POLITECNICO DI MILANO

Theoretical and Experimental Investigation of Aeroelastic Rotorcraft-Pilot Coupling

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Outline

- Aeroelastic Rotorcraft/Pilot Couplings
- Investigation Description
- Simplified Aeroelastic Model
- Experimental Activity
- Discussion of Results
- Conclusions

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Aeroelastic Rotorcraft/Pilot Couplings

Aircraft/Rotorcraft-Pilot Couplings are

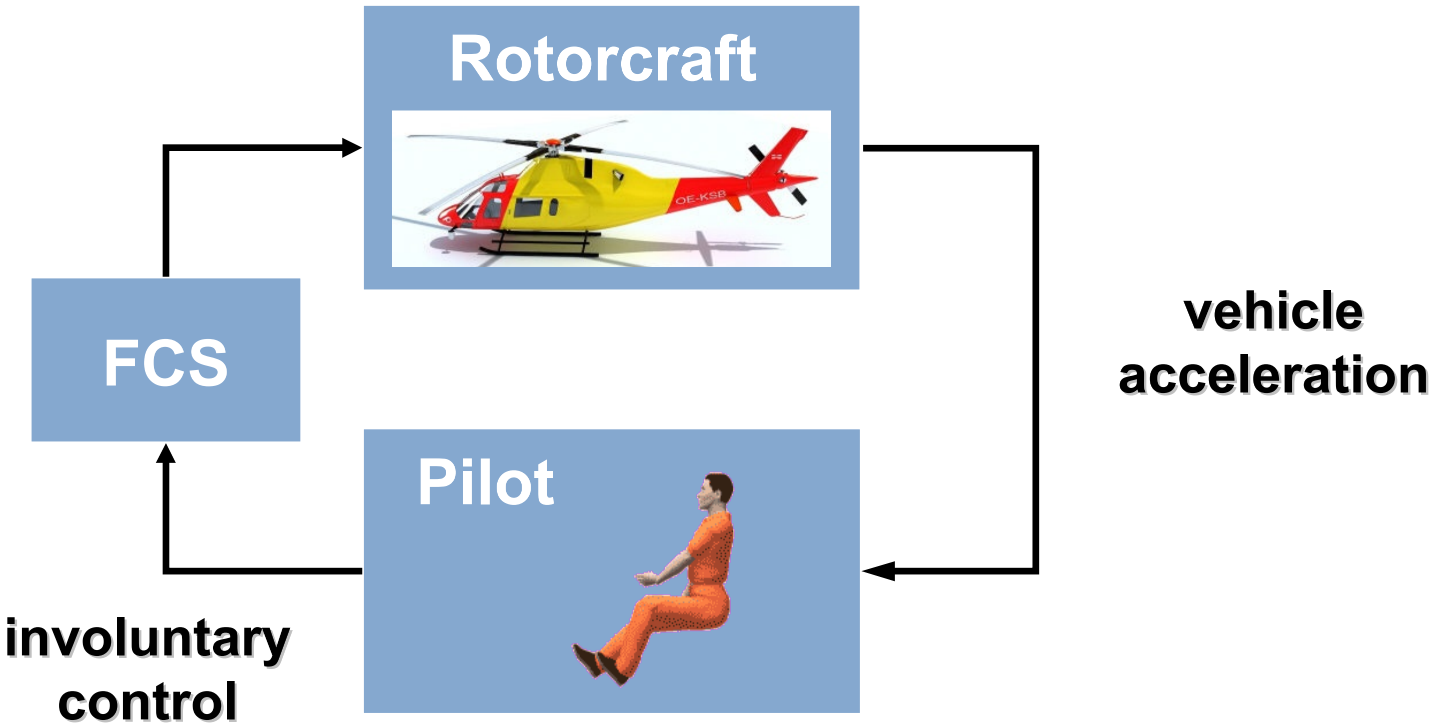
“unintentional (inadvertent) sustained or uncontrollable vehicle oscillation characterized by a mismatch between the pilot’s mental model of the vehicle dynamics and the actual vehicle dynamics.” (Mc Ruer)

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 experimental research on aeroelastic RPC resulting from involuntary control inputs generated by the pilot as a consequence of vibrations of the vehicle in pilot-in-the-loop conditions.

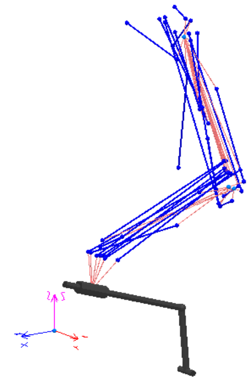
- Voluntary interaction (PIO) “active” pilot intervention
- Involuntary interaction (PAO) “passive” pilot intervention (biodynamic feedthrough)

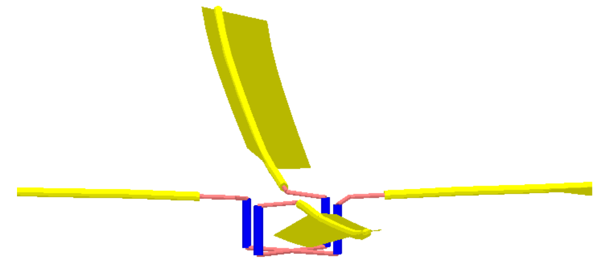


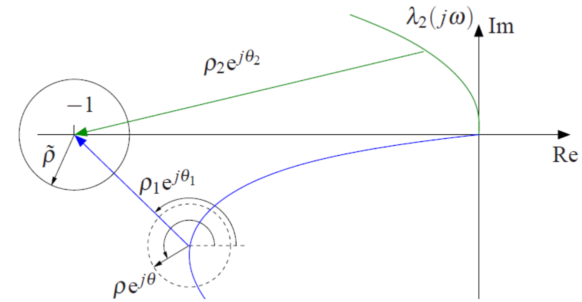
Aeroelastic Rotorcraft/Pilot Couplings

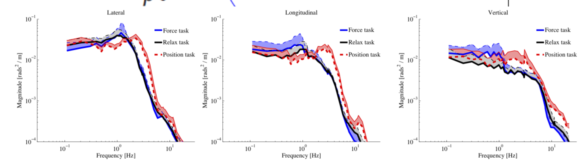
Within ARISTOTEL, aeroelastic RPCs:

- POLIMI working on
  - Vehicle modeling
    & fidelity requirements
  - Pilot biomechanics:
    detailed biom. models
  - Tools for prediction and means
    for prevention (robust stability)
- UoL working on
  - Flight simulation of aeroelastic rotorcraft
  - Experimental investigation of pilot BDFT









