

Integrated Rotorcraft Stability through Pilot Biomechanics: A Human Factors Perspective

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Abstract. Aircraft- and Rotorcraft-Pilot Couplings remain a critical concern for handling qualities and flight safety. Pilots play a central role, yet fully understanding their contribution and the factors that govern it remains an open challenge. Awareness of adverse couplings and their potential impact on operations is essential for testing protocols and training syllabi.

Introduction

Aircraft- and Rotorcraft-Pilot Couplings (APCs and RPCs), undesirable interactions between pilot biomechanics and vehicle dynamics, continue to challenge handling qualities and flight safety [1, 2]. Over the past fifteen years, research has focused on modeling pilot biodynamic feedback and assessing its influence on vehicle stability and control. Building on these contributions, this paper aims at reframing RPCs from a human-centered perspective, examining how pilot biomechanics, transmitted through biodynamic feedthrough (BDFT), shape handling qualities.

Early studies showed that involuntary pilot body motion, particularly of the arm and torso, closes a biomechanical feedback loop that affects control inceptor inputs and vehicle response. For example, Quaranta et al. [3] used robust control techniques to treat pilot biodynamics as model uncertainty, quantifying proneness to RPC under collective-bounce excitation. Gennaretti et al. [4] explicitly examined BDFT in RPC onset, identifying mechanisms by which pilot body dynamics degrade damping and excite resonance modes.

Subsequent work deepened biomechanical modeling. In [5], multibody models of the spine, torso, and limbs were calibrated against experimental input data collected in passive (involuntary, control-unrelated) tasks, while [6] extended this to bioaeroservoelastic modeling, formalizing pilot body impedance contributions across flight axes. Masarati et al. [7] further investigated the role of muscular activation, showing how co-contraction patterns influence transmissibility and phase lag.

These developments, along with contributions such as [8, 9, 10]), emphasized the relevance of biomechanical modeling for pilot-vehicle system stability and handling qualities, and revealed task-dependent variability driven by posture, muscle tone, and workload.

Quaranta et al. [11] provided a comprehensive overview of aeroelastic RPC phenomena, consolidating modeling approaches, validation strategies, and classification schemes. Numerical studies of specific RPC events, such as collective bounce [12] and lateral oscillations [13], used simplified yet representative rotorcraft models, incorporating the participating rotor states and highlighting the most influential parameters.

More recently, Zanoni et al. [14] introduced a conceptual-design methodology embedding handling qualities and pilot response variability, motivating the inclusion of biomechanics early in design. This view of RPC-informed flight simulation was reinforced in simulation-focused studies such as [15].



Pilot Biomechanics as a Rotorcraft Control Subsystem

Building on these foundations, the present study treats pilot biomechanics as an active subsystem within rotorcraft control dynamics [16], with direct implications for human factors. Instead of representing the pilot purely as a command source, we model biodynamic feedthrough—anatomical impedance shaped by resonances and reflexive dynamics—as an integral component of the closed-loop response, affecting both stability and perceived handling qualities.

Pilot biomechanical models derived from experimental data and detailed multibody simulations are integrated into pilot-in-the-loop simulation campaigns that use mid-fidelity rotorcraft models of medium-lift utility helicopters and tiltrotor aircraft. Experimental data collected using the RPC testbed (Fig. 1) and robust modeling methods support an evaluation of performance metrics (RMS control input, task performance, workload) across hover, low-speed maneuvering, and obstacle-avoidance tasks inspired by ADS-33 [17] (Fig. 2). Following [14, 18], we explicitly incorporate pilot biomechanics into these investigations.

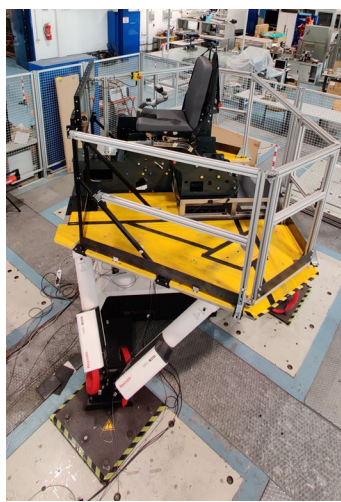


Figure 1: RPC testbed.

