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Trim Tab Flight Stabilisation System Performance Assessment under Degraded Actuator Speeds

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Abstract: One of the areas involved in changing current aircraft into more electric ones is decreasing energy consumption by the aircraft's automatic flight control. Therefore, some aircraft types have tested the possibility of controlling the flight in automatic mode or stabilising the flight with trimmers. Previous research on cost-effective and less electrical-energy-consuming automatic stabilisation systems for an aircraft resulted in constructing a laboratory model of the system. Such a feature is beneficial for initiatives like Future Sky, electric aircraft and aircraft stabilisation system retrofits. The system was developed using model-based design and next tuned and tested in model, pilot and hardware-in-the-loop simulations. The implementation of this system does not modify the pilot's primary manual controls. Instead, the electrical trim system is used for automatic stabilisation or manual trimming, depending on the chosen operation mode. The paper presents the development process of the laboratory model of the system and its simulation under degraded actuator speeds. The results were the basis for its control performance assessment. First, the control performance measure was defined. Then the simulation scenarios that compare system behaviour in stabilisation mode after aerodynamic disturbance with three different trim tab actuator speeds were described. The performance measure is highly degraded by the slower actuator speeds, although altitude and heading are finally stabilised in all cases. Moreover, the performance of stabilisation in a lateral channel is less affected by the slowest actuator than in a longitudinal channel.

Keywords: flight tests; automatic flight stabilisation system; trim tab; trim system

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1. Introduction

In the case of some general aviation and commercial aircraft, the engine and the hydraulic system, which actuates primary flight control surfaces, are indirectly responsible for carbon dioxide emissions [1,2]. This is because the secondary control surfaces, such as flaps, slots, and airbrakes, only change the aerodynamic characteristics during take-off and landing. In contrast, primary flight control surfaces, such as the rudder, elevator, and ailerons are necessary for all the phases of flight. For this reason, a control system with three primary control surfaces will be the subject of further analysis. Furthermore, the aim is to find what could be done to operate the primary control surfaces more efficiently regarding power consumption.

In summary, energy optimisation in a control system involves developing an alternative, energy-efficient method for the deflection of primary control surfaces. For this purpose, trim tabs may be used. These tabs counteract aerodynamic forces and control the aircraft. They also compensate for the incorrect balance when the centre of gravity moves due to improper aircraft loading or fuel consumption. All these factors generate additional undesirable moments of force. Trim tabs compensate for these moments and reduce the stick force. Technically, tabs are additional small surfaces connected to the primary control surfaces. Deflection of a trim tab causes deflection of a control surface so that the hinge moments balance each other. Figure 1 shows an example of a system of trimmers—ailerons, elevator, and rudder—of the PZL-130 Orlik turboprop single-engine plane. The solution shown in Figure 1 is the most advanced and enables trimming the plane in both the lateral and longitudinal channels. In the case shown here, the role of the rudder trimmer is to balance the non-symmetrical deflecting moment caused by the intense airstream behind the propeller [3], which is generated by the drive system, namely a high-power turbo propeller engine.

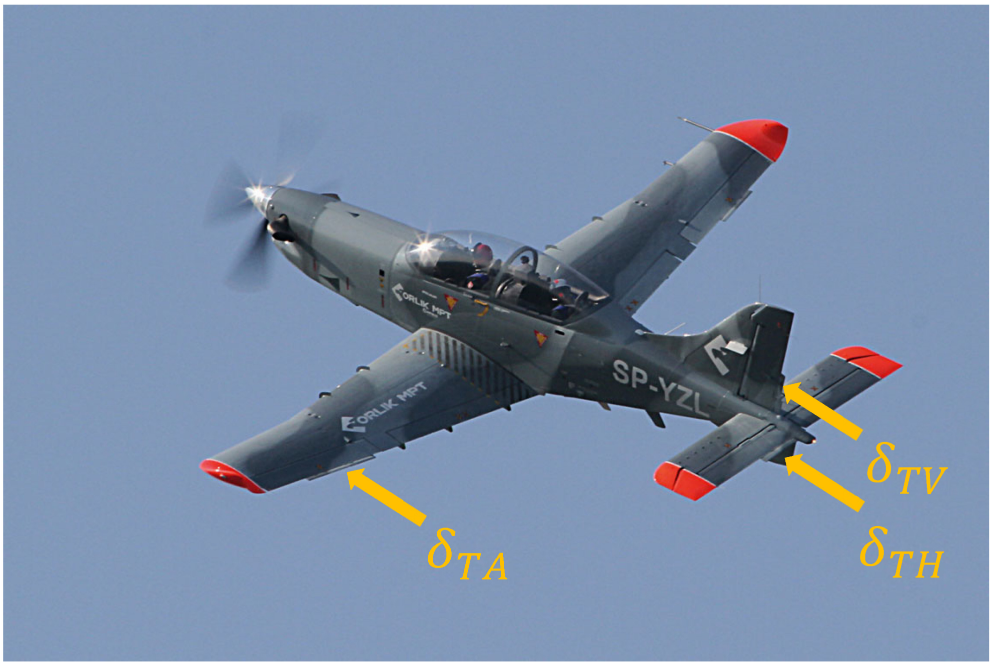

Figure 1. Trim tab location on PZL-130 Orlik aircraft.

