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Pilot-Vehicle Interaction From a Multibody Dynamics and Experimental Perspective

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1 Introduction

Demands to the design process of aircraft, particularly of rotorcraft, has been ever-increasing in the last few years. One important aspect that has to be considered carefully in the early design process is the pilot-vehicle interactional dynamics, generally referred to under the name of Rotorcraft-Pilot-Couplings (RPC), that can be at the root of different kind of unwanted feedback loops:

- PIO (Pilot-Induced Oscillations);
- PAO (Pilot-Assisted Oscillations).

While the first attracted the vast majority of the research focus in the last six decades, starting from the seminal work of Ashkenas et al [1] in 1964, through the profound refactoring introduced by McRuer in the 1990s [2, 3] through modern-day activities [4–10]; the second kind, involving vibration feedback loops between the rotorcraft structural and aeroelastic behavior and the pilot biomechanics, can be just as important and have recently received increasing research attention [4].

The major difference between the two kind of pilot-vehicle interaction resides in the participation of the pilot voluntary action. In the case of PIO, the deliberate action of the pilot on the aircraft controls is the principal source of the instability. In the case of PAO, it is instead the *involuntary* action of the pilot to be the major source of dynamic interaction. Thus, in the latter case, it is the biomechanical characteristics of the pilot body that play a major role in defining the boundaries and properties of the unwanted feedback loop [11, 12].

Correlated to the aforementioned difference in the pilot participation is the fact that the two classes of phenomena *live* in different frequency domains: PIO events occur in the frequency band associated with flight mechanics i.e. $(0, 1]$ Hz, while PAOs typical frequencies are associated with the aeroelastic behavior of the aircraft and the biomechanical behavior of the human body, i.e. typically in the frequency range $(1, 8]$ Hz.

Effort is needed in developing a comprehensive approach to rotorcraft design for RPC avoidance. The numerical modeling, particularly following the multibody approach, of the aircraft vibratory dynamics and the pilot upper body has been the focus of this research group in the past several years, with the goal of enabling a-priori evaluation of RPC proneness of rotorcraft during the design process. The focus on numerical modeling has been flanked, in the past two years and with the support of Leonardo Helicopter Division, by the development of a dedicated test-bed, able to support the validation of numerical models, to identify the BDFT of the pilot-rotorcraft system and the NMA of the pilot and to eventually enable the investigation of nonlinear effects, especially regarding the triggering of potential PAO interactions.

The approach to the experimental identification of the BDFT of the pilot-rotorcraft system will be presented, together with the first results of the preliminary test campaign involving a professional test pilot.

2 Experimental approach

The pilot-rotorcraft interaction, when the analysis is restricted to the linear domain, is represented by the Biodynamic Feedthrough (BDFT), defined as the transfer function between the control rotation $\theta(s)$ and the acceleration input $A(s)$ evaluated at the MPS or directly at the pilot seat:

$$H_{\mathrm{BDFT}}(s) = \frac{\theta(s)}{A(s)} \tag{1}$$

The dedicated test-bed (Cf. Figure 1) has been realized at the Department of Aerospace Science and Technology of Politecnico di Milano. It is composed of the following subsystems:

1. a 6-DOF motion platform system (MPS);
2. a reconfigurable cockpit mock-up;
3. a customized measurement system.

The MPS is able to carry a maximum payload of 1500 kg and provide acceleration inputs of adequate intensity in the frequency band of interest [1, 8 Hz]. The cockpit mock-up is composed of the pilot seat, collective and cyclic inceptors, pedals, and a glass cockpit made of two touchscreen monitors. The cockpit structures are supported by a frame made of stainless steel tubes. The data acquisition system is able to manage up to 40 channels. Currently, 9 accelerometers are fixed to MPS, 3 to the seat and 3 to the collective and cyclic grips. The rotation of the inceptors is measured by 3 absolute encoders. Furthermore, in the collective and cyclic grip, an optical force sensor is embedded.

During BDFT identification tests, the human-machine system has been forced by prescribing the MPS Motion Reference Point (MRP) translational acceleration in the three directions X, Y, Z. Tests were performed with single-axis input and simultaneous multi-axis input. The pilot was asked to perform simple tracking tasks, keeping as much as possible the command input into an optimal $\pm 3\,\%$ range with respect to reference values. An error of $\pm 5\,\%$ was considered acceptable.