**All activities in strict cooperation
with the other partners.**

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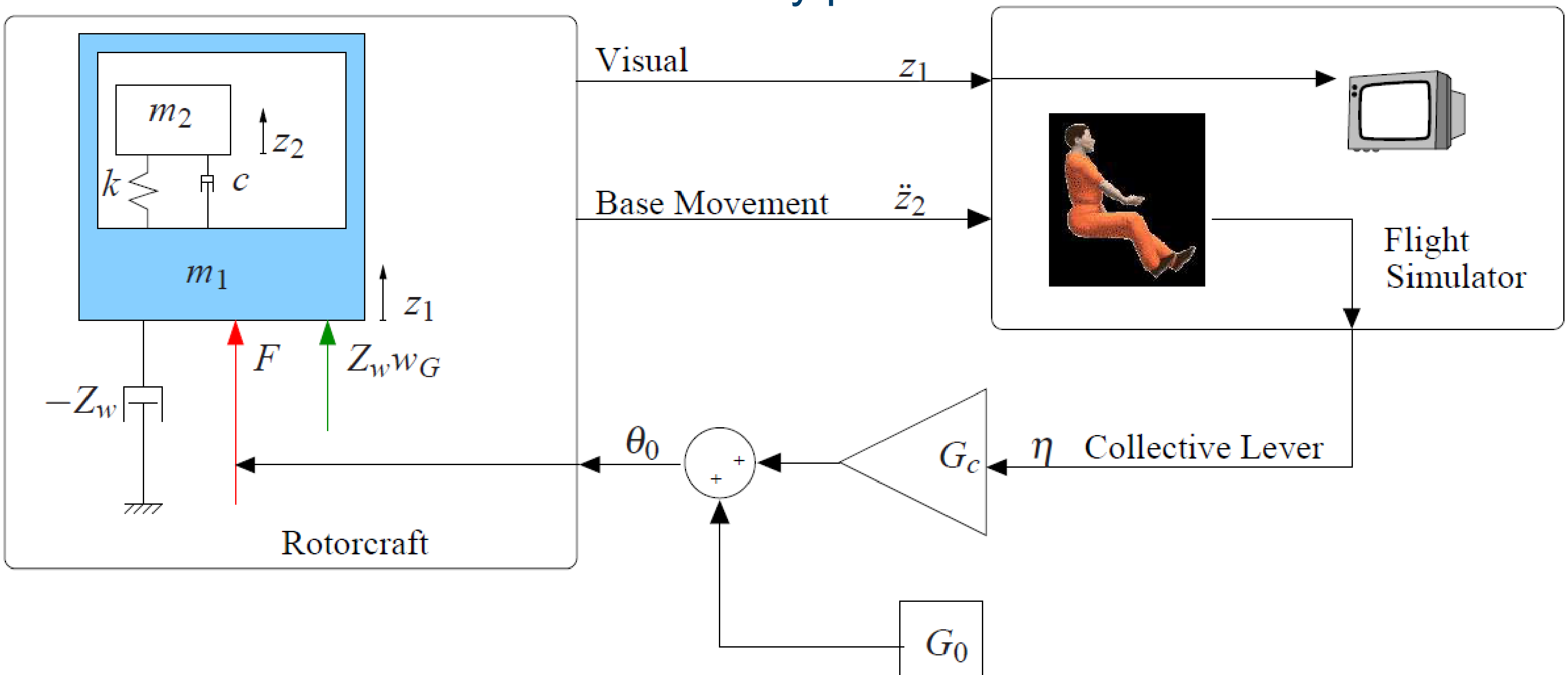
Investigation Description

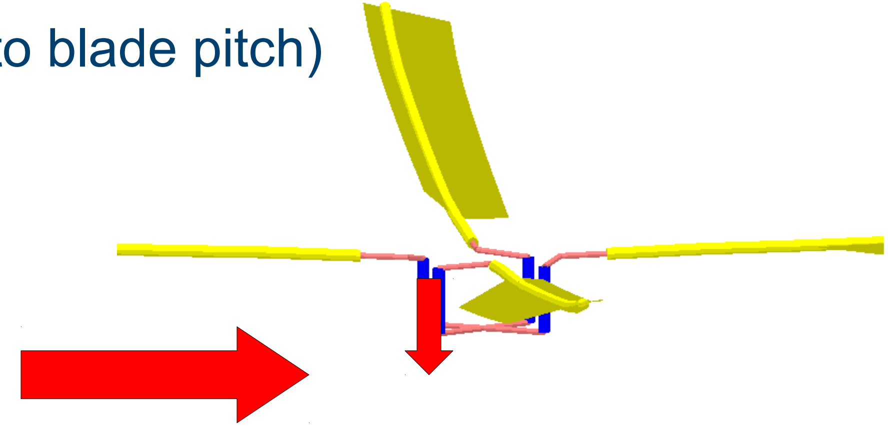
- Implement simple “aeroelastic” flight mechanics model in flight sim.
  - restricted to **heave only**, with **elastic** degree of freedom
- Test with pilot-in-the-loop, to:
  - trigger bioaeroelastic instabilities
  - understand how the human operator interacts with true feedback
  - determine the influence of key parameters



Investigation Description

Investigated parameters include:

- stiffness and damping of elastic mode
- gearing ratio G_c (collective lever to blade pitch)



- presence/absence of (emulated) friction in collective control lever
- task

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Simplified Aeroelastic Model

- Heave degree of freedom only

$$m_t \dot{w} = Z$$

- Aerodynamics linearized about hover condition

$$Z = Z_w \left(w - w_G \right) + Z_{\theta_0} \theta$$

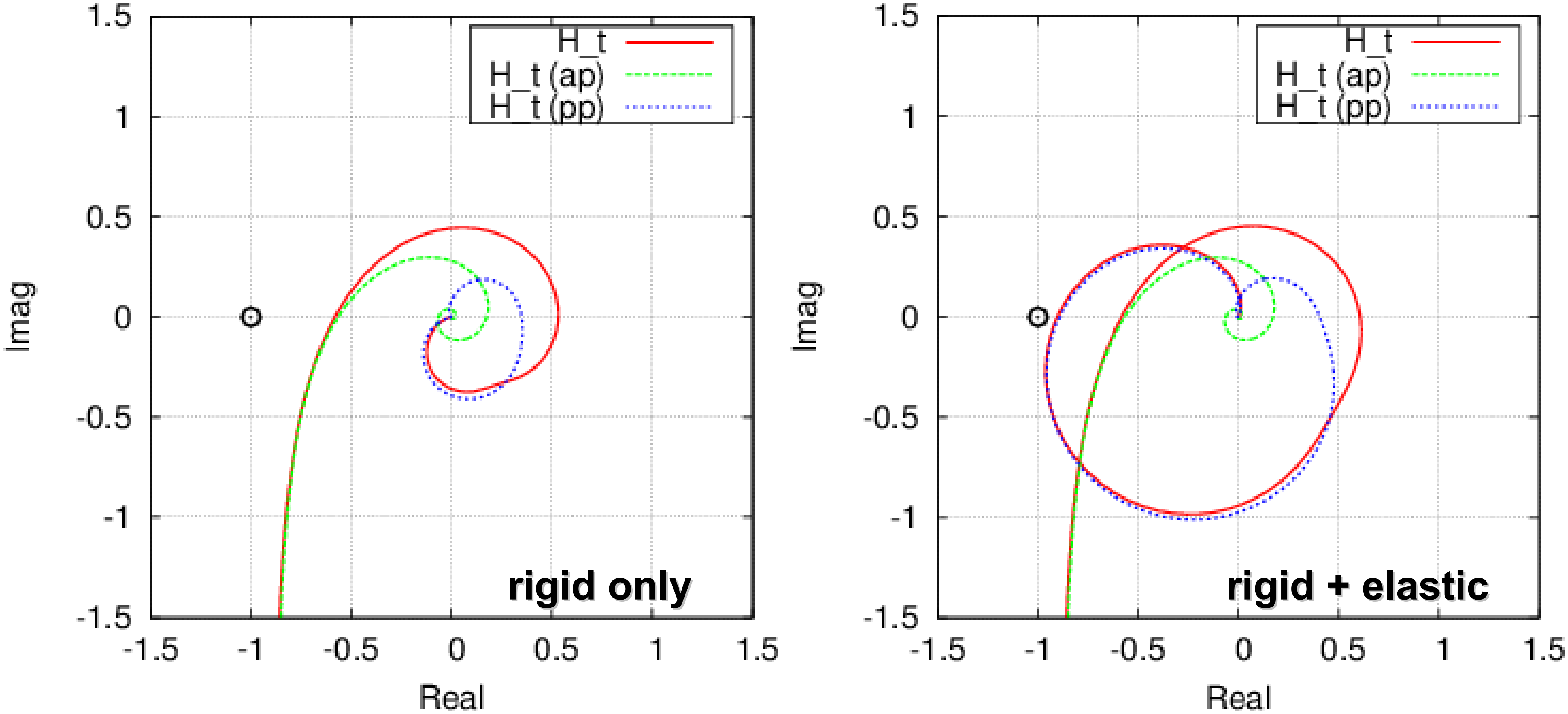
- Motion of pilot's seat associated with “elastic” degree of freedom

$$m_t \ddot{z}_1 - Z_w \dot{z}_1 = Z_{\theta_0} \theta - Z_w w_G$$
$$m_2 \ddot{z}_2 + c \dot{z}_2 + k z_2 = c \dot{z}_1 + k z_1$$

