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TRIMMING SURFACES IN THE AUTOMATIC PLANE CONTROL PROCESS

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Abstract

The directions and speed of development of plane avionics systems are determined by three factors: economical consideration, required safety levels, and optimized working conditions for the pilot. This article presents the concept of a system in which the automatic control and stabilization process is effected because of coordinated deflections of trimming surfaces: the rudder, the elevator, and the ailerons. In particular, this article presents the structure of the system in the longitudinal movement steering channel by way of deflection of the trimmer of the elevator. Furthermore, it discusses the results of numerical model simulations, which are compared to the results obtained during in-flight tests. Additionally, this article specifies general technical requirements for the servomechanisms intended for the system class discussed herein.

Selection of sufficiently large amplification makes control the plane with relatively small deflections of the trimmer. In particular, relationship between the deflection of the elevator and the deflection of trimmer, view of a tail plane and dimensions of the elevator trimmer, the structure and results of the pitch angle control system and simulation are presented in the article.

Keywords: *optionally piloted airplane, automatic control system, trimming, trim control system*

1. Introduction

The purpose of balancing surfaces, which are commonly referred to as trimmers, is aerodynamic balancing of the plane and to compensate the consequences of its improper weight distribution (longitudinal and transverse) that may be due, for example, to incorrect placement of the cargo. Both factors affect the plane by generating undesirable moments of forces. The essential role of the trimmers is to balance these moments of forces, thus causing a reduction of the forces that the pilot has to exert in the process of operation of the control instruments. Trimmers are present in the pitch, yaw, and roll channels being elements of the control system. In practice, the technical solution related to trimmers consists of fitting the plane's control surfaces with additional elements: control surfaces whose rotation makes an aerodynamic impact on the control surface, thus causing its equivalent deflection. Fig. 1 shows an example system of trimmers – ailerons, elevator, and rudder – of the PZL-130 Orlik plane. The solution shown in Fig. 1 is the most advanced and enables trimming the plane in both the transverse and longitudinal channels. . In the case shown here, the role of the trimmer of the rudder is to balance the non-symmetrical deflecting moment caused by the strong air stream behind the propeller [1], which is generated by the drive system, namely a high-power turbo propeller engine. In other technical solutions, there are less advanced systems that act only on the elevator or on the elevator and the ailerons. The selection of a specific control system, on the one hand, depends on the aerodynamic properties of the plane and, on the other hand, is a compromise between the cost of the equipment and the expectations of the pilot – operator of the aircraft.

The remaining part of the article discusses only planes with full trimming systems, i.e. systems that enable trimming in the longitudinal channel and in the transverse channel, using trimmers that act on the following control surfaces: ailerons, rudder, and elevator. In particular, this article discusses the concept of expanding the functional properties of the trimming system by adding a new function of stabilization of selected flight parameters.

Fig. 1. PZL-130 Orlik with marked trimming surfaces

2. Dynamic properties of the controlled object

For the purpose of design of automatic flight control systems intended for small and mid-sized civilian planes, particularly useful are requirements related to dynamic properties, such as those imposed on the largest military planes belonging to class III. In the case of the latter planes, it is assumed that for flight categories B and C [2], namely take-off, cruise, and landing, depending on the involvement of the pilot – operator [2] (levels 1, 2, and 3), a roll angle equal to 30° should be achieved after 2 to 6 seconds. These values appear to conform to the assumptions mentioned in the specification CS-23.157 [3], according to which in the take-off and approach to landing phases, depending on the weight of the plane, when the control surfaces are used in an optimized manner, it must be possible to change the roll angle in the range of -30° do +30° in 4 to 10 seconds.

The compiled requirements apply to manoeuvring flights. The characteristics of flights performed in an automatic mode, where an autopilot controls the plane, are a little different. In such flights, a majority of the flight phases are stable ones; they are combined with transient phases that can be performed in less demanding regimes with regard to both angular speed and limit spatial orientation angles of manoeuvres.

