ARISTOTEL

Warning the pilot for PIO Problems – a solution to avoid instability?

A Retrospective Survey of Recent Research Activities within the European Project ARISTOTEL

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COOPERATION

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ARISTOTEL Consortium

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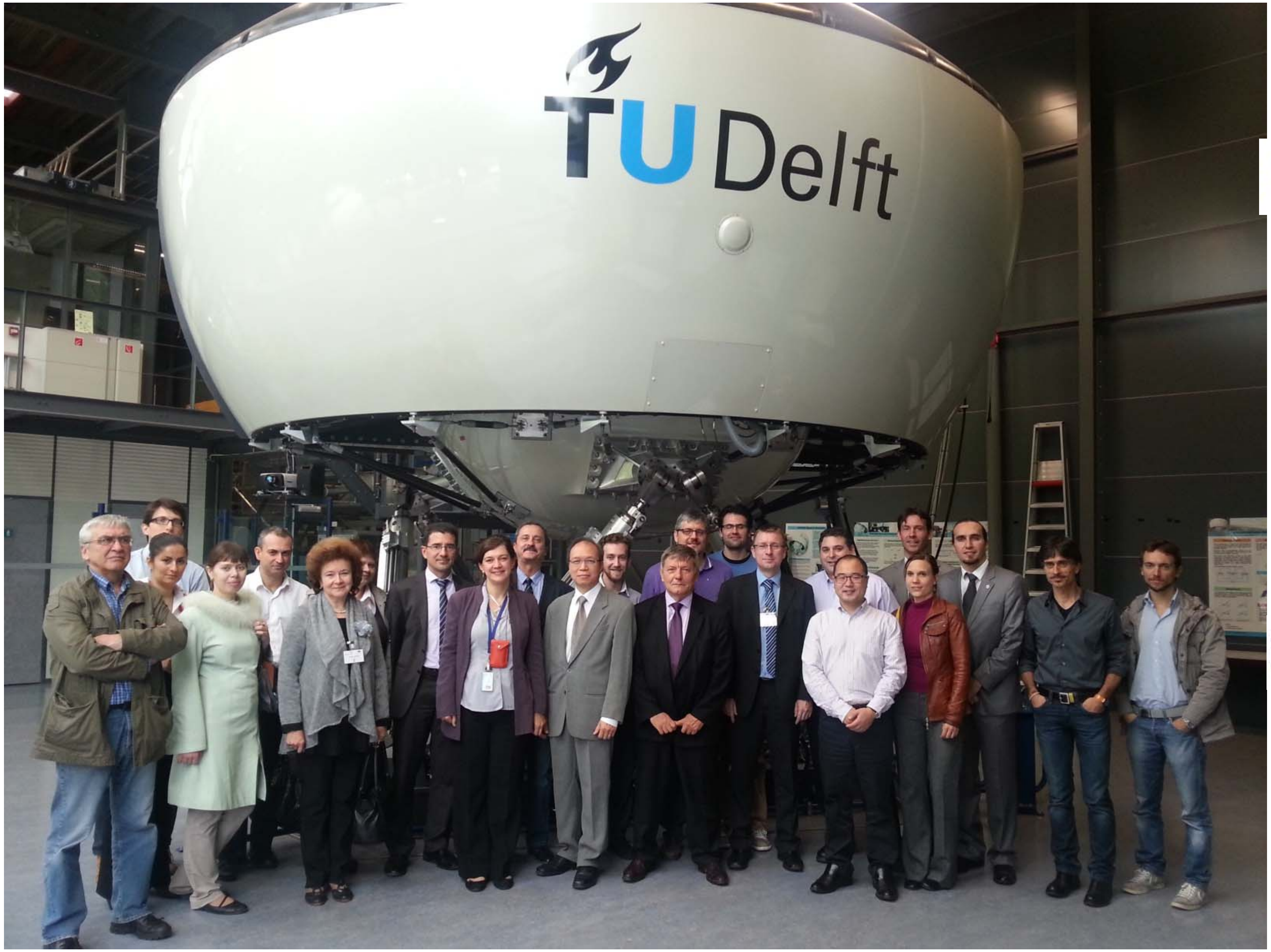

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Presentation themes

1 Definition and Understanding of A/RPCs
- Importance of A/RPCs
- Potted history of A/RPCs with some recent examples

2 What we achieved

3 Simulation trials

4 ROVER as a warning system for the pilot

5 Conclusions

Subject

- Fixed and rotary wing pilots alike are familiar with potential instabilities or with annoying limit cycle oscillations that arise from controlling aircraft with high response actuation systems.
- The destabilization of a vehicle due to active and/or passive pilot participation in the control loop is a well-known phenomenon called pilot induced oscillations (PIO) and pilot assisted oscillations (PAO), respectively.
- In the mid-1990’s PIO/PAOs were renamed as Aircraft/Rotorcraft-Pilot-Couplings (A/RPC) implying that the key causal factor of such instabilities was not always the pilot

Problem

The understanding, controlling and suppressing of pilot's voluntary/involuntary participation in a PIO/PAO is recognized to be a demanding problem, especially for actual helicopters with high bandwidth actuation systems and enlarged operational ranges.

EU set a joint initiative to cut aviation accidents by 80% in 2020…

EU set a joint initiative to cut aviation accidents by 80% in 2020…

PIO are still a matter of high concern for safety.

Boeing 737 van Turkish Airlines rond het middaguur in een bij Schiphol. Op dat tijdstip werden de laatste slachtoffers uit het toest Foto Bram Budel

Modern designs seem even more sensitive to A/RPCs

Rotorcraft RPCs are significantly more problematic than aircraft APCs.

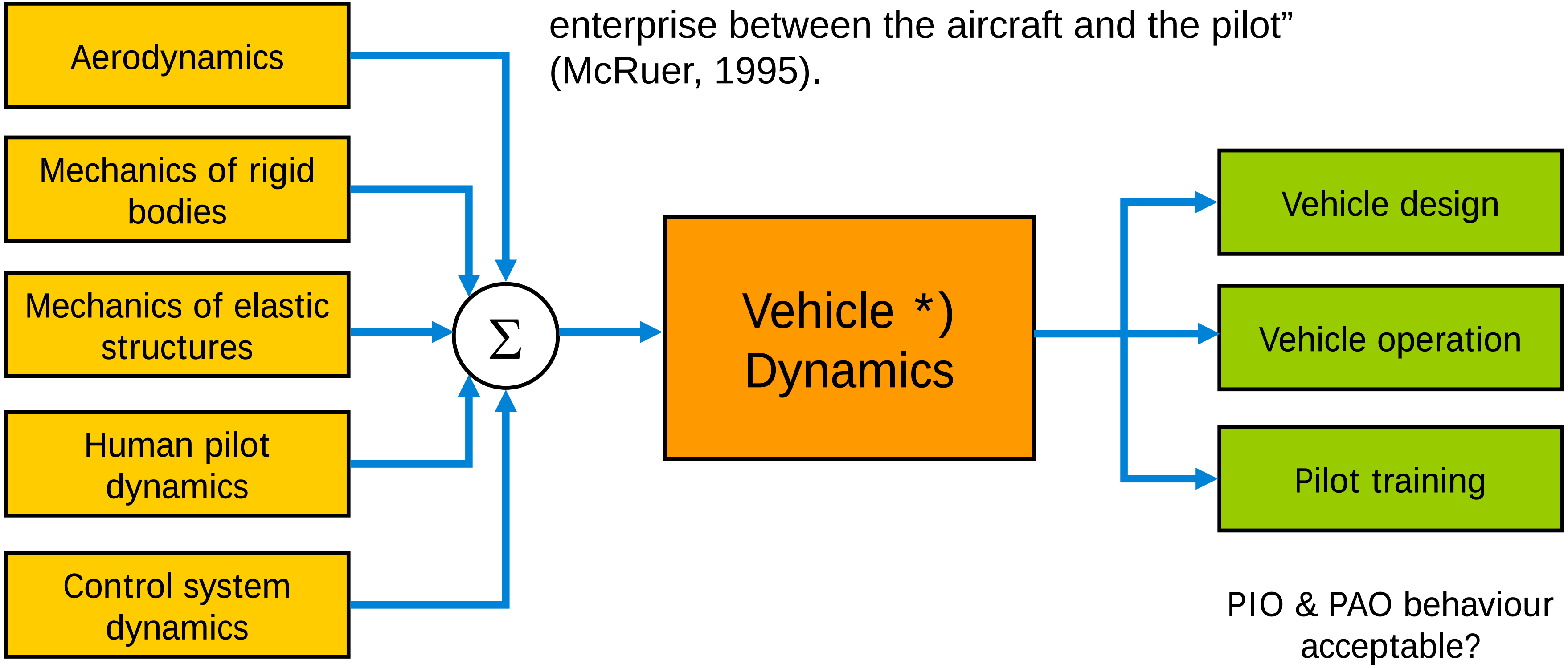
We hardly possesses guidelines for designing A/RPCs free configurations.

ARISTOTEL Project

- ARISTOTEL = *Aircraft and Rotorcraft Pilot Couplings – Tools and Techniques for Alleviation and Detection*
  - 7TH FRAMEWORK EUROPEAN UNION PROJECT
  - Started in October 2010 with a duration of 3 years (Nov. 2013)
  - Involving partners from all Europe
- Goal:
  - Advance the state of the art in Modeling and Predicting A/RPCs. Define design guidelines for A/|RPCs; Define protocols A/RPC flight simulator training

Pilot Induced Oscillation (PIO) and Pilot Assisted Oscillation (PAO) A Complex Interdiciplinary Subject

An "inadvertent, sustained aircraft oscillation which is the consequence of an abnormal joint enterprise between the aircraft and the pilot" (McRuer, 1995).