- “rigid” helicopter degree of freedom associated with visual demand
- “elastic” DOF associated with flight simulator motion demand
- collective control resulting from control inceptor (pilot-in-the-loop)
- gust velocity used to “disturb” the simulation

Simplified Aeroelastic Model

- Nyquist plot of loop TF (data representative of SA 330 Puma):
  - “active” pilot (Mc Ruer's “crossover” model + low-pass filter)
  - BDFT (Mayo's function adapted to UoL's cockpit layout + h.p.f.)
- Elastic mode tuned for marginal stability at about 3.5 Hz (as of BDFT)



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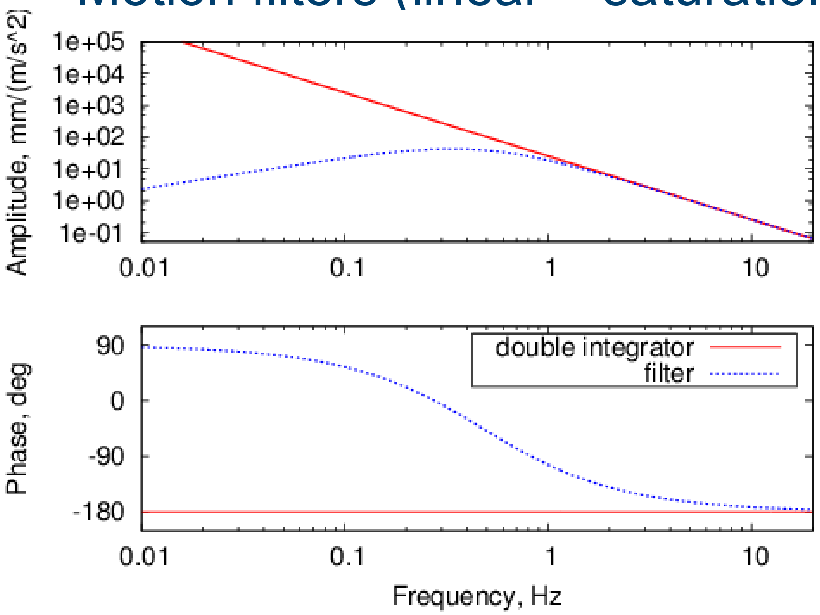
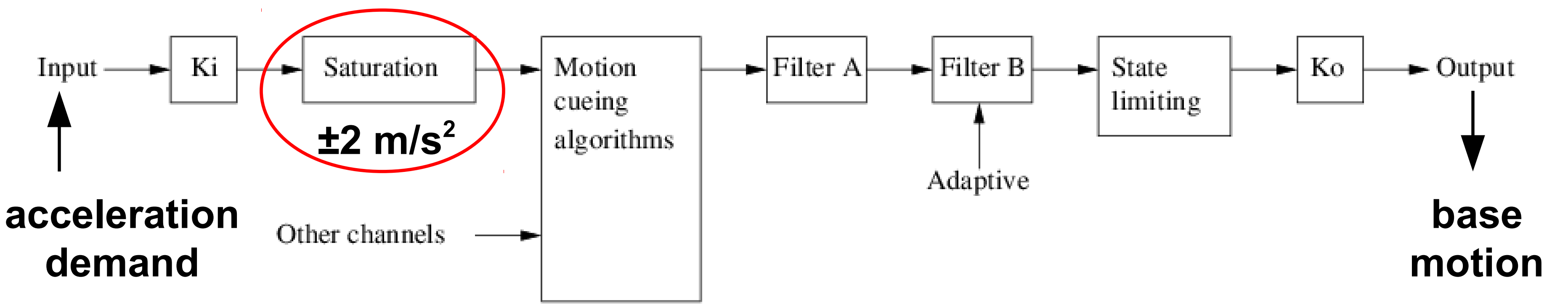
HELIFLIGHT simulation facility at The University of Liverpool

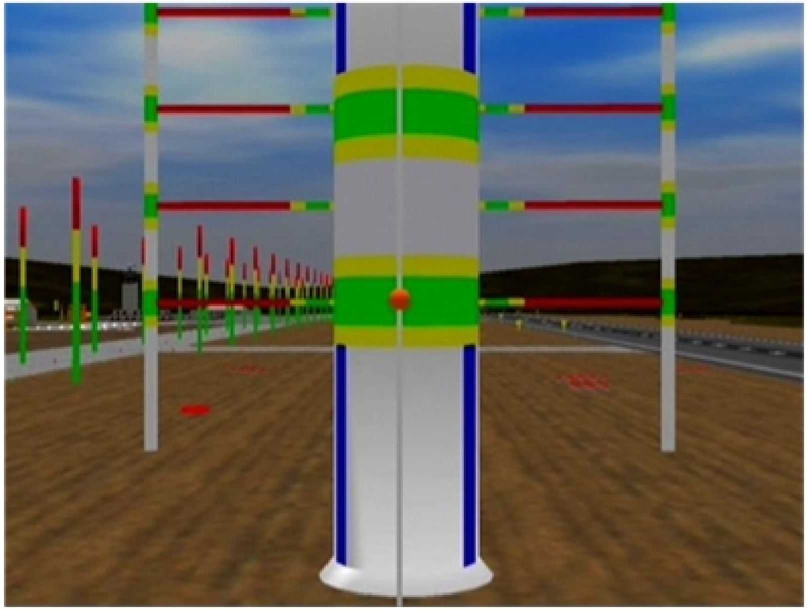
Motion filters (linear + saturation)

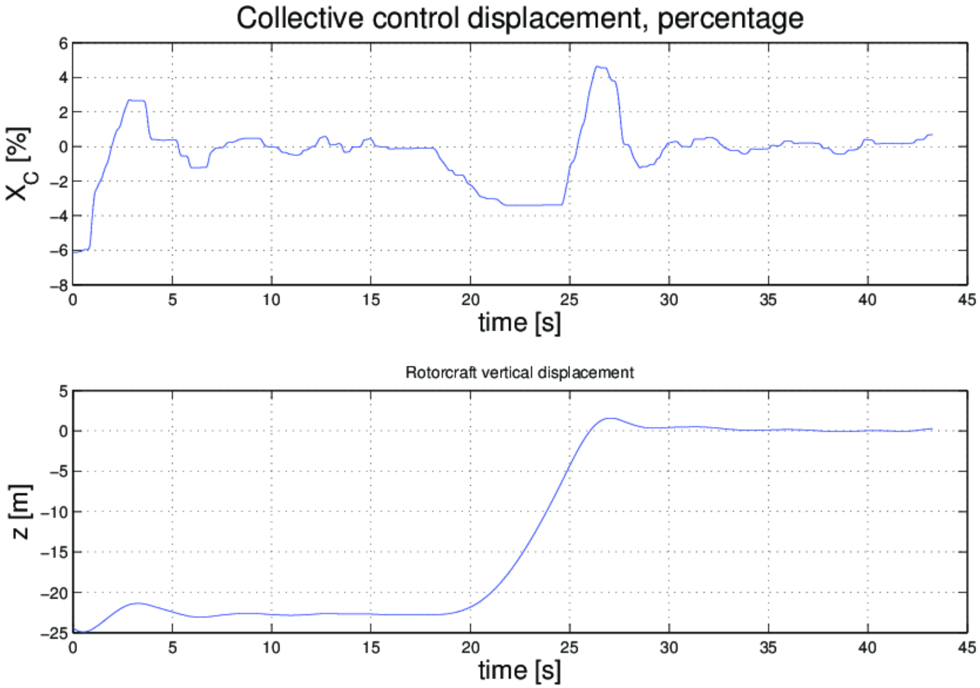




Vertical maneuver (ADS-33)