Such an electric trimming system can be further developed to operate not only in manual mode, but also in automatic mode, where it could stabilize level flight and counteract aerodynamic disturbances, e.g., the slipstream effect. Such functionality would be very beneficial in terms of pilot workload reduction. Less experienced pilots that usually fly general aviation aircraft could focus on other primary tasks required by the current flight exercise, or this functionality can help them in poor visibility conditions to level the aircraft when the pilot is disoriented. A system that can stabilize flight and let the pilot focus on preparation for exercise during flight to the training zone could also benefit military training aircraft like the PZL-130 Orlik. In future, such systems may also be used by the flight reconfiguration system (currently in the research phase) that takes over the control of the aircraft in emergencies [4].

The literature in the area of flight stabilisation or control systems that use trim tabs or surfaces other than primary control surfaces is very limited. In [5], a wing leveller system that uses an aileron trim tab was presented. The system aimed to enhance safety in instrumental meteorological conditions (IMC) by preventing loss of lateral control by the pilot. The proposed control structure had one roll rate feedback loop and a single proportional gain in the forward path. The influence of atmospheric disturbances and turbulence on the system was not presented, and only a linear model of the actuator was used—without speed and position limits. The aircraft model used in the analyses was linear in the form of transfer functions. Additionally, the presented results did not include time domain simulations. Another wing levelling system was proposed in [6]. In contrast to the former one, rather than using trim tabs, it used a mechanically separated part of the aileron as a new control surface. The control system was similar to one roll rate feedback loop. The primary objective of the research presented in [7] was to determine whether an attitude command control system could be implemented on a Beech Model 99 airliner using separate surface controls. The proposed solution does not use trim tabs but additional control surfaces separated mechanically from primary surfaces, which reduced their surface area. The system aimed to support pilot control commands with automatic trimming and heading hold. The proposed control system was divided into three separate channels: roll, pitch, and yaw. Their structure consisted of an aircraft rate inner feedback loop and an angular displacement outer feedback loop with shaping transfer functions in the forward path.

In the system proposed in this study, for obvious reasons, it is possible to eliminate some elements typical for autopilots, such as a mechanism that enables the device to be switched on/off from the control system and an overload clutch that enables manual control of the plane when the servomechanism is switched on, e.g., in the case of a failure of the autopilot system. Additionally, such a complex design of the autopilot's servomechanisms eventually yields relatively high prices compared to the rather simple servomechanisms used in trimming systems.

2. Methods for Trimmer Control Effectiveness Assessment

The concept of the presented system assumes that at least one of the functions of the autopilot, namely flight stabilisation, can be replaced using a comparatively simple plane-trimming system that acts indirectly on the primary control surfaces. However, the possibility to design such a system depends on two factors.

The first is the appropriate value of the relative (compared to the object's inertia) angular speed with which the servomechanism deflects the trimmer tab. If that angular speed is too low, the reserve of the system's phase is reduced, and if it is too high, it is, for obvious reasons, difficult to properly perform the trimming process in manual mode. This contradiction can be eliminated by forcing a higher speed of adjusting the trimmers in the automatic control mode and slower in the manual control.

The second factor that ensures the correct operation of the proposed system is the appropriate effectiveness of the trimmer system, defined as the deflection of a primary control surface as a function of the deflection of its trimmer. In a stable condition during a flight with the stick free, the moment generated by the lift force on the surface of the trimmer balances the hinge moment of the free control surface.

The analytical methods of determining the hinge moment coefficients carry a high error probability [5,8,9]. Consequently, identification of the trimmer-elevator system was performed based on an analysis of the data obtained during in-flight tests performed on a PZL-130 Orlik aeroplane. During these tests, the pilot controlled the aircraft only by using trim tabs, with a stick and rudder pedals left free. The tests included manoeuvres such as level flights at different speeds, stable turns, climbs, and descents. Even aerobatic manoeuvres like barrel rolls were possible to perform using only trim tabs. Figure 2 presents one such aerobatic figure. The manoeuvre took 15 s to accomplish a full 360° roll. The pilot had to deflect the aileron trim tab from -6° up to -21° to initiate the roll at t = 6 s and then back to initial deflection to stop the roll at t = 20 s. In this case, the trim tab deflection caused the aileron to deflect from 0.5° to 7.5° at the beginning and in the opposite way at the end of the manoeuvre.

Figure 3 shows part of a level cruise flight, which represents the conditions in which the trim tab stabilisation system is intended to operate. During this 50 s flight, the pilot was flying level at cruise speed and maintained a pitch angle between -3° and 3° by using only the elevator trim tab (the aircraft stick was left free). The task was accomplished with small trim tab deflections ranging from -0.2° to 0.6°, which means that the elevator trim tab is effectively deflecting the elevator in the cruise speed range (350–370 km/h).

Those flight tests, performed before starting the stabilisation system design, led to the conclusion that the trim tabs of the PZL-130 Orlik aircraft allow the pilot to manually fly the aircraft in all planned cases and conditions, so its trim tab effectiveness is high enough for the operation of the stabilisation system.

