Materials Research Proceedings **26** (2023) 219-224 https://doi.org/10.21741/9781644902431-36

Sizing and control system definition of an intelligent facility for qualification tests and prognostic research activities for electrical landing gear systems

Antonio Carlo Bertolino[a], Andrea De Martin[b,*]
Giovanni Jacazio[c] and Massimo Sorli[d]

[1]Politecnico di Torino, Corso Duca degli Abruzzi 24, Torino, Italy

[a]antonio.bertolino@polito.it, [b]andrea.demartin@polito.it,
[c]giovanni.jacazio@formerfaculty.polito.it, [d]massimo.sorli@polito.it

Keywords: Electric-Brakes, Landing Gear System, LGS, Test-Rig, Prognostics, PHM

Abstract. The evolution towards "more electric" aircrafts has seen a decisive push in the last decade affecting both the propulsion components and the aircraft systems. An interesting and fast-developing application field of electro-mechanical actuators is that of the aeronautical brakes. The E-LISA research project under way within the Clean Sky 2 framework has the objective of developing an innovative iron bird dedicated to executing tests on the landing gear of a small aircraft transport equipped with electro-mechanical landing gear and electrical brake. The paper details the process required to the definition of such iron bird, with a particular focus on the control system.

Introduction

The evolution towards "more electric" aircrafts has seen a decisive push in the last decade, due to growing environmental concerns and the development of new market segments, such as the flying taxis. Such trend affects both the propulsion components and the aircraft systems, with the latter seeing a progressive trend in replacing the traditional solutions based on hydraulic power with electrical or electro-mechanical devices. Although more attention is usually devised towards the flight control actuation, an interesting and fast-developing application field for electro-mechanical systems is that of the aeronautical brakes. Electro-mechanical brakes, or E-Brakes hereby onwards, would present several advantages over their hydraulic counterparts, mainly related to the avoidance of leakage issues and the simplification of the system architecture. The E-LISA research project under way within the Clean Sky 2 framework has the objective of developing an innovative iron bird dedicated to executing tests on the landing gear of a small aircraft transport equipped with electro-mechanical landing gear and electrical brake. Literature on landing gear test rig is rather limited and focused on the different aspects of the certification process. A test rig dedicated to the study of the fatigue behavior of a landing gear is reported in [1], while a hydraulic solution to execute the drop-test is re-ported in [2]. In [3], the authors present the implementation of a high-dynamics force control loop to test the actuation system of a main landing gear within the M-346 iron bird. In [4] the authors performed the experimental validation of a simulation model of a landing gear leg through a comparison with the results obtained with a dedicated experimental setup. Literature on the development of PHM systems for landing gear legs is thus far limited to preliminary simulation studies for the actuation system [5], or to certain components of the electrical brakes [6], while a preliminary comparative analysis of data-driven methods was re-ported in [7]. The proposed iron bird is set to provide meaningful experimental data by collecting signals difficult to extract from the currently in-service aircraft. To this end, the E-LISA iron bird is able to reproduce fully comprehensive test scenarios and conditions, following the workflow described in [8]. The E-LISA iron bird, firstly presented in [9], aims at providing a significant advancement on the current state-of-the-art by defining a new test-rig able to cover different tests procedures without resorting to different test-benches and acts as a technological demonstrator for new prognostic functionalities for the electrical brake system. The paper is organized as follows. At first, the test-rig architecture is introduced, while requirements are detailed and discussed. Hence the sizing process is presented, along with the definition of the control system. The control system is at first designed through the classical linear-dynamics approach and then verified against a high-fidelity, non-linear model. Results are finally presented, highlighting the system capabilities.

Design Requirements and Test-Rig Architecture

The main purposes of the proposed iron-bird are to support the testing and certification of a novel E-Brake system and to foster the definition of dedicated prognostic logic. The iron bird is organized as depicted in in Figure 1 [9]. The mechanical structure can be divided between a fixed part and a moving platform integral with the landing gear leg, complete with a wheel and electrical brake. The moving platform slides along low friction vertical guides according to the force provided by an electro-hydraulic servoactuator controlled through a dedicated servovalve, reproducing the portion of the 6 tons aircraft weight acting on one landing gear leg. A calibrated by-pass orifice connects the two hydraulic lines serving the actuator to improve the dynamic response of the force-controlled system. The test-rig behavior is continuously monitored through one linear variable differential transformer (LVDT) sensor measuring the hydraulic actuator travel, a load cell measuring the force exchanged between the actuator and the moving platform and a differential pressure transducer sensing the pressure drop across the two actuator’s chambers. The hydraulic power available for the test-rig operation is that of the facilities in which the rig will be installed and is limited at 207 bar. The contact between the landing gear wheel and the runway is represented through a runway simulator, a rotating disk, connected to a selected number of inertia disks, representative of the aircraft inertia, through a gearbox. A different solution, based on a novel hydraulic system, was considered in [10] but discarded due to cost concerns. A gearbox is interposed to significantly reduce the mass and the encumbrance of the flywheels, the number of which can be increased or decreased to scale-up or scale-down the weight of the simulated aircraft. The runway simulator includes the possibility to change the external coating to achieve the variation of the friction forces between the wheel and the runway and allow the verification of the anti-skid logic behavior in different operating conditions, while a sprinkler can be activated to reproduce the wet-runway conditions. An electric motor is used to accelerate the runway simulator up to the angular frequency corresponding to the aircraft horizontal speed given the diameter of the rotating disk. An emergency brake is installed in-line with the rotating cylinder, allowing to bring the full system to a complete stop in less than 60 s. The iron bird operation is managed by an engineering test station (ETS), which accepts the inputs from a central control unit (CCU) that in turn receives the commands from an operator via a user interface. The input signals are then sent together with rig measurements to a dedicated computer running a real-time (RT) representation of the aircraft dynamics during landing. Such real-time model is then used, along with a model of the runway and a model of the landing gear dynamics, to compute in real-time the load that must be applied to the test-article. The ETS also include the rig control logic, which is designed to manage both the position of the moving platform and the force exerted by the hydraulic

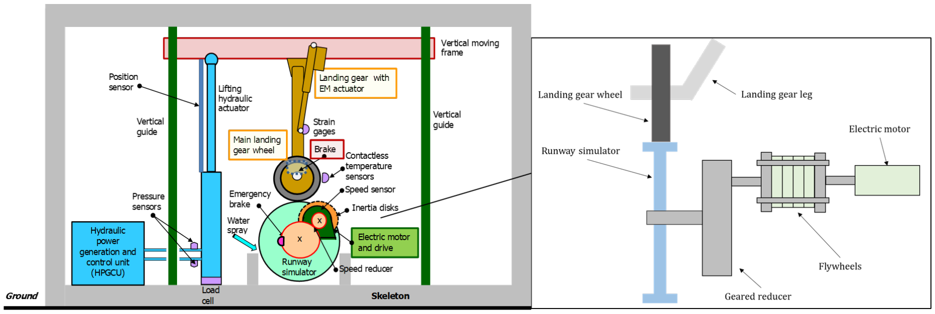

Figure 1. Iron bird schematics.

actuator and include a safety routine check to limit the damages to the rig and to the test article in case of a failure of the anti-skid system during the execution of a test. The structure of the control system is depicted in Figure 2, where three main modules can be identified. The Simulation Module involves the real-time representation of the landing dynamics, including a real-time representation of the aircraft dynamics [9], a runway model, which allows to describe the presence of periodical or localized runway irregularities, and the model of the landing gear legs, each modelled as a two-degrees of freedom vibrating systems, where the mechanical characteristics of the shock-absorber, of the tires and of the mechanical structure are provided by the industrial partners of the project. The control system is based on two control loops. The position control loop operates as a modulating element. It is based on a simple Proportional regulation which output does not act directly on the power lines of the block diagram, instead operating on the dynamic saturation defining the minimum and maximum current absorbed by the servovalve. The main, or basic, control loop is that used to manage the force exerted by the hydraulic actuator and is similar to the control systems of other demanding applications such as iron birds for flight control systems [11] and test rigs for actuators under PHM experimentation [12]. The final component of the control system is the safety module, designed to react to the eventual failure of the anti-skid. A failure of such system during the test can be potentially dangerous to both the rig and the test article, since blocked wheels tends to rapidly fail, hence causing a direct contact under load between the wheel structure and the runway simulator. To avoid catastrophic damages the safety module commands a positive (extract) force set, quickly lowering the load on the test article and achieving the separation between the wheel and the runway simulator.

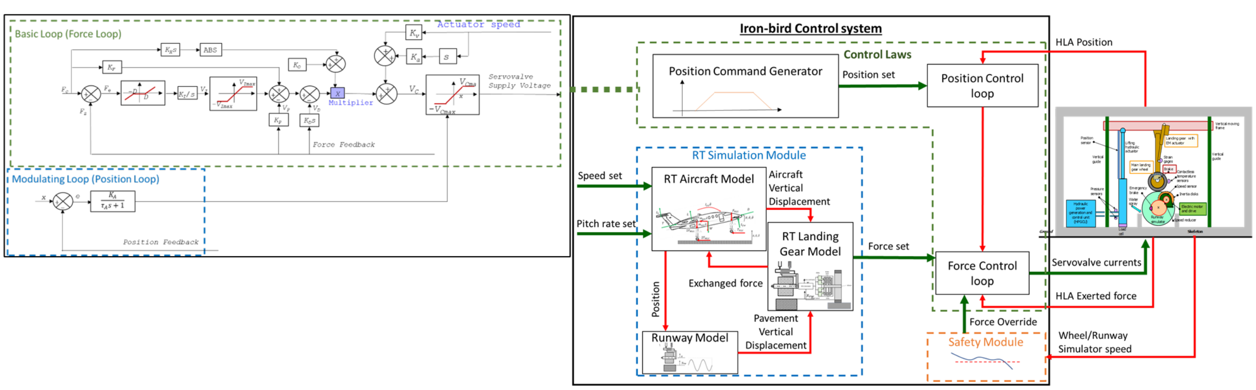

Figure 2. Control system structure.

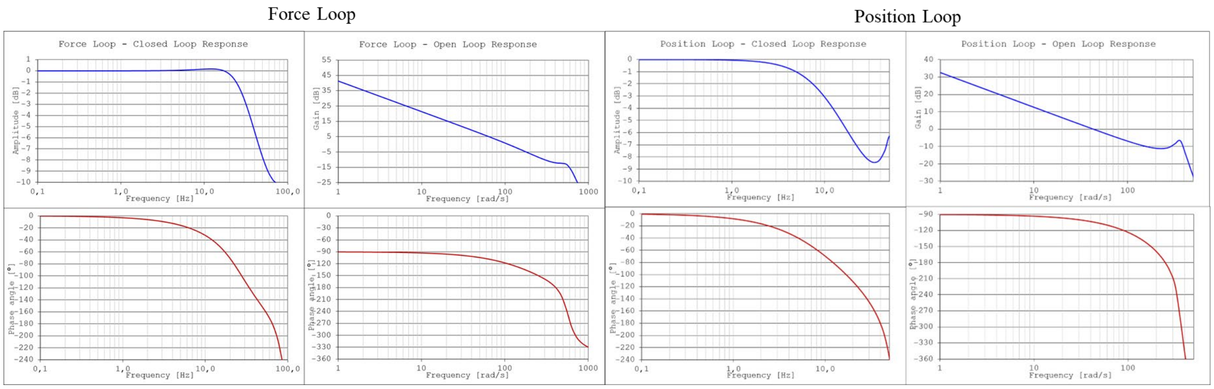

Figure 3. Bode diagrams for the linear dynamics model

Sizing process and Control System Definition

Given the geometrical and physical properties of each component of the loading system, it is possible to perform a preliminary assessment of the control system gains by considering separately the behavior of the force control loop and that of the position control loop. Each control loop can be then at first described as two linear electro-hydraulic servosystems, neglecting the presence of friction, the occurrence of flow-rate saturation of the servovalve and the non-infinite stiffness of the mechanical attachments. As shown in Figure 3, the chosen gain values ensure the system stability and high bandwidth. The latter however is expected to be significantly affected by the flowrate saturation of the servovalve and is expected to be significantly lower for high-amplitude force oscillations.

To check the results of the linear model and provide a more accurate assessment of the test-rig performances we resolved to the definition of a high-fidelity dynamic model. The model, implemented in Matlab/Simulink, is representative of the whole test-rig system, including both the hardware and the software components, and has been already published in [9]. Such model is used to test the control system performances both in the frequency and in the time domain and to verify the test-rig response to an emergency lift of the moving platform following the occurrence of blocked wheel conditions. Since the role of the position control loop is limited to the descent/lift phase of the test procedure, the frequency analysis is limited to the force control loop. Results for both the closed loop analysis are provided in Figure 4 for two different cases: on the left side, the behavior of the system in presence of the 160 l/min defined through the design analysis is depicted,

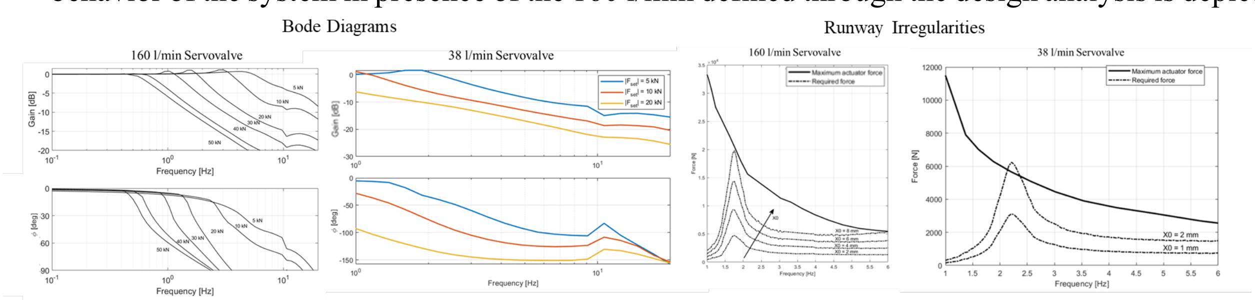

Figure 4. Closed Loop response of the force control loop with variable force amplitude

while on the right-hand side results with a 38 l/min servovalve with similar flow gain made available for the project are presented. It is evident that the use of the 38 l/min servovalve involves a significant downgrade from the 160 l/min case and from the linear analysis expectations. The impact of the servovalve limitations on the test bench performances can be best explained looking at the rig capabilities of reproducing the effects of periodical runway irregularities by comparing the maximum dynamic force applied by the hydraulic servo actuator against the dynamic force required to reproduce the effect of such pavement defects within a certain frequency range. The test-rig equipped with the 160 l/min servovalve is able to fully replicate the occurrence of periodical runway irregularities up to 8 mm deep, while the 38 l/min one is limited to just 2 mm oscillations of the runway pavement. The behavior of the safety system was also investigated. As shown in Figure 5, the force applied to the landing gear leg is cut to 0 N in 0.5 s, becoming positive and hence allowing the separation between the wheel and the runway simulator in less than 0.7 s. Please notice that this simulation was performed considering the 38 l/min servovalve, thus the slower option.

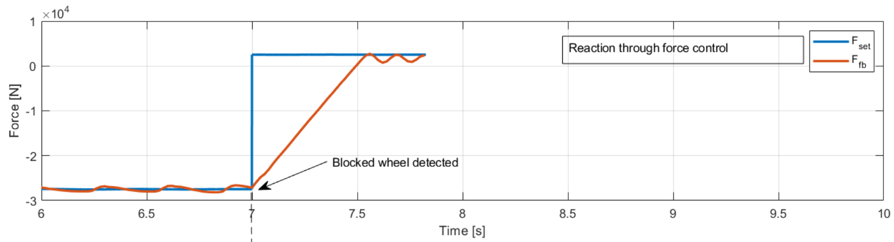

Figure 5. Test-rig reaction to blocked wheel occurrence

Conclusions

The E-LISA iron bird has been designed with to fulfill two main purposes. To support the certification procedures for a new, fully electrical landing gear system and act as a technological demonstrator for prognostic techniques developed for a few key components. As such, the need to closely reproduce a wide array of possible operating conditions including the presence of runway irregularities was assessed as a necessary feature. These considerations apply directly to the definition of the test-rig control system, which involves a real-time simulation model of the aircraft to continuously compute the force command used by the test rig to reproduce a realistic loading pattern on the landing gear under analysis. The definition of a novel control scheme, based on the combination of a simple position control loop with an advanced force control loop was also required. To support the design of the iron bird and contribute to the definition of its control laws, a high-fidelity model of the system was prepared according to well established equations. Simulation results showed that the iron bird control system was stable, although its expected performances are currently limited with respect to the original expectations. Such limitations are however mainly caused by the servovalve made available for the project and can be overcome through the adoption of servovalves with higher flowrate performances. Further work is required to properly characterize the test rig, through the proper identification of the dynamic parameters of the simulation model, the validation of the proposed control scheme, and the experimental verification of the iron bird performance.

