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Politecnico di Milano
Department of Aerospace Science and Technology

PILOT-VEHICLE INTERACTION FROM A MULTIBODY DYNAMICS AND EXPERIMENTAL PERSPECTIVE

(IN APPLICATION TO ROTORCRAFT AEROMECHANICS)

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MAGIC 2022

Date: September 20, 2022

AIRCRAFT/ROTORCRAFT-PILOT COUPLINGS

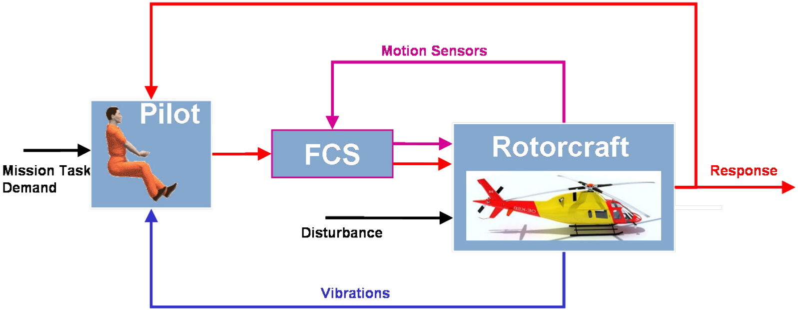
(Aircraft/)Rotocraft-Pilot Couplings

Adverse, unwanted phenomena originating from anomalous and undesirable couplings between the pilot and the aircraft/rotorcraft [1]

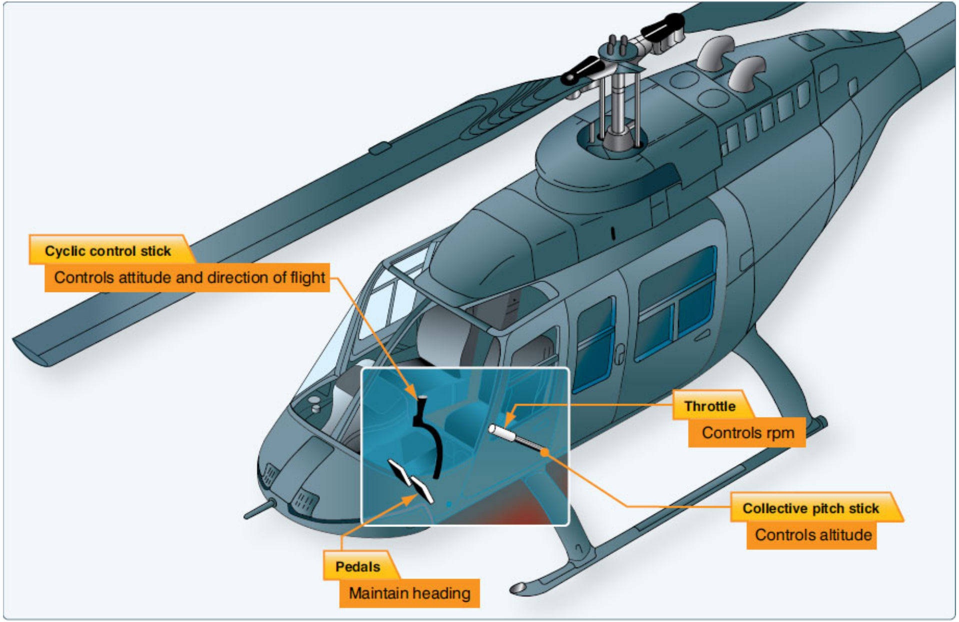
Can result in several, potentially dangerous, always undesired effects:

- instabilities, both oscillatory and non-oscillatory
- degradation of the aircraft Handling Qualities
- increase in structural strength requirements

[1] Pavel et al., Progress in Aerospace Sciences, 2013



Helicopter flight controls



Helicopter flight controls - How do they really work? `https://www.youtube.com/watch?v=bj6fDrRT7Ag`

Car controls: steering wheel

Walton, 2005, Transportation Research Part F, `http://doi.org/10.1016/j.trf.2005.04.010`

The pilot action on the rotorcraft controls can be split into two contributions:

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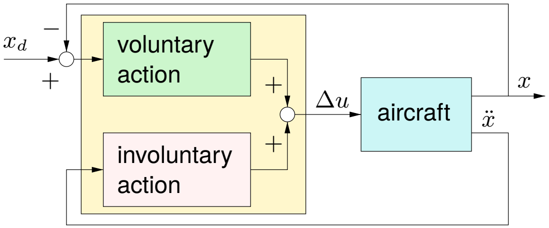
Voluntary (active)

The application of **intentional control input** to follow the **desired trajectory**

Involuntary (passive)

The application of **inadvertent control input** as a consequence of **exogenous** accelerations of the cockpit



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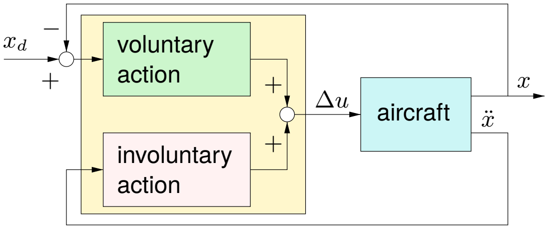
Pilot-Induced Oscillations (PIO)