A comparison of the existing technical solutions of various systems (e.g. GFC 700 Automatic Flight Control System) leads to the conclusion that the value of plane orientation angles in automatically controlled flights should be within the ranges specified in Tab. 1 below.

Tab. 1. The assumed permissible spatial orientation of a class CS-23 plane during an autopilot flight

Angle of rotation/orientation	Autopilot's limit
Pitch angle Θ	$+20^{\circ}$ to -15^{0}
Roll angle Φ	$\pm 25^{\circ}$

Sometimes the limits specified in Tab. 1 are reduced even further. For example, in the True Track autopilot, it is assumed that, depending on the selected control mode (Low, Medium, or High); the maximum values of the roll angle Φ of a plane controlled by the autopilot may have the following values: ±12.5°, ±19°, or ±25°.

3. Concept of plane control using trimmers

In a standard plane control system with a biaxial autopilot, flight in the automatic mode is controlled by way of coordinated deflections of the ailerons, the elevator and, in some cases, additionally the rudder. The movements of the control surfaces are controlled by the servomechanisms installed in the manual control system that constitute its integral part. This fact imposes certain requirements on the functional solutions used in the design of the servomechanisms. In addition to such operating parameters as available force or moment of force, range and speed of rotation or movement, the servomechanisms used in autopilots should:

- make it possible, at specific times, to connect/disconnect the device to/from the control system, and
- make it possible for the pilot to control the plane in a manual mode with the device switched on.

The aforementioned functionalities of servomechanisms of aviation autopilots require that their designs include such elements as a mechanism that enables connecting/disconnecting the device to/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 event of a failure of the autopilot system. The complex design of the servomechanisms eventually results in their relatively high prices compared to the rather simple servomechanisms used in trimming systems.

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 complex plane trimming system that acts on the main control surfaces. The possibility to design such a system depends on two factors.

The first is appropriate size of the relative (compared to the inertia of the object) angular speed with which the servomechanism deflects the trimmer flap. If the 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 properly to perform the trimming process in the manual mode. This contradiction can be eliminated by either performing the trimming process only in the automatic mode or assuming the highest trimmer flap deflection speed that, on the one hand, enables proper performance of the trimming process and, on the other hand, ensures correct operation of the control system.

The second factor that ensures correct operation of the proposed system is appropriate effectiveness of the trimmer system, defined as deflection of a control surface as a function of 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 determination of the hinge moment coefficients carry a high probability of error [4, 5]; 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 plane. The tests consisted of recording the deflections of the elevator, shown in Fig. 2, which took place as a result of deflection of its trimmer during a flight with the yoke lowered.

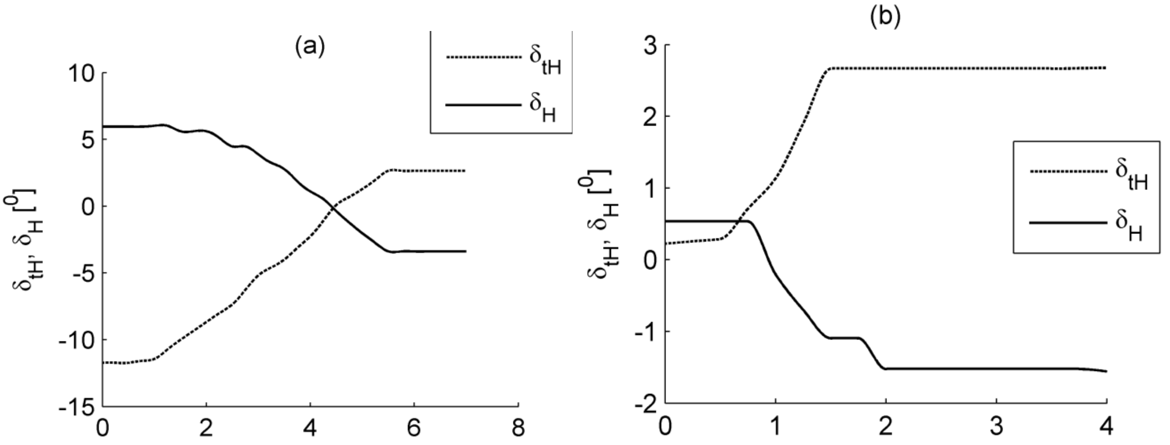

Fig. 2. Deflections of the elevator as a result of deflection of the trimmer tab: a) V_0=187 km/h, H_0=3,030 m, θ_0=7°, b) V_0=350 km/h, H_0=2.913 m, θ_0=0°

