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Next-generation more electric aircraft control system

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Abstract

One of the areas of changing the current aircraft into the more electric one is diminishing 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 stabilizing its flight with trimmers.

Previous research on the cost-effective and less electrical energy consuming automatic stabilization system 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 stabilization system retrofit. 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 stabilization 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 results. First, computational unit software was prepared for porting automatically generated code from the Simulink model containing system state machine and control model previously tested in simulations including Model, Pilot and Hardware in the Loop. Next, hardware was prepared and tested to meet the DO-160G environmental and electrical conditions and restricted electromagnetic compatibility tests. Finally, after Hardware in the Loop laboratory tests, onboard computer ground tests were performed.

Keywords: flight tests, automatic flight stabilization system, trim tab, trim system

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, like flaps, slots, and airbrakes, only change the aerodynamic characteristics during take-off and landing. In contrast, primary flight control surfaces, 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, they aim to find what could be done to operate the primary control surfaces more efficiently regarding power consumption.

It can be assumed in a conventional aircraft that the $I_x{:}I_y{:}I_z$, the ratio of the principal moments of inertia in a body-fixed coordinate frame, regardless of its MTOW, is as 1:2:3. Moreover, all the aerodynamic moments created by control surfaces arise due to aerodynamic forces acting on similar moment arms. If this is the case, why are the ailerons, rudder and elevator of a similar area? First, the ailerons must provide required lateral dynamics and control; hence their area cannot be too small. Second, the primary role of the rudder is a compensation of the yawing moment stemming from the spiralling slipstream generated by the running propeller or compensation of the yaw effect of asymmetric thrust in the case of engine failure at multi-engine aircraft.

In conclusion, energy optimization in a control system consists of developing an alternative, energyefficient method for primary control surfaces deflection. For this purpose, trim tabs may be used. These tabs counteract aerodynamic forces and control the aircraft. They also compensate the incorrect balance when the centre of gravity moves due to improper aircraft loading, fuel consumption or slipstream. All these factors generate additional undesirable moments of force. Trim tabs compensate 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 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.

In the proposed system, 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 autopilot's servomechanisms eventually yields relatively high prices compared to the rather simple servomechanisms used in trimming systems.

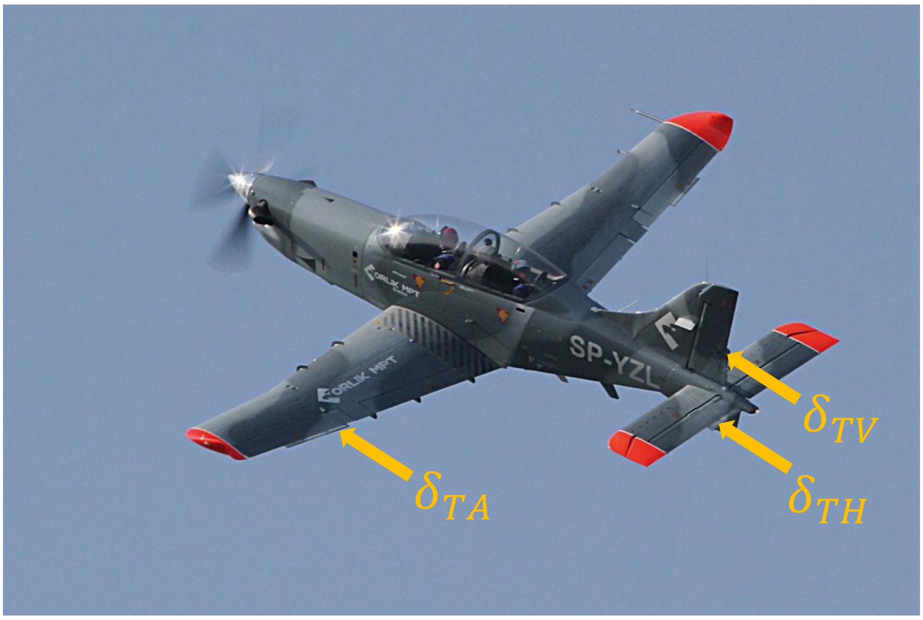

Figure 1 - Trim tabs location on PZL-130 Orlik aircraft.

