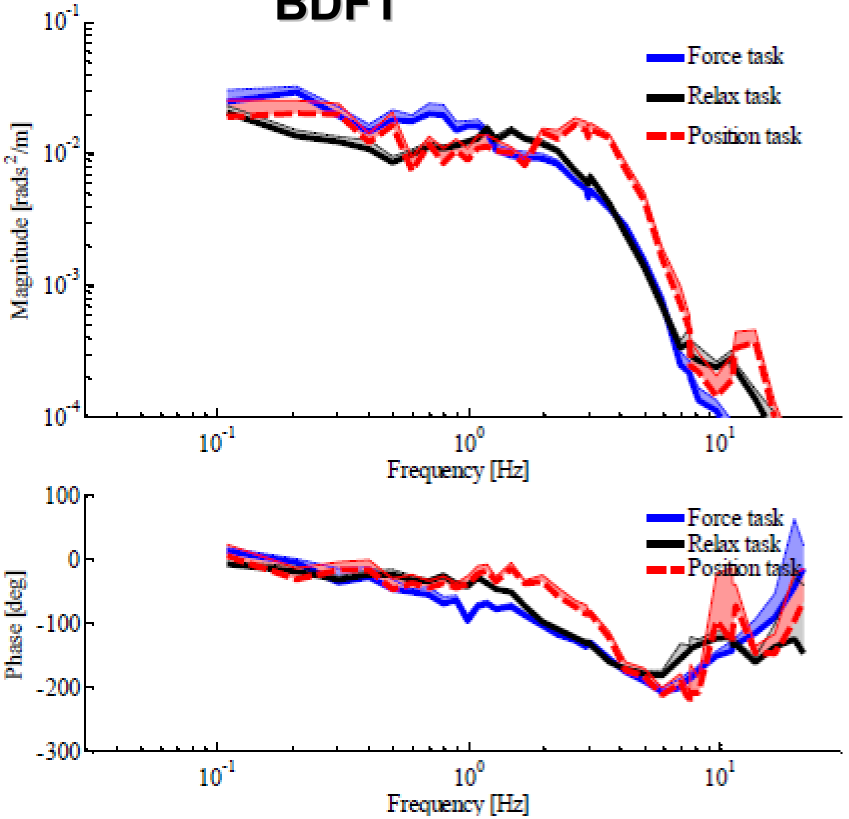
Admittance & BDFT are task dependent

Admittance not so important for collective

admittance



BDFT



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Robust Stability of RPC

Current focus: BDFT associated to collective bounce

- Vehicle TF: collective pitch to vertical acceleration of seat
- Pilot BDFT: vertical acceleration of seat to collective control inceptor

Loop TF:

$$H_L(j\omega) = -\underbrace{H_{\ddot{z}\theta}(j\omega) G_c}_{G_{22}(j\omega)} \underbrace{H_{\eta\ddot{z}}}_{-\Delta(j\omega)}$$

Gearing ratio G_c logically belongs to vehicle, but is intrinsically related to haptics and ergonomy considerations

<u>**Reference pilot control TF is 0!**</u>:

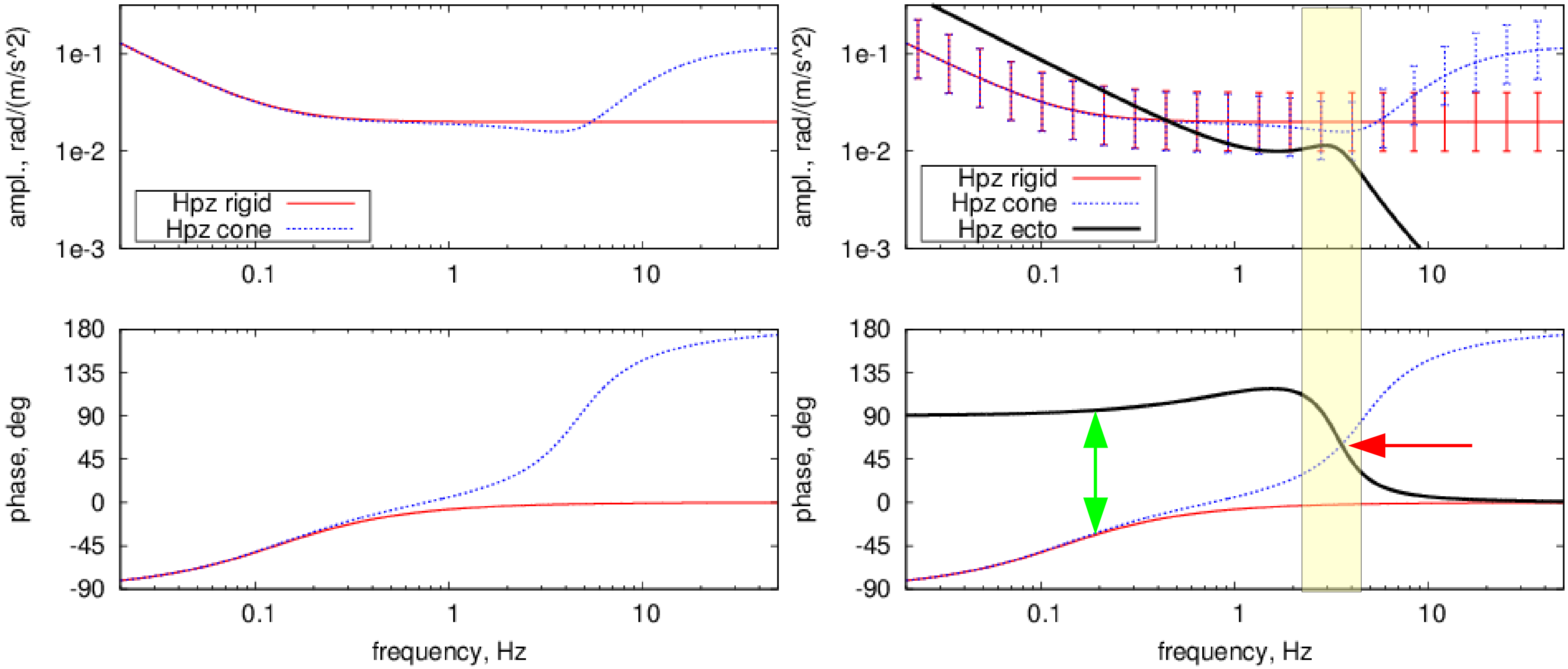
- Free controls (no control input)
- Infinitely stiff pilot (no involuntary input)

Limits on pilot TF:

$$H_{\eta\ddot{z}}(j\omega) = \frac{1}{G_c H_{\ddot{z}\theta}(j\omega)}$$

Robust Stability of RPC

- Stability limits of simplified heave models of helicopters
  - “rigid” (one dof)
  - “cone” (two dofs: rigid + rotor cone)
  - detailed (shown later)
- “ectomorphic” pilot BDFT function (Mayo, 1989)
- “bands”: half/double gearing ratio



Pilot band of interest

Robust Stability of RPC

Detailed aeroservoelastic rotorcraft model obtained using MASST [1,2]

- Elastic airframe (normal modes)
- Aeroelastic rotors (linear, time-averaged, trimmed)
- Drive train dynamics
- Servoactuator dynamics
- Control system dynamics
- Pilot biodynamics
- Selected nonlinearities (time domain, descriptive function)