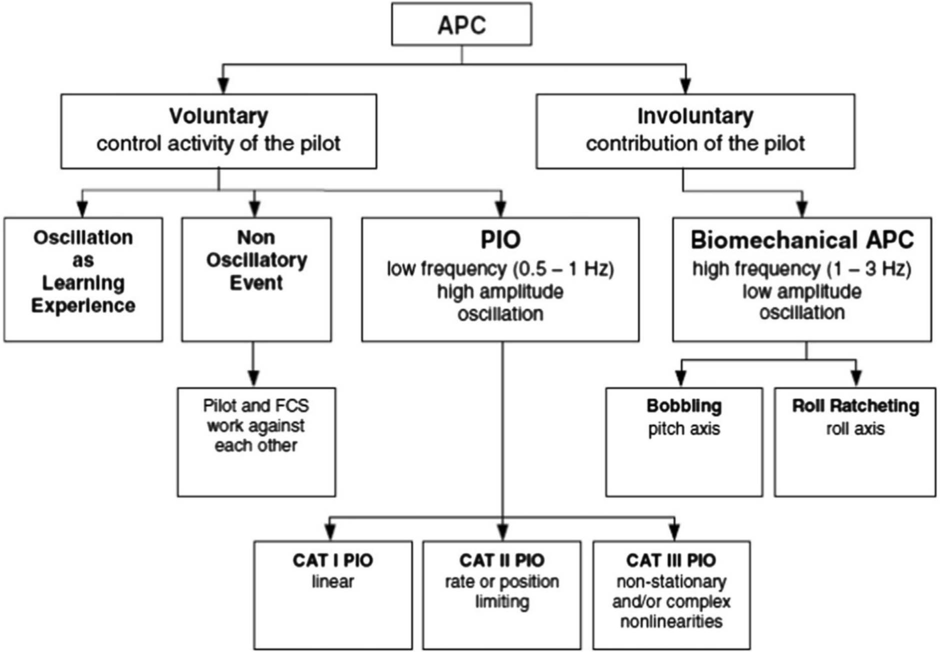
The pilot, often misled by inconsistent/insufficient cues, inadvertently excites **sustained or divergent** vehicle **oscillations** by applying **control inputs** that are in the **wrong direction** or have **phase lag** with aircraft motion.

Pilot-Assisted Oscillations (PAO)

The pilot body **biomechanical response** is excited in such a way that the pilot **involuntarily** interacts with the **commands** in a manner that **sustains** or even **augments** the vibration level of the vehicle

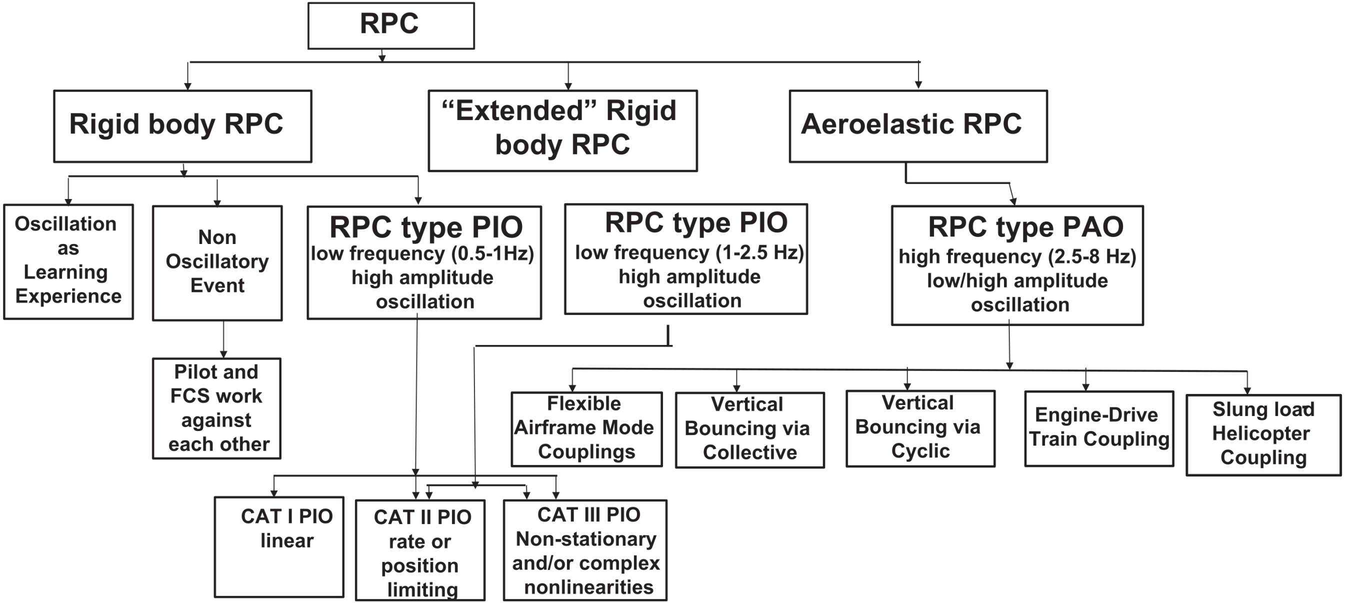


Classification of Aircraft-Pilot Couplings (APC)