References

[1] R. K. Schmidt and P. Eng, "an Integrated Modular Test Rig for Landing Gear Fatigue and Strength Testing," in *ICAS2002 CONGRESS*, 2002, pp. 1–6.

[2] J. Han, Y.-S. Lee, and O.-S. Ahn, "Design & Fabrication for Small Aircraft Landing Gear Drop Test Rig System," *J. Korean Soc. Aeronaut. Sp. Sci.*, vol. 36, no. 11, pp. 1121–1125, 2008. https://doi.org/10.5139/JKSAS.2008.36.11.1121

[3] G. Jacazio and G. Balossini, "A Mechatronic Active Force Control System," in *Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Proceedings of the ASME 2009 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference August 30 -*

September 2, 2009, 2009, pp. 1–8.

[4] L. Dravico, M. Tanelli, and S. M. Savaresia, "Experimental validation of landing-gear dynamics for anti-skid control design," *2018 Eur. Control Conf. ECC 2018*, pp. 2751–2756, 2018. https://doi.org/10.23919/ECC.2018.8550258

[5] C. S. Byington, M. Watson, and D. Edwards, "Data-driven neural network methodology to remaining life predictions for aircraft actuator components," 2004. https://doi.org/10.1109/AERO.2004.1368175

[6] G. Ramesh, P. Garza, and S. Perinpanayagam, "Digital simulation and identification of faults with neural network reasoners in brushed actuators employed in an e-brake system," *Appl. Sci.*, vol. 11, no. 19, 2021. https://doi.org/10.3390/app11199171

[7] A. Oikonomou, N. Eleftheroglou, F. Freeman, T. Loutas, and D. Zarouchas, "Remaining Useful Life Prognosis of Aircraft Brakes," *Int. J. Progn. Heal. Manag.*, vol. 13, no. 1, pp. 1–11, 2022. https://doi.org/10.36001/ijphm.2022.v13i1.3072

[8] S. Autin, A. De Martin, G. Jacazio, J. Socheleau, and G. J. Vachtsevanos, "Results of a feasibility study of a Prognostic System for Electro-Hydraulic Flight Control Actuators," *Int. J. Progn. Heal. Manag.*, vol. 12, no. 3, pp. 1–18, 2021. https://doi.org/10.36001/ijphm.2021.v12i3.2935

[9] A. De Martin, G. Jacazio, and M. Sorli, "Simulation of Runway Irregularities in a Novel Test Rig for Fully Electrical Landing Gear Systems," *Aerospace*, vol. 9, no. 2, p. 114, 2022. https://doi.org/10.3390/aerospace9020114

[10] A. De Martin, G. Jacazio, A. Ruffinatto, and M. Sorli, "A Novel Hydraulic Solution to Simulate Inertial Forces on a Landing Gear Qualification Test Rig," in *Proceedings of the ASME/BATH Symposium on Fluid Power and Motion Control, FPMC2022*, 2022, pp. 1–9. https://doi.org/10.1115/FPMC2022-89900

[11] G. Jacazio and G. Balossini, "Real-time loading actuator control for an advanced aerospace test rig," *Proc. Inst. Mech. Eng. Part I J. Syst. Control Eng.*, 2007. https://doi.org/10.1243/09596518JSCE269

[12] P. Chiavaroli, A. De Martin, G. Evangelista, G. Jacazio, and M. Sorli, "Real Time Loading Test Rig for Flight Control Actuators Under PHM Experimentation," in *ASME International Mechanical Engineering Congress and Exposition, Proceedings (IMECE)*, 2018, vol. 1, p. V001T03A032. https://doi.org/10.1115/IMECE2018-86967