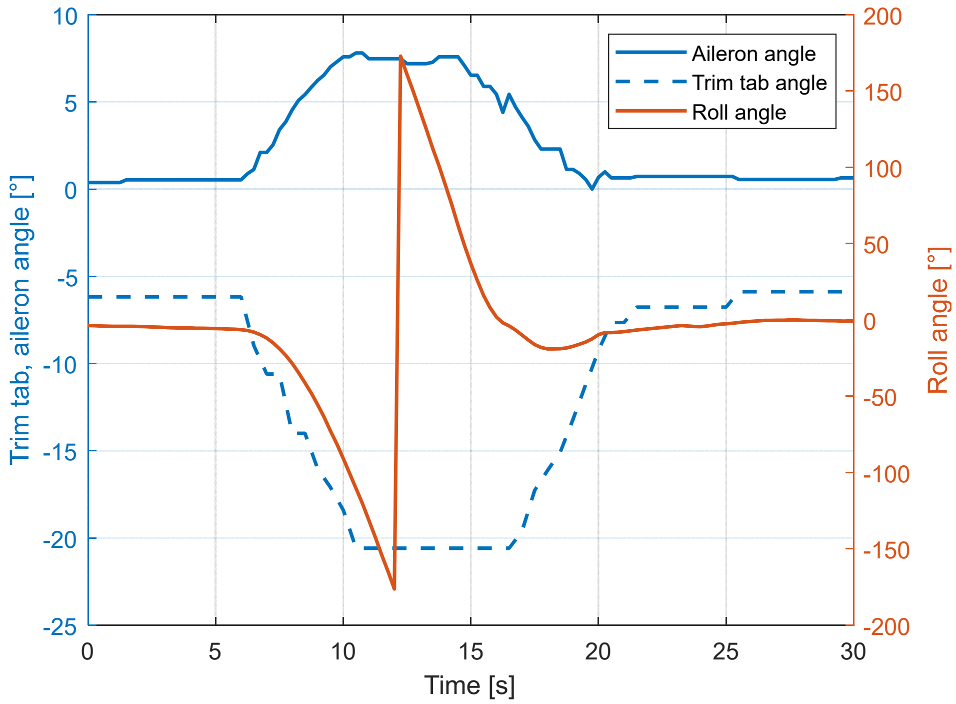

Figure 2. Flight test results during trim-tab-only manually controlled flight—barrel roll manoeuvre.

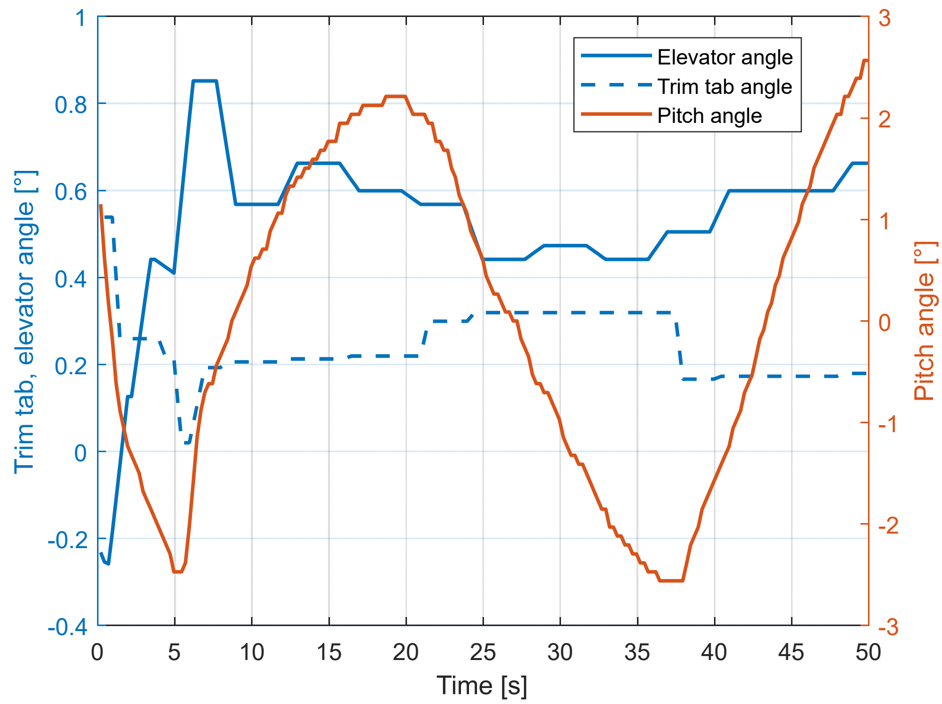

Figure 3. Flight test results during the trim-tab-only manually controlled flight–level cruise flight.

Furthermore, an analysis of the results obtained during the in-flight tests made it possible to determine the transfer functions (1)–(3) that describe the relationship between the values of the ailerons, elevator, and rudder deflections caused by the deflections of adequate trimming surfaces. Based on flight test results, the dynamics of the primary control surface and its trimmer deflection can be approximated by first-order transfer functions with the following values for each of the control channels:

$$\delta_H = \frac{-0.6}{0.25s + 1}\delta_{TH} \tag{1}$$

$$\delta_A = \frac{-0.42}{0.25s + 1}\delta_{TA} \quad (2)$$

$$\delta_V = \frac{-0.75}{0.3s + 1}\delta_{TV} \quad (3)$$

where δ_H—elevator angle, δ_{TH}—elevator trim tab angle, δ_A—aileron angle, δ_{TA}—aileron trim tab angle, δ_V—rudder angle, δ_{TV}—rudder trim tab angle, and s—Laplace operator.

Failure cases of the proposed system, consisting of incorrect positioning of the trimmer's surface at its maximum or minimum angle limit, were also investigated during the flight tests. For example, Figure 4 illustrates the response of the aircraft to the elevator trimmer's runaway (taking on the top position), starting at t = 3 s, resulting in a nosedive. However, it can be observed that the pilot effectively corrected the wrong behaviour of the aircraft in such a case for the full range of flight speed. At t = 11 s, the nosedive is stopped by the pilot elevator movement. The pitch angle decrease is stopped, and it starts to increase even with a trim tab at an extreme position. Furthermore, analogous trials performed with roll and yaw motion (trimmers of rudder and ailerons) proved that manual control is possible in case the proposed system fails.