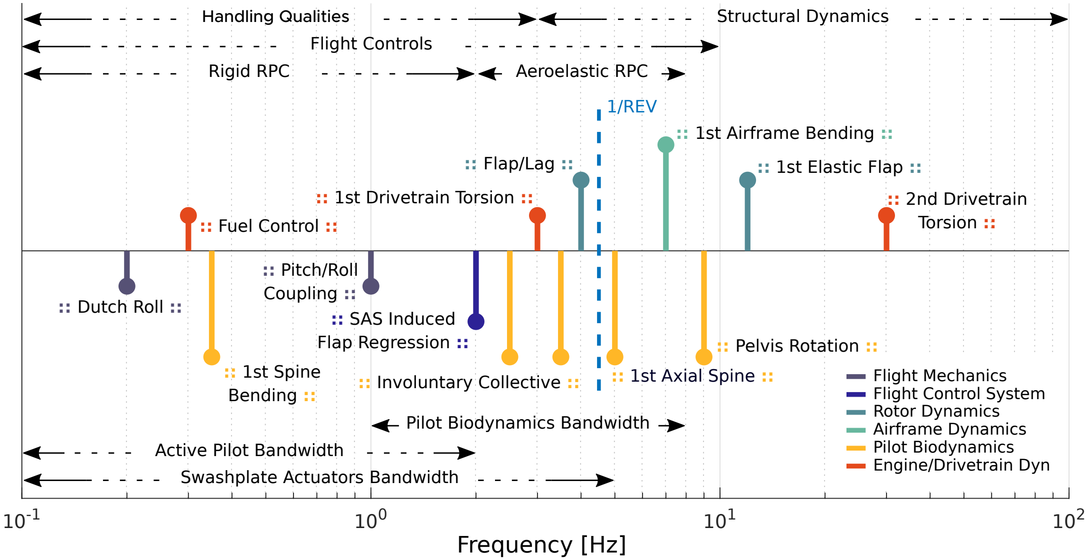


Pavel et al., Progress in Aerospace Sciences, 2013 `http://doi.org/10.1016/j.paerosci.2013.04.003`

Classification of Rotorcraft-Pilot Couplings (RPC)



Pavel et al., Progress in Aerospace Sciences, 2013 `http://doi.org/10.1016/j.paerosci.2013.04.003`



Frequencies associated with pilot biodynamic response fall into the range of the vehicle response spectrum.

	Low frequency A/RPCs	High frequency A/RPCs	
		Rigid body aircraft	**Elastic body aircraft**
Frequencies	**Below 1.5 Hz** *APC frequencies are usually within* 0.5–1.6 *Hz* (3–10 *rad/s*).	**Between 1.5 and 2 Hz(APC)** **Below 3.5 Hz (RPC)** *APCs frequencies usually exceed 2 Hz. Examples: Roll Ratchet, bob-weight.*	**Between 2 and 8 Hz**
Causes	1) Inadequate vehicle dynamic characteristics (aircraft+control system): • High order of the system, large phase delay, low damping, and others. • Control system delay. • Actuator or control surface rate limit. 2) High control sensitivity (command gain), low force-displacement gradient.	1) Biodynamic interaction: The biodynamic interaction in the "pilot+manipulator+aircraft" system arises due to high-frequency aircraft response to pilot activity caused by inadequate aircraft characteristics (high natural frequencies, low roll mode time constant, high control sensitivity, large pilot location relative to the centre of gravity)	1) Biodynamic interaction: The biodynamic interaction in the pilot-aircraft system arises due to aircraft structural elasticity and leads to involuntary manipulator deflections transferred to control system.
Characteristics	Pilot closes the loop according to the information received through visual or acceleration perception channels.	The pilot closes the control loop due to **aircraft accelerations** acting on the body and the arm cause involuntary manipulator deflections which go to the control system and lead to high-frequency A/RPC.	The pilot closes the control loop due to **structural oscillations and inertial forces** acting on the body and the arm cause involuntary manipulator deflections which go to the control system and provoke high-frequency A/RPC.
Critical components		Flight control system	Airframe modes
Pilot modelling	'Active' pilot concentrating on a task	'Active' pilot concentrating on a task	'Passive' pilot subjected to vibrations
Vehicle dynamics modelling	Flight mechanics	Flight mechanics	Structural dynamics

Type of aircraft[a]	Accident year	Exact accident date	Aircraft model	Experienced PIO/PAO	RPC type
H	1945	June 21, 1945	XR-9	Floated gimbal rotorhead produced inadequate aircraft control	PIO/ PAO
H	1964	–	Bo-46	Rotor control/gyro system coupling	
H	1967	–	CH-46D	Flexible mode air resonance “Shuffle Mode”	
H	1967	–	CH-46D Sea Knight	3.2 Hz ‘shuffle’ oscillation. Out of phase coupling of rotors w/ aft pylon fuselage mode; changes made to the aircraft and operations	PAO
H	1968	–	CH-47	Rotor/sling load bouncing	
H	1970	–	AH-56	Flexible control actuation system	
H	1978	1978–1985	CH-53E	APC with flexible modes, several major instances in precision hover and with heavy sling loads, including heavy landings, dropped loads. Extreme Category I to Category II PIOs	PIO
H	1978	–	CH-53E (USN)	Flexible modes/sling loads	
H	1980	–	CH-53G (GAF)	Flexible modes/sling loads	PAO
H	1980	–	CH-46E	Flexible mode-air resonance “Shuffle Mode”	
H	1981	–	SH-60	Flexible mode ground resonance	
H	1988	–	UH-60 ADOCS	Excessive time delays	
T	1989	–	V-22	3.0 Hz roll mode; coupling with roll and main rotor system's regressive lead–lag mode; PAO from large aft rotor flapping. Procedural centring of control stick, reducing rotor flapping and increased rotor lead–lag damping	PAO
T	1990	–	V-22A Osprey [FSD]	3.2 Hz asymmetric wing chord mode due to aerodynamic phenomena; coupling with lateral cyclic inputs; addition of a notch filter at 3.2 Hz	PAO
T	1991	–	V-22A Osprey [FSD]	3.8 symmetric wing chord bending mode w/4000 lb load; pilot coupling through longitudinal cyclic; Notch filters introduced at frequency	PAO
T	1991	–	V-22A Osprey [FSD]	4.2 Hz symmetric wing chord mode coupled with the pilot Thrust Control Lever (commanding rotor collective); minor coupling at 5.3 Hz with symmetric wing torsion mode. Asymmetric notch filters added	PAO