Aerodynamics

Mechanics of rigid bodies

Mechanics of elastic structures

Human pilot dynamics

Control system dynamics

Σ

Vehicle *) Dynamics

Vehicle design

Vehicle operation

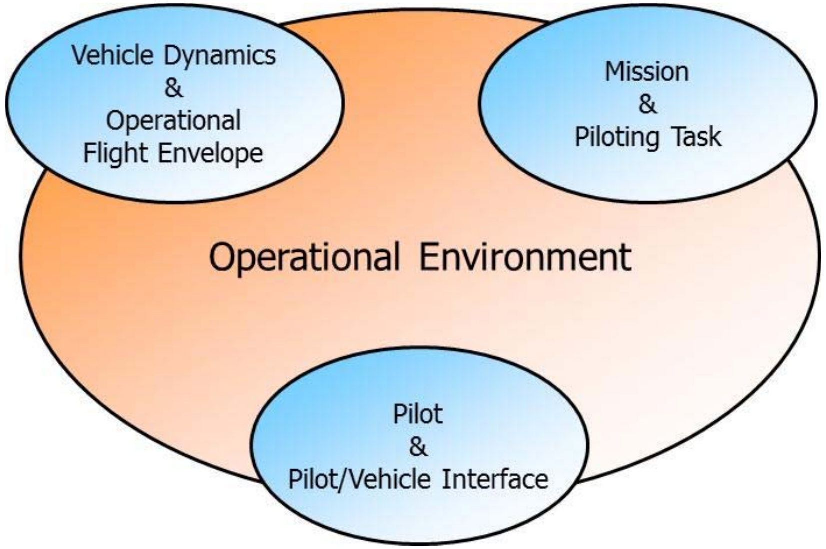
Pilot training

PIO & PAO behaviour acceptable?

*) Aircraft or Rotorcraft

Source: Etkins, 1972

PIO/PAO are Related to 4 Reference Points and 3 Necessary Conditions



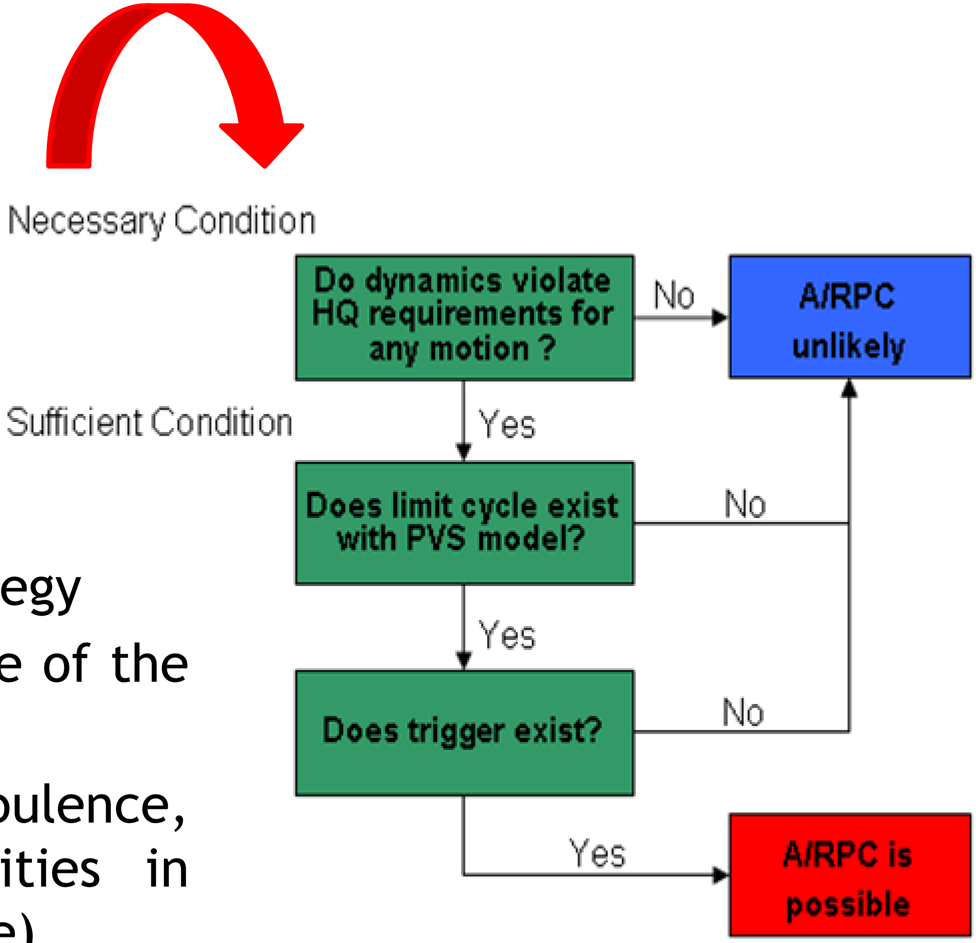
Vehicle Dynamics & Operational Flight Envelope

Mission & Piloting Task

Operational Environment

Pilot & Pilot/Vehicle Interface

Four reference points to relate A/RPC



Necessary Condition

Sufficient Condition

Do dynamics violate HQ requirements for any motion ?

No → **A/RPC unlikely**

Yes ↓

Does limit cycle exist with PVS model?

No → **A/RPC unlikely**

Yes ↓

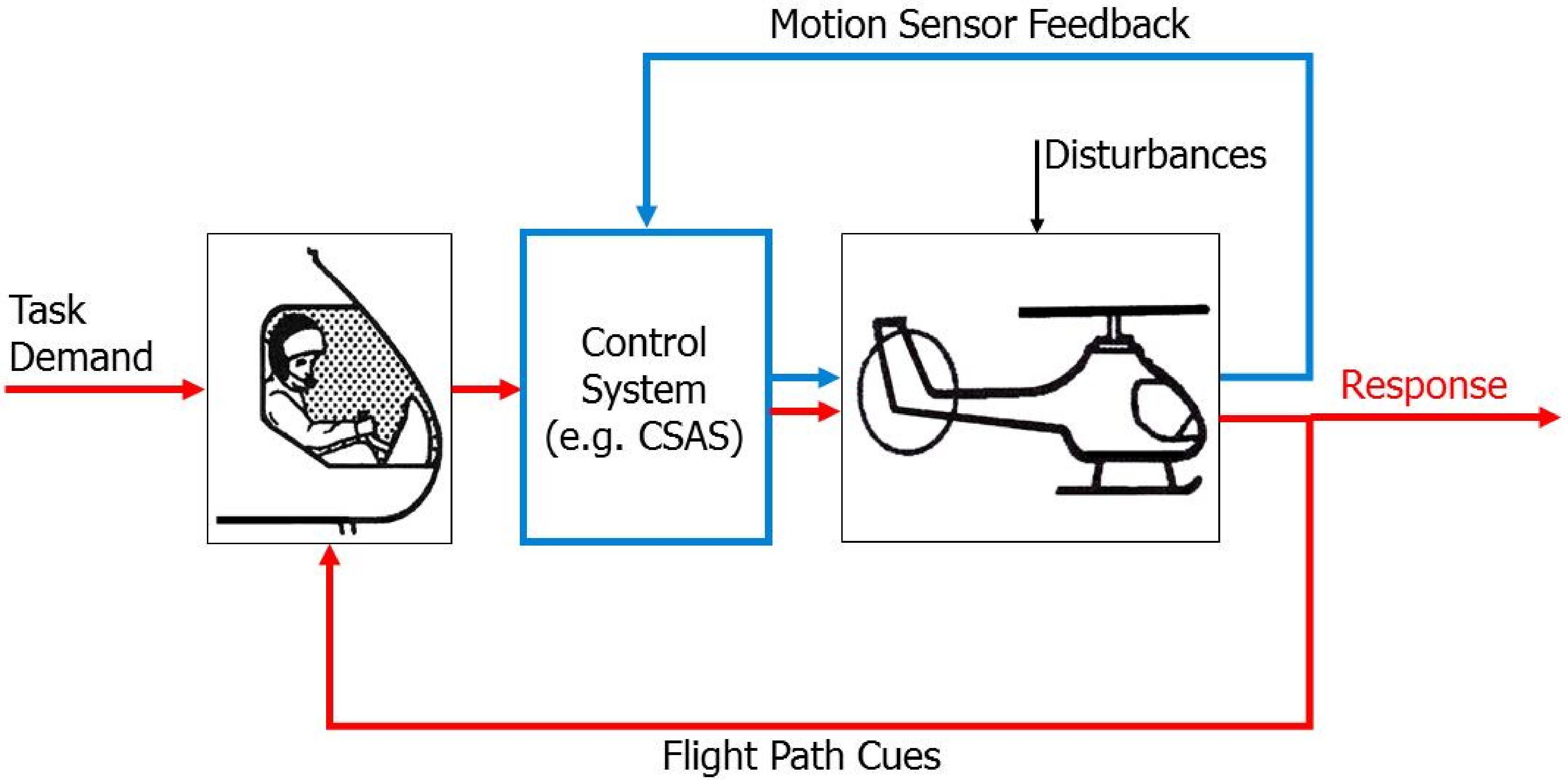
Does trigger exist?