The time series for the input signals were generated summing individual harmonic components in the frequency band $[0.5, 7.5]$ Hz. The amplitude of the input spectrum was modulated to produce an input acceleration with the desired RMS value. In all the tests considered in the present discussion, the RMS value was either $0.5\,\mathrm{m\,s^{-2}}$ or $1.0\,\mathrm{m\,s^{-2}}$. The duration of each single-axis test was set at 90 s, while multi-axis tests run were 120 s long. The experimental approach followed best-practices identified in previous efforts [13, 14].

Acquired waveforms of the inceptors rotation and of the base and seat accelerations were first bandpass filtered using a double-pass filtering algorithm, to avoid phase distortion, in the same frequency band of the input. The BDFT transfer function has been then estimated using the $H_1(j\omega)$ estimator:

$$H_{\mathrm{BDFT}}(j\omega) = \frac{S_{\theta A}(j\omega)}{S_{AA}(j\omega)} \tag{2}$$

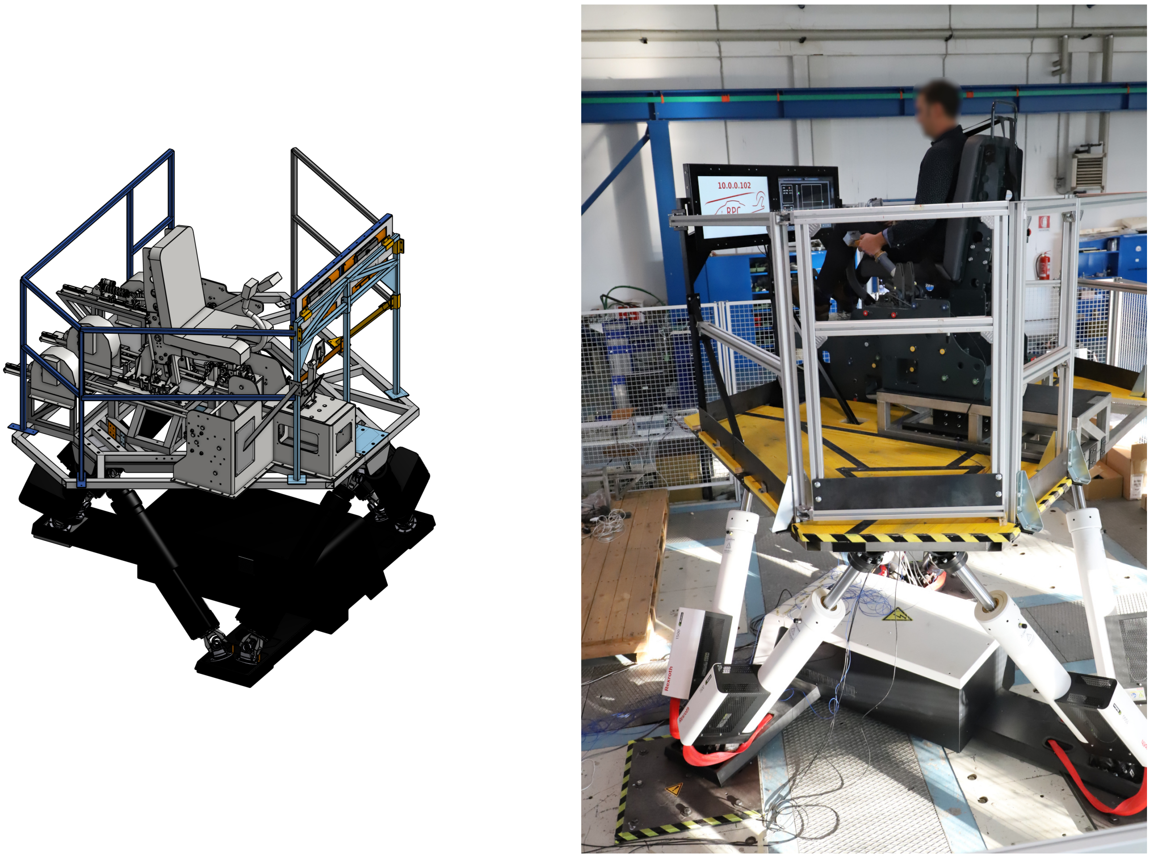

Figure 1: The RPC testbed.

where $S_{\theta A}(j\omega)$ is the cross-spectrum of the output inceptor rotation with respect to the input acceleration, and $S_{AA}(j\omega)$ is the auto-spectrum of the input MPS acceleration. Both spectra were calculated using the Welch method on 30 s windows, overlapping by half of the window width.