H	1992	–	S-76B	Flight control mode shifting	PIO
H	1993	–	Bo-105 ATTHeS	Time delay/attitude command	
H	1994	June 2, 1994	BELL 47D-1	Pilot inducted lateral oscillation due to heavy cyclic control forces in hover	PIO
H	1995	–	Bo-105 ATTHeS	Biomechanical/Airframe coupling	PAO
T	1997		V-22B Osprey [EMD]	1.4 Hz high focal roll mode oscillation due to change in mass balance weight; relaxation of pilot gripon cyclic	PAO
H	1998	December 3, 1998	Eurocopter EC-135-P1	Helicopter encountered wake turbulence of a MD 80 airplane and PIO's occurred during recovery	PIO
T	1999	February 2, 1999	V-22	Hover over ship	PAO
H	2000	August 8, 2000	Bell OH-58C	PIO during a practice autorotation	PIO
H	2000	December 18, 2000	SA365-N1	Longitudinal and lateral PIO during landing	
G/C	2003	April 23, 2003	DENZER RAF 2000	Abrupt lift-off caused longitudinal PIO during take off	
G/C	2003	January 1, 2003	Air Command Commander Elite	Inadvertent phugoid pilot induced oscillation due to wind gust	PIO

Type of aircraft[a]	Accident year	Exact accident date	Aircraft model	Experienced PIO/PAO	RPC type
G/C	2003	November 16, 2003	Northam RAF 2000	Longitudinal oscillations during level flight	
H	2003	June 28, 2003	Schweizer 269C	Lateral Oscillation	
H	2004	May 8,2004	Robinson R44	Longitudinal PIO due to experiencing low cyclic force while initiating a hover after take off	PIO
H	2005	August 13, 2005	Robinson R44	The inadequate remedial action during landing by the pilot caused pitch oscillations	PIO
H	2006	January 26, 2006	Eurocopter AS350BA	Yaw initiated PIO caused helicopter to crash	PAO/PIO
H	2006	October 16, 2006	Robinson R22 BETA	PIO in yaw axis started during cruise flight	
H	2007	December 5, 2007	Bell UH-1B	Pilot caused vertical oscillations due to collective bouncing	PAO/PIO
H	2008	May 1, 2008	Robinson R22 Beta II	Student pilot started a lateral PIO in hover	
H	2008	June 29, 2008	Bell UH-1B	Collective bounds lead to vertical oscillations during autorotation	PAO/PIO
H	2009	May 12, 2009	Robinson R44	Initiated yaw oscillations turned into yaw-pitch PIO	
H	2009	November 15, 2009	Robinson R44 Astro	Inexperienced pilot caused mixed PIO	

[a] H: Helicopter, G/C: GyroCopter, T: Tiltrotor.
[b] NTSB: National Transportation Safety Board, AAIB: Air Accidents Investigation Branch.

ROTORCRAFT-PILOT COUPLINGS: EXAMPLES

Danish Air Force Leonardo Helicopters AW101, 2014

- night training
- sand, brownout
- high-gain task
- vertical oscillation triggered by contact with ground

FlightGlobal

Danish AW101 damaged in Afghan mishap

By Craig Hoyle | 13 October 2014

One of Denmark's AgustaWestland AW101 transport helicopters has been damaged in a landing incident in Afghanistan, the nation's defence ministry has confirmed.

An aircraft operating from Mazar-e-Sharif air base ended up on its side after a landing incident away from the site, the defence ministry said in a 12 October statement. The crew and personnel aboard the aircraft escaped without suffering serious injury, but the aircraft was seriously damaged, it adds.

Sikorsky S-97 Raider, 2017

NTSB releases more details on S-97 Raider accident

BY **OLIVER JOHNSON** | APRIL 30, 2019

Estimated reading time 6 minutes, 32 seconds.

The Sikorsky S-97 Raider prototype destroyed by a hard landing in 2017 suffered extreme roll oscillations as the aircraft's flight control software transitioned from ground to air modes during takeoff, according to the National Transportation Safety Board's (NTSB's) newly-released factual report.

Several accidents reports mention feedback loops on the collective axis:

- NTSB SEA08LA043 (May 2007)
  As the helicopter was lifting from the ground, it began to vibrate, that turned into a severe "hop or a bounce." Inspection of the helicopter revealed that the collective control absolute friction was less than the manufacturer's specified setting and the maintenance manual indicated that if the friction is not set properly, a collective bounce could be induced.