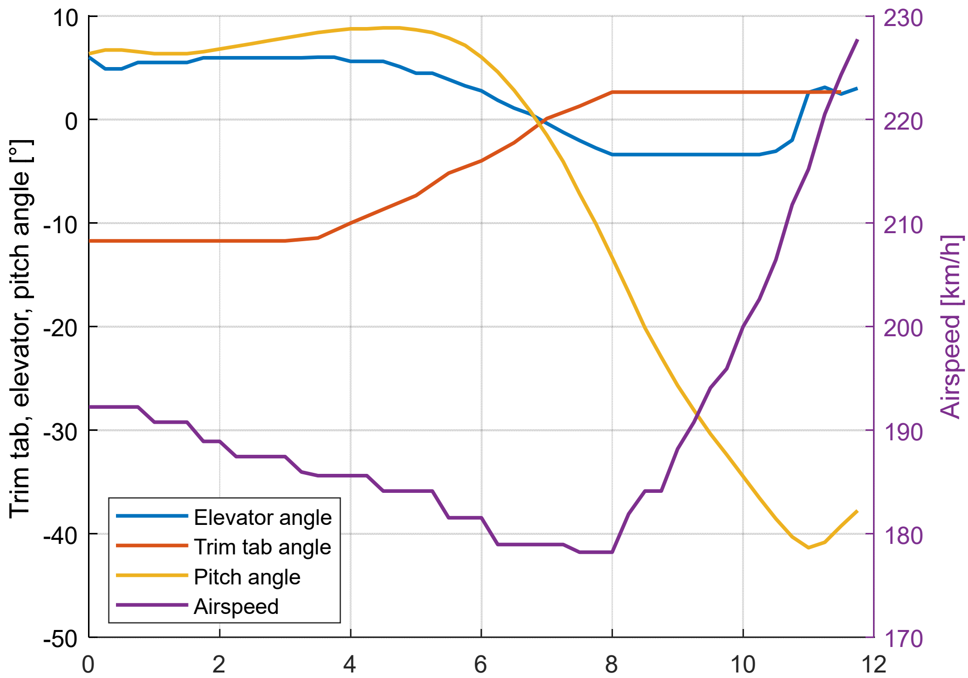

Figure 4. Flight test results of elevator trimmer movement to an extreme position.

3. Methods for Stabilisation System Design and Testing

The design of the stabilisation system was based on a model. The nonlinear 6-degrees-of-freedom aircraft model in cruise flight configuration was developed in the Simulink environment. Its parameters were obtained from manufacturer data and, in the case of aerodynamics, from CFD analysis. At first, the aircraft model was linearised at chosen flight conditions. Then, regulators were designed and initially tuned using classical methods such as Bode plot shaping and modern methods such as linear–quadratic regulator (LQR) tuning. Next, the gains were verified and corrected with a nonlinear aircraft model in simulations at different levels: model in the loop (MiL), and after the hardware was manufactured—hardware in the loop (HiL), using a real-time prototype computer, for which a dedicated test stand was developed [10]. Finally, the model of the stabilisation system developed during previous stages was implemented on an onboard computer [11] using automatic code generation, avoiding the risk of errors present when the model is translated into code by a programmer. Real-time simulation flights allowed for early tests, with the pilot assessing the performance of the designed system. The corrections could be made before ground and flight testing in real aircraft.

The control system presented in Figure 5 has a cascade structure with separated altitude and heading channels [12,13]. It means that the altitude control can be performed entirely by deflection of elevator trimmer δ_{TH}, whereas heading control is provided by deflection of aileron trimmer δ_{TA}. In both cases of pitch angle Θ and roll angle Φ stabilisation (realised in the inner loops), the PID controllers were used to eliminate static error and introduce damping of pitch and roll velocities—Q and P. In outer loops, the PI controllers were implemented. They ensure the elimination of static errors of altitude H and heading Ψ.

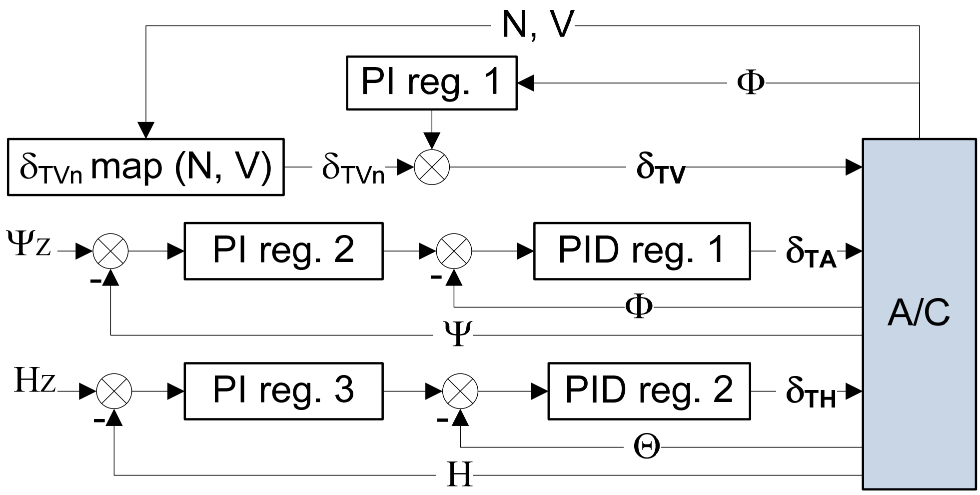

Figure 5. Automatic 3D aircraft stabilisation system.