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 stabilization, 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 the 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 yoke lowered, 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 [4, 5, 6]. 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. Furthermore, an analysis of the results obtained during the in-flight tests made it possible to determine the transition functions (1), (2) and (3) that describe the relationship between the values of the ailerons, elevator and rudder deflections caused by the deflections of the adequate trimming surfaces.

$$\delta_H = \frac{-0{,}6}{0{,}25s+1}\delta_{TH} \tag{1}$$

$$\delta_A = \frac{-0{,}42}{0{,}25s+1}\delta_{TA} \tag{2}$$

$$\delta_V = \frac{-0{,}75}{0{,}3s+1}\delta_{TV} \tag{3}$$

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, s – Laplace operator.

Failure cases of the proposed system consisted in incorrect positioning of the trimmer's surface at its maximum, or minimum angle limit were also investigated during the flight tests. For example, Figure 2 illustrates the response of aircraft to the escape of the elevator's trimmer (taking on the top position), resulting in a nosedive. However, it can be observed that the pilot effectively corrected the wrong behaviour of aircraft in such a case for the full range of flight speed. In 11th second the nose dive is stopped by the pilot elevator movevement. Pitch angle decrease is stopped and its starts to increase even with trim tab at 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.

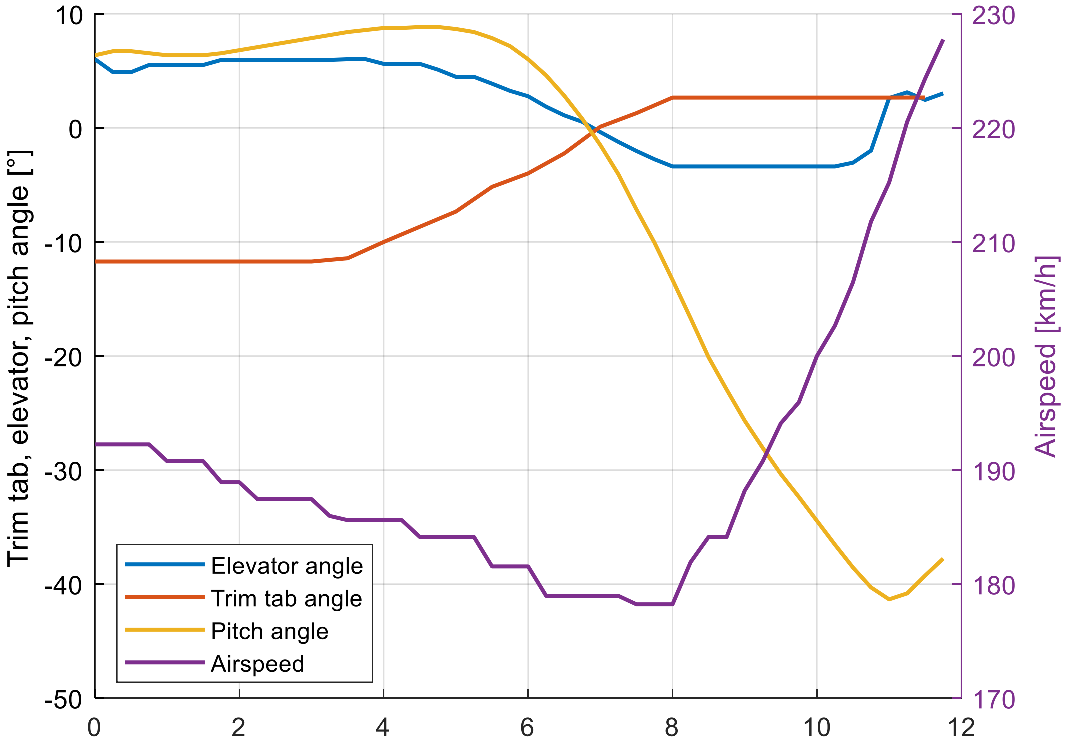

Figure 2 – Flight test results of elevator trimmer movement to an extreme position.