- NTSB ANC08LA083 (June 2008)
  As [the pilot] lowered the collective to enter the autorotation, the helicopter began to vibrate violently. The failure of company maintenance personnel to ensure the helicopter was properly maintained, resulting in a severe in-flight vibration due to collective bounce.

- NTSB DCA16FA199 (June, 2016)
  The crew initiated the final planned OEI test at a speed of 185 knots. [. . .] About 6 to 7 seconds into the test, the helicopter began vibrating at a frequency of 6 hertz (Hz).
  The "nonzero" relationship between the control stick amplitude and the seat vibration illustrates that biomechanical feedback contributed to the helicopter's vibration.

'Severe vibrations' caused in-flight breakup of Bell 525 prototype during OEI tests

Posted on January 17, 2018 by Oliver Johnson

The in-flight breakup of the first Bell 525 prototype was caused by unanticipated severe vibrations as the aircraft attempted to recover rotor rotation speed following a one-engine inoperative (OEI) test at 185 knots, the U.S. National Transportation Safety Board (NTSB) has found in its final report on the accident.

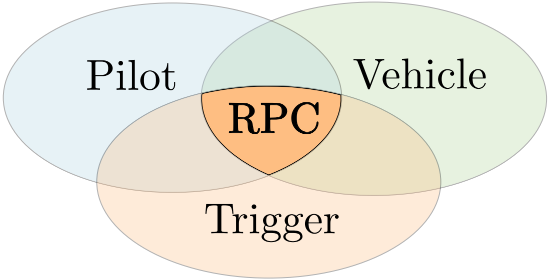
The first prototype of the Bell 525 Relentless crashed on July 6, 2016, halting flight testing on the program for over a year while the investigation into the accident continued. Sheldon Cohen Photo

The report also highlighted the role played by "feedback loops" from unintentional control inputs on the collective and attempts at corrective actions from the aircraft's attitude and heading reference system (AHRS) that were caused by the vibration, and then served to sustain and amplify it.

Vertical

MODELING OF RPC

- A/RPCs involve both the pilot and the vehicle, in a *collaborative effort*
- they are associated with three main ingredients:
  1. an abnormal/unexpected change in pilot behavior
  2. an abnormal/unexpected change in the vehicle dynamics state or configurations
  3. an initiation mechanism commonly referred to as a *trigger*



- Typically, during an adverse A/RPC event, pilots switch their strategy (*mental model*) from using small, gentle control inputs to overcorrecting with large inputs even for small errors. The result is often an out-of-phase condition, which results in pilot-induced changes in vehicle attitude
- A/RPCs are very often explosive in nature, the instability of the Pilot-Vehicle System develops in a few seconds to levels uncontrollable for the pilot

Typically, RPC problems arise:

- when new designs and technologies, such as fly-by wire (FBW), are introduced in aviation
- when existing aircraft are tasked with new operational missions

Rotorcraft are more susceptible to RPC occurrences than fixed wing aircraft are to APCs since their high-order dynamics play a prominent role in the development of the phenomena

Why do we expect rotorcraft to be prone to RPCs, and in particular to PAOs?

- In key flight conditions, rotorcraft are inherently dynamically unstable
- rotorcraft are often required to execute demanding manoeuvres such as precision landings, hovering (with or without slung-loads), tracking tasks or autorotation
- rotorcraft generate vibrations in all major axes
- rotorcraft are characterised by many control couplings
- in rotorcraft, control inputs are transmitted through the swashplate to the blade pitch, resulting in flap response with nearly 90° phase delay ($1/4$ of the rotor revolution period)
- the main rotor coning motion, at about 1/rev, may be in the pilot biomechanics bandwidth
- cyclic rotor modes couple with the airframe rigid-body motion; their frequency, in the non-rotating system, is $\omega_{nr} = \Omega \pm \omega_r$; the regressive one may well fall in the pilot's biomechanics bandwidth, or even in the voluntary action bandwidth

- Rigid-Body RPC
  - Category I: can be described by linear models
  - Category II: caused by localized nonlinearities (typically actuator saturations or rate limits)
  - Category III: caused by complex interaction of systems (for example FCS mode switching)
- Aeroelastic RPC
  - Sometimes called Category IV: involving involuntary/biomechanical pilot contribution, are usually described using linear models, but require a higher number of degrees of freedom

In the linear domain, two fundamental indices of the pilot-vehicle interaction are be defined:

BioDynamic FeedThrough (BDFT)

The BioDynamic FeedThrough, i.e. the transfer function relating the vehicle acceleration (input) and the control deflection (output)

$$H_{\mathrm{BDFT}}(s) = \frac{\delta(s)}{\ddot{x}(s)}$$

- encapsulates the behavior of the pilot-control device system
- (relatively) easy to measure

NeuroMuscular Admittance (NMA)