- Primary task: keep the red ball in the green band
- Secondary task: move to a different level (50 ft) when told (workload, trigger)
- Disturbance: oscillatory force with variable frequency and amplitude
- Visual: driven by “rigid body” state
- Motion: driven by “elastic” state





Experimental Activity

- Tested configurations
  - most planned
  - some designed to better understand incoming results

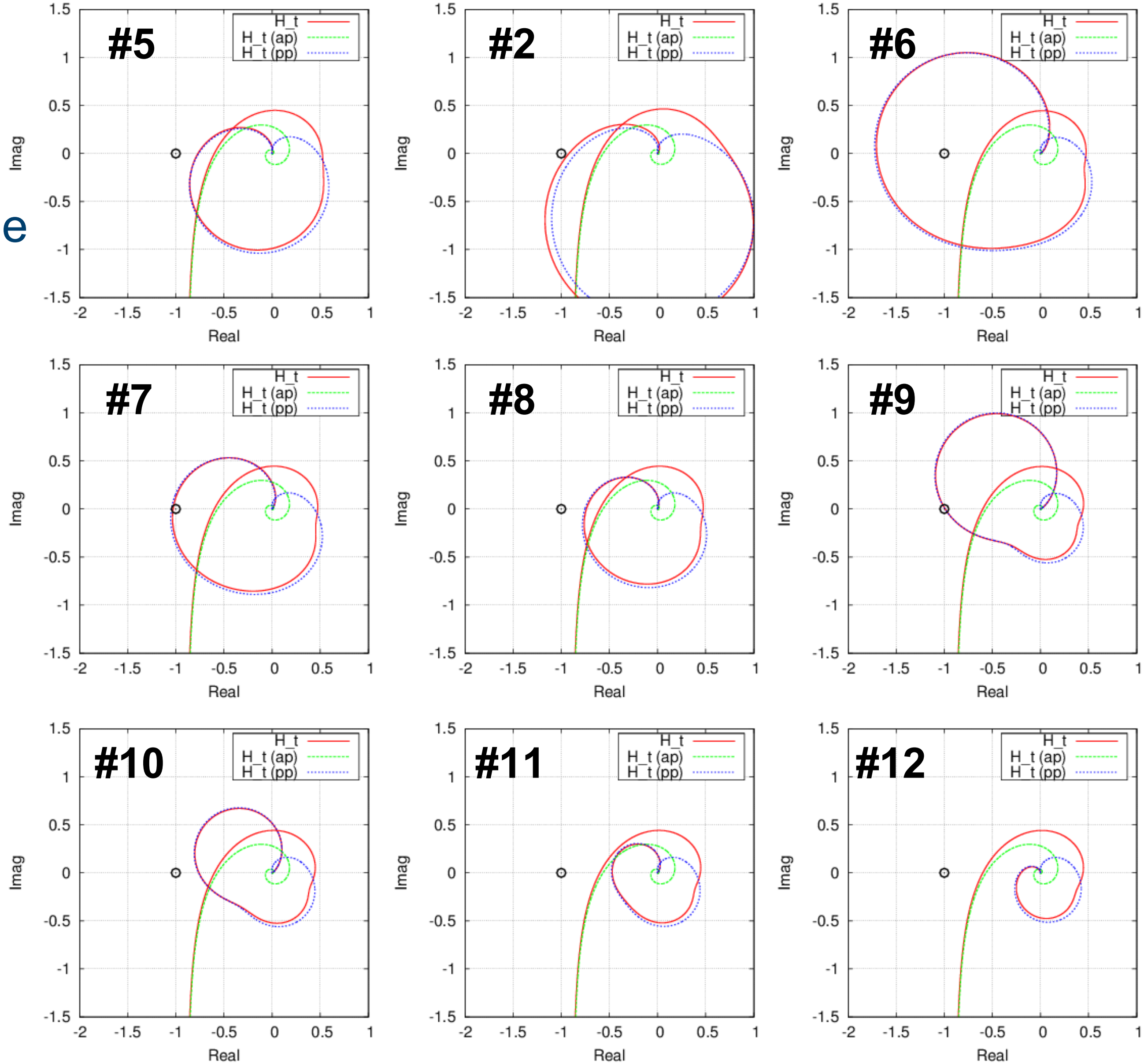
nominal →

#	Pilot	k/k_{ref}	c/c_{ref}	friction	freq. Hz	damp. %
1	2	0.50	0.15	on	2.53	4.29
2	1,2,3,4	0.50	0.40	off	2.51	11.41
3	2	1.00	0.10	on	3.58	2.02
4	1	1.00	0.20	on	3.57	4.04
5	1,2,3,4	1.00	1.00	off,on	3.50	20.15
6	1,2	1.60	0.40	off	4.51	6.38
7	2,3	1.60	0.70	off	4.50	11.15
8	1,2	1.60	1.00	off	4.47	15.93
9	2	2.80	0.35	off	5.98	4.22
10	1,2,3	2.80	0.50	off	5.97	6.02
11	1	2.80	1.00	off	5.94	12.04
12	1,2,3	3.00	3.00	off,on	5.80	34.89

Experimental Activity

Predicted loop TF of tested cases

Nominally unstable ones generated during tests while looking for LCO



Experimental Activity

Test procedure:

- “pilot” (occupant) required to perform primary task (maintain altitude)
- “pilot” (occupant) occasionally instructed to perform secondary task (change altitude)
- disturbance force applied with arbitrary amplitude and frequency
- gearing ratio G_c modified without informing occupant
- increasingly high levels of G_c tested until LCO appears (and higher)
  - *safety: motion base saturation, control release procedure*
- 4 occupants: only one professional pilot (former helicopter test pilot)

<u>*task does not require specific piloting skills*</u>

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Results

- Gearing ratio of LCO first appearance and corresponding frequency
- Nominal G_c is about 0.35 radian

		Pilot #1		Pilot #2		Pilot #3		Pilot #4	
k/k_{ref}	c/c_{ref}	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian
Friction off									
3.0	3.0	3.95	∞[a]	3.8–4.0	∞	3.9–4.3	∞		
1.0	1.0	3.47	0.7	3.0	0.6	3.2	1.1	2.8	2.5
1.6	1.0	3.93	0.8	3.3	∞				
0.5	0.4	2.56	0.7	2.41	0.4–0.6	2.45	0.7	2.63	0.1
1.6	0.4	3.98	0.4	3.8	1.2				
2.8	1.0	4.5	∞						
2.8	0.5	4.05	1.4	3.8	1.8	4.7	∞		
2.8	0.35			3.85	2.4				
1.6	0.7			4.0	1.6	4.1	2.0		
Friction off, no close-in visual reference									
1.0	1.0			3.5–4.0	1.6–1.8				
Friction on									
0.5	0.15			4.1	1.1				
1.0	0.1			3.5	0.1				
1.0	0.2	3.5	0.8						

[a] ∞ means that no instability was found.

Results

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		Pilot #1		Pilot #2		Pilot #3		Pilot #4	
k/k_{ref}	c/c_{ref}	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian
				Friction off					
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0.5	0.4	2.56	0.7	2.41	0.4–0.6	2.45	0.7	2.63	0.1
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2.8	0.5	4.05	1.4	3.8	1.8	4.7	∞		
2.8	0.35			3.85	2.4				
1.6	0.7			4.0	1.6	4.1	2.0		
				Friction off, no close-in visual reference					
1.0	1.0			3.5–4.0	1.6–1.8				
				Friction on					
0.5	0.15			4.1	1.1				
1.0	0.1			3.5	0.1				
1.0	0.2	3.5	0.8						

Much stiffer (ideally rigid):
- **no LCO**
- **different BDFT frequencies**

[a] ∞ means that no instability was found.