References

[1] Ashkenas, I. L., Jex, H. R., and McRuer, D. T., "Pilot-Induced Oscillations: Their Cause and Analysis," NCR 64-143, Norair Report, June 20 1964.

[2] McRuer, D. T., "Pilot-Induced Oscillations and Human Dynamic Behavior," CR 4683, NASA, 1995.

[3] McRuer, D. T., *Aviation Safety and Pilot Control: Understanding and Preventing Unfavourable Pilot-Vehicle Interactions*, Washington DC: National Research Council, National Academy Press, 1997.

[4] Pavel, M. D., Jump, M., Dang-Vu, B., Masarati, P., Gennaretti, M., Ionita, A., Zaichik, L., Smaili, H., Quaranta, G., Yilmaz, D., Jones, M., Serafini, J., and Malecki, J., "Adverse rotorcraft pilot couplings — Past, present and future challenges," *Progress in Aerospace Sciences*, Vol. 62, doi:10.1016/j.paerosci.2013.04.003, October 2013, pp. 1–51.

[5] Pavel, M. D., Masarati, P., Gennaretti, M., Jump, M., Zaichik, L., Dang-Vu, B., Lu, L., Yilmaz, D., Quaranta, G., Ionita, A., and Serafini, J., "Practices to identify and preclude adverse aircraft-and-rotorcraft pilot couplings — A design perspective," *Progress in Aerospace Sciences*, doi:10.1016/j.paerosci.2015.05.002, 2015.

[6] Pavel, M. D., Jump, M., Masarati, P., Zaichik, L., Dang-Vu, B., Smaili, H., Quaranta, G., Stroosma, O., Yilmaz, D., Jones, M., Gennaretti, M., and Ionita, A., "Practices to identify and prevent adverse aircraft-and-rotorcraft pilot couplings — A ground simulator perspective," *Progress in Aerospace Sciences*, doi:10.1016/j.paerosci.2015.06.007, 2015.

[7] Muscarello, V., Quaranta, G., and Masarati, P., "The Role of Rotor Coning in Helicopter Proneness to Collective Bounce," *Aerospace Science and Technology*, Vol. 36, doi:10.1016/j.ast.2014.04.006, July 2014, pp. 103–113.

[8] Muscarello, V., Colombo, F., Quaranta, G., and Masarati, P., "Aeroelastic rotorcraft–pilot couplings in tiltrotor aircraft," *Journal of Guidance, Control, and Dynamics*, Vol. 42, (3), 2019, pp. 524–537.

[9] Zanoni, A., Cocco, A., and Masarati, P., "Multibody dynamics analysis of the human upper body for rotorcraft–pilot interaction," *Nonlinear Dynamics*, Vol. 102, (3), doi:10.1007/s11071-020-06005-7, 2020, pp. 1517–1539.

[10] Olivari, M., Nieuwenhuizen, F. M., Venrooij, J., Bülthoff, H. H., and Pollini, L., "Methods for Multiloop Identification of Visual and Neuromuscular Pilot Responses," *IEEE Transactions on Cybernetics*, Vol. 45, (12), Conference Name: IEEE Transactions on Cybernetics, December 2015, pp. 2780–2791. doi: 10.1109/TCYB.2014.2384525

[11] Quaranta, G., Masarati, P., and Venrooij, J., "Impact of pilots' biodynamic feedthrough on rotorcraft by robust stability," *Journal of Sound and Vibration*, Vol. 332, (20), doi:10.1016/j.jsv.2013.04.020, September 2013, pp. 4948–4962.

[12] Venrooij, J., Abbink, D. A., Mulder, M., van Paassen, M. M., Mulder, M., van Helm, F. C. T. d., and Bulthoff, H. H., "A Biodynamic Feedthrough Model Based on Neuromuscular Principles," *IEEE Transactions on Cybernetics*, Vol. PP, (99), doi:10.1109/TCYB.2013.2280028, 2013, pp. 1–1.

[13] Venrooij, J., Yilmaz, D., Pavel, M. D., Quaranta, G., Jump, M., and Mulder, M., "Measuring Biodynamic Feedthrough in Helicopters," 37th European Rotorcraft Forum, September 13–15 2011.

[14] Masarati, P., Quaranta, G., and Jump, M., "Experimental and Numerical Helicopter Pilot Characterization for Aeroelastic Rotorcraft-Pilot Couplings Analysis," *Proc. IMechE, Part G: J. Aerospace Engineering*, Vol. 227, (1), doi:10.1177/0954410011427662, January 2013, pp. 124–140.