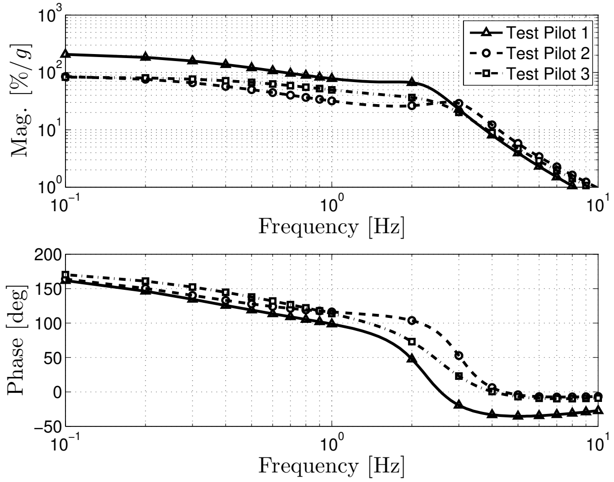
The NeuroMuscular Admittance, i.e. the transfer function relating the force acting on the pilot body (input) and the control deflection (output)

$$H_{\mathrm{NMA}}(s) = \frac{\delta(s)}{f(s)}$$

- is affected only by the pilot biomechanics and control geometry
- (relatively) difficult to measure

The BDFT depends on a moltitude of **parameters**:

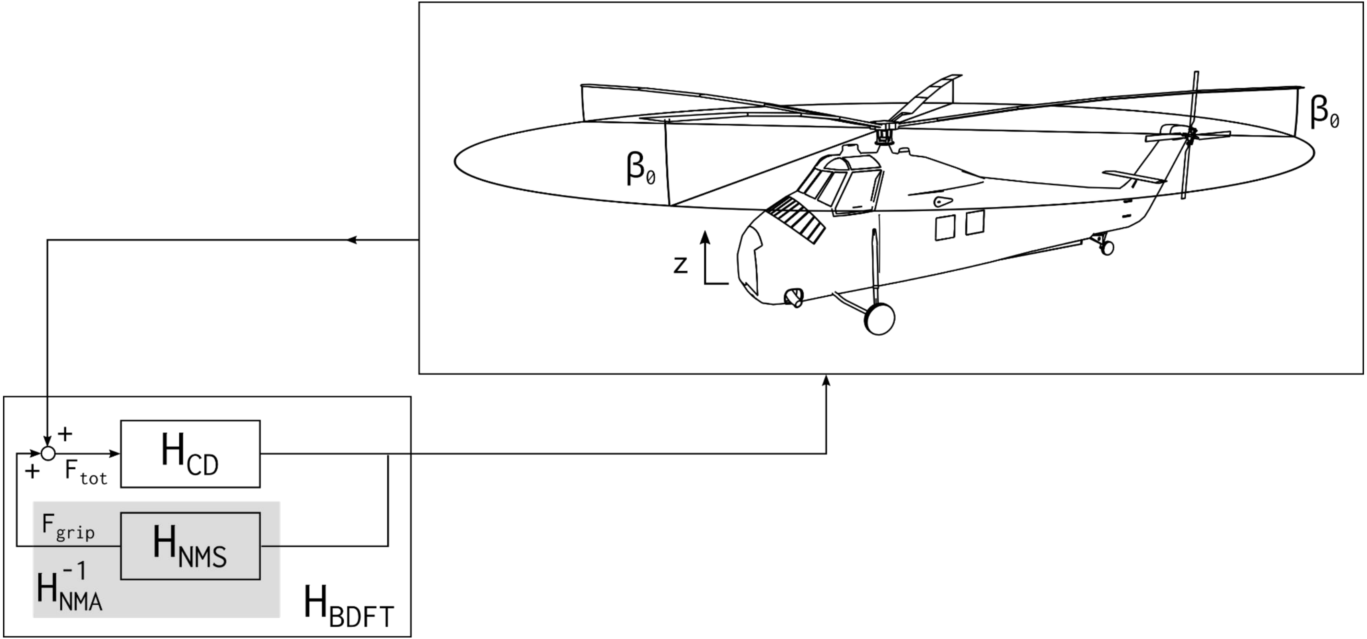
- pilot body-type
- body pose and (underdetermined, estimated) kinematics
- muscular activation and its dynamics
- task
- pilot state of tension / relaxation
- …



AEROELASTIC RPCs

A control loop along the vertical axis is involuntarily closed by the pilot:

- the thrust of the rotor directly depends on the collective pitch of the blades
- the collective pitch of the blades is controlled through the collective inceptor by the pilot’s left hand
- the motion of the pilot’s left hand is notionally vertical: up $\rightarrow$ increase, down $\rightarrow$ decrease
- an oscillatory perturbation of the thrust produces vertical vibrations of the airframe, including the cockpit
- the vertical vibration of the cockpit excites the pilot’s biomechanics through the seat and the floor
- the vibration of the pilot may produce involuntary motion of their left hand, and thus of the collective inceptor
- the (involuntary) motion of the inceptor further excites the thrust perturbation (back to square one)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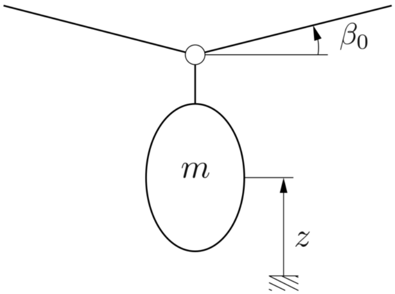
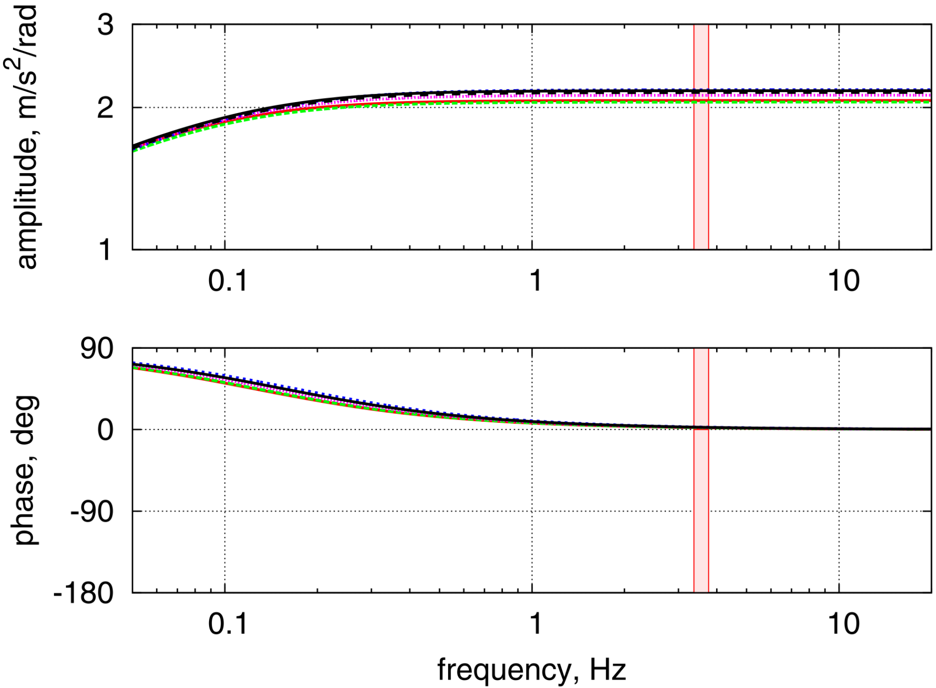
Bare airframe, linear model

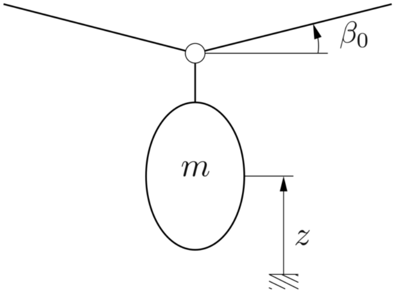
1. only rigid body heave dynamics

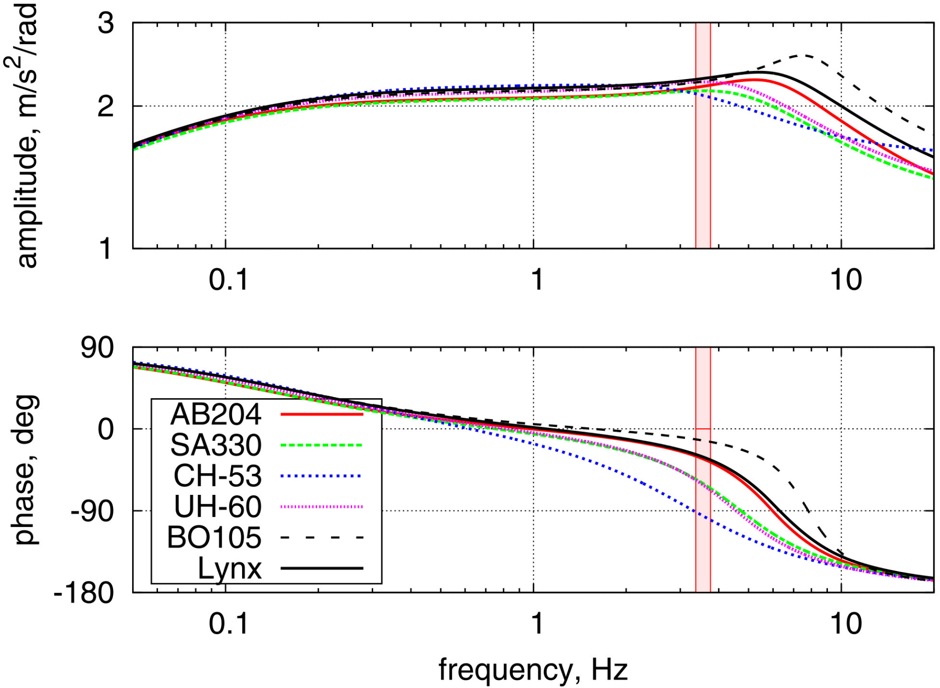




Bare airframe, linear model

1. only rigid body heave dynamics
2. rigid body heave + first collective flapping mode (coning mode)





Pilot model: third order transfer function:

$$H_{BDFT}(s) = \frac{}{}$$

Pilot model: third order transfer function:

- neuro-muscular response: complex conjugate poles at frequency ω_n and damping ζ_n

$$H_{BDFT}(s) = \frac{}{(s^2/\omega_n^2) + 2\zeta s/\omega_n + 1}$$

Pilot model: third order transfer function:

- neuro-muscular response: complex conjugate poles at frequency ω_n and damping ζ_n
- a pure time delay, τ, related to cognitive activity

$$H_{BDFT}(s) = \frac{e^{-\tau s}}{(s^2/\omega_n^2) + 2\zeta s/\omega_n + 1}$$

Pilot model: third order transfer function:

- neuro-muscular response: complex conjugate poles at frequency ω_n and damping ζ_n
- a pure time delay, τ, related to cognitive activity
- active, low frequency behavior of the pilot, represented by the self canceling pole/zero pair (T_s, T_z)