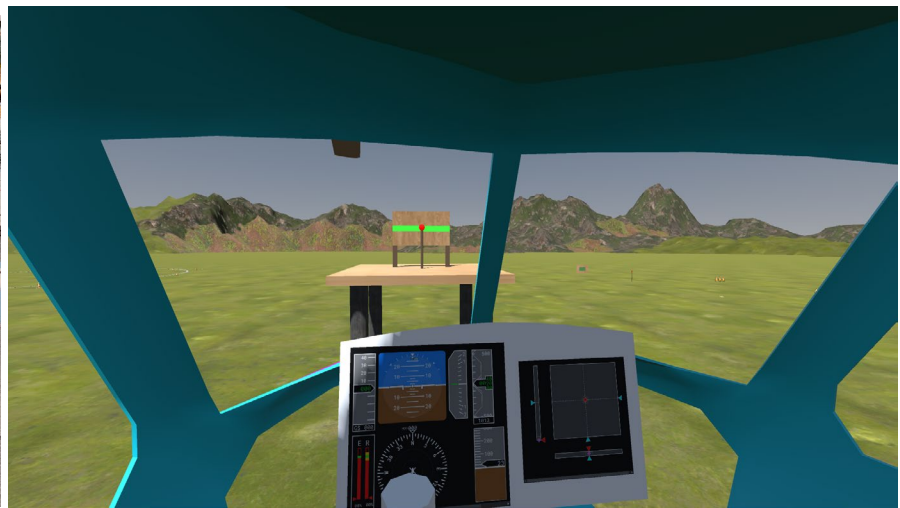


Figure 2: VR pilot view for ADS 33 vertical positioning.

A biomechanical sensitivity analysis was performed based on experimental data (Figs. 3 and 4). Key where pilot body parameters (stiffness, damping, mass distribution, reflex latency) were varied to emulate different postures and neuromuscular states. Stability margins, phase lag, axis coupling, and limit-cycle tendencies were evaluated under both linear and nonlinear control laws. Resonant modes were typically found in the 3–7 Hz range, overlapping rotor excitation frequencies (e.g., coning and slow cyclic lag modes in the non-rotating frame), thus influencing control fidelity.

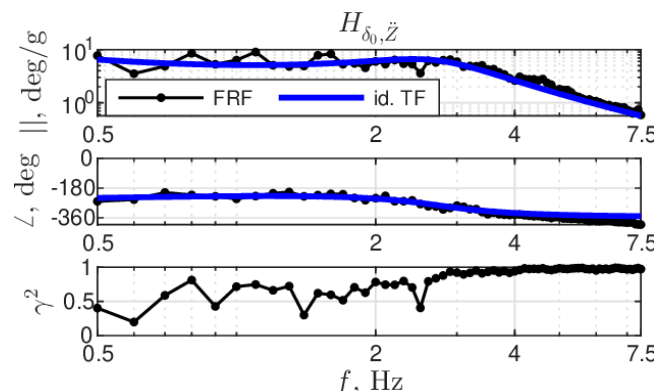


Figure 3: example BDFT identification of collective rotation due to vertical acceleration.

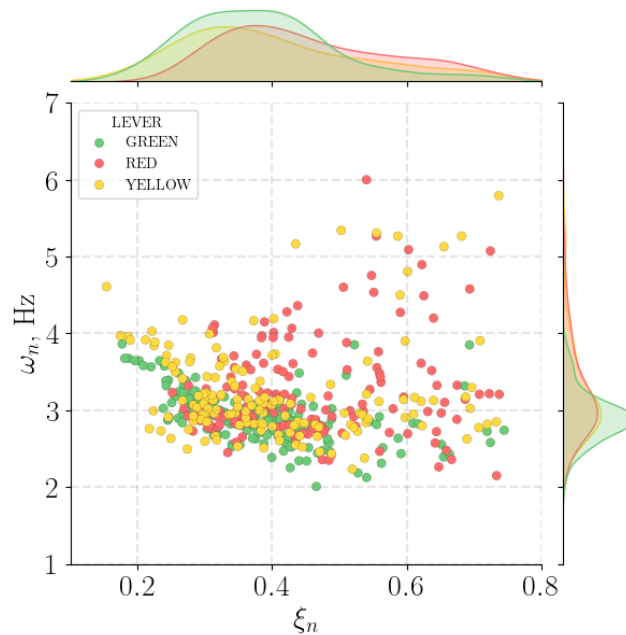


Figure 4: example of experimental distribution of BDFT dominant pole frequency ω_n and damping ζ_n for 15 subjects and 3 different collective levers.

The results indicate that anatomical resonance can reinforce lightly damped rotorcraft modes, potentially inducing instability or limit cycles, particularly under collective bounce conditions. Inter-pilot variability (e.g., BMI, posture, muscle co-contraction level) can qualitatively alter system behavior. Incorporating biomechanical modeling in early handling-qualities assessment reveals vulnerabilities not captured by conventional methods. Adaptive mitigation strategies, including seat damping, inceptor-response tuning, and control-law augmentation, can mitigate feedthrough-induced degradation while maintaining pilot authority.

The Way Forward

This perspective motivates revisiting both training and certification practices. Several questions remain open, such as:

- How do individual physical characteristics influence pilot control strategy?
- Can simulators meaningfully emulate posture-dependent biomechanical effects for training?
- Should aeromechanical stability clearance (and eventually certification) include robustness margins across a population of biomechanical models?

Introducing biodynamic sensitivity analysis into handling-quality frameworks may offer more robust design criteria by extending traditional bandwidth/phase-delay requirements. Simulator testing and pilot training should likewise incorporate posture- and stiffness-dependent modeling into protocols and syllabi, respectively, to raise awareness of involuntary control coupling.

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