The third channel controls rudder deflection δ_{TV}. It aims at automatically compensating the undesirable yawing moment stemming from the spiralling slipstream generated by the running propeller and altering the airflow around the aeroplane. This effect is quite complex, and analytical methods of calculating the yawing moment as a function of flight parameters and aircraft configuration (control surfaces and landing gear) fail to provide reliable results. Considering the geometrical features of a specific aeroplane is crucial. Moreover, computational fluid dynamics analyses and costly wind tunnel testing are not sufficient. For these reasons, the only method for spiralling slipstream impact assessment is experimental, which consists in performing flight tests. Figure 6 illustrates the nominal deflection of the rudder trimmer δ_{TNn} that compensates the undesirable yawing moment, valid with regards to the modelled control object, PZL-130 Orlik.

The essential parameters for quantitative assessment of the yawing moment generated by spiralling slipstream are the aircraft velocity V and the power plant thrust N. According to Figure 6, the most significant yawing moment corresponds to flight with minimum velocity and maximum surplus thrust that appears during take-off and landing.

The accuracy of the results presented in Figure 6 is limited due to measurement errors and simplifications that exclude other effects potentially affecting yawing moment. For this reason, the PI controller was chosen for the rudder trimmer control channel. This type of regulator can fully compensate the errors and provide accurate trimming.

Testing methods were described and planned in a test plan. At first, they were mostly focused on the automatic stabilisation system model during simulated flight, then Hardware in the loop simulation, and finally real flight tests. One of the challenges was that the actuator speed used before for manual trimming was much slower than the actuator typically used in aircraft stabilisation systems. The designed actuator nominal angular velocity for automatic stabilisation was 30°/s, while the trimmers used by the pilot in manual mode were at 2.6°/s. The solution to this problem could be to programmatically limit the actuator speed in manual mode and increase it in stabilisation mode or permanently limit the actuator speed mechanically to the slower setting. One of the biggest benefits of the second solution is that it does not need to introduce software changes to the design. Therefore, it was the motivation for conducting tests on how degraded actuator speed affects stabilisation system performance. Scenarios used in those simulation tests are described in the next sections.

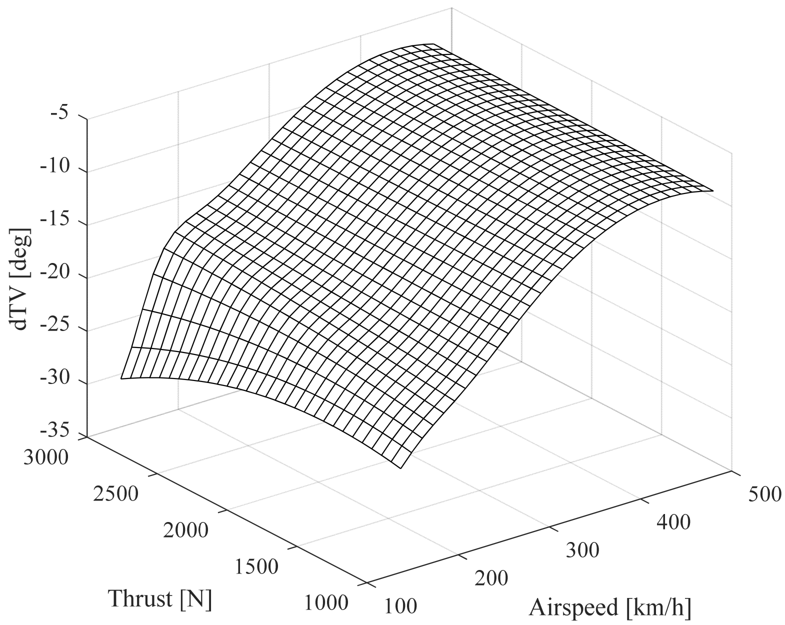

Figure 6. Relation between rudder trim tab deflection compensating slipstream effect, thrust and airspeed.

4. Simulation Results

The model-based design approach allowed for performing simulations with models of system elements before manufacturing. In the case of the flight stabilisation system, those models included trim tab actuators and a control algorithm.

At first, models of trim tab actuators used in the simulation were verified. Commonly used in control system step response testing [14,15], an input of, in this case, 15° amplitude was compared with the response of an actual electrical actuator installed on an aircraft and connected to a trim tab by a rod. Figure 7 shows the achieved results. The speed of the actuator model is the same as the speed of the genuine actuator. There are minor differences at the beginning of the response and when the response is achieving a steady state. These minor differences result in a lag time of 0.05 s between responses. The genuine actuator steady-state value is smaller by 0.2°. Considering the low values of those differences, the model of the trim tab actuator is accurate enough for flight stabilisation system simulations.

After positive verification of trimming actuators, simulation tests of the flight stabilisation system were performed. During the first of the tests, the performance of flight stabilisation was checked with actuators with different speed limits. Three actuators were used during the test—the fastest with speed limits ±30°/s, the middle ±15°/s, and the slowest ±2.6°/s. The presented results show the reactions of the stabilised aeroplane to atmospheric disturbance, which causes a 15°/s step increase in pitch rate for 1 s. After 1 s, that disturbance disappears. Before the disturbance started in the 5th second of the simulation, the aircraft was flying in stabilisation mode at an altitude of 1000 m and speed of 380 km/h. That airspeed value was stabilised during the simulation tests.