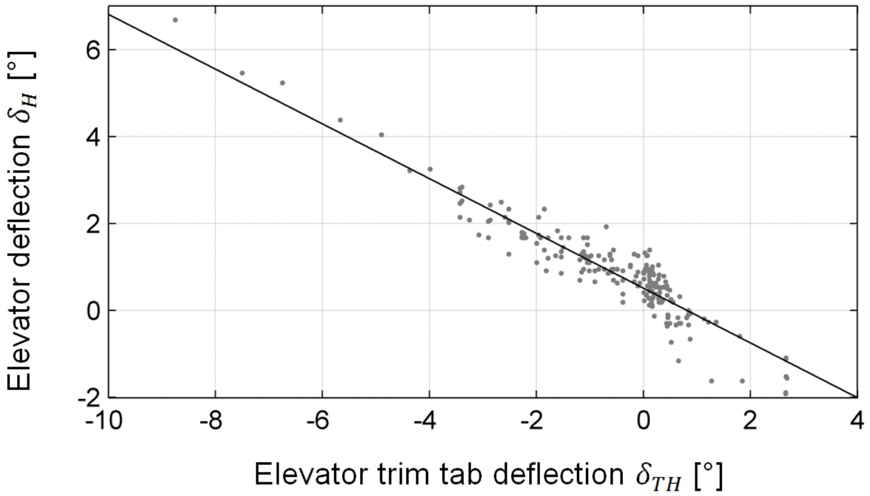

Fig. 3. Relationship between the deflection of the elevator and the deflection of its trimmer

An analysis of the results obtained during the in-flight tests made it possible to determine the transition function that described the relationship between the values of the elevator deflection caused by the deflection of the trimmer surface. The data shown in Fig. 3 was approximated to a linear function using the least squares method. No noticeable impact was observed in the angle of attack, the normal gravity load, and the flight speed on the determined relationship; consequently, the relationship between the value of elevator deflection and the trimmer deflection can be considered as a linear relationship.

$$\delta_{\mathrm{TH}} = \frac{C_{\mathrm{H}\delta_{\mathrm{H}}}}{C_{\mathrm{H}\delta_{\mathrm{TH}}}}\ \delta_{\mathrm{H}} = \mathrm{k}\delta_{\mathrm{H}}, \tag{1}$$

where:

$C_{\mathrm{H}\delta_{\mathrm{H}}}$ – the coefficient of elevator hinge moment in relation to the elevator angle of deflection,

δ_{H} – the elevator angle of deflection,

$C_{\mathrm{H}\delta_{\mathrm{TH}}}$ – the coefficient of elevator hinge moment in relation to the trimmer deflection,

δ_{TH} – the trimmer deflection angle.

Relationship (1) takes place within the range of limited trimmer deflection angles, until the streams of air are detached. For example, for the NACA 0009 profile, the trimmer maintains its linearity in the range of ±15° [6].

Based on an analysis of the recorded timelines, the dynamics of the trimmer-elevator system was modelled as the inert element of the I level and eventually the following transition function with operator transmittance was obtained.

$$G_{\delta_{TH}}^{\delta_{\mathrm{H}}}(\mathrm{s}) = (-0.63\delta_{\mathrm{TH}} + 0.51)\ \frac{1}{(0.2\mathrm{s}+1)}, \tag{2}$$

where:

$G_{\delta_{TH}}^{\delta_{\mathrm{H}}}(\mathrm{s})$ – trim tab to elevator transfer function,

s – Laplace operator.