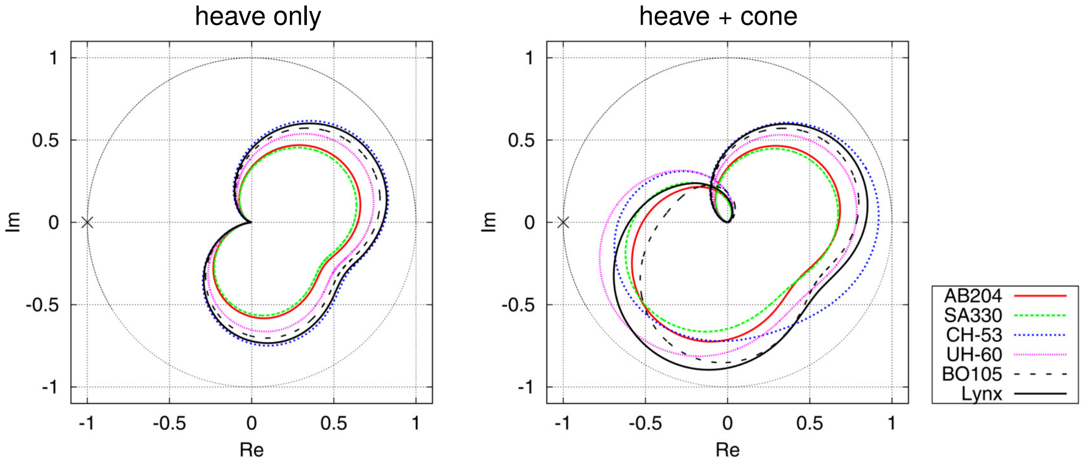
$$H_{BDFT}(s) = \frac{(1 + T_z s)}{(1 + T_p s)} \cdot \frac{e^{-\tau s}}{(s^2/\omega_n^2) + 2\zeta s/\omega_n + 1}$$

Pilot model: third order transfer function:

- neuro-muscular response: complex conjugate poles at frequency ω_n and damping ζ_n
- a pure time delay, τ, related to cognitive activity
- active, low frequency behavior of the pilot, represented by the self canceling pole/zero pair (T_s, T_z)
- the static gain μ, related to geometrical and inertial properties of pilot and inceptor

$$H_{BDFT}(s) = \mu \cdot \frac{(1 + T_z s)}{(1 + T_p s)} \cdot \frac{e^{-\tau s}}{(s^2/\omega_n^2) + 2\zeta s/\omega_n + 1}$$

Coupled dynamics: loop transfer function

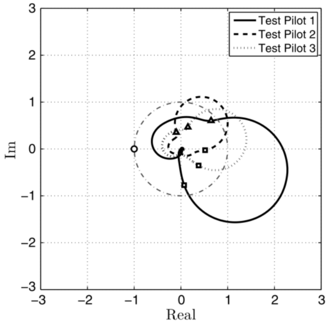


The coning degree of freedom, **per se a significantly damped motion**, drastically reduces the stability margins

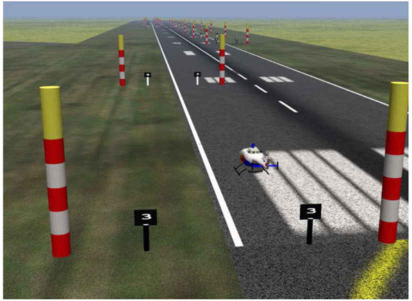
V. Muscarello, G. Quaranta, P. Masarati, *The Role of Rotor Coning in Helicopter Proneness to Collective Bounce*, Aerospace Science and Technology, 36:103-113, July 2014, `http://doi.org/10.1016/j.ast.2014.04.006`.

Something analogous may occur in the lateral axis, with lightly damped in-plane modes (hingeless rotors)

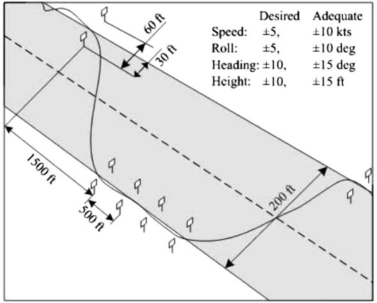
V. Muscarello, G. Quaranta, P. Masarati, L. Lu, M. Jones, M. Jump, *Prediction and Simulator Verification of Roll/Lateral Adverse Aeroservoelastic Rotorcraft-PilotCoupling*, AIAA Journal of Guidance, Control, and Dynamics, 39(1):42-60, 2016, `http://doi.org/10.2514/1.G001121`



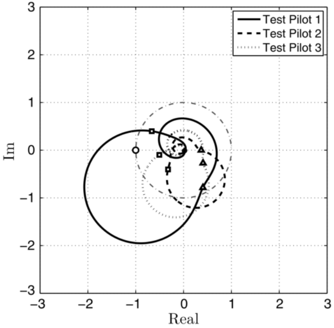
e) $V_\infty = 120$ kt – $G_Y = 2.5$, $\tau_Y = 0.0$ ms



a) Course layout for roll step maneuver



b) Test course and performance requirements



f) $V_\infty = 120$ kt – $G_Y = 2.5$, $\tau_Y = 140.0$ ms

The Bell V-22 Osprey experienced several types of RPC

Two examples: