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Flight test verification of Hardware in the Loop simulations of PZL-130 Orlik aircraft stabilization system that uses trim tabs in the lateral channel

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Abstract
This article presents an assessment of an automatic flight stabilization system that utilizes trim tabs. The system, known as AST-1, was designed for the Polish military turboprop trainer aircraft PZL-130 Orlik. The AST-1 differs from traditional automatic flight control systems as it moves only the trim tabs of the primary control surfaces instead of the surfaces themselves. This solution offers benefits such as reduced complexity, cost, and energy consumption. The article describes the development of the AST-1 using model-based design and its evaluation through flight tests and hardware in the loop (HIL) simulations.

The controller structure of the AST-1 system includes internal and external control loops with proportional-integral-derivative regulators. The system was tested in simulations at various levels of advancement, including model, software, and hardware in the loop simulations. The real flight data were compared with hardware in the loop simulations results, where the controller software ran on the same onboard computer connected to actuators as in the actual aircraft. Flight tests were conducted to verify the control system, and various parameters were analysed to assess control quality, including step response analysis and the integral square error metric.

The results of the flight tests were compared with the simulation results. The article provides detailed comparisons for the lateral control channel of the AST-1 system. Overall, the responses in real flight were stable and converged to setpoints, however they exhibited larger over/undershoots and settling times compared to the simulations. The discrepancies were attributed to factors such as air turbulence and the need for further refinement of the aerodynamic model to include asymmetrical effects. The article also suggests potential improvements to reduce the differences between simulation and real flight, such as modifying the controller gains during flight and expanding the trim tab and primary control surface interaction model.

1. Introduction

Over the years, many aircraft manufacturers have introduced more electric architecture to their aircraft. These upgrades often involve the replacement or modification of hydraulic systems, actuators and mechanical controls with electric solutions. As a result, the reduction in aircraft mass, fuel consumption, emissions, system complexity and maintenance costs makes it very beneficial for the suppliers and users [1, 2].

One area where electric systems can be applied is the aircraft trimming system. Such a system retrofit creates an opportunity for aircraft that require automatic stabilization and have a trim tab on every primary control surface: aileron, elevator and rudder. Although not common in smaller aircraft, control systems that uses trim tabs are used in large aircraft due to the high moments required to deflect primary control surfaces.

The paper presents an assessment of the compared results from flight tests and hardware in the loop (HIL) simulations of an automatic flight stabilization system that uses trim tabs (AST-1). The comparison will provide a basis for

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assessing whether the models used in HIL simulations accurately represented aircraft dynamics, allowing for pre-flight controller gain tuning that ensures similar control quality in flight as in the simulations.

The AST-1 was designed for the polish military turboprop trainer aircraft PZL-130 Orlik (Fig. 1). It was developed using model-based design and went through all of the project stages, including flight tests. The AST-1 differs from classical AFCS because instead of moving primary control surfaces of the aircraft it moves only their trim tabs. Such a solution is much easier and cost-effective in the case of e.g. aircraft retrofit. Especially, for aircraft with manually controlled electric trim-tabs. Moreover, as aerodynamic loads on trim tabs are smaller, the electric actuators can be smaller, less energy consuming and have a simpler in structure. They do not require safety clutch mechanisms to prevent the primary control system blockage, as the system is not mechanically connected to it.

Products available on the market that uses the same principle include SuperECO [3] and iLevil AP [4], which require additional tabs that have to be attached to the aircraft wing structure and are designed for experimental ultralight aircraft. Several studies on using tabs for flight control have been conducted. In [5], a special control surfaces were separated from the primary control surfaces: aileron, elevator and rudder of the Beech Model 99 research aircraft. An automatic flight control system used them to stabilise the flight. The drawback of this solution was that the area of the primary surfaces was reduced and complex mechanical modifications were required. A wing leveler system that uses an aileron trim tab was presented in [6, 7]. It was developed to help the pilot maintain level flight in degraded meteorological conditions and low visibility.