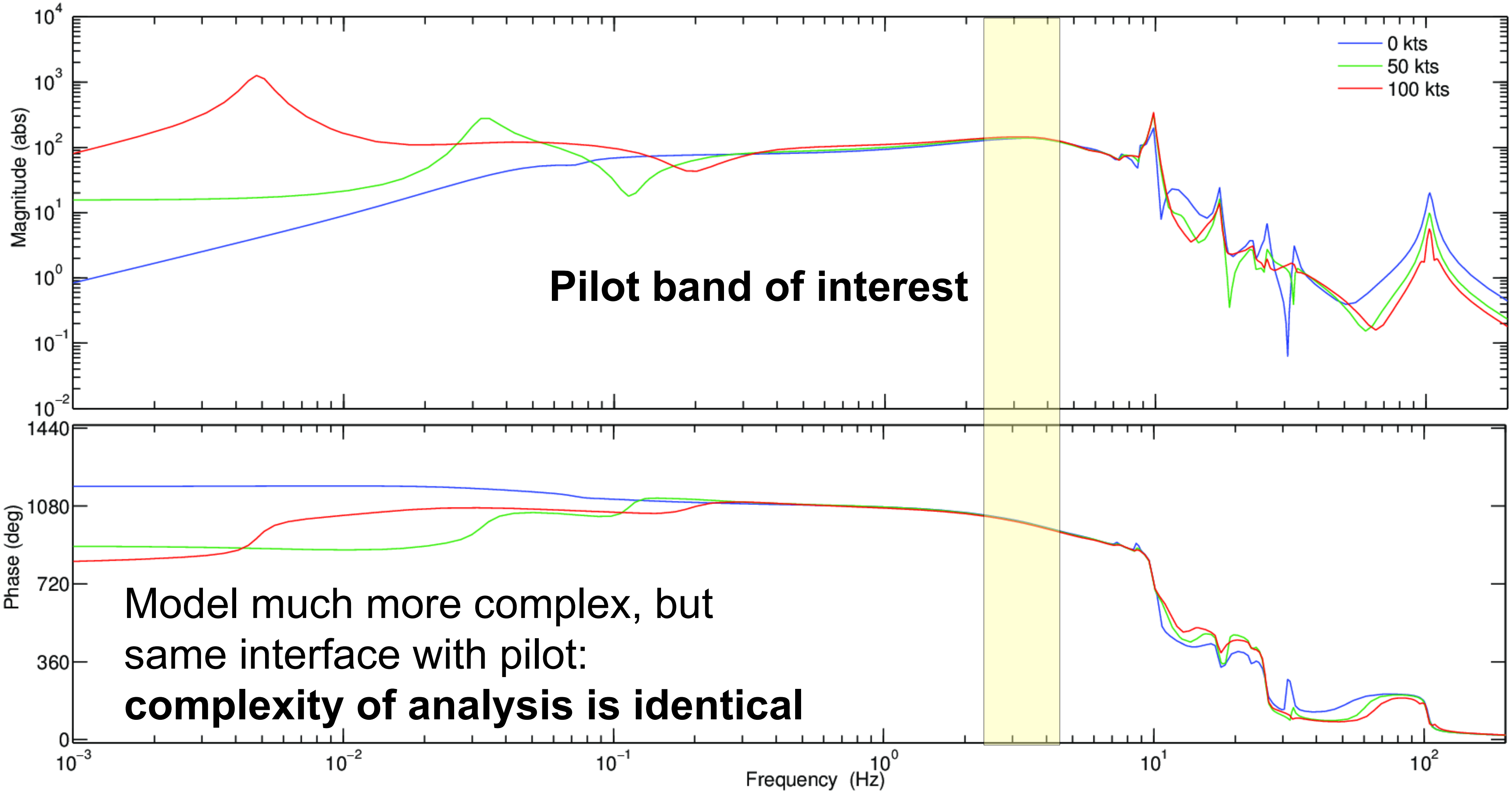
- Frequency and time domain analysis

[1] Masarati, P., Muscarello, V., and Quaranta, G., “Linearized Aeroservoelastic Analysis of Rotary-Wing Aircraft,” 36th ERF, 2010

[2] Masarati, P., Muscarello, V., Quaranta, G., Locatelli, A., Mangone, D., Riviello, L., and Viganò, L., “An Integrated Environment for Helicopter Aeroservoelastic Analysis: the Ground Resonance Case,” 37th ERF, 2011

Robust Stability of RPC

SA 330 TF between collective and vertical acceleration (0, 50, 100 kts) includes actuators delay but no FCS delay

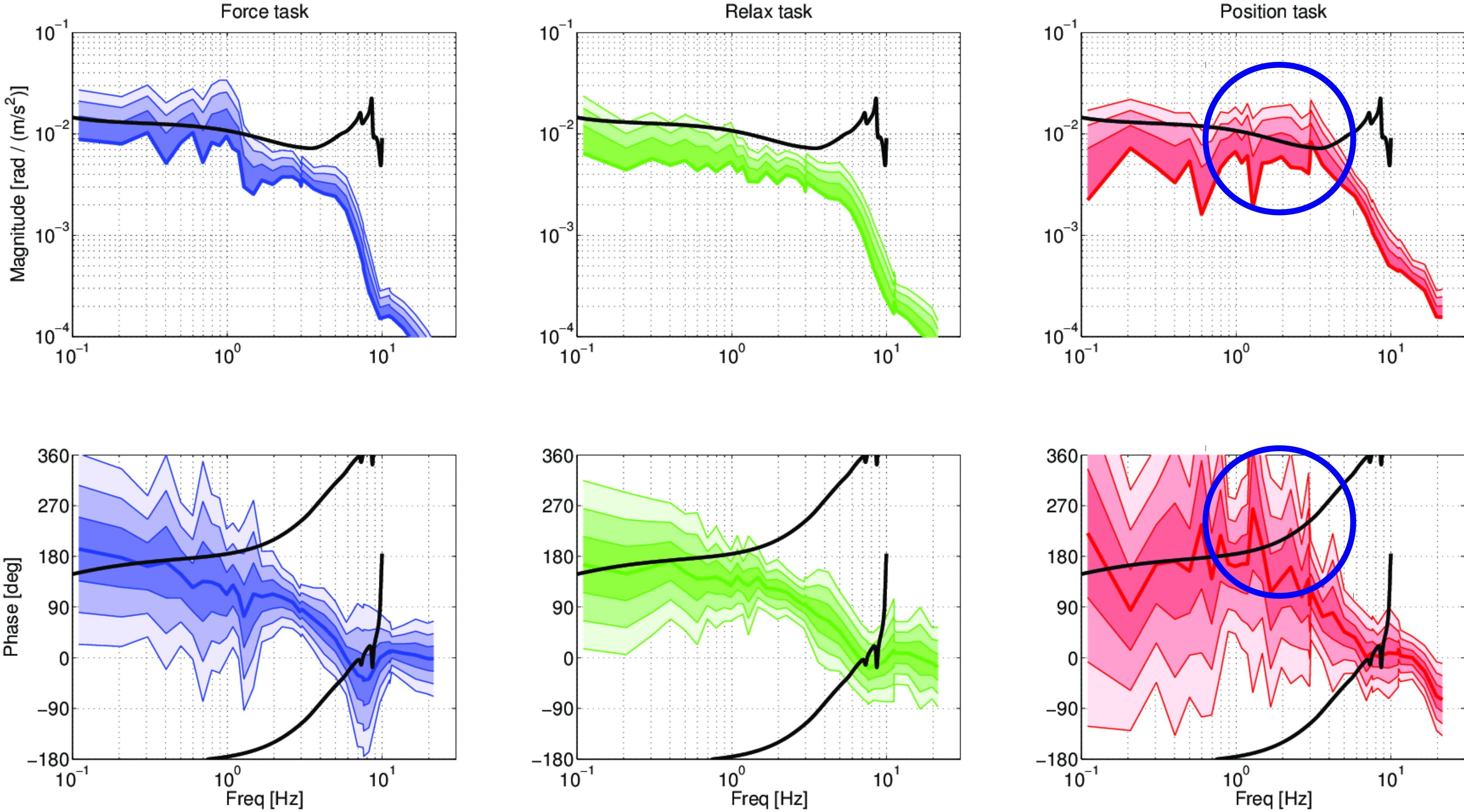


Pilot band of interest

Model much more complex, but
same interface with pilot:
complexity of analysis is identical

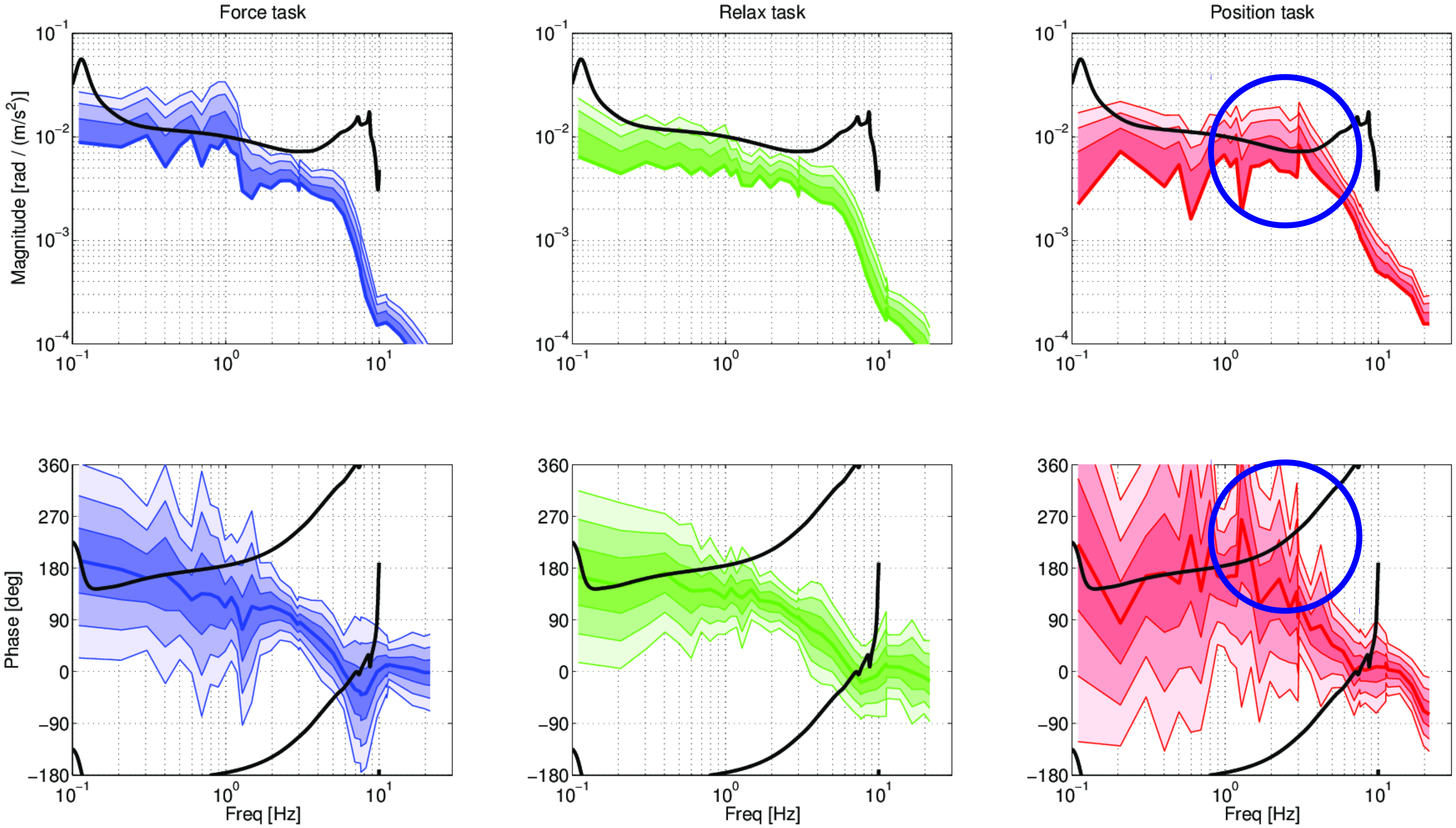
Robust Stability of RPC

Vertical axis BDFT compared to stability margins at 0 kts



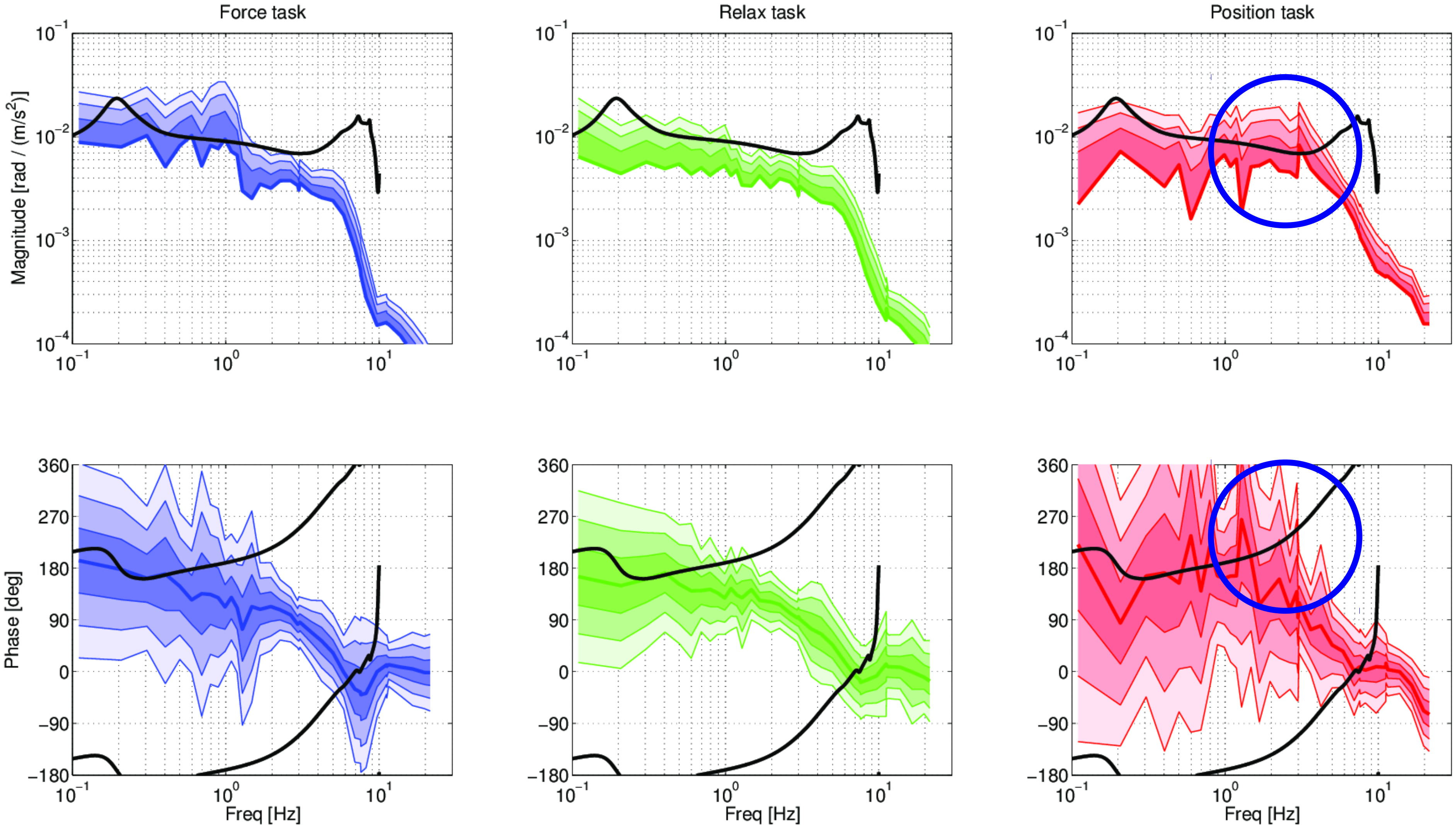
Robust Stability of RPC

Vertical axis BDFT compared to stability margins at 50 kts



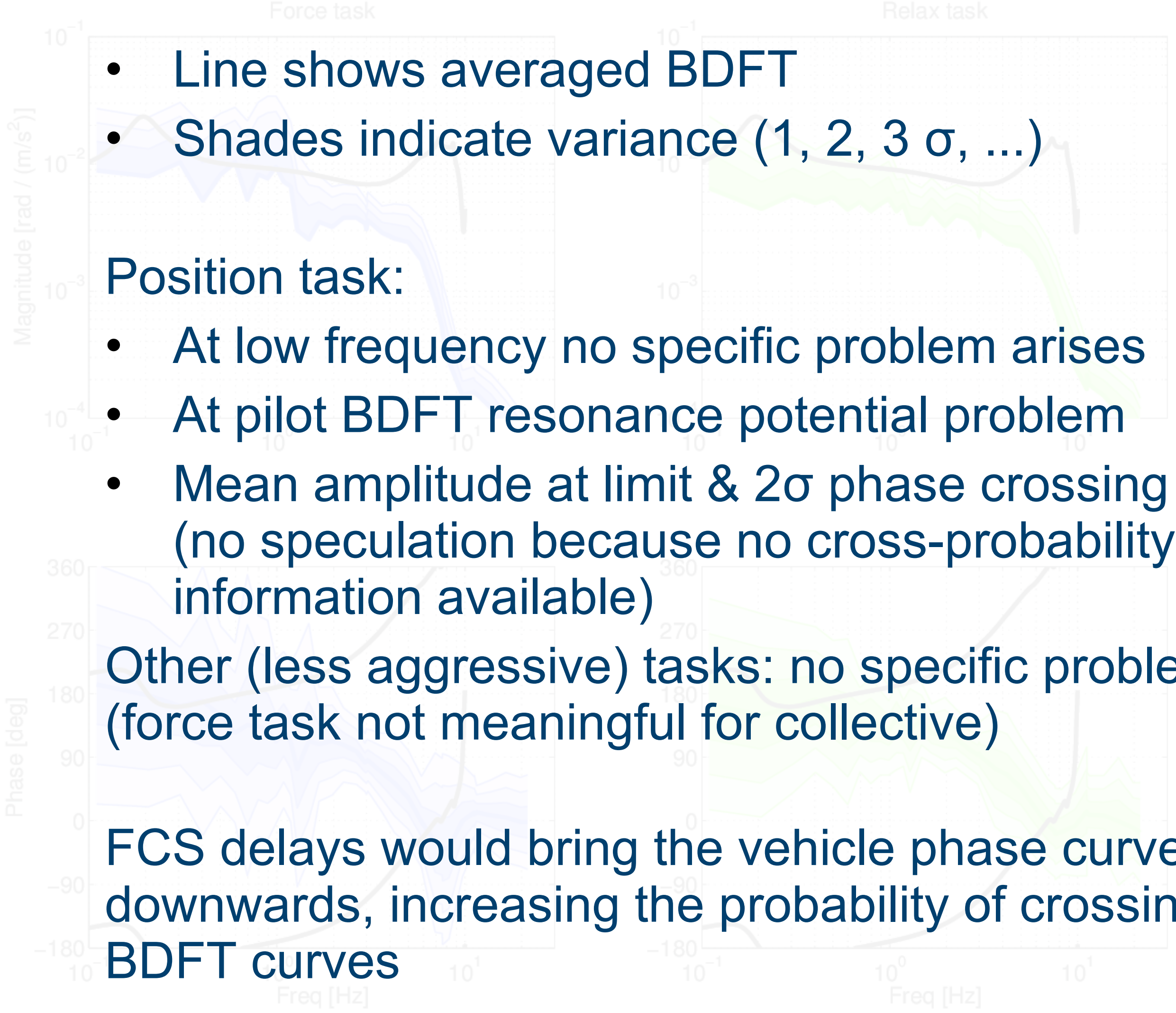
Robust Stability of RPC

Vertical axis BDFT compared to stability margins at 100 kts



Robust Stability of RPC

Vertical axis BDFT compared to stability margins at 100 kts



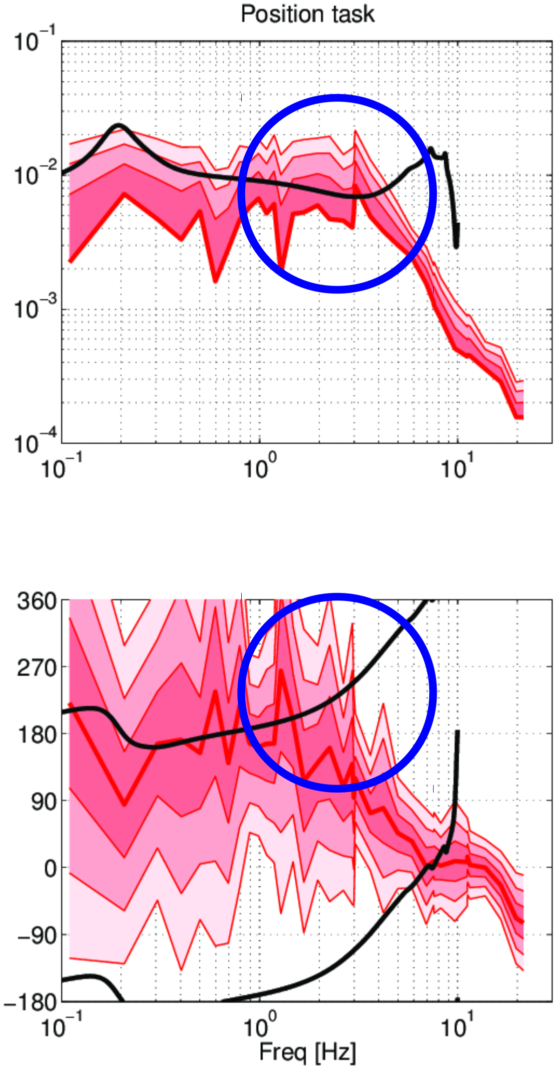
- Line shows averaged BDFT
- Shades indicate variance (1, 2, 3 σ, ...)

Position task:

- At low frequency no specific problem arises
- At pilot BDFT resonance potential problem
- Mean amplitude at limit & 2σ phase crossing (no speculation because no cross-probability information available)

Other (less aggressive) tasks: no specific problem (force task not meaningful for collective)

FCS delays would bring the vehicle phase curve downwards, increasing the probability of crossing BDFT curves



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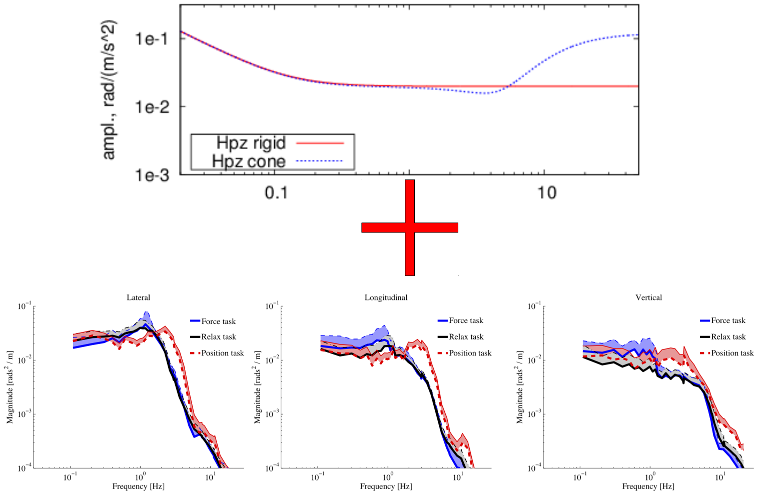
Conclusions & Future Work

Conclusions

- Robust stability analysis applied to RPC using BDFT data
- Powerful, simple and intuitive graphical approach presented
- Example application to vertical axis of conventional helicopter
- Effective tool for RPC proneness evaluation



Future work

- Multi-input multi-output problems (longitudinal and lateral axes)
- Further statistical interpretation of results
- Include control device dynamics in “certain” portion of model (friction, bobweights & other mechanical devices in uncertainty)

Acknowledgements

The research leading to these results has received funding from the European Community's

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Thank you for your attention

Questions?