Results

- Gearing ratio of LCO first appearance and corresponding frequency
- Nominal G_c is about 0.35 radian

		Pilot #1		Pilot #2		Pilot #3		Pilot #4	
k/k_{ref}	c/c_{ref}	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian
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1.6	1.0	3.93	0.8	3.3	∞				
0.5	0.4	2.56	0.7	2.41	0.4–0.6	2.45	0.7	2.63	0.1
1.6	0.4	3.98	0.4	3.8	1.2				
2.8	1.0	4.5	∞						
2.8	0.5	4.05	1.4	3.8	1.8	4.7	∞		
2.8	0.35			3.85	2.4				
1.6	0.7			4.0	1.6	4.1	2.0		
Friction off, no close-in visual reference									
1.0	1.0			3.5–4.0	1.6–1.8				
Friction on									
0.5	0.15			4.1	1.1				
1.0	0.1			3.5	0.1				
1.0	0.2	3.5	0.8						

[a]∞ means that no instability was found.

Nominal:
- **LCOs**
- **at about twice nominal G_c**

Results

- Gearing ratio of LCO first appearance and corresponding frequency
- Nominal G_c is about 0.35 radian

		Pilot #1		Pilot #2		Pilot #3		Pilot #4	
k/k_{ref}	c/c_{ref}	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian	freq., Hz	G_c, radian
Friction off									
3.0	3.0	3.95	∞[a]	3.8–4.0	∞	3.9–4.3	∞		
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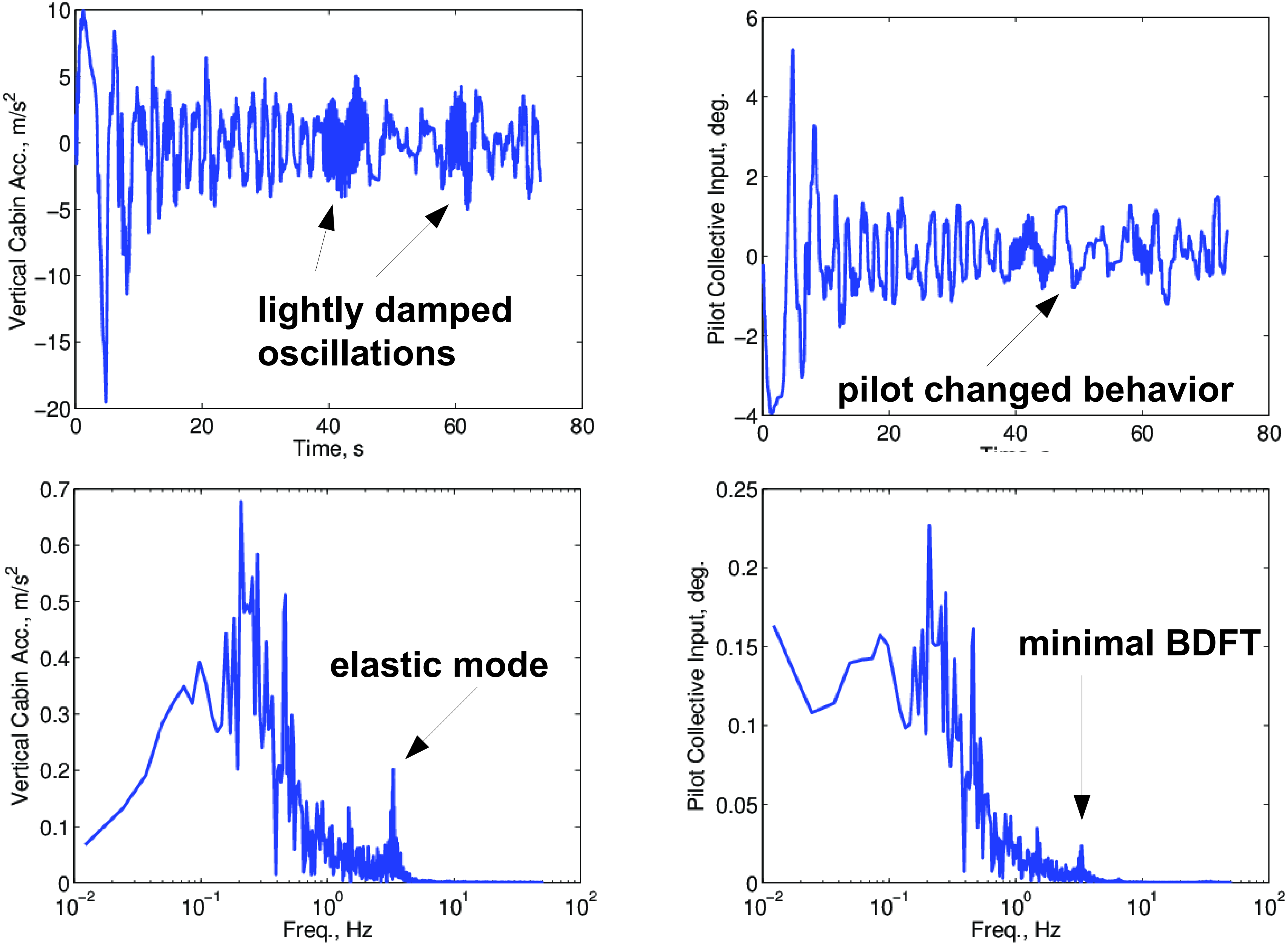
1.6	0.7			4.0	1.6	4.1	2.0		
Friction off, no close-in visual reference									
1.0	1.0			3.5–4.0	1.6–1.8				
Friction on									
0.5	0.15			4.1	1.1				
1.0	0.1			3.5	0.1				
1.0	0.2	3.5	0.8						

[a]∞ means that no instability was found.

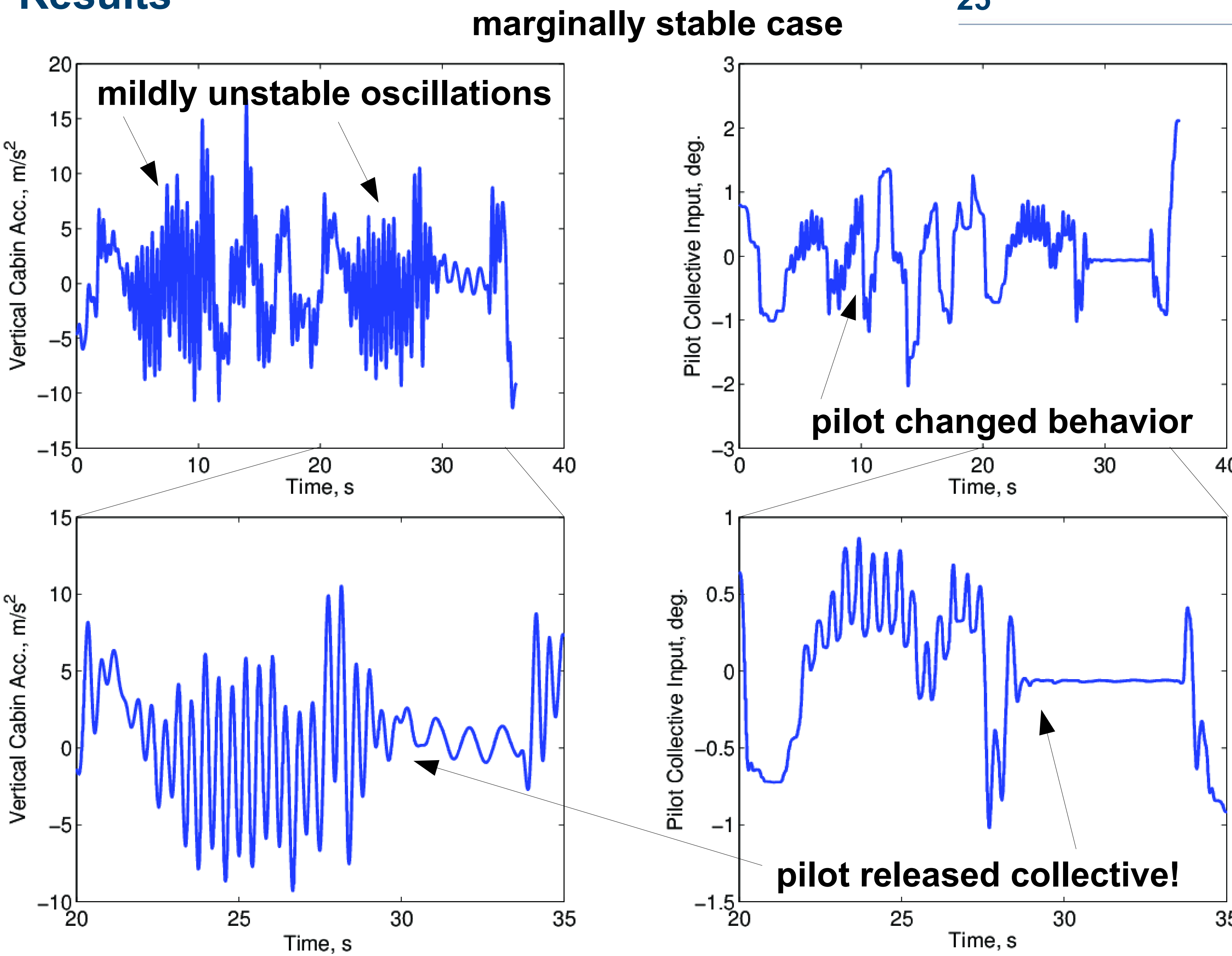
Low stiffness & damping:
- **pronounced LCOs**
- **quite variable G_c**