Figure 1: PZL-130 Orlik with marked trimming surfaces [Airbus Poland]. TA – aileron trim tab, TH – elevator trim tab, TV – rudder trim tab

2. Automatic flight stabilisation system that uses trim tabs

The main mode of operation of the AST-1 system is automatic flight stabilisation in three channels: altitude stabilisation (longitudinal channel), heading angle stabilisation (lateral channel) and propeller slipstream effect compensation [8]. The channels are independent of each other and command only one associated trim tab actuator. Other modes that can be selected by the pilot using two buttons in the cockpit (Fig. 3) are full manual trim tab control and semi-manual control: aileron and elevator trim tab controlled manually with automatic propeller slipstream compensation by the rudder trim tab.

The onboard computer (Fig. 2) and the three trim tab actuators were designed, manufactured and tested internally in a certified environmental laboratory according to the DO-160 aviation standard [9]. The system software can be divided into a lower-level layer and a higher-level layer. The lower-level layer concerns data interfaces, scheduling, fault detection and data registration. The higher-level layer concerns the flight controller, state machine, safety disengagement and manual control. This part of the code was automatically generated from its Simulink model.

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Figure 2: AST-1 onboard computer.

The system was developed using model-based design and underwent extensive model, software and hardware in the loop simulation. Pilot in the loop simulations allowed the use of expert knowledge to further tune the aircraft and controller models.

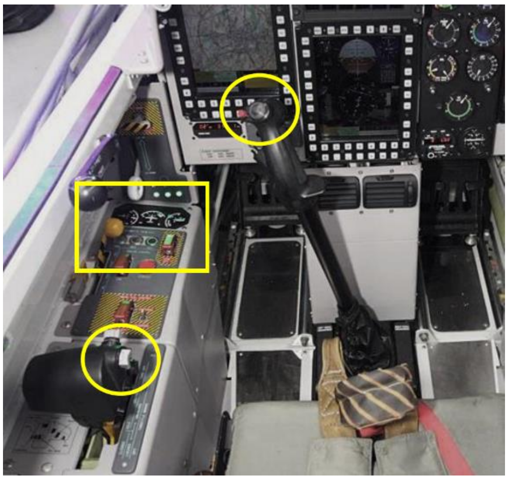

Figure 3: AST-1 system pilot interface buttons. Rectangle – two mode change grey buttons below trim tab angle indicators, circles – manual trim tab control [Airbus Poland].

The structure of the controller (Fig. 4) for the altitude and heading stabilisation channels includes internal and external control loops with PI and PID regulators in the forward path. The third channel, propeller slipstream compensation, computes the commanded angle of the rudder trim tab based on a predefined relation between engine thrust, airspeed and the rudder trim required to compensate for slipstream. The regulator gains were tuned using bode plots with a linearised model of the aircraft at operating points within the system's flight envelope using optimization algorithms [10]. Subsequently, nonlinear elements such as trim tab angle limits, pitch and roll angle limits, and integrator limits were added to the controller. The control quality was then verified using a nonlinear aircraft model.

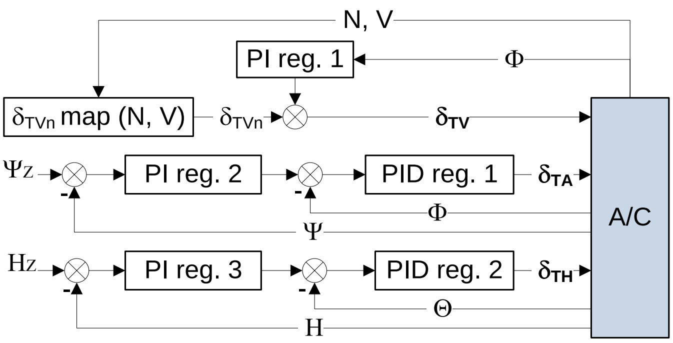

Figure 4: Flight stabilisation system controller structure. N – engine shaft torque, V – airspeed, δ_{TVn} map(N, V) - predefined relation between engine thrust, airspeed and rudder trim required to compensate slipstream, PI/PID

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reg. – Proportional-Integral-Derivative regulators, δ_{TVn} – rudder trim tab angle from predefined map, δ_{TV} – rudder trim tab angle, δ_{TA} – aileron trim tab angle, δ_{TH} – elevator trim tab angle, Ψ_Z – commanded heading angle, Ψ – measured heading angle, H_Z – commanded altitude, H – measured altitude.

The 6 degrees of freedom aircraft model used in simulations was based on data provided by the producer, including information on mass and inertia. Aerodynamic model coefficients were obtained through CFD simulations. Sensor models used included typical errors and noise [11]. Some of these coefficients were fine-tuned based on pilots' feedback regarding the simulated aircraft's dynamic behaviour after conducting pilot-in-the-loop simulations.

3. Methods for simulation and real flight data assessment

Before conducting flight tests, the AST-1 system underwent testing in simulations at various level of advancement: model/software/hardware in the loop simulations [12]. The simulation results were compared with real flight data obtained from hardware in the loop simulations where the controller software ran on the same onboard computer connected to actuators as in the actual aircraft. Instead of developing dedicated testing hardware [13], real-time computer served as the platform for running the simulation and exchanging data with the onboard computer through the same interfaces (Arinc429 and analogue) as would occur after installation in aircraft.

Flight tests serve as the final stage of verifying the control system. Thanks to the data recording capability of the onboard computer, the controller internal data can be reviewed and analysed post-flight. One of the methods to assess how the controller, tuned in modelled environment, performs in real flight is to recreate the same control inputs used during the flight and compare the achieved control quality. Another essential capability required for this method is the ability for the flight engineer to send reference values of control variables for the altitude and heading channels during the flight test. To facilitate this, an application was developed and run on a touchscreen tablet (Fig. 5). As one of the most common input signals for analysing control system responses, a step input was chosen. The flight engineer could select the setpoint value and send step inputs to the controller during the flight. The application also allowed for in-flight gain tuning and separate internal controller loop tuning.

Figure 5: In-flight controller tuning touchscreen application.

Flight tests were conducted in accordance with the approved plan from the aviation authority. The initial tests focused on tuning the internal roll angle control loop of the lateral channel, while the subsequent tests focused on tuning the internal pitch angle control loop of the longitudinal channel. This sequencing was influenced by two factors. Firstly, it is easier for the flight engineer to first tune the internal angle stabilization loops and then, once the desired control quality is achieved, proceed to the external heading and altitude loops. Secondly, from a safety perspective, it is important to tune the lateral channel first, as it does not involve manoeuvres that could lead to nose-up or dive situations resulting in stall or overspeed conditions.

To establish clear objectives and specific parameters for comparing flight test data with simulation results, methods for assessing control quality were analysed. The step response analysis provides insights into the system's transient response, stability, and performance characteristics. It is crucial for the simulations to replicate the initial conditions of the flight test, including airspeed, altitude, and aircraft orientation before applying the step input. Despite the pilot's efforts to stabilize the aircraft in level flight before each experiment, air turbulence had an impact. The Integral Square Error (ISE) is a metric commonly used to evaluate the performance of a control system's response. The ISE is calculated

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by squaring the error at each time instance, summing these squared errors over time, and integrating the result. Mathematically, the ISE can be expressed as follows:

$$ISE = \int e(t)^2 dt \tag{1}$$

Where:
e(t) represents the error at time t, defined as the difference between the desired value and the actual output of the system.

The ISE metric reflects both the magnitude and duration of the error. A smaller ISE value indicates better performance, as it represents less cumulative deviation from the desired value over time.

4. Results

The flight tests were conducted in a designated test zone near Warsaw, with EPWA airport being used for takeoff and landing. During the first flight, the engineer applied three consecutive step commands (-12,5°, -3°, 11°) to the roll angle internal loop of the lateral channel (Fig. 6). After each command, the pilot waited for approximately 30 seconds to observe and record the response of the aircraft's roll angle. The same step inputs were used in the simulation, and the responses of both the real aircraft and the simulation were compared.

In the real aircraft, the roll angle did not reach a steady state for the first input before the second one began, causinga change in the turning direction from left to right (right wing down roll). The response to the second input increased at the same rate as in the simulation but was delayed by 3 seconds. Both responses exhibited overshoot, but the real aircraft's overshoot was twice as high (5° compared to 2,5°). The simulated response settled and achieved a steady state after 5 seconds. On the other hand, the real roll angle exhibited a second overshoot peak of 4.5°, followed by two undershoot peaks of -1.5° and 3°. It then stabilized with a slight tendency to increase the error over time, reaching up to 2.5°. The simulated response for the third step input behaved similarly to the previous one. The real response had a lower rise time by 1 second and an overshoot of 5°. It then undershot the setpoint before settling.

Fig. 7 illustrates the aileron trim tab angle in both the real flight and simulations. After each step input, the trim tab angle reached its maximum value (12,5°) in both cases. However, during the steady state phase, there was a difference of 6° between the real flight and the simulations.

The roll angle error (Fig. 8) was used as the input for the ISE metric, which is presented in Tab. 1.

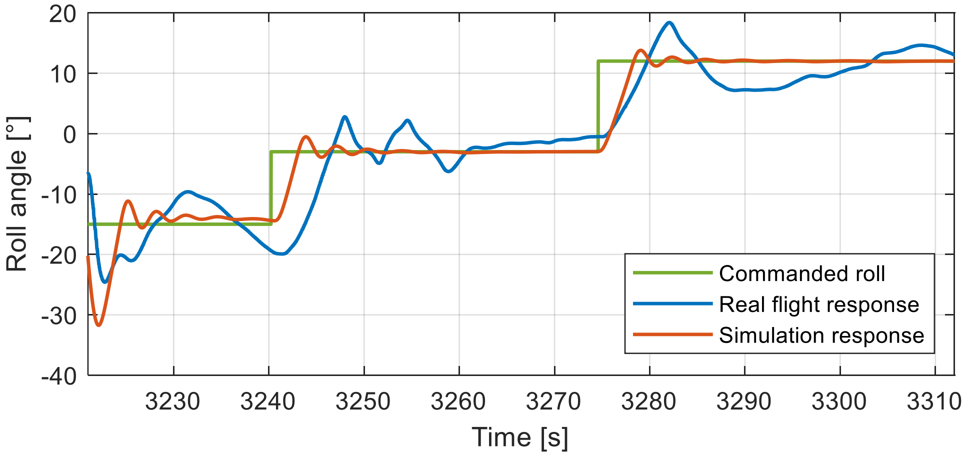

Figure 6: Comparison of real flight response to roll angle step inputs and simulated response – first test case.

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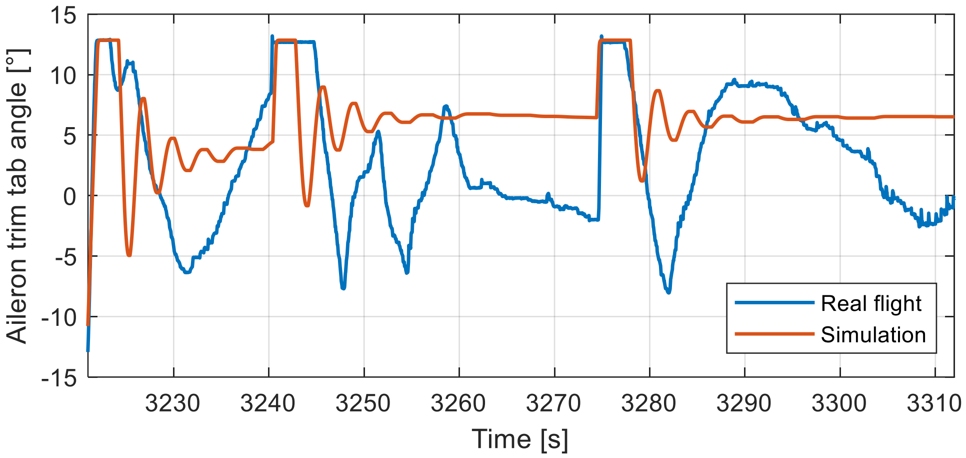

Figure 7: Aileron trim tab angle during real flight and simulation under the same roll angle step inputs – first test case.