No → **A/RPC unlikely**

Yes → **A/RPC is possible**

- A/RPC ingredients
  - A change in pilot control strategy
  - A change in the dynamic state of the aircraft
  - Trigger (atmospheric turbulence, changes in FCs, discontinuities in pilot perception of the vehicle)

Pilot-In-The-Loop: The Key for Understanding Pilot Induced/Assisted Oscillations



Source: Padfield, 1996

The Cause of Pilot Induced & Assisted Oscillations at Helicopter

- PIO/PAO‘s in Flight Mechanics
  - Associated with flight mechanical frequencies
  - Related to high control sensitivities (e.g. about roll axis)
  - Attributed to an overlap of guidance and control task (research activities by G. Padfield)

- PIO/PAO’s in Dynamics/Aeroelastics
  - Associated with structural dynamic or aeroelastic resonances
  - Related to excitations of main rotor collective or cyclic modes
  - Supported by high bandwidth servo-hydraulic control systems

Source: Strehlow, ECD, 2004

Example of RPC à la PIO

Excitation of low -damped main rotor regressive inplane mode

Source: Cyclic control inputs

⇩

Body roll and pitch vibrations

⇩

Affects: Blade strength limits

Excitation of low frequency pendulum mode of external slung loads

Source: delayed collective and/or cyclic control inputs due to couplings of the load dynamics via elastic cables

⇩

Comfort & strength limit

Source: H. Strehlow (Eurocopter, 2003)

Example of RPC à la PAO

Destabilization of the main rotor blade bending – torsion motion at high rotor loadings and flight speeds during maneuvers by stall effects

Aggravated by Unintended cyclic control inputs

⇩

Airframe vibrations

Destabilization of low-damped main rotor – engine – drive train modes

Aggravated by pilot assisted collective control inputs.

⇩

Airframe vibrations

Augmentation of transient airframe bending oscillation by feedback – type couplings of the airframe structure by the main rotor via the actuation system

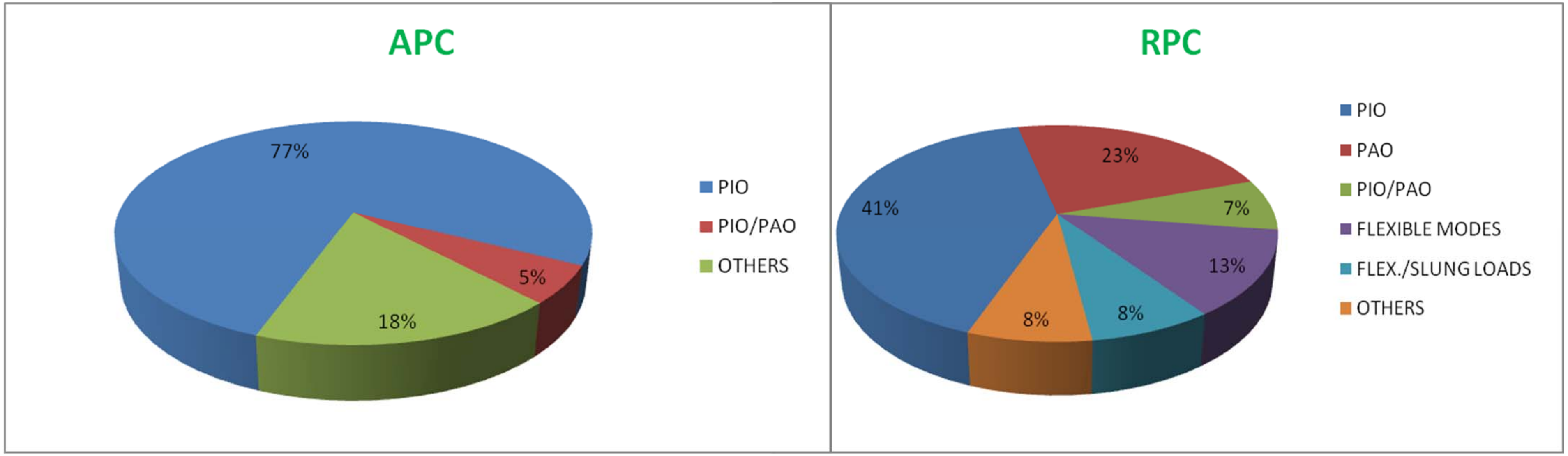
“Assisted” by collective and/or cyclic control inputs.

⇩

Airframe vibrations

Source: H. Strehlow (Eurocopter, 2003)

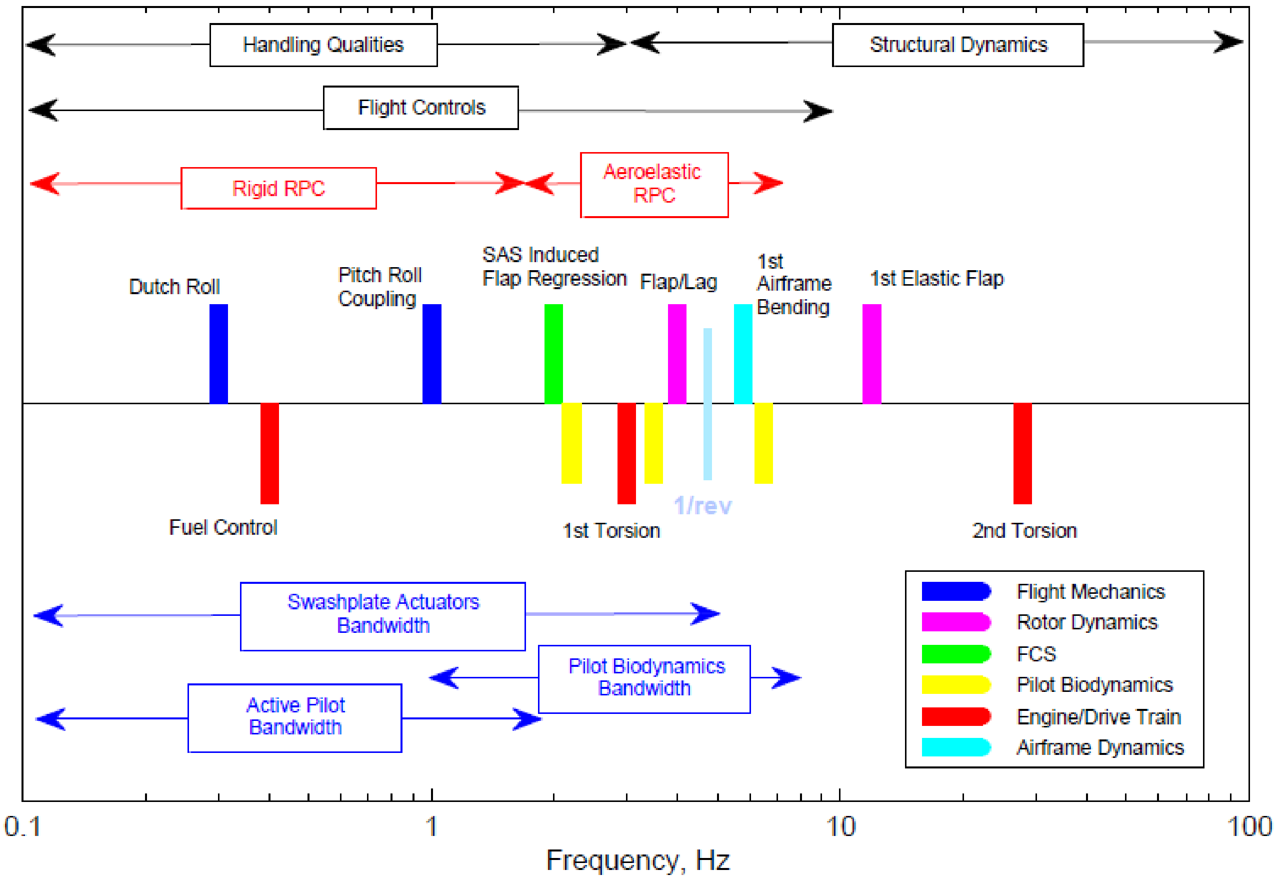
Some statistics



77% of APC is related to PIO, not involving elasticity, RPC situation is much more entangled.
At least 50% of reports, in fact, involve **aero-servo-elastic phenomena** (sections named PAO, PAO/PIO, Flexible modes, Slung-loads)

Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Aeroelasticity for PAO



Major structural dynamic modes (airframe bending, rotor dynamics, SAS, FCS, servo-systems) are positioned in the pilot biodynamic frequency band. **All of them should be modelled for RPC prediction.**

Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Brief History of famous PAO events

Rotorcraft Case studies: PAO

SH-60B SEAHAWK

6.5 Hz First Vertical Bending Mode Oscillation

- Task: high speed autorotation and turn, and dive recoveries.
- Interaction between structural deformation, pilot biodynamic response, pitch SAS and longitudinal boost servo
- Solutions:
  - Notching to reduce the SAS participation: partially successful
  - Pilot disabling the longitudinal boost servo
  - Collective recovery
  - Release the cyclic stick

Rotorcraft Case studies: PAO

CH-53E SUPER STALLION

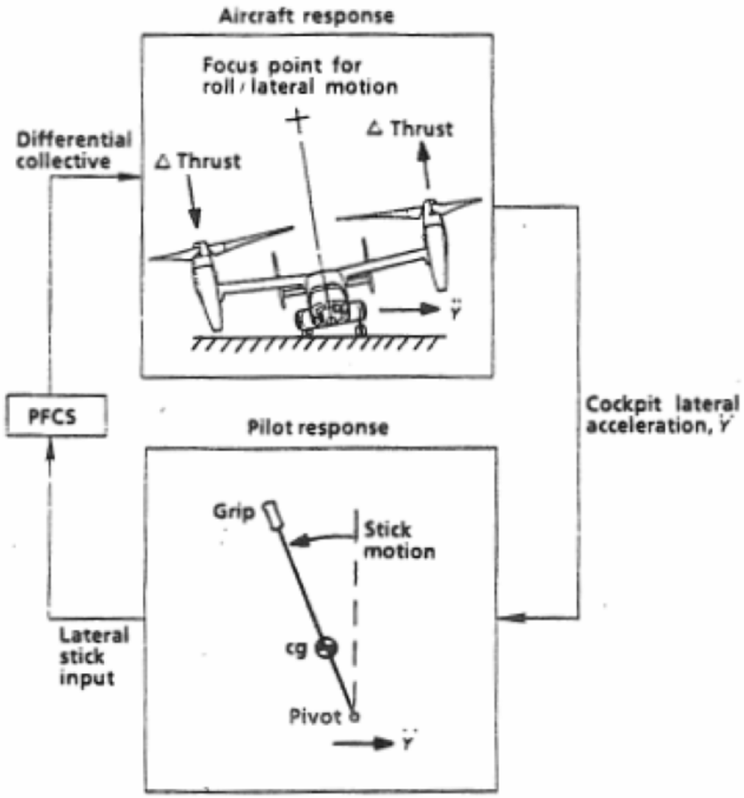
Vertical (3.4 Hz) and Lateral (4.3 Hz) Bending Mode Oscillation