Results

stable case

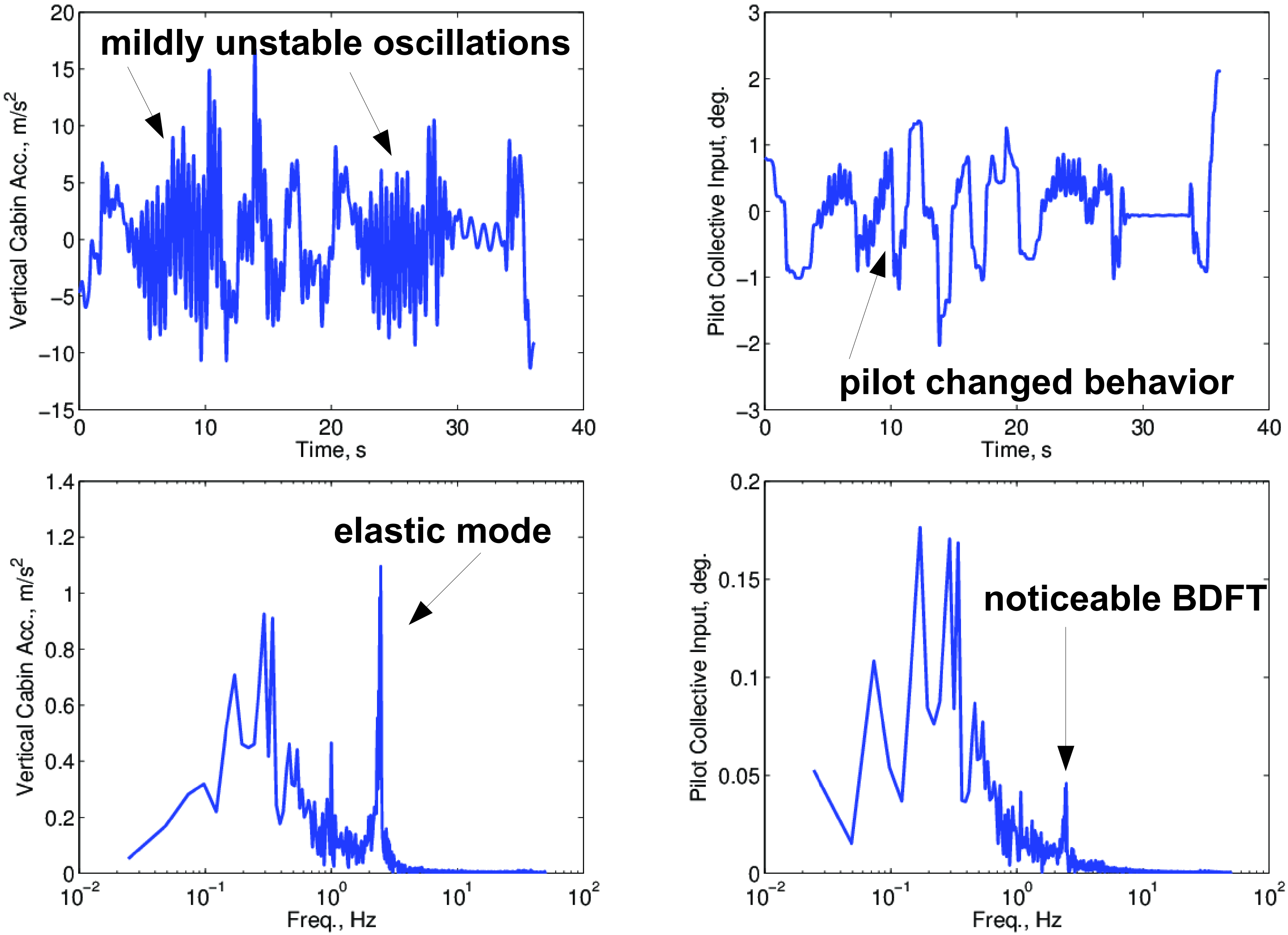


Results


marginally stable case
mildly unstable oscillations
pilot changed behavior
pilot released collective!
Vertical Cabin Acc., m/s^2
Pilot Collective Input, deg.
Time, s
20
15
10
5
0
−5
−10
−15
3
2
1
0
−1
−2
−3
0.5
−0.5
−1.5
25
30
35
40

Results

marginally stable case



Results

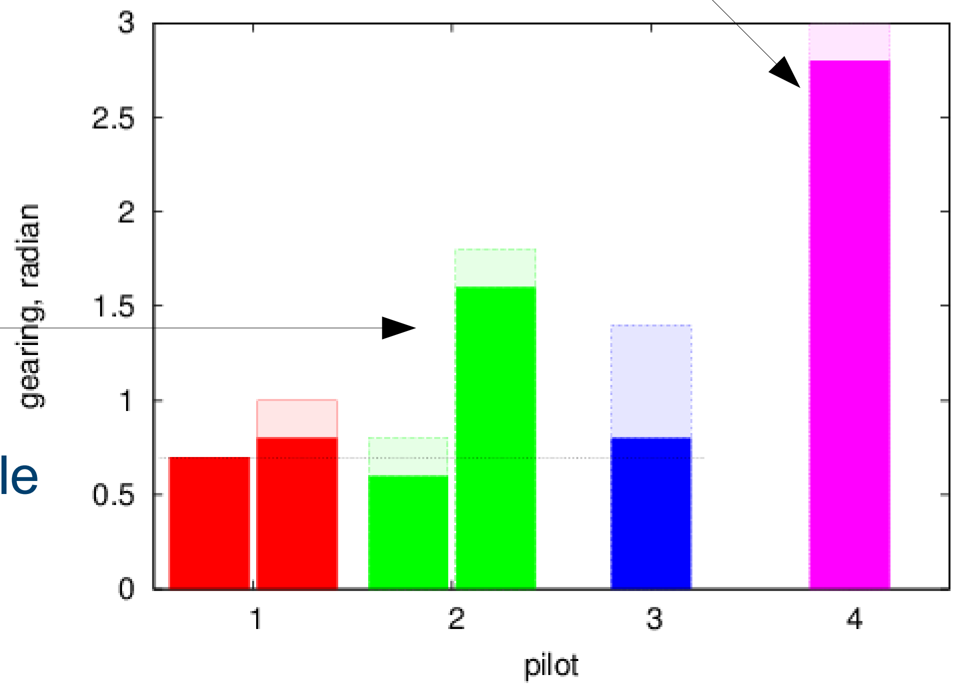
- Baseline case tested with all 4 occupants

- All non-professional pilots: LCO at about 3.5 Hz, G_c twice nominal
- Professional pilot (#4): LCO at about 2.8 Hz, blurred by intensive intentional activity (saturation? task dependent BDFT modification?)