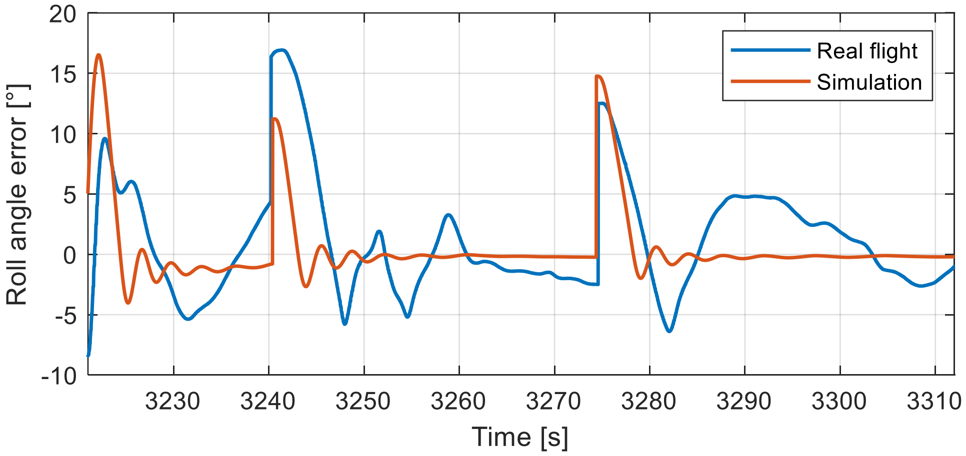

Figure 8: Roll angle error in real flight and simulation under the same roll angle step inputs – first test case.

The second lateral channel test case involved rolling in the opposite direction compared to the previous test - a right-wing-up roll (Fig. 9). Initially, the aircraft was in a quasi-steady state with a stabilized roll angle of 5°. A step input of 0.5° was then applied, causing the aircraft to roll right-wing up. In the real flight response, there was a significant undershoot of -15°, followed by a settling period of 15 seconds. On the other hand, the simulated response exhibited a much smaller undershoot (2°) and settled faster, within 7 seconds. For the second step input of -4.5° roll, the real flight response resulted in an undershoot of -8°, while the simulation showed an undershoot of -3°. The settling time for the real flight was 12 seconds, whereas for the simulation, it was 7 seconds.

The aileron trim tab angle (Fig. 10) demonstrates the corrective action taken due to the large overshoot in the real flight, where the aileron trim tab reaches its limit. During steady state, there is a difference of 6° between the simulation and real flight.

Fig. 11 shows the comparison of the roll angle error, indicating a good correlation after the transient phase when the responses settle.

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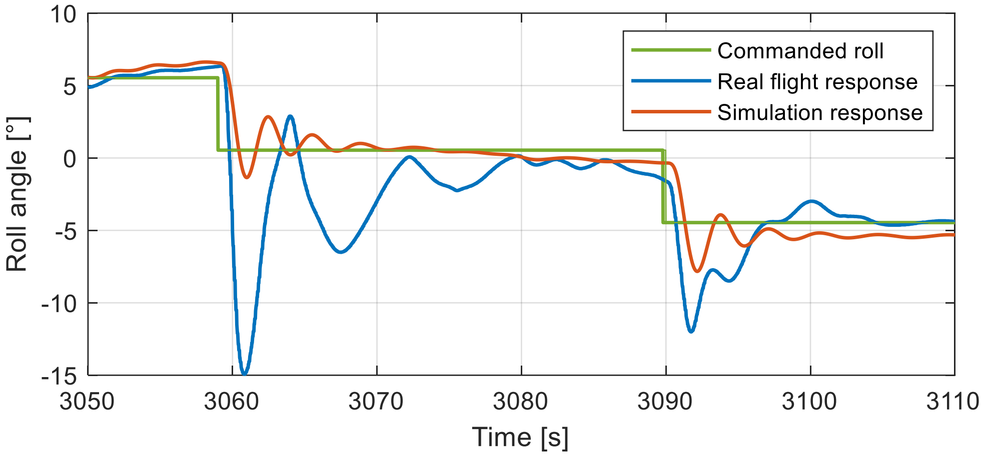

Figure 9: Comparison of real flight response to roll angle step inputs and simulated response – second test case.