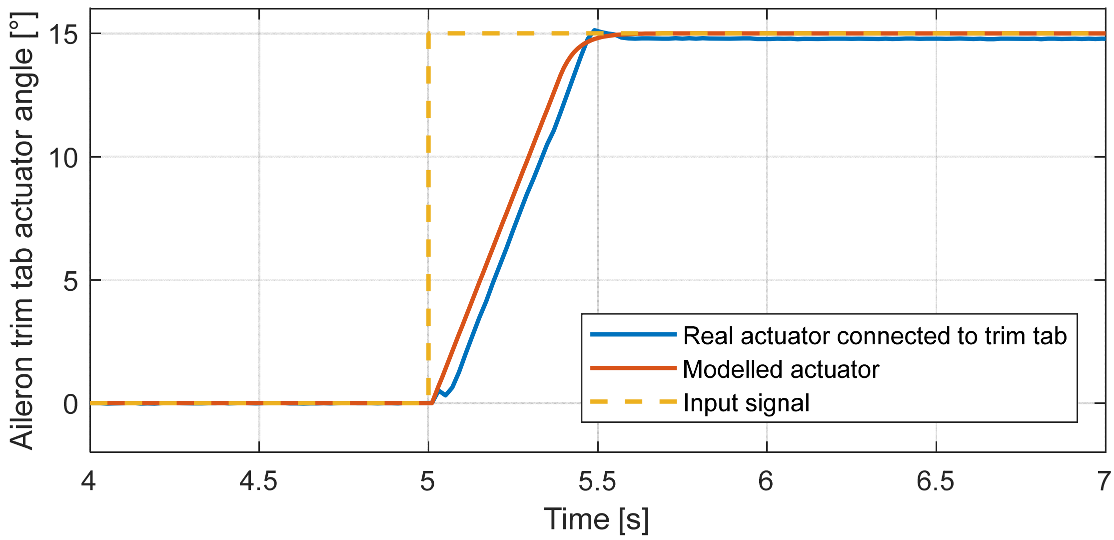

Figure 7. Comparison of the genuine actuator and its model response.

Figure 8 shows how the system stabilizes the altitude with different actuators. The slower the actuator is, the higher the initial loss of altitude after the disturbance: 4 m for the fastest actuator, 9 m for the middle, and 23 m for the slowest—also, the overshoot and settling time increase with decreasing actuator speed. With the fastest actuator, the overshoot reaches 4 m, with the medium, it is 7 m, and with the slowest, 11.5 m. Moreover, with the slowest actuator, overshoot peak happens later: 15 s from the disturbance, compared to 8 s in other cases. Settling time (15 s from the disturbance start) and accuracy (±3 m) are the same with the first two actuators. The third one's settling time is longer (28 s from the disturbance start), but the settling accuracy is in the same range. The shape of responses in steady state is a result of the Dryden wind turbulence model used in the simulation. Pitch angle (Figure 9) at the initial stage after disturbance reached 6.3°, 7°, and 9.3° for the first, second, and third actuators, respectively. The pitch was stabilised for the quickest actuator after 10 s and for the slowest actuator, after 15 s. In the case of the slowest actuator, due to its speed limits, the trim tab angle reached only half of the maximum angle reached by the faster actuators during stabilisation (Figure 10).

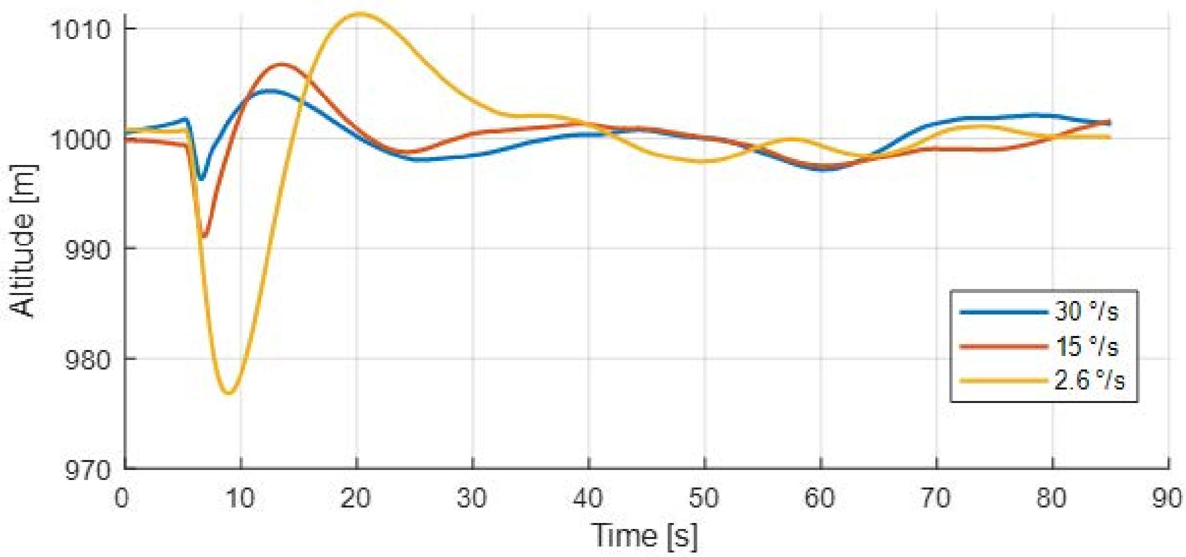

Figure 8. Altitude stabilisation after disturbance in the longitudinal channel.