3. Methods for stabilization system design and testing

The design of the stabilization system was based on a model. The aircraft model 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 linearized at chosen flight conditions. Then, regulators were designed and initially tuned using classical methods like Bode plot shaping and 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 real-time prototype computer, for which a dedicated test stand was developed [7]. Finally, the model of the stabilization system developed during previous stages was implemented on an onboard computer using automatic code generation. 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.

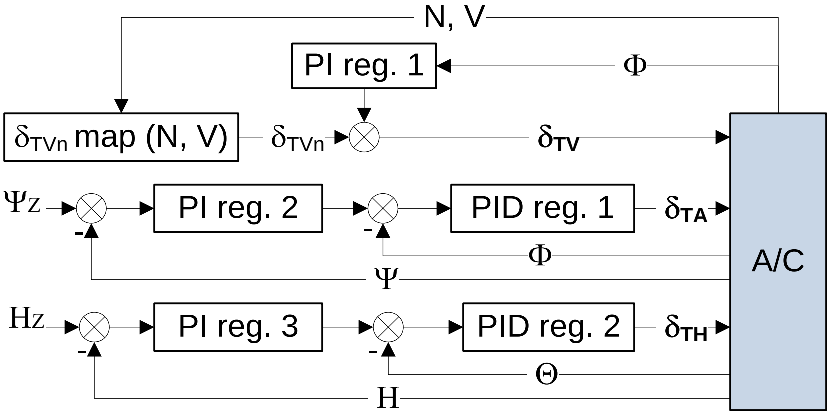

Figure 3 - Automatic 3D aircraft stabilization system.

The control system presented in Figure 3 has a cascade structure with separated altitude and heading channels [8]. 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 stabilization (realized 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.

The third channel controls rudder deflection δ_{TV}. It aims at compensating automatically 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 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 consist in performing flight tests. Figure 4 illustrates the nominal deflection of the rudder trimmer δ_{TNn} that compensates the undesirable yawing moment valid concerning the modelled control object PZL-130 Orlik.

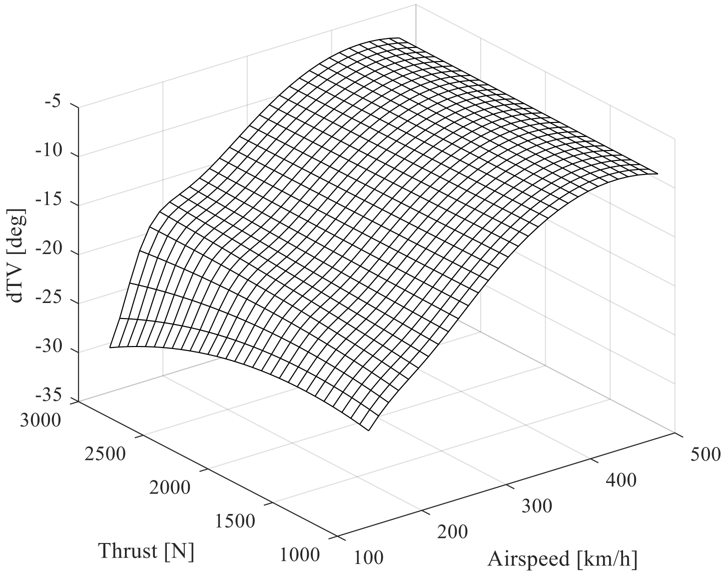

Figure 4 - Relation between rudder trim tab deflection compensating slipstream effect, thrust and airspeed.

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 4, 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 4 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.

4. Simulation results

At first, models of trim tab actuators used in the simulation were verified. Commonly used in control system testing step response [9, 10] input of, in this case, 15° amplitude was compared with the response of an actual actuator installed on aircraft and connected to trim tab by a rod. Figure *5* shows 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 stabilization system simulations.