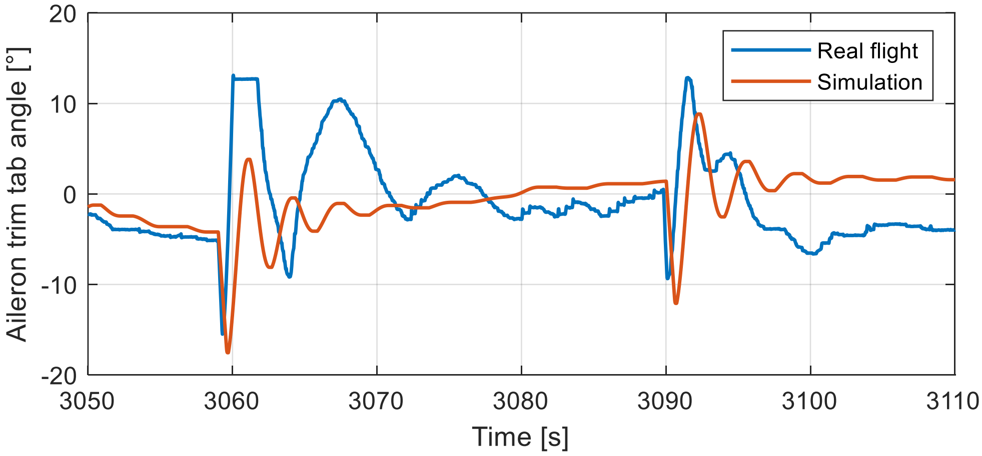

Figure 10: Aileron trim tab angle during real flight and simulation under the same roll angle step inputs – second test case.

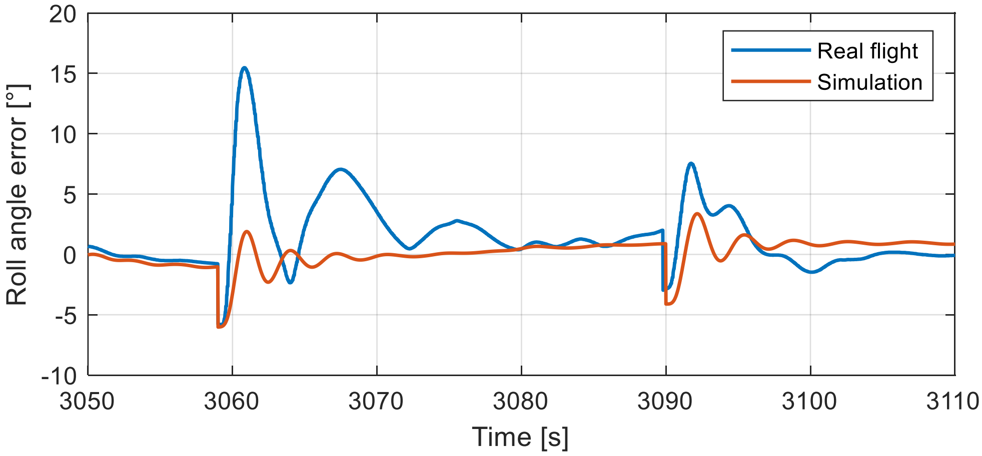

Figure 11: Roll angle error in real flight and simulation under the same roll angle step inputs – second test case.

In both test cases, the simulation and real flight roll angle responses were stable. However, the behaviour of the aircraft in real flight exhibited larger over/undershoots and settling times. There was also a noticeable difference in the movement between right-wing-up and right-wing-down rolls. In the case of a right-wing-up roll, the undershoot in real

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flight reached higher values, although the controller achieved the setpoint. The flight engineer also reported a difference in the dynamic response to different roll directions after the test flight. To tune the gains during flight, the roll angle internal loop gain in the lateral channel controller was modified. A gain scheduling mechanism was added to smoothly change the proportional gain depending on the roll direction, which would be tuned separately during flight. Improving the compliance of the simulation with real flight can be achieved by modifying the aircraft's aerodynamic model to include asymmetrical effects in the lateral channel behaviour. Additionally, the presence of air turbulence, which could not be precisely replicated in the simulation, contributes to the discrepancies between the simulation and real flight tests.