The error between the elevator deflection, calculated using formula (2), and the real deflection recorded during the in-flight tests does not exceed 5% of the full range of elevator deflection. The transition functions for the remaining control surfaces can be determined in the same way by analysing the results obtained during an experiment performed on a real object.

The primary task of trimming systems is to reduce the load on the control surfaces during flights in stable conditions (e.g. during cruise); it is not stabilization or control of the flight. This is achieved by relatively small deflections of control surfaces compared to those used during control, during complex navigation flights [7, 8] or during performance of the functions of the control system that are intended to improve flight safety [9, 10]. In some cases and in specific aircraft, it is possible that a system that is able fully to perform the trimming function is not very effective in the control process. In order to compensate for this problem, one should consider a modification of the transition function to enhance the feedback in the trimmer-control surface system. Assuming that the relationship shown in Fig. 3 is linear and a certain way that aerodynamic forces and moments of forces are generated, this can be done by increasing the trimming surface $S_{TH}(x_{TH}, y_{TH})$, its distance from the control surface rotation axis x_{TH}, or both those things at the same time, as shown in Fig. 4.

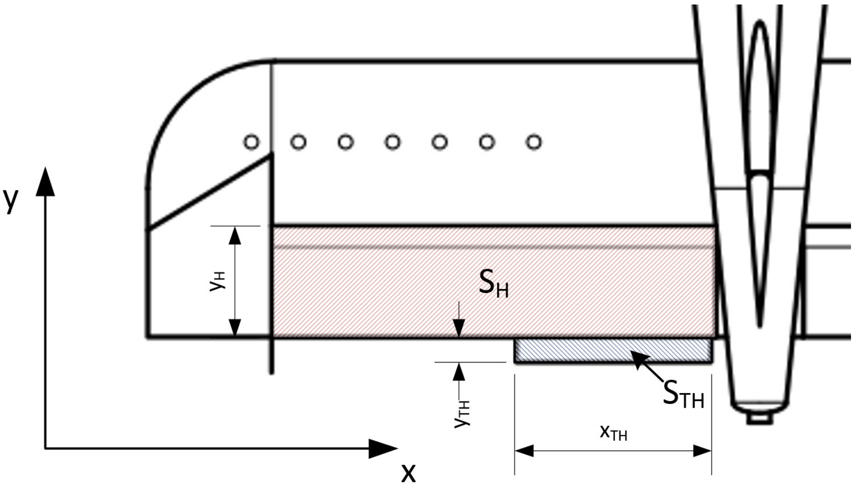

Fig. 4. Top view of a tail plane and dimensions of the elevator trimmer

4. Concept of plane control using trimmers

The controlled object was assumed a PZL 130 Orlik training plane. It was assumed that the plane is a rigid solid with six degrees of freedom, with fixed weight and moments of inertia, which is symmetrical geometrically and weight. The dynamics formulas were determined in the plane's own *Oxyz* system so that *Oxz* is a plane of symmetry of the airframe, and a gravitational $Ox_gy_gz_g$ system related to the Earth with the Oz_g axis directed in accordance with the direction and sense of acceleration due to gravity. In order to perform a synthesis of the pitch angle control system controller shown in Fig. 5, the non-linear model was linearized using the small perturbation theory around the following stable flight conditions: angle of attack α=4°, angle of bank β=0°, flight speed u=83.33 m/s, v=0 m/s, w=-5.83 m/s, flight altitude h=500 m, angular speeds p, q, r=0 °/s, and spatial orientation angles θ=4°, φ=0°, ψ=0°. A cascade structure of the system was assumed, with an internal and external feedback loop [11]. The servomechanism of the actuator system was modelled as an inert component with the time constant of T=0.1 s [12]. The transition function of the servomechanism is defined by relationship (2). An appropriate reserve of the module and the phase was achieved by introducing into the system the PI controller and a feedback from the angular speed of pitch. Eventually, the system's pitch angle control law can be expressed as:

$$\delta_{TH} = \left(K_p + \frac{K_I}{s} \right) (\theta_z - \theta) - G_q q \,, \tag{3}$$

where:

δ_{TH} – the elevator angle of deflection angle,

θ_z – the preset pitch angle,

θ – the current pitch angle,

q – the angular pitch speed, and the calculated amplifications and the filter time constant have

the following values:
G_q=0.1 – pitch rate transfer function,
K_P=0.294, K_I=0.547 – calculated gains.

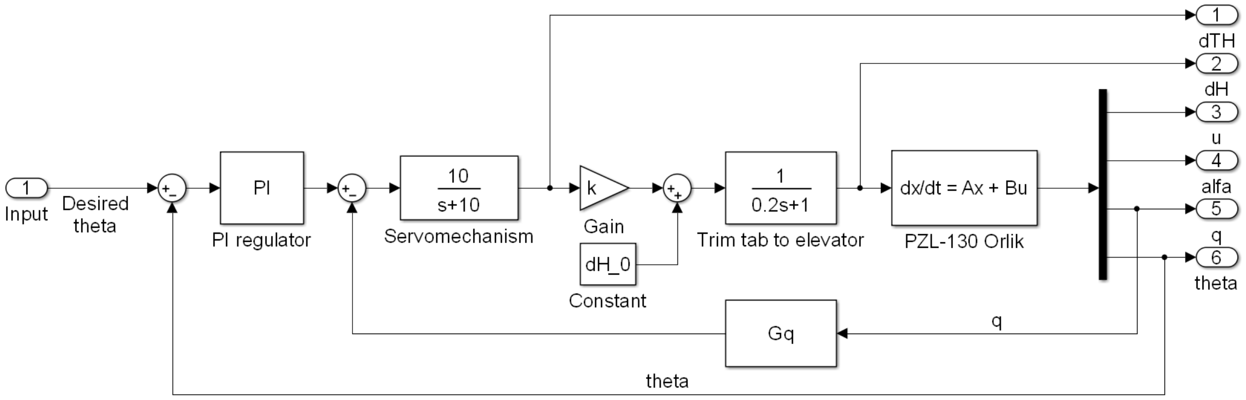

Fig. 5. The structure of the pitch angle control system

5. Model tests

Model tests related to the quality of the pitch angle control were performed using the system shown in Fig. 5 in the MATLAB environment, using a linear model of the PZL-130 Orlik plane. The k=0.63 feedback values of the trimmer-elevator system (2) were assumed to be different than the nominal value and equal to the following three amplification values k=(0.2; 0.63; 1.05), which in practice can be achieved by reducing the current size of the trimmer surface. After an analysis of the Bode diagrams, the analysed amplifications were selected to demonstrate:

- *k=0.1* – the limit value of the *k* coefficient at which poorly dampened natural vibrations of low frequency occur,
- *k=0.63* – the behaviour of a real system present in the analysed plane,
- *k=4.5* – the limit value of the *k* coefficient at which little oscillations occur, which demonstrate that with the preset amplification the system is reaching the limit of stability.

During the simulation tests, in each of the three cases it was assumed that for the start time t=0 s, the current pitch angle θ=0° and the value of the rapidly increasing deviation is equal to Δθ=4°.

An analysis of Fig. 6 leads to the conclusion that in the case of the selected plane, whose technical solutions related to the trimming system are determined, in the longitudinal channel there is a possibility to improve the effectiveness of the proposed control system. Such improvement of the quality of control is manifested most of all in a shorter adjustment time. What is important is that selection of sufficiently large amplification makes it possible to control the plane with relatively small deflections of the trimmer. An obvious consequence of this situation is presence of higher pitch angular speed and a larger angle of attack after the manoeuvre has started.

6. Conclusion

The possibility to control a plane with coordinated deflections of the trimming surfaces is a low-cost alternative to more complex autopilot systems. The research conducted by the authors demonstrates that the proposed technical solution does have some limitations. In the case of certain objects, their dynamic properties, combined with their geometry, causes the control system that uses trimming surfaces to be unstable. An example is an attempt at synthesis of the flight altitude control system for the I-23 Manager plane, which was performed on the SOFIA project [13], where during a model experiment and then during in-flight tests, phugoid movements were observed. On the other hand, the model tests of such a system designed for the PZL-130 Orlik training plane were successful, as demonstrated by the results discussed herein.

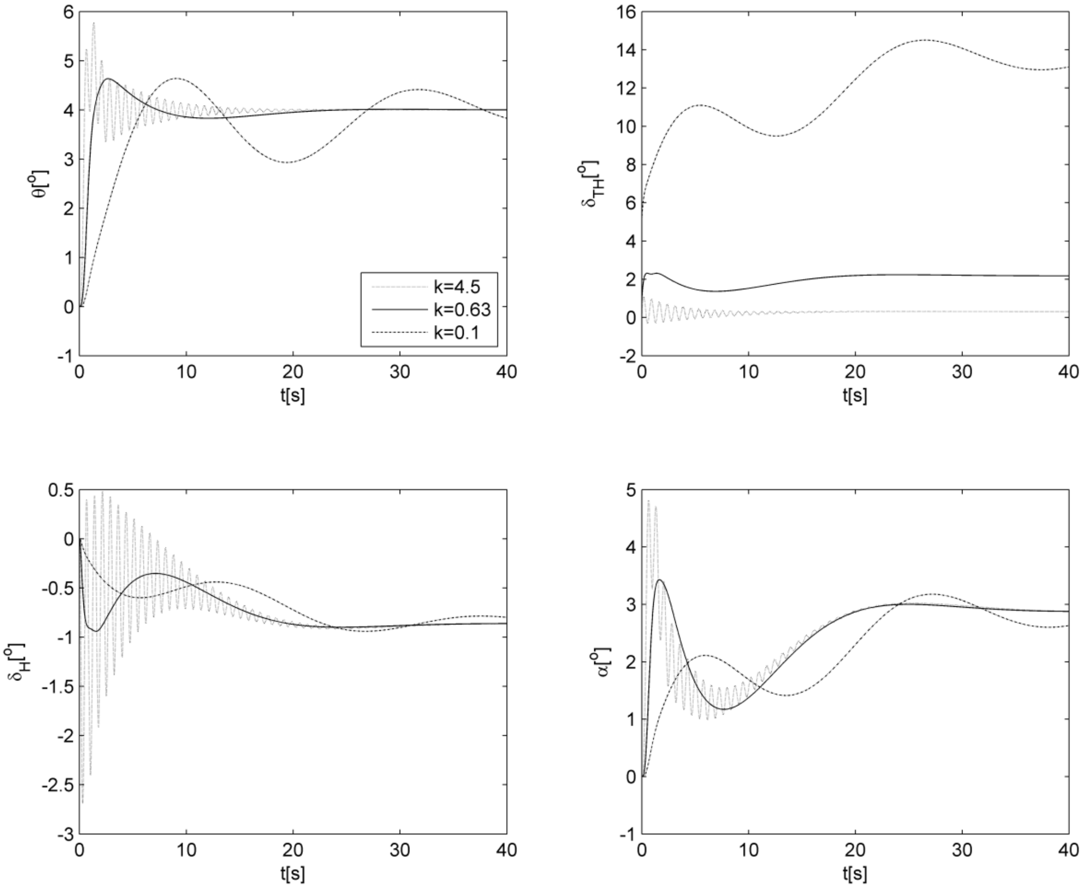

Fig. 6. The results of the pitch angle control simulation

The control system discussed herein is certainly distinguished by the class of the actuator elements used, which are generally less complex than those used in autopilot systems are. The significant difference is due to the fact that they do not require a system that switches on the mechanism and the so-called overload clutch that enables manual control of the plane in the event of a failure of the autopilot system. For obvious reasons, this property makes the solution presented herein competitive compared to a standard one [14, 15, 12], with regard to manufacturing and maintenance costs.

In conclusion, it appears that from the economic point of view the automatic flight control system presented herein can be recommended for use in particular in general aviation planes.

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