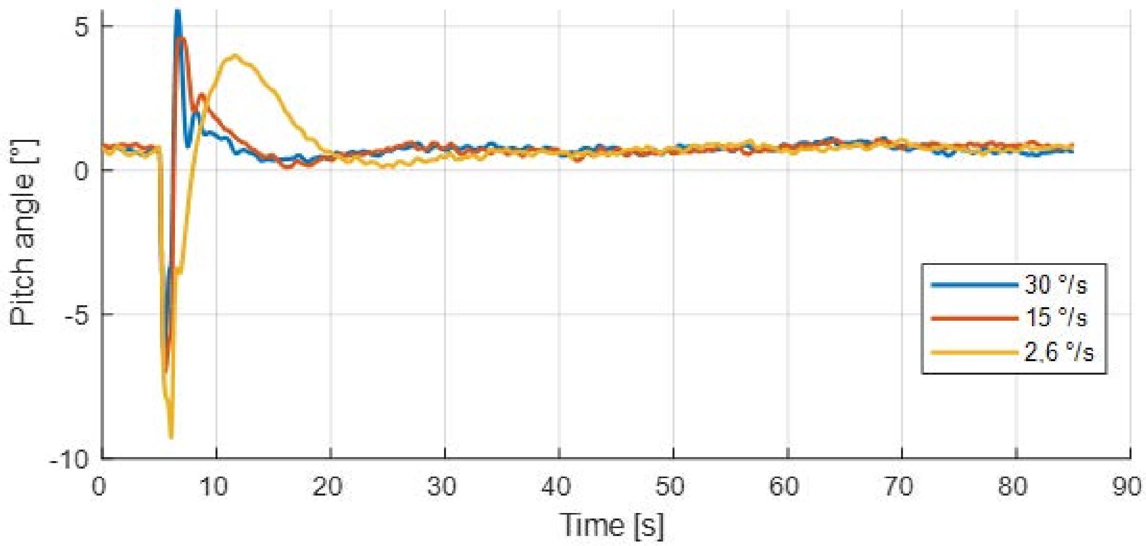

Figure 9. Pitch angle stabilisation after disturbance in the longitudinal channel.

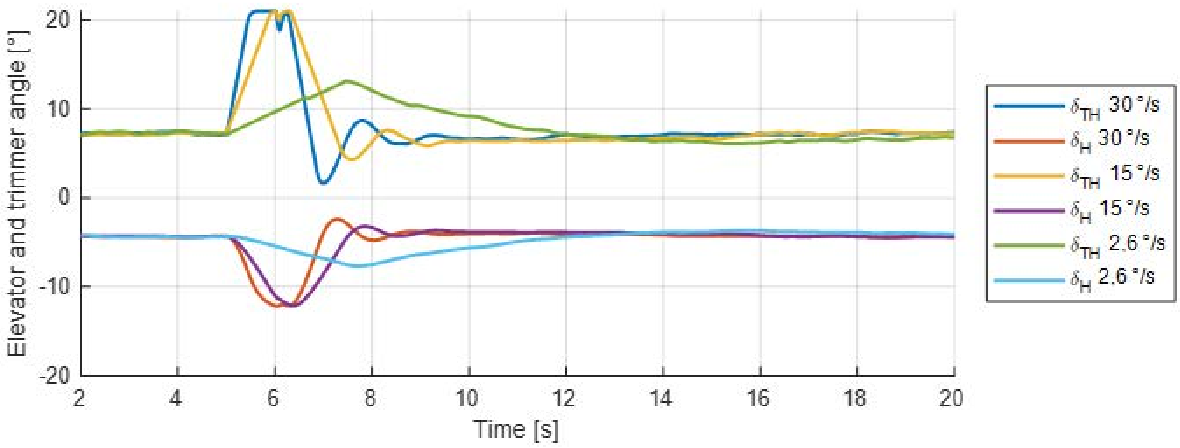

Figure 10. Elevator and trimmer angles during stabilisation after disturbance in the longitudinal channel.

To obtain quantifiable results from the comparison of these three cases, and later, to compare it with the second scenario where disturbance acts in the roll channel, a performance measure can be chosen. To assess the performance of the stabilisation system, an integral square error measure was applied [16]:

$$J = \int_{t_0}^{t_k} {H_e}^2 dt \tag{4}$$

where J—performance measure, t_0—start time of the simulation, t_k—end time of the simulation, and H_e—altitude error.

Results are shown in Table 1. For easier comparison, values were divided by the smallest achieved J value (best stabilisation performance). The best performance according to the chosen measure was achieved by the fastest actuator. The use of a medium-velocity actuator by the stabilisation system degraded its performance by a factor of 1.72. It was observed that the relationship is not linear because of a bigger drop in stabilisation performance with the slowest actuator. The performance measure loss is almost 13 times bigger for the slowest actuator than for the fastest.

Table 1. Integral square error values—longitudinal channel.

Actuator Speed Limit	J/Jmin
±30°/s	1.00
±15°/s	1.72
±2.6°/s	12.86

The lateral stabilisation channel that uses the aileron trim tab to stabilize aircraft heading was evaluated in the second scenario. In this case, atmospheric disturbance caused a 15°/s roll rate for 1 s. Figure 11 shows the results of aircraft heading stabilisation when the system is affected by such disturbance. The actuators compared in these simulations were the same as in the previous scenario. In all cases, the heading was stabilised, but the initial heading change was 40% greater for the slowest actuator. Heading rise time is 1 s faster and 4 s faster when we compare the fastest actuator with the medium and slowest one. The peak overshoot of about 1° happens after 25 s from the beginning of disturbance for all three cases. Settling time and settling accuracy are also similar.