The aileron-trim tab model used in the simulations was represented as a first-order inertia, with parameters gathered during the initial flight test. The trim tab actuator model included actuator dynamics with position and speed limits. Despite the simplifications in the model, the differences in aileron angles between the simulation and real flight were within a few degrees (excluding the largest undershoot moment in test case 2). These differences could be reduced by expanding the model through the identification of trim tab and primary control surface hinge moment coefficients and incorporating them into the trim tab-primary control surface interaction model.

On the other hand, Fig. 12 presents a comparison of the results from the longitudinal channel test. In the third test case shown, the internal loop of the pitch angle control was subjected to a 7.5° pitch angle step input. The simulated response exhibited a slightly slower rise time by 0.5 seconds and a smaller overshoot by 2°. In both cases, the response was stable. The comparison of the longitudinal channel demonstrates that the differences between the simulation and real aircraft behaviour are smaller compared to the lateral test cases.

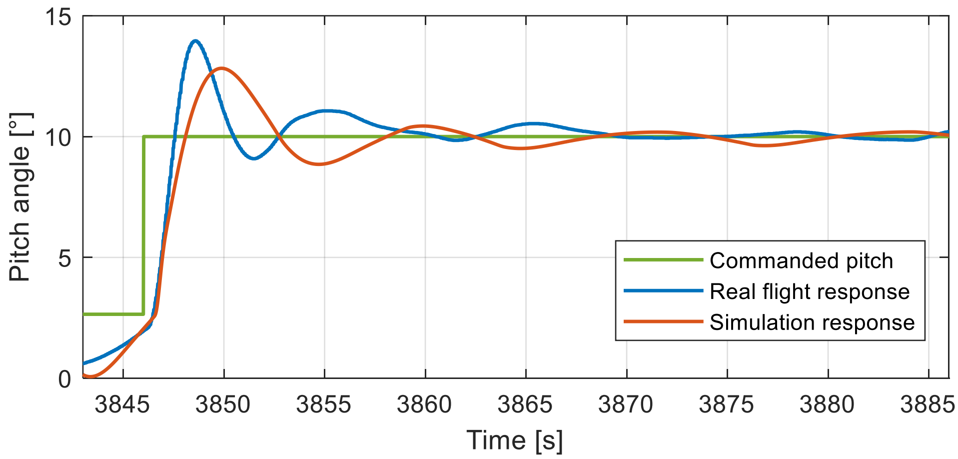

Figure 12: Comparison of real flight response to pitch angle step input and simulated response – third test case.

Tab. 1 provides a summary of the ISE metric for the presented test cases. The results confirm that in all lateral cases, the control quality was worse in real flight when using the same gains as tuned during simulations. In case 1, the ISE in real flight was approximately 2 times higher, while in case 2, it was 7.5 times higher. The reason for the higher ratio in case 2 is the large undershoot that occurred during the right-wing-up roll, which is related to the aircraft's asymmetric dynamic characteristics in this channel.

Table 1: ISE values for three test cases.

	Case 1 **Lateral**	**Case 2** **Lateral**	**Case 3** **Longitudinal**
Simulation ISE	532	45	43
Real flight ISE	1121	338	58

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5. Conclusions

The adoption of the model-based design methodology and the use of simulation in the automatic stabilization system project proved beneficial in eliminating design errors and fine-tuning controller gains prior to flight tests on the PZL-130 Orlik aircraft. The initial flight tests aimed to assess the aircraft's dynamic response to step inputs in the lateral channel's roll angle control internal loop. The flight engineer's expertise and the data recorded during the flight allowed for a comparison between the simulation results and the real flight test data.

Two test cases were evaluated in the lateral channel, and one in the longitudinal channel, and the ISE metric was applied. In case 1, a step input was applied to the roll angle, causing the aircraft to roll in the right wing down direction. In case 2, the step input was applied in the up direction. The results demonstrated that using the same controller during the flight as tuned in simulation ensured a stable roll angle response that converged to the setpoint. However, the rise times of the undershoots/overshoots and the settling times were longer in real flight compared to the simulation.

Analysis revealed differences in the aircraft's roll angle response depending on the direction of the roll. During right wing up movements, the overshoot was up to three times higher compared to the other direction. To accurately reflect this effect in the simulation, the model must be enhanced with asymmetric characteristics. This discrepancy between real flight and simulation was the main reason for the higher ISE ratio in case 2 compared to case 1. The differences between simulations and real flight are attributed to unmodeled dynamics and simplifications inherent in the modelling process. Additionally, the implementation of gain scheduling for the roll angle regulator, with different gains based on the roll direction, should be considered.

The longitudinal channel test case, which compared the pitch angle response to a step input, exhibited a better correlation between the simulation and the real flight. This was supported by the smaller ratio of ISE between them, indicating that the modelled longitudinal aircraft dynamics better reflected the actual aircraft characteristics.

Future analyses will focus on implementing the identified modifications, verifying the longitudinal channel, and fine-tuning the outer loops of the controller, specifically the heading angle and altitude regulators, during in-flight operations.

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References

[1] Okhapkin, A.; Steblinkin, A. An Approach to Fuel Savings and Environmental Benefits Assessment of Electrified Primary Flight Control Actuation System for Short/Medium-Range Passenger Aircraft. More Electric Aircraft 2017 Proceedings, 2017.
[2] Garriga, A.G.; Govindaraju, P.; Ponnusamy, SS.; Cimmino, N.; Mainini, L. A modelling framework to support power architecture trade-off studies for More-Electric Aircraft. Transportation Research Procedia, 2018, vol. 29, pp. 146-156, https://doi.org/10.1016/j.trpro.2018.02.013
[3] https://www.aircraftautomation.com/products/supereco-autopilot, accesed 15.04.2023.
[4] https://shop.levil.com/products/ilevil-ap, accesed 15.04.2023.
[5] Jenks, Gerald E., Howard F. Henry, and Jan Roskam. Flight test results for a separate surface stability augmented Beech model 99. No. NASA-CR-143839. 1977.
[6] Levy, D. Design of a Full-Time Wing Leveler System Using Tab Driven Aileron Controls. Proc of the Guidance, Navigation and Control Conference, Hilton Head, 1992, doi:10.2514/6.1992-4193
[7] Roskam, Jan. Flight Test Results of a Separate Surface Wing-Leveling System. No. 740369. SAE Technical Paper, 1974. https://doi.org/10.4271/770471.
[8] Krawczyk, M.; Graffstein, J. A Proposition of Control Augmentation System for Dumping the Harmful Impact of Slipstream in Turboprop Airplanes. Scientific Papers of Rzeszów University of Technology-Mechanics, Rzeszów 2013, Vol. 288, pp. 287-295, DOI: 10.7862/rm.2013.26

DOI: 10.13009/EUCASS2023-088

[9] Filipowicz, M., Szczepański, C. (2022). Hardware and Software Design of Onboard Computer Controlling the Flight Stabilisation System. In: Szewczyk, R., Zieliński, C., Kaliczyńska, M. (eds) Automation 2022: New Solutions and Technologies for Automation, Robotics and Measurement Techniques. AUTOMATION 2022. Advances in Intelligent Systems and Computing, vol 1427. Springer, Cham. https://doi.org/10.1007/978-3-031-03502-9
[10] Ozdemir U. Comparison of the Newton–Raphson Method and genetic algorithm solutions for nonlinear aircraft trim analysis. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering. 2023;237(3):725-740. doi:10.1177/09544100221107726
[11] Welcer, M.; Szczepański, C.; Krawczyk, M. The Impact of Sensor Errors on Flight Stability. Aerospace 2022, 9, 169. https://doi.org/10.3390/aerospace9030169
[12] Krawczyk, M.; Zajdel, A.; Szczepański, C. Simulation and Testing of Flight Stabilisation System Using Trimmers. Automation 2021: Recent Achievements in Automation, Robotics and Measurement Techniques. Springer, 2021, vol. 1390, pp. 185-196, https://doi.org/10.1007/978-3-030-74893-7_18
[13] Szpakowska-Peas, E. The Tester of the Actuator with ARINC 429 Data Bus. Recent Advances in Automation, Robotics and Measuring Techniques. Advances in Intelligent Systems and Computing, Springer, 2014, vol. 267, pp. 285-294, https://doi.org/10.1007/978-3-319-05353-0_28