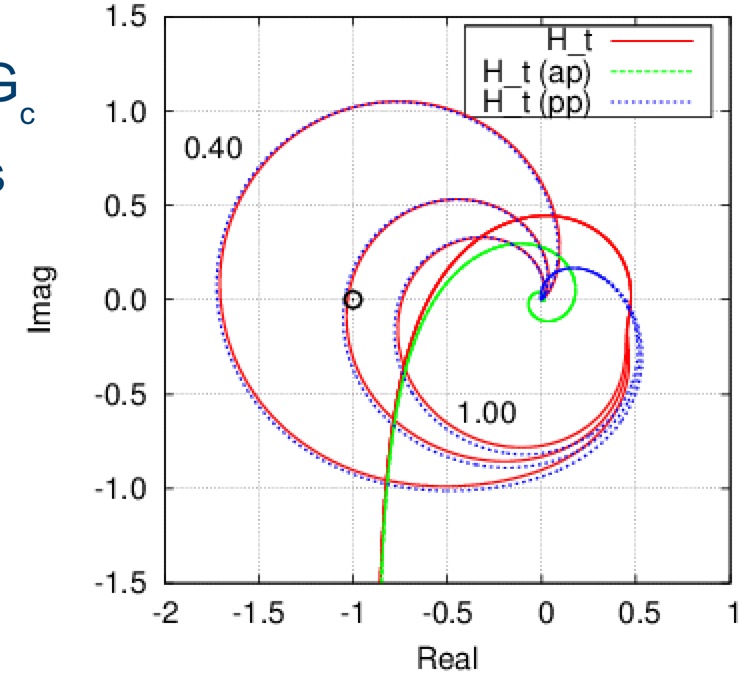
- LCO at 2.8 Hz suggests biomechanic instability (elastic mode: 3.5 Hz)

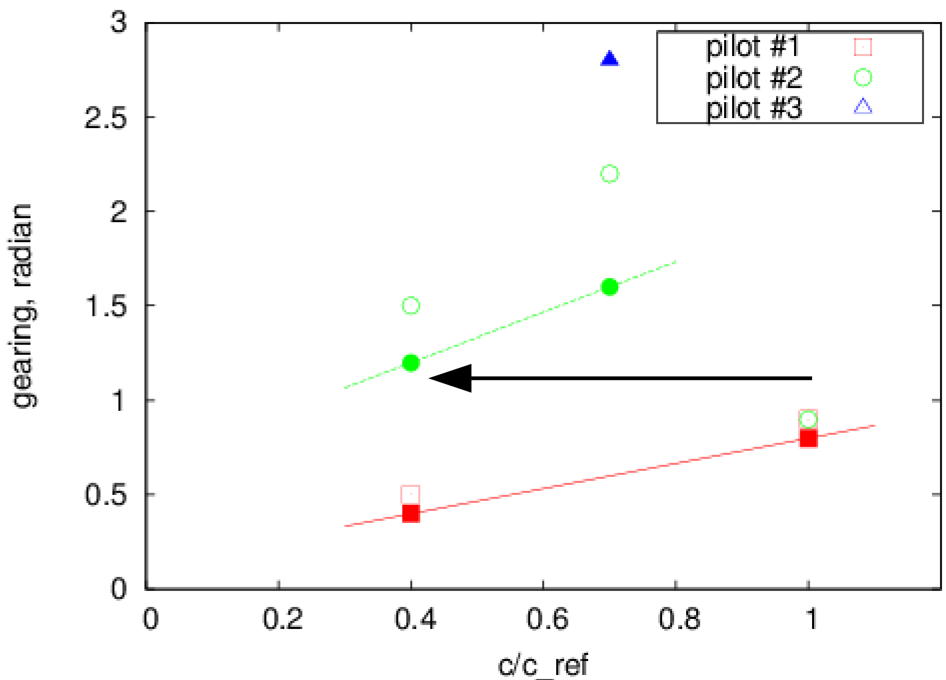
- Pilot #2 shows instability at higher G_c when performing a similar task with different visual cueing environment (VCE): horizon instead of pole

- Pilot #1: LCO after alarm set by data acquisition system



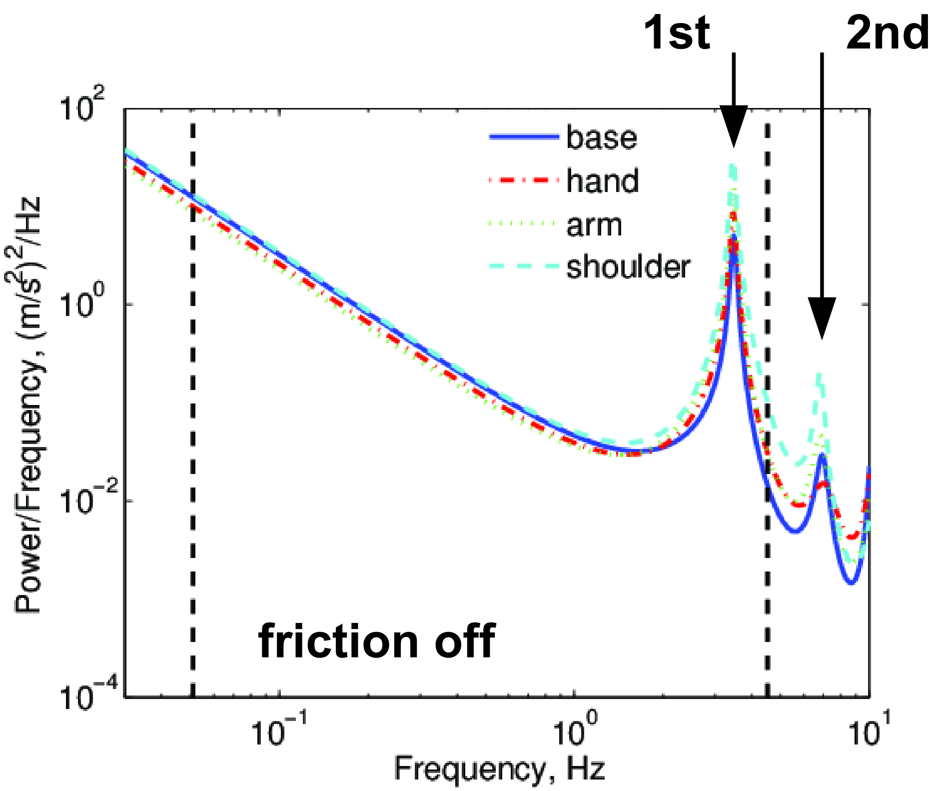
- Stiffer elastic mode: k/k_{ref} = 1.6 and c/c_{ref} = 0.4, 0.7, 1.0 (about 4.5 Hz)
- nominally unstable
- In practice, always stable w/ nominal G_c
  - large variability amongst occupants
  - damping reduction result-driven