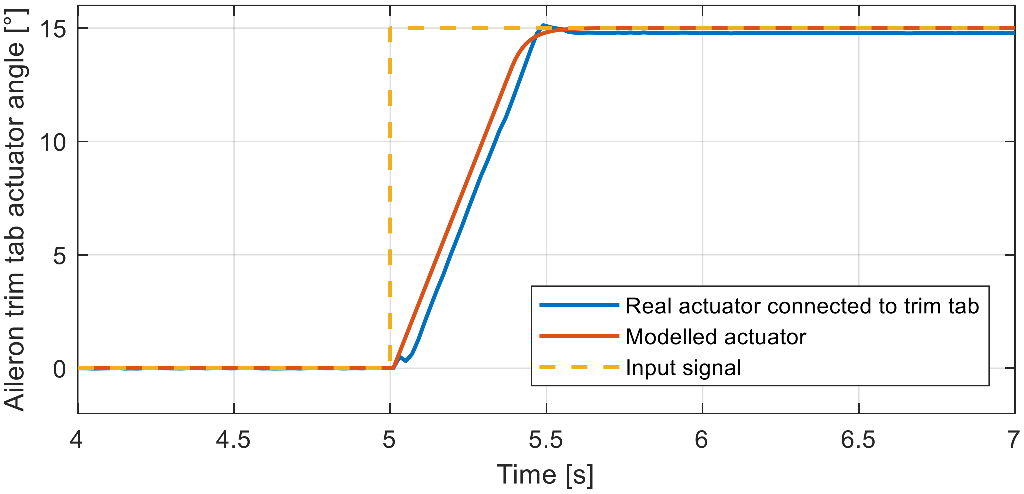

Figure 5 – Comparison of the genuine actuator and its model response.

After positive verification of trimming actuators, simulation tests of the flight stabilization system were performed. During one of the tests, the performance of flight stabilization was checked with actuators with different speed limits. Three actuators were used during that test — the fastest with speed limits ±30°/s, the middle ±15°/s and the slowest ±2,6°/s. Presented results show the reactions of the stabilized aeroplane to atmospheric disturbance, which causes a 15°/s step increase of pitch rate for 1s. After a 1s, that disturbance disappeared. Before the disturbance started in the 5th second of simulation, the aircraft was flying in stabilization mode at an altitude of 1000 m and speed of 380 km/h. That airspeed was stabilized at this value during the simulation tests.

Figure 6 shows how the system stabilizes the altitude with different actuators. The slower the actuator is, the higher the initial loss of altitude after disturbance: 4 m for the fastest actuator, 9 m for the middle, and 23 m for the slowest — also, the overshoot and settling increase with decreasing actuator speed. The shape of responses in steady-state is a result of the Dryden wind turbulence model used in the simulation. Pitch angle (Figure 7) at the initial stage after disturbance reached 6,3°, 7° and 9,3° for the first, second and third actuator, respectively. Pitch was stabilized 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 reaches only half of the maximum angle reached by the faster actuators during stabilization (Figure 8).

To assess the performance of the stabilization system integral square error measure was applied [11]:

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

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

Results are shown in Table 1. Their values were divided by the smallest achieved J value (best stabilization performance). 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 / J_{min}
±30°/s	1,00
±15°/s	1,72
±2,6°/s	12,86

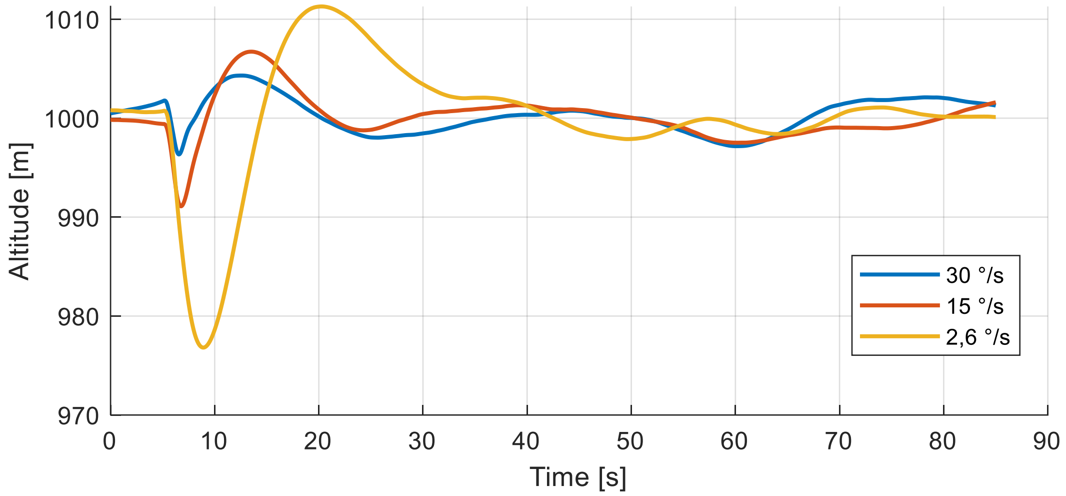

Figure 6 – Altitude stabilization after disturbance.