- Task: low speed flight and precision over with external loads.
- Interaction between structural deformation, pilot biodynamic response, FCS
- Solutions:
  - Desensitizers and notch on the pilot input: partially successful
  - Reduction of roll axis FCS gain
  - Procedural mitigation
  - Load jettison

Rotorcraft Case studies: PAO

V-22A OSPREY

- 1.4 Hz High focal Roll Mode on ground
- The aircraft translate laterally & pilot introduce lateral cyclic input
- Solutions:
  - Addition of a viscous damper & notch; adverse effects on the handling qualities
  - Addition of a balance mass of 17lb to the lateral cyclic stick

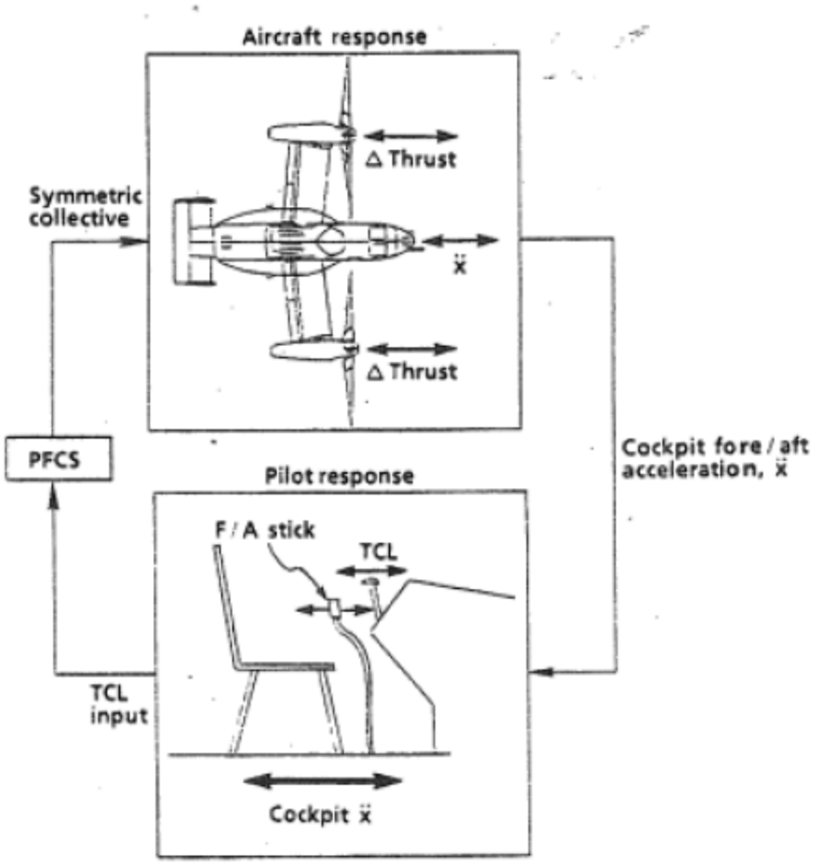


Source: Parham, T. J., Popelka, D., Miller, D. G. and Frobel, A. T.V-22 Pilot-In-The-Loop Aeroelastic Stability Analysis, 47th Annual Forum, Phoenix, AZ, May 1991

Rotorcraft Case studies: PAO

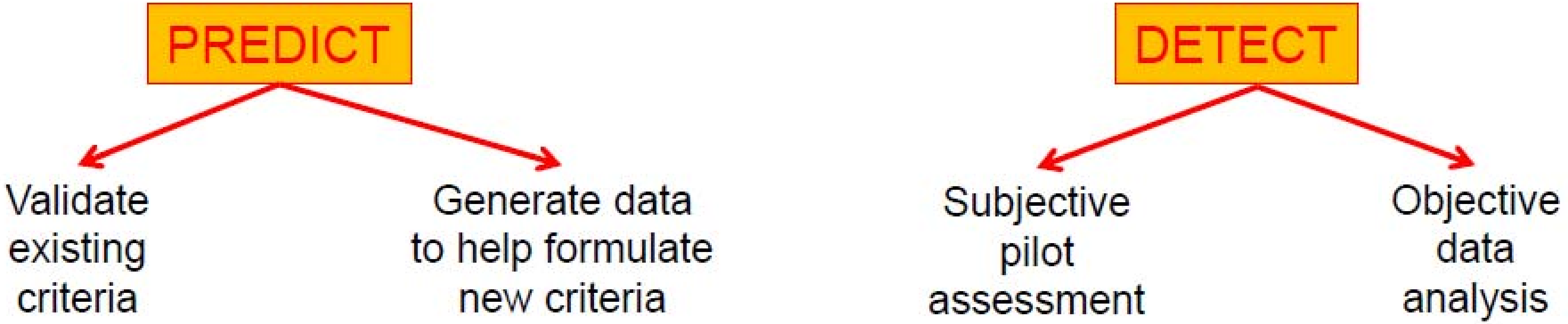
V-22A OSPREY

- 4.2 Hz Wing chord symmetric bending
- The vibration caused the inadvertent introduction of commands in the Thrust Control Lever, causing oscillation of thrust
- Solutions:
  - Addition of a notch filter on TCL



Source: Parham, T. J., Popelka, D., Miller, D. G. and Frobel, A. T.V-22 Pilot-In-The-Loop Aeroelastic Stability Analysis, 47th Annual Forum, Phoenix, AZ, May 1991

ARISTOTEL's Goals and What did we achieve?



PREDICT

Validate existing criteria

Generate data to help formulate new criteria

DETECT

Subjective pilot assessment

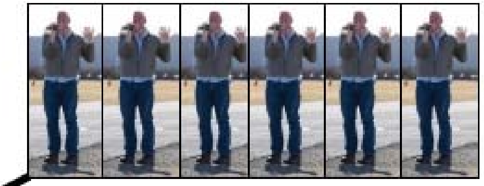
Objective data analysis

- We conduced 4 test campaigns for rigid body and aeroelastic PIO/PAO for fixed and rotary wing
- We conducted 4 test campaigns to understand biodynamic effects in PAO
- We generated a suitable database for the engineer for PIO/PAO analyses
- We investigated the effects of using different simulation facilities, inceptor characteristics etc.
- We assessed current prediction criteria and explored some interesting (novel) PIO/PAO-related topics
- Goal: To NOT break the simulators (Desirable = at all; Adequate = repairable)
- Have some fun?

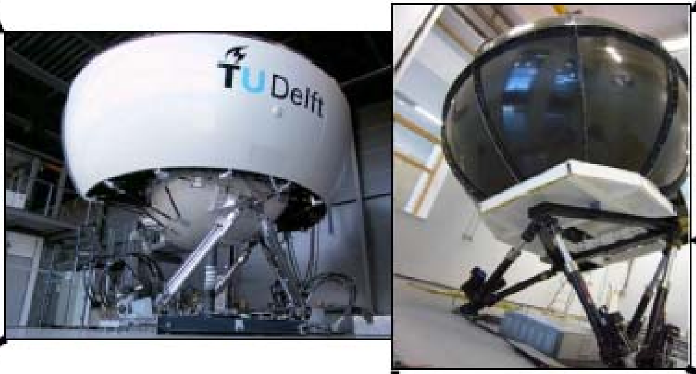
Example: Rigid body test campaigns

- Prediction techniques, detection techniques, pilot identification, pilot modelling, rating techniques, effect of simulator parameter differences

Non-linear models



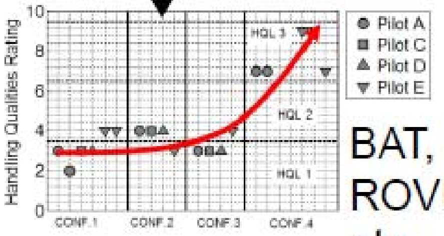
3 test pilots



8 MTEs

Campaign reported in (amongst others):

Jones et al., "Exposing Rotorcraft Pilot Couplings Using Flight Simulation", 39th European Rotorcraft Forum, Moscow, Russia, 2013



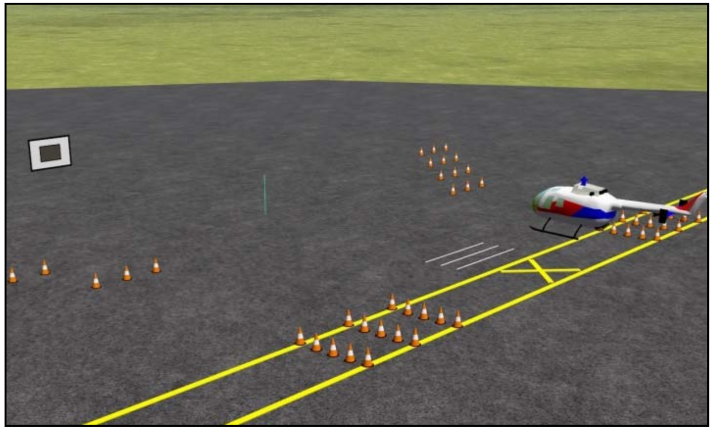
1100+ Test Points

BAT, PAC, Pre-PAC, Bifurcation
ROVER+, NPIO-R
etc.

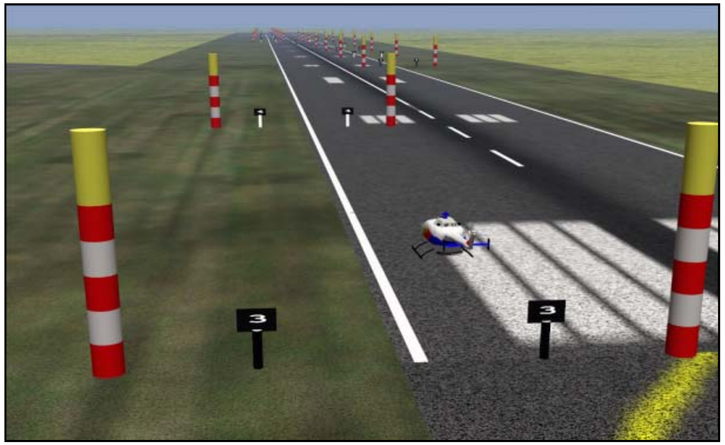
Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Task Development

- Considerations
  - *Pilots like real flying tasks*
  - *Increase in realism drives pilot performance, improves motivation*
  - *High bandwidth tasks required to force consistent levels of pilot performance*
- ADS-33 tolerances not necessarily stringent enough to force RPCs
  - *Dependency upon vehicle HQs*
  - *Tasks not necessarily exposing all RPCs*
- Two tasks selected as most effective
  - *But still improvements could be made*
- *In 2nd RBTC, modifications to task performance requirements*
  - *Force pilot to apply closed-loop control…*
  - *Without making task inappropriate or unrealistic*



ADS-33 Precision Hover Manoeuvre

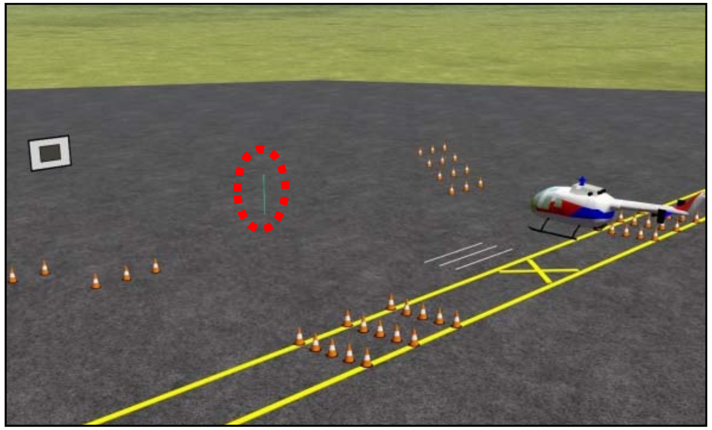


Roll Step Manoeuvre

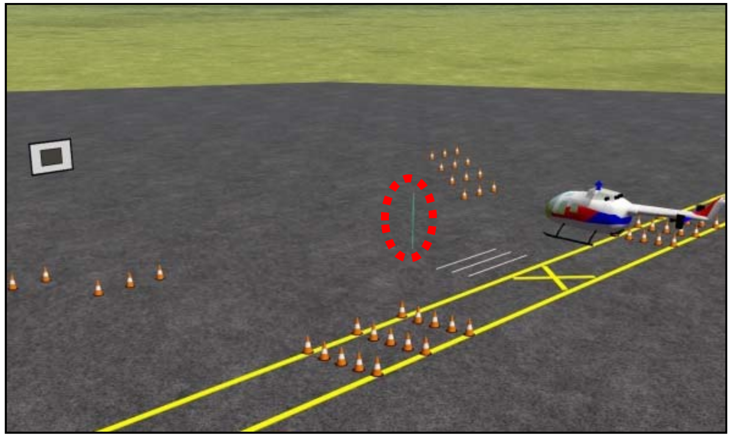
Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Task Development: Precision Hover

- Change to ‘Precision Hover’
  - *Forward tolerances defined by position of reference pole*
  - *Usually mid-way between vehicle and board*
- Placing pole closer to the vehicle
  - *Reduces tolerances*
  - *Tightens pilot control – particularly during stable hover*
- Three configurations tested
  - *Pole = 75ft from vehicle (mid-way, ADS-33 tolerances)*
  - *Pole = 40ft from vehicle*
  - *Pole = 25ft from vehicle*
- Analysis of HQs and pilot comments (determine appropriateness of task)
- Analysis of PIORs (determine PIO susceptibility)



Hover Pole = 75ft from vehicle
Hover Board = 150ft from vehicle



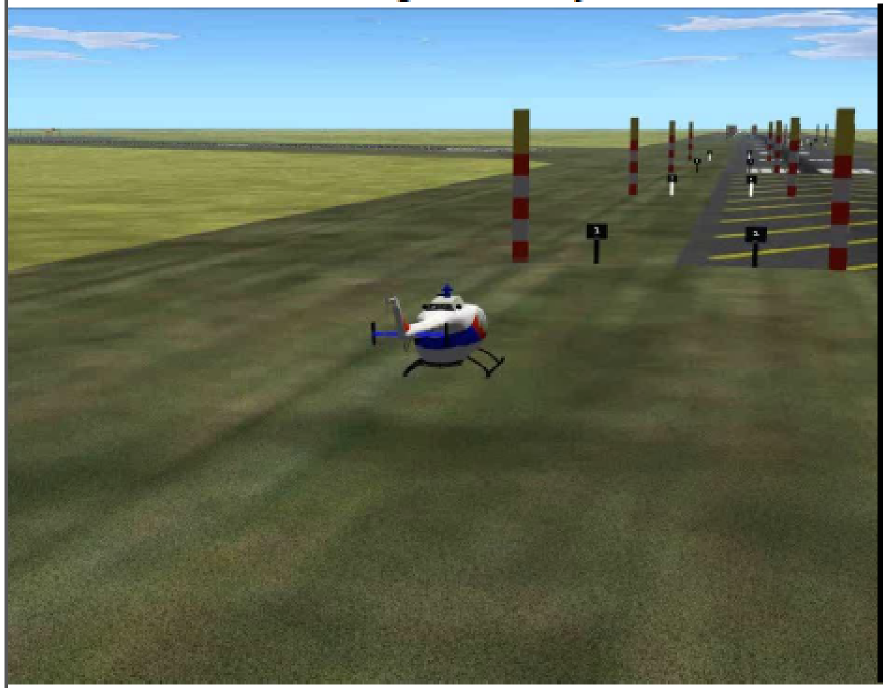
Hover Pole = 20ft from vehicle
Hover Board = 150ft from vehicle

Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Rigid body versus aeroelastic test campaigns

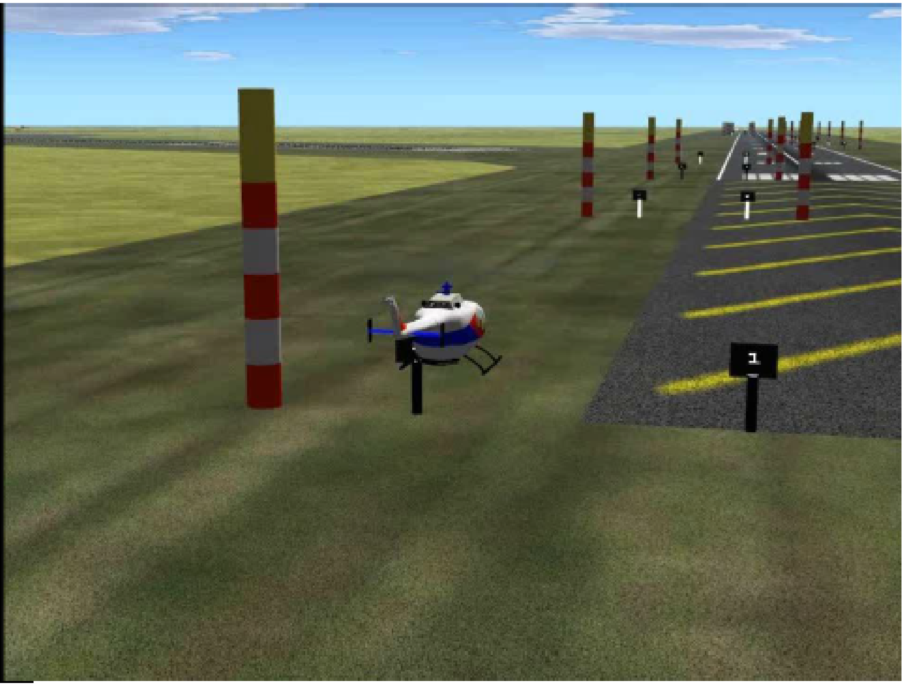
- RB vs AE: example result, V = 80kts

Rigid Body



Pilot 1, τ=100ms, K_{lon}=3, lateral disturbance
HQR = 4; PIOR = 1; Workload = 6
"Little biodynamic bumps reduce the tracking performance"

74 State Aeroelastic Model



Pilot 1, τ=100ms, K_{lon}=3, lateral disturbance
HQR = 4; PIOR = 4; Workload = 8
"Undesirable PAO occurred"

Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

Example: Fixed wing test campaigns

$$\dot{\beta} = Y_\beta \beta + \frac{g\cos\theta}{V}\phi - R\cos\alpha + P\sin\alpha + Y_P P + Y_R R + Y_{\delta a}\delta_a + Y_{\delta r}\delta_r + Y_{\dot\beta}\frac{w}{V_T} + Q_Y$$

$$\dot{P} = L_\beta \beta + L_R R + L_P P + L_{\delta a}\delta_a + L_{\delta r}\delta_r + L_{\dot\beta}\frac{w}{V} + Q_P$$

$$\dot{R} = N_\beta \beta + N_R R + N_P P + N_{\delta a}\delta_a + N_{\delta r}\delta_r + N_{\dot\beta}\frac{w}{V} + Q_R$$

$$\ddot{\eta} + (D_{Sn} + \rho V D_{an})\dot{\eta} + (G_n + qB_{an})\eta = q b_{\beta n}\left(\beta + \frac{w}{V}\right) + \frac{\rho V_T}{2}(d_{Pn}P + d_{Rn}R) + q b_{an}\delta_a + q b_{rn}\delta_r$$

$$\dot{U} = RV - QW - g\sin\theta + n_x g$$

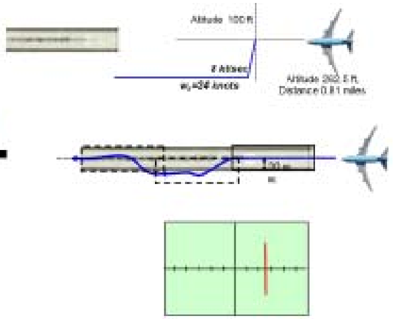
$$\dot{W} = QU - PV + g\cos\phi\cos\theta + n_z g$$

Generic fw model

3 pilots

3 Inceptors

3 MTEs



Campaign reported in:

Zaichik, Yashin, Desyatnik, Perebatov, Smaili, "An approach to assess aircraft-pilot coupling caused by structural elasticity", 39th European Rotorcraft Forum, Moscow, 2013

~ **1000** test points

Source: ARISTOTEL Workshop, TU Delft, Sept, 23rd, 2013

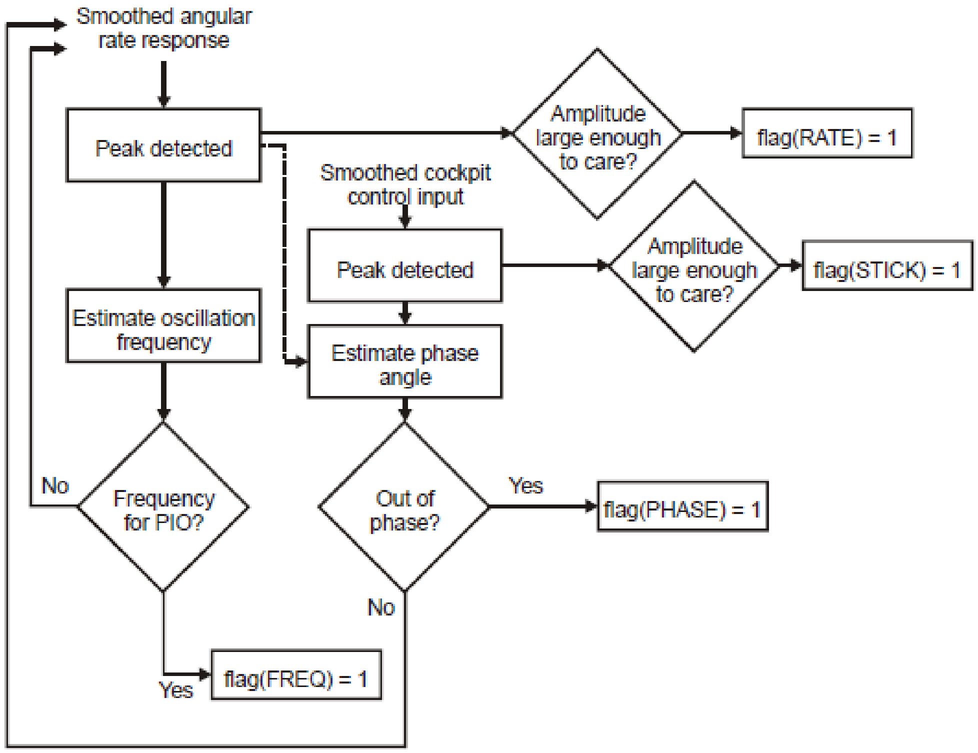
Warning the pilot for PIO in the cockpit

- Fundamental assumption: *'There is no such thing as "pre-PIO" condition. PIO will never be prevented in real-time, so the best we can hope to do is detect it early and minimize the effect on the aircraft'*

- In 2000 ROVER tool (REAL TIME OSCILLATION VERIFIER) was developed for the U.S. Air Force for detecting APC problems by Dave Mitchell

- We applied the ROVER in ARISTOTEL's test campaigns and tried to be used by the pilot as a warning instrument

ROVER Methodology



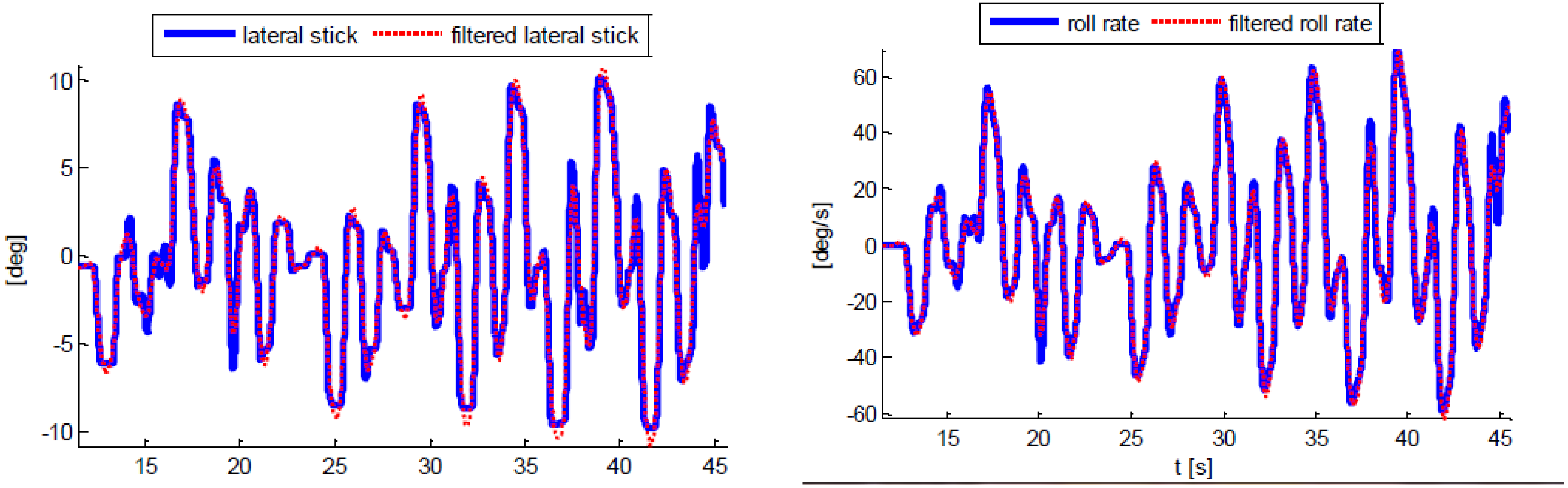
Source: Mitchell, D.G., PIO Detection with a Real-time Oscillation Verifier (ROVER), NASA/CP-2001-210389

- Two inputs: pilot control stick input and body angular rate response.
- Three outputs: The peak-to-peak amplitudes are analyzed, the frequency of body rate and the phase delay between the stick input and body rate.
- Pre-defined threshold values must be set by the user for the angular rate and also for the control input
- A score of 4 flags corresponds to a detected APC.
- When a score 3 happens and there is rate limiting, the angular rate can be suppressed by the rate limiting.
- Two consecutive scores of 3 → 3.5 score and APC warning.

Drawbacks of classical ROVER

- The algorithm is prone to false alerts.
  - For the classical case for the USAF: in 91 % both pilot and ROVER detected APC.
  - In 34 per cent of the cases ROVER detected APC and pilot did not.

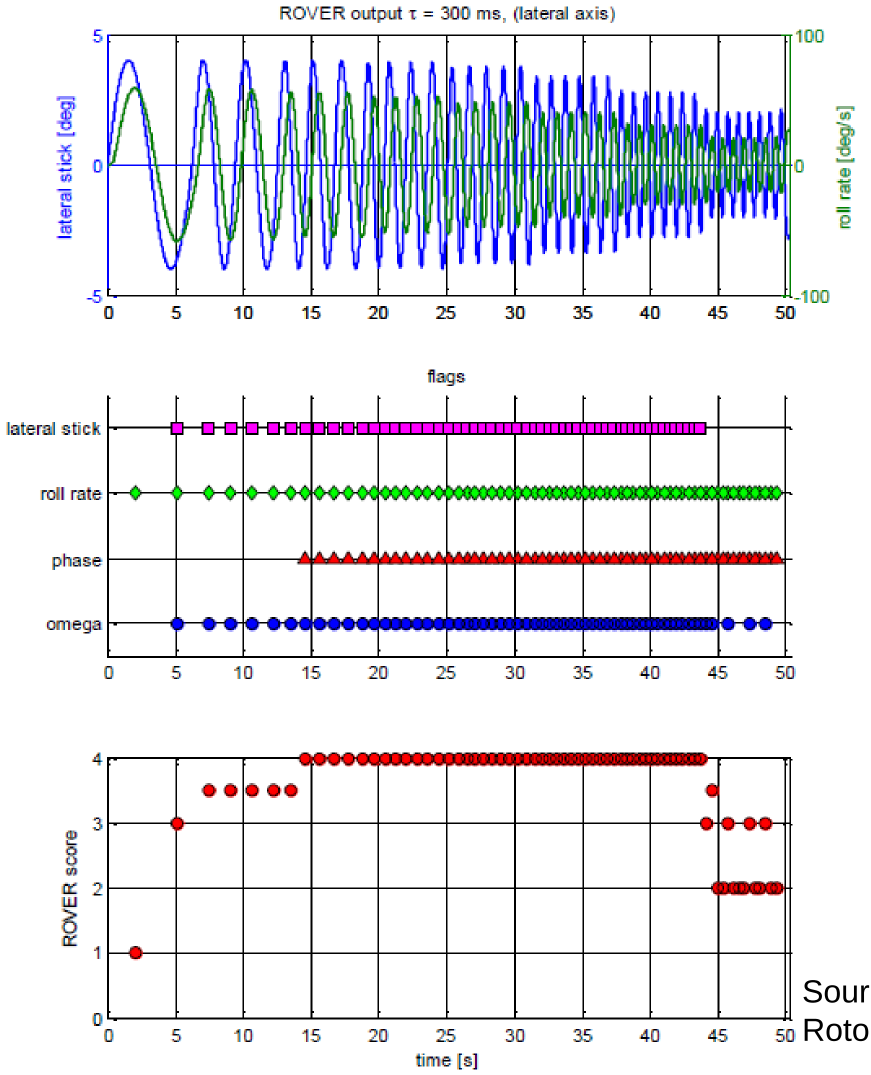
Unfiltered and filtered signal



Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

Simple example of ROVER

Frequency sweep in lateral stick, 60 kts



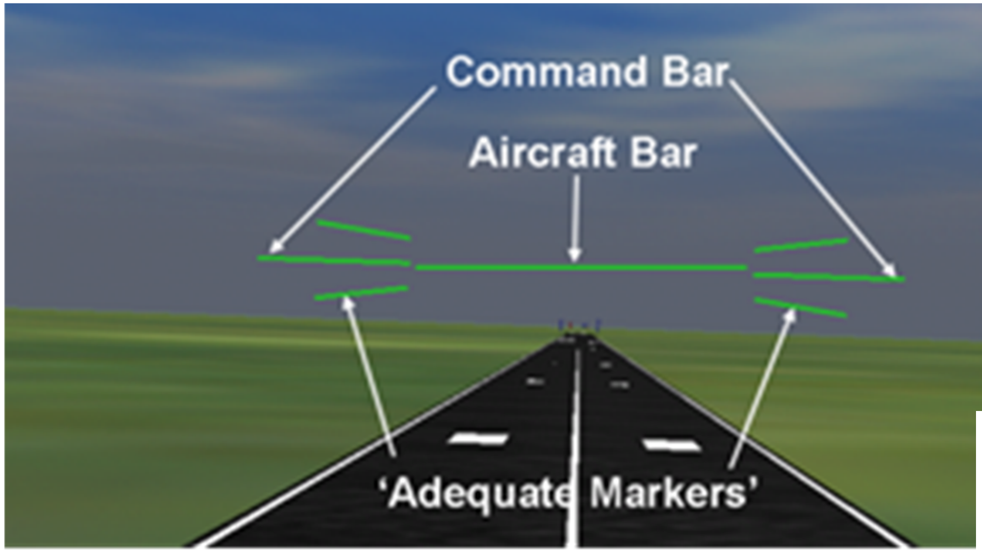
$$ampl = \frac{peak_{curr} - peak_{prev}}{2}$$

$$freq = \frac{2\pi}{t_{peak\_curr} - t_{peak\_prev}}$$

$$phase = \frac{2\pi \cdot \Delta t}{freq_{body}}$$

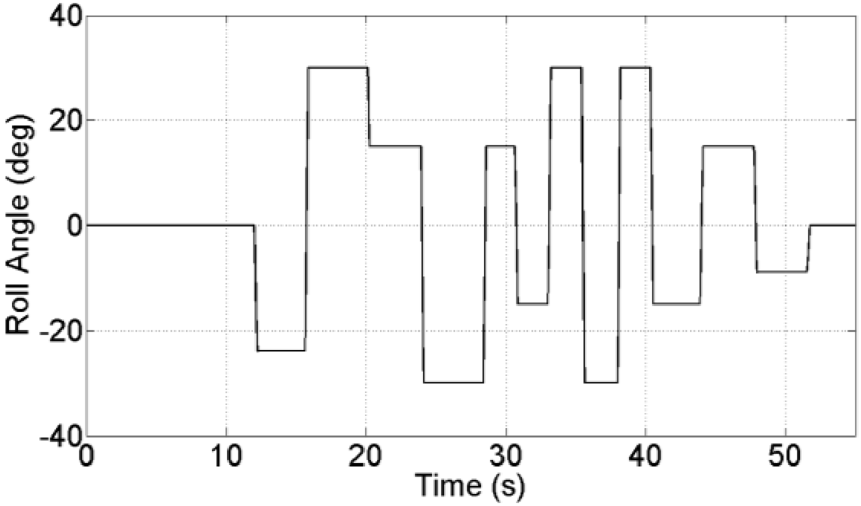
Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

Experiment set-up in the simulator test campaings within ARISTOTEL



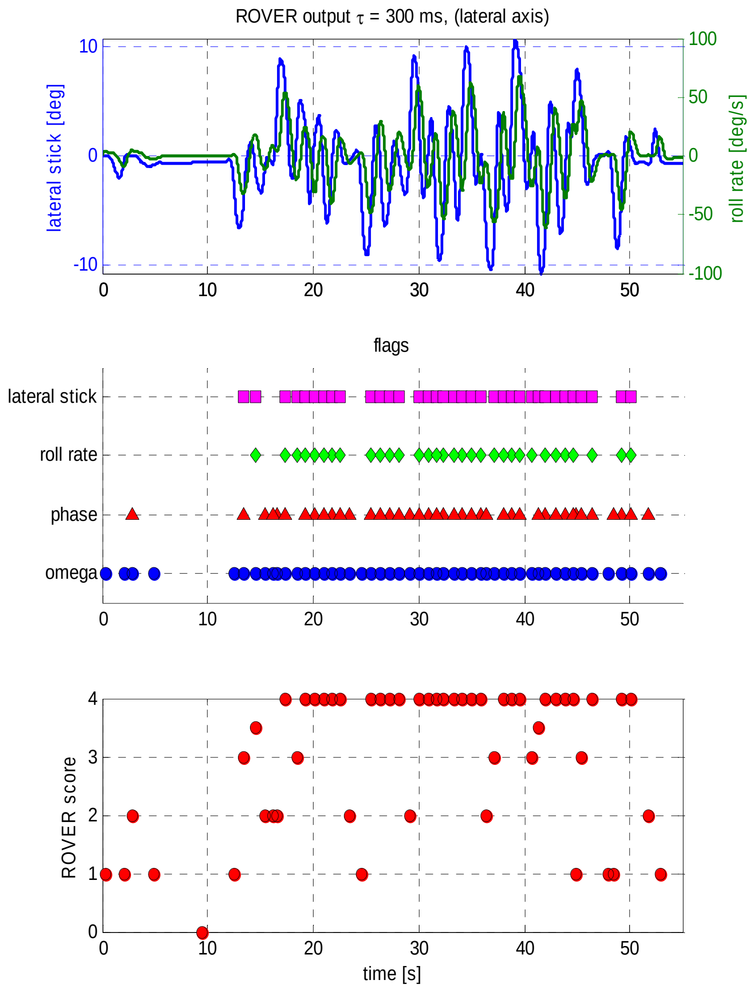
Roll Tracking Task

Roll command sequence R1 for tracking task

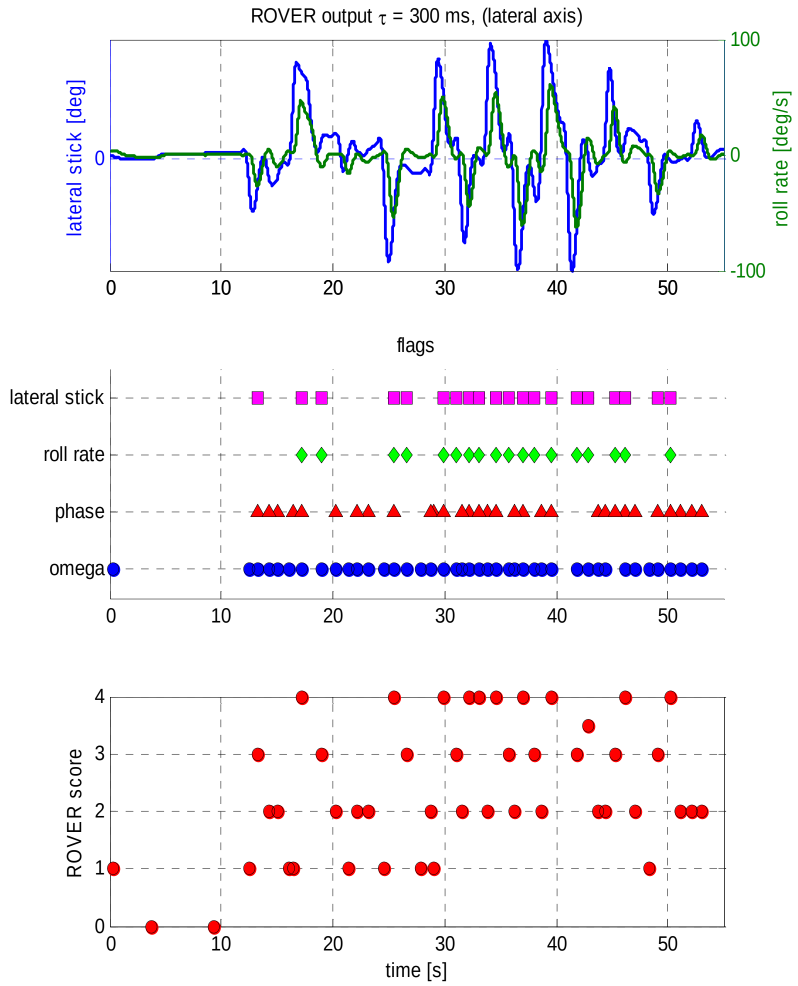


Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

ROVER output (1)



Roll tracking task pilot 1



Roll tracking task pilot 2

Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

Pilot 1

τ [ms]	*RO4*	*RO3.5*	*HQR*	*PIOR*
0	0	10	4	1
100	1	9	7	1
200	10	8	7	4
300	28	2	7	3

Pilot 2

τ [ms]	*RO4*	*RO3.5*	*HQR*	*PIOR*
0	-	-	-	-
100	2	8	3	2
200	8	1	4	2
300	10	1	4	2

Conclusion: Pilot 2 did not experience the trials as a RPC event. Probably, he has more ability to control the helicopter in a degraded situation.

Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

ROVER shortcomings

“ARISTOTEL’s” Threshold values for ROVER

Threshold name	Value	Unit
Stick amplitude	2.5	Deg
Roll rate amplitude	18	Deg/s
Frequency	1 to 8	Rad/s
Phase delay	75	Deg
Peak selecting threshold	Value	Unit
Δstick extreme	0.2	Deg
Δtime stick extreme	0.3	Sec
Δroll rate extreme	1.2	Deg/s
Δtime roll rate extreme	0.3	Sec

The thresholds depend on :

- The order of the filter as well as the cut-off frequency.
- The system dynamic behaviour: the thresholds were adjusted after every trail (change in the time delay)

Conclusion: the thresholds must be chosen with care as they depend on flight task, helicopter and configuration.

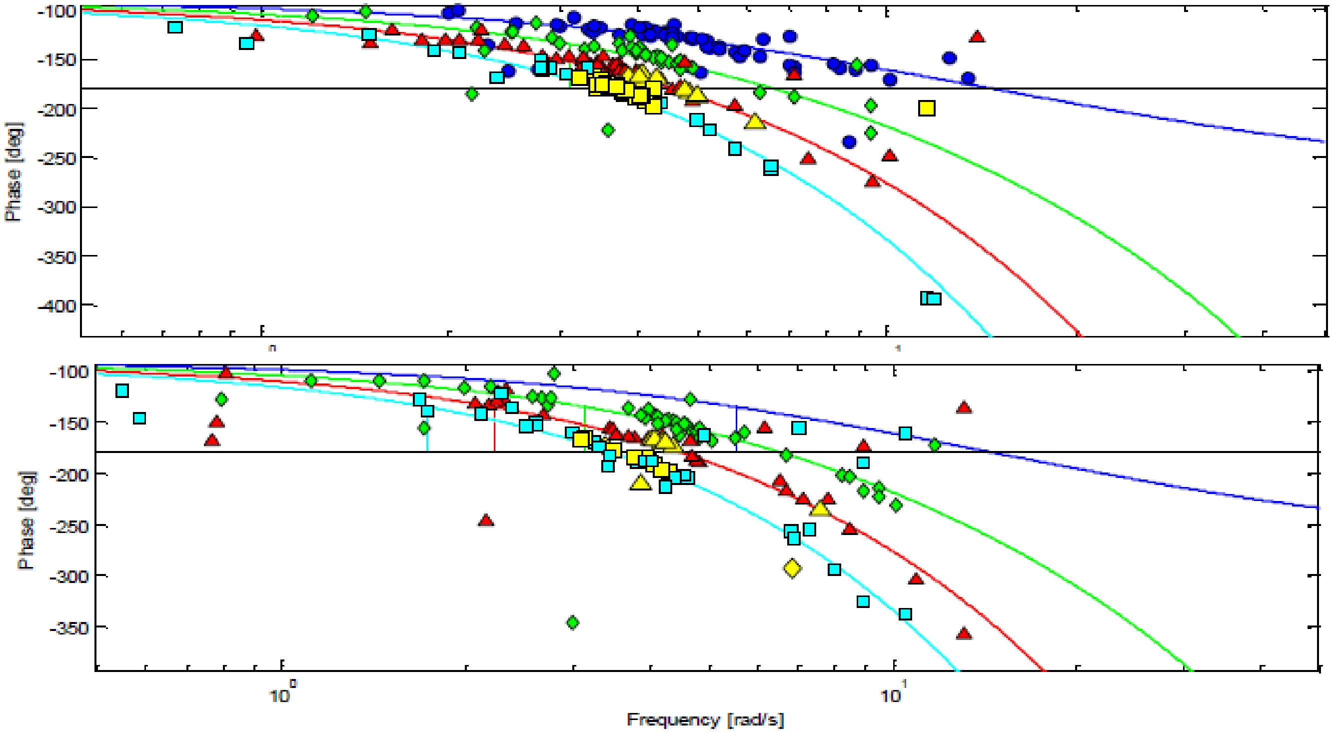
Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

Proposed improvement of ROVER algorithm

Superimpose the ROVER output on the Phase diagram of the bode plot. If the ROVER points deviate from the original Bode plot, the HQs are changed

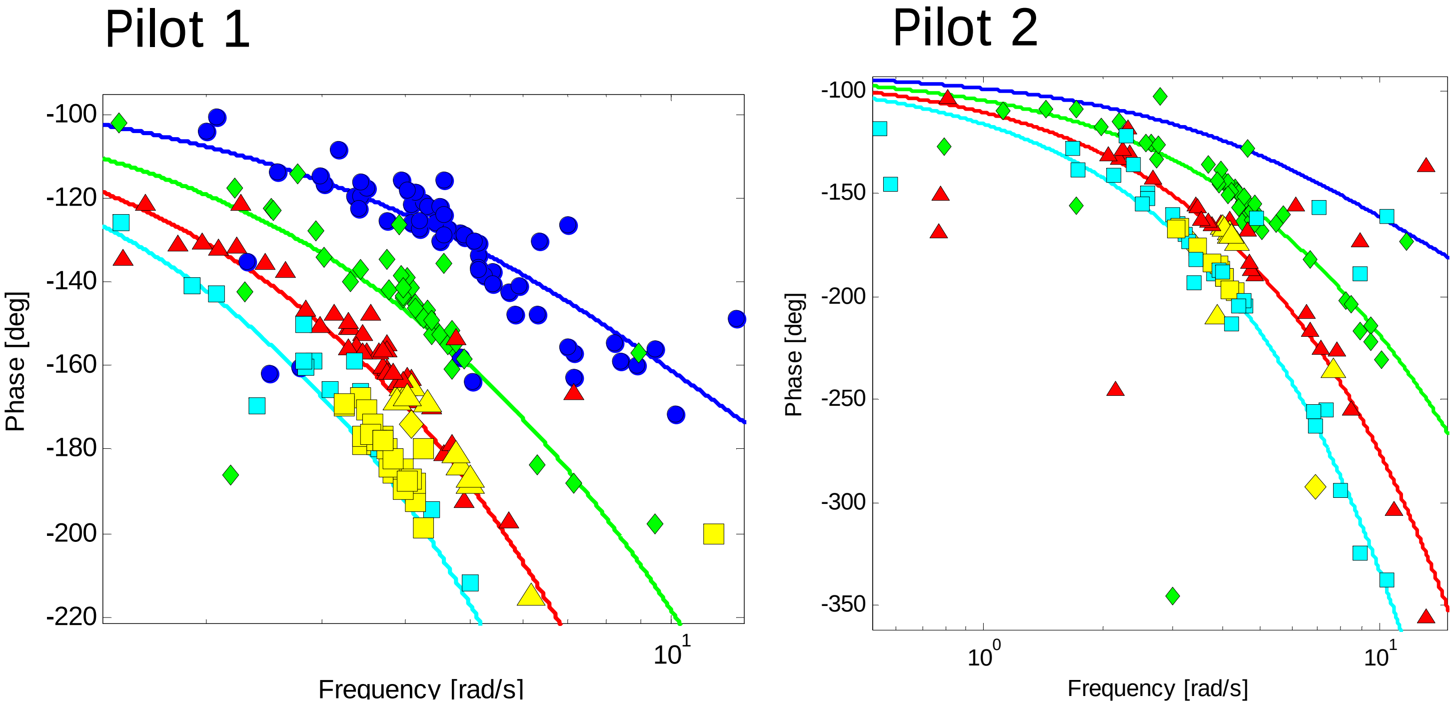
Pilot 1

Pilot 2



Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

Proposed improvement of ROVER algorithm



● **ROVER output, no time delay**
◆ **ROVER output, 100 ms time delay**
▲ **ROVER output, 200 ms time delay**
□ **ROVER output, 300 ms time delay**
□ **ROVER RPC detected points**

Source: Suliman, S.M.T., Yilmaz, D., Pavel, M.D., 38th European Rotorcraft Forum, Amsterdam, September 2012

ROVER and Handling Qualities

- In general, when the time delay is increased or decreased the ROVER scatter points are mainly matching the corresponding phase graph on the Bode plot.
- Degradation in HQ can be detected in quasi real-time if the algorithm is applied on streaming data.
- Most RPC detected markers (yellow) are in the crossover region (180 degrees).
- Pilot 2 gives only a PIOR of 2 at level 3 HQ. Further, he does not experience the degradation of HQ to level 3.
- Even when the pilot experiences that the rotorcraft behaves as Level 1 or Level 2 HQ, the improved ROVER would warn him that actual HQ level has degraded and that the chance of a RPC event has increased.

Severity indication of RPC using improved ROVER

- The combination of ROVER with the HQ degradation detection indicates the “severity” of the RPC in quasi real-time process.
    - *No RPC*: If ROVER score is other than four and HQ level is not degrading.
    - *RPC danger*: If ROVER score is other than four but the HQ is degrading.
    - *Moderate RPC*: If ROVER score is 4 and the HQ is not degrading.
    - *Severe RPC*: If ROVER score is 4 and the HQ is degrading.

Conclusion

- It has been demonstrated that in the classical ROVER, with degraded HQs, the number of RPC detections increase.
- The idea presented relates to improving ROVER by inclusion of real-time detection of the degradation in HQs using the bandwidth/phase delay criterion.
- From this degradation in HQs, a warning to the pilot can be provided. By inclusion of the HQ information in ROVER, the onset of RPC can be detected earlier → RPC detection technique is improved.

Limitations

- Only single axis detection is possible.
- The improved ROVER is only applicable for velocity around trim conditions.
- The improved ROVER algorithm only uses time delay as trigger. The applicability to rate limiting cases needs to be investigated.
- Only small deflections of helicopter response are allowed for the ADS-33E HQ requirements to be applicable.
- Due to the averaged data usage, it is only possible to alert the pilot in quasi-real-time.

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Thank you for your attention!

COOPERATION