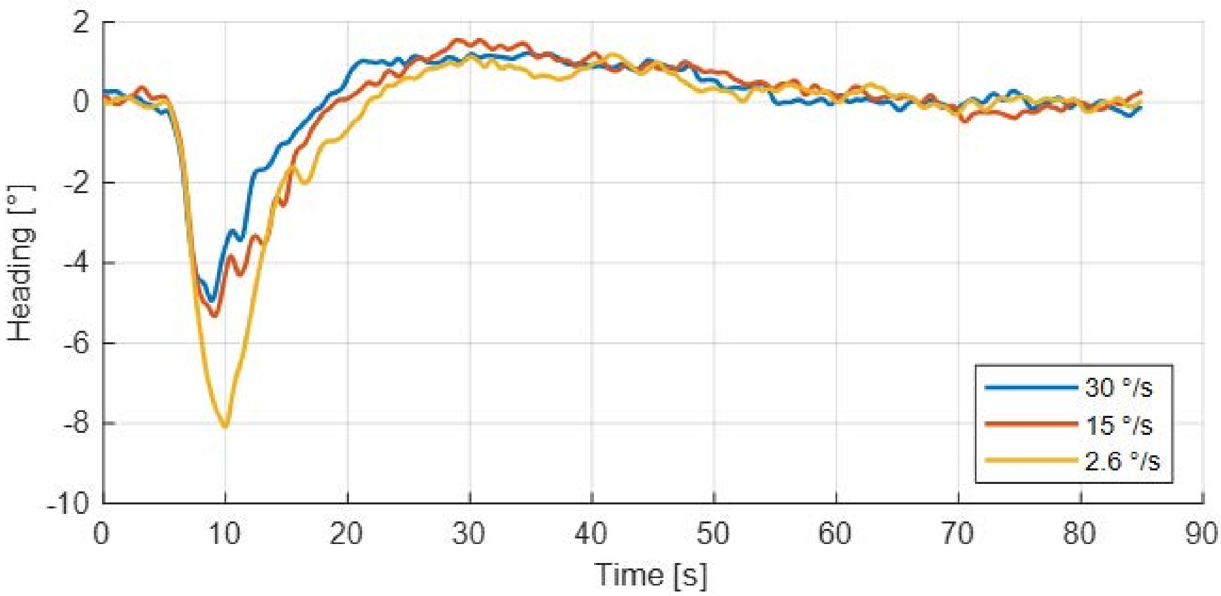

Figure 11. Heading stabilisation after disturbance in the lateral channel.

The performance measured by integral square error (Table 2) shows that it decreases with decreasing actuator speed. Again, the best stabilisation performance was achieved with the fastest actuator, but there are differences in the level of degradation for the lower-velocity actuators compared to the previous longitudinal scenario. Stabilisation performance degrades by 1.42 with the medium-velocity actuator, which is 17.4% less than in the longitudinal case. What is more significant, the difference between the fastest and the slowest actuator is 2.39 times lower. Thus, the performance of stabilisation in a lateral channel is much less affected by the slowest actuator.

Table 2. Integral square error values—lateral channel.

Actuator Speed Limit	J/Jmin
±30°/s	1.00
±15°/s	1.42
±2.6°/s	2.39

5. Conclusions

The possibility to stabilize/control an aircraft by coordinated deflections of trimming surfaces is a beneficial alternative for solutions currently used in more complex, direct, fly-by-wire autopilot systems. Analysis of the presented results of the flight stabilisation system performance assessment allowed us to decide on whether to use the lower speed actuator in both manual and stabilisation mode or to programmatically change the actuator speed—higher speed for stabilisation mode, lower for manual mode. Because stabilisation performance is highly degraded with the slowest actuator ($\pm 2.6^\circ$/s velocity), by a factor of 12.86 in the case of altitude stabilisation and 2.39 in the case of heading stabilisation, the programmatic solution was chosen. In stabilisation mode, the actuator velocity is kept at $\pm 30^\circ$/s, while in manual mode the velocity is changed to $\pm 2.6^\circ$/s. This solution ensures the highest stabilisation performance and fulfils the pilot's requirement in manual mode. Additionally, it can be confirmed that the responses of the trim tab actuator models used in simulations match real actuator responses, with a minor difference of 0.05 s lag. At this stage, the real actuator data used for comparison were gathered in a lab without airloads. Comparison with airloads will be published after the final flight test campaign. A series of presented simulation tests carried out proved the following benefits (as well as questions) that appeared due to the application of the presented system:

- The performance measure is highly degraded by the slower actuator speeds, although altitude and heading are finally stabilised in all cases.
- Performance of stabilisation in a lateral channel is less affected by the slowest actuator than in a longitudinal channel. This indicates that the aileron and its trim tab have higher effectiveness than the elevator.
- In the case of the slowest actuator, due to its speed limits, the trim tab angle reaches only half of the maximum angle reached by the faster actuators during stabilisation.
- It should be decided whether the sensitivity of the stabilisation process to disturbances caused by turbulence has to be reduced, as it will reduce loads exerted on servomechanisms.
- A flight test campaign of the stabilisation system is planned. Its result will be used in the verification of simulation results.

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