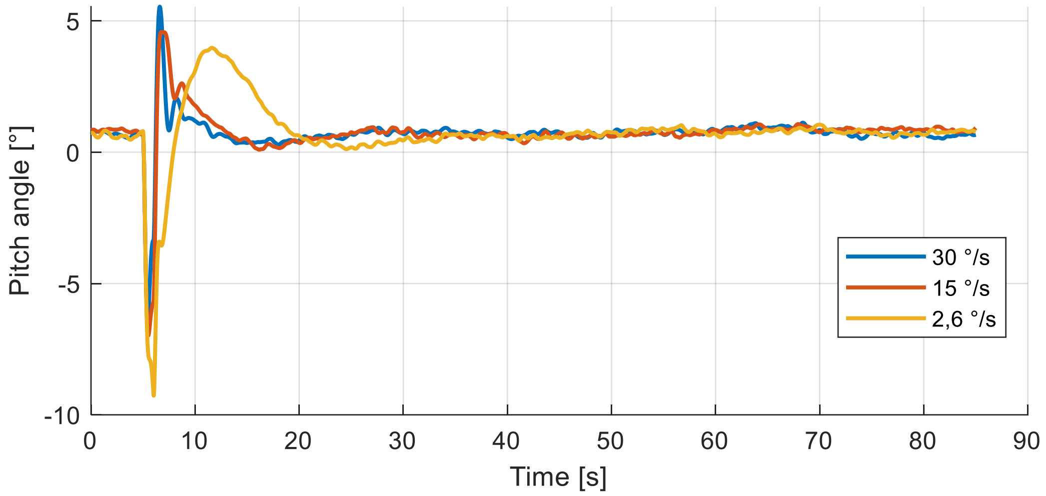

Figure 7 – Pitch angle stabilization after disturbance

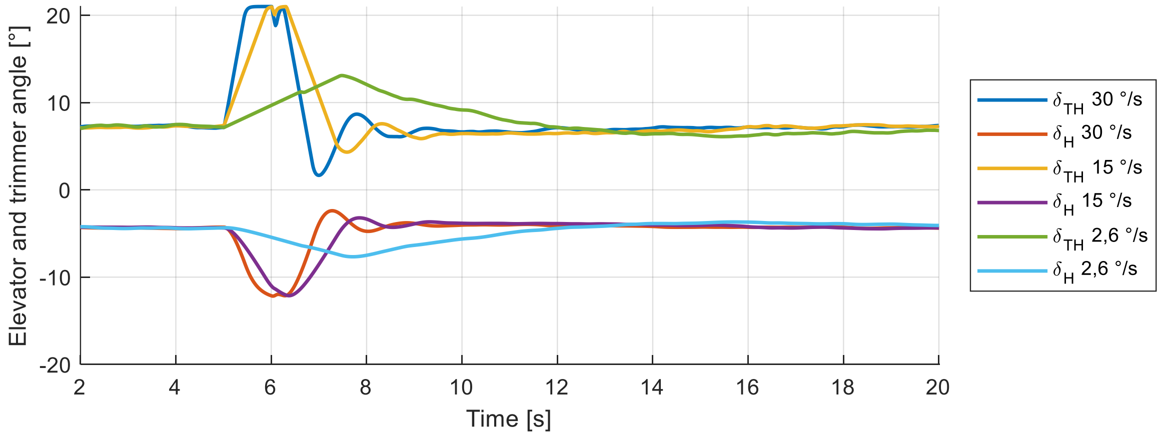

Figure 8 – Elevator and trimmer angles during stabilization.

The lateral stabilization channel that uses the aileron trim tab to stabilize aircraft heading was tested in the second scenario. In this case, atmospheric disturbance caused a 15°/s roll rate for 1 s. Figure 9 shows the results of aircraft heading stabilization when the system is affected by such disturbance. Actuators compared in these simulations were the same as in the previous scenario. In all cases, the heading was stabilized, but the initial heading change was 40% greater for the slowest actuator. The performance measured by integral square error (Table 2) shows that it decreases with decreasing actuator speed. The difference between the fastest and the slowest actuator is over five times lower than in the longitudinal channel. Thus, the performance of stabilization in a lateral channel is less affected by the slowest actuator.

Table 2 – Integral square error values – lateral channel

Actuator speed limit	J / J_{min}
±30°/s	1,00
±15°/s	1,42
±2,6°/s	2,39

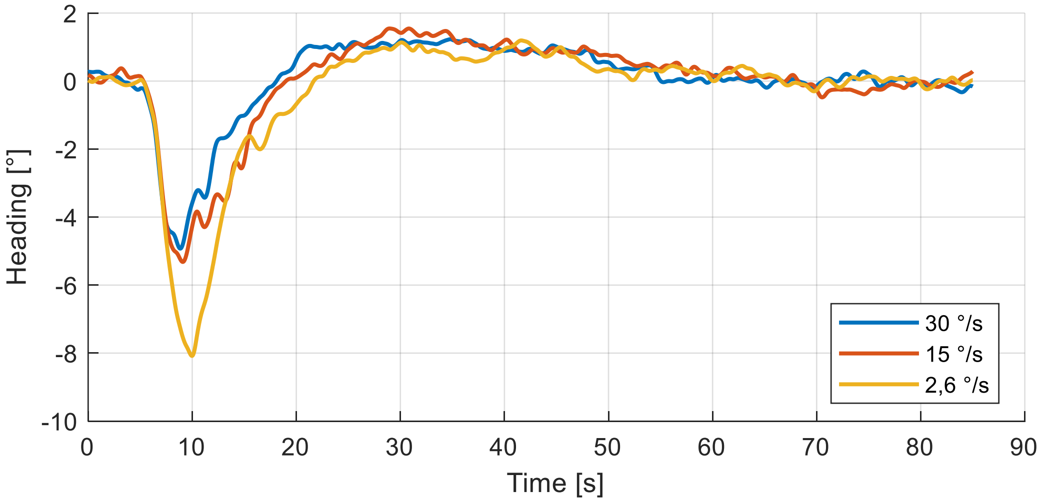

Figure 9 – Heading stabilization after disturbance.

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. In particular, a series of complex simulation tests carried out, HIL tests and ground tests proved the following benefits (as well questions) that appeared due to the application of the presented system:

- Trim tab flight stabilization system is capable of automatical 3D control of the aircraft motion, even in scenarios typical for autopilots;
- Simple servomechanism structure compared to this used in autopilots allows manual trimming of primary flight control surfaces and automatic control of flight;
- It should be decided whether the higher speed of the trim servos applied for the automatic control process does not hinder the manual trimming of the aeroplane executed by the pilot;
- It should be decided whether the sensitivity of the stabilization process to disturbances caused by turbulence has to be reduced, as it will reduce loads exerted on servomechanisms.

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