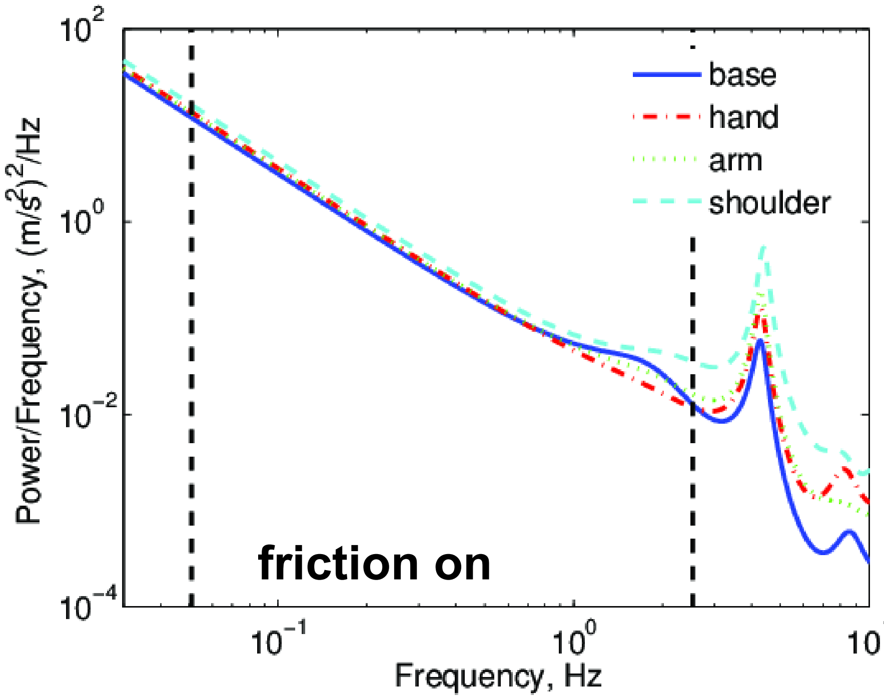




Effect of friction:

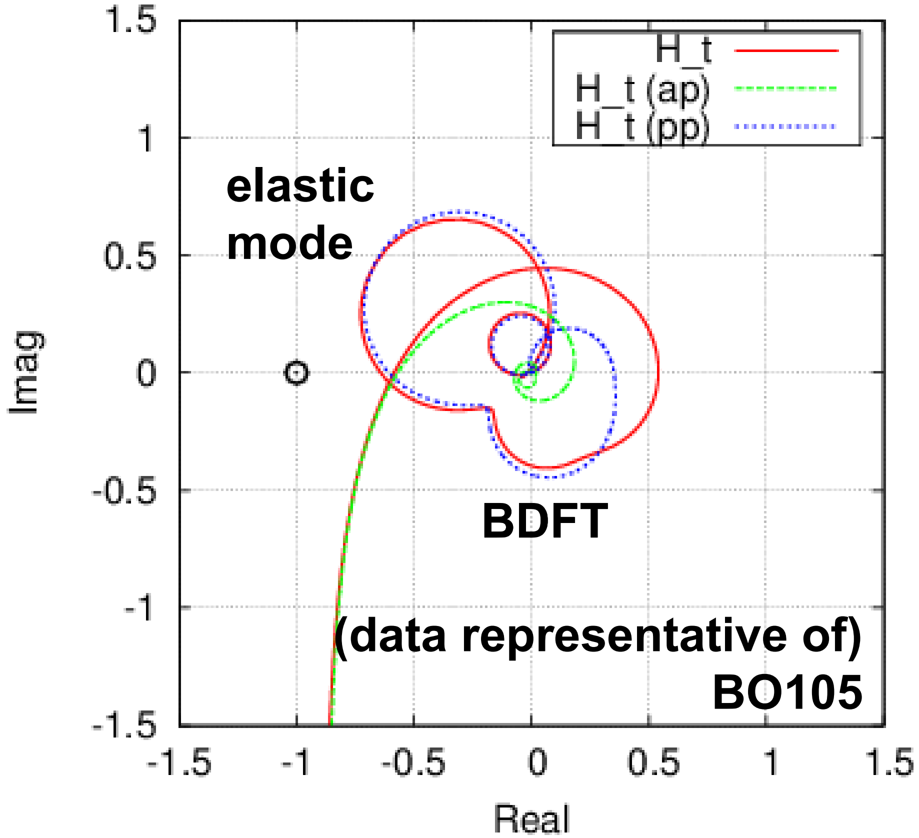
- very low structural damping required for LCO to appear
- without friction, second harmonic of biomechanical mode appears
- with friction, only a biomechanical mode appears
- in a quasi-linear dynamics sense, friction represents equiv. damping

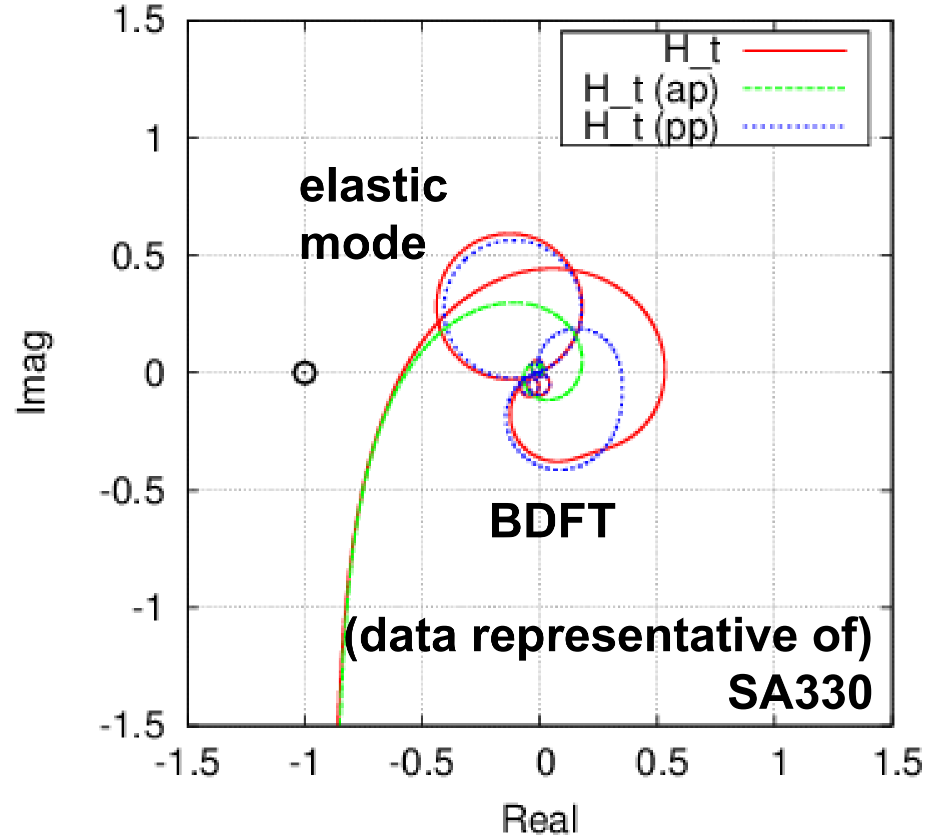




Was this just a nice game? Analysis with deformable airframe model

- Clear similarities with simple aeroelastic model
- Typical light/medium helicopter relevant airframe dynamics show higher frequencies (6 to 9 Hz) than present (2.5 to 4.8 Hz)
- Interaction with pilot biomechanics less likely





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Conclusions

- Experimental investigation of helicopter pilot biomechanics
- Pilot-in-the-loop tests of simple marginally stable heave motion model
- Highlighted several aspects of helicopter-pilot interaction:
  - task dependence
  - variability among occupants, but clear common trends
  - instability caused by coupling of structural and biomech. modes
  - friction in control inceptor can alleviate but not eliminate the effect
  - results partially affected by saturation, especially at FM freq.
- Results partially scale on realistic airframe dynamics models

Acknowledgements

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ARISTOTEL

Thank you for your attention

Questions?