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Design and Implementation of a TECS-based Longitudinal Autopilot Architecture

Sebastian Mroginski Kapelius Product Development Engineer, Embraer, São José dos Campos, Brazil. sebastian.kapelius.60892@ga.ita.br
Master of Engineering student, Instituto Tecnológico de Aeronáutica.

Karl Heinz Kienitz Professor, Instituto Tecnológico de Aeronáutica. kienitz.ita@gmail.com

Guilherme Maximiliano Verhalen Product Development Engineer, Embraer, São José dos Campos, Brazil. guilherme.verhalen@embraer.com.br

ABSTRACT

This paper presents the design and implementation proposal of a Total Energy Control System (TECS)-based longitudinal autopilot for a conventional twin-engine commercial aircraft, aiming to reduce the complexity of the Automatic Flight Control System.

The challenge addressed in this work is the prioritization between commanded Flight Path Angle and airspeed, specifically under conditions of thrust saturation. Two TECS-based longitudinal autopilot architectures from the literature are analyzed and compared, and one is selected for the implementation of vertical autopilot modes. The evaluation is done using a nonlinear model of the Research Civil Aircraft Model (RCAM), restricted to longitudinal dynamics. The pitch control innerloop is designed via pole placement, while the outerloop is tuned using parameterized optimization. Highlights are given to nonlinearities introduced in the architecture, such as the automatic mode switching from Path priority to Speed priority, as well as the pitch control authority limitation.

Simulation results demonstrate that TECS is a viable framework for integration into a modern autopilot structure, satisfying industry's performance requirements, while keeping the potential of simplifying the Automatic Flight Control System from the system's and pilot's perspective.

Keywords: TECS, AFCS, Control, Guidance, Longitudinal, Autopilot, RCAM, Mental, Map

Nomenclature

E = Total Energy
L = Energy Distribution
$\dot{E}$ = Total Energy rate
$\dot{E}_{err}$ = Total Energy rate error
$\dot{L}$ = Energy Distribution rate
$\dot{L}_{err}$ = Energy Distribution rate error
Kep = Proportional Energy Distribution rate error gain
Kei = Integral Energy Distribution rate error gain

Ktp = Proportional Total Energy rate error gain
Ktp = Integral Total Energy rate error gain

1 Introduction

Modern Automatic Flight Control Systems (AFCS) are complex systems that evolved incrementally, incorporating automatic modes of climb, cruise, descent, take-off, go-around, and landing. As a result, AFCS became increasingly complex. Since the Flight Path Angle (FPA) and airspeed control capabilities were replicated in various flight control computers (Flight Control Computer, Autothrottle, and Flight Management Computer), there is a significant functional overlap in those computers [1]. Despite this complexity, AFCS are often deemed non-flight-critical, under the belief that pilots will detect any malfunction and intervene manually [2]. However, this requires active pilot monitoring and an accurate mental model of the system, which is not always the case. Discrepancies between human comprehension and the real state of the system can lead to "automation surprises" and even to Loss of Control (LOC) [3], [4], and [5]. Some accidents illustrate this risk: The crew of a Boeing 777, Asiana Airlines Flight 214 [6], and of an Indian Airlines Airbus A-320 [7], both in approach, suffered from mode confusion, leading to inadequate crew response. These events motivated recommendations to reduce the complexity of the automatic flight systems.

The main objective of this work is to study an unconventional approach to designing the AFCS using the Total Energy Control System (TECS), with a focus on the longitudinal modes. TECS is an energy-based method for integrating FPA and airspeed control. This architecture potentially reduces AFCS complexity by centralizing all automatic control modes within the FCC, thereby eliminating functional overlap [1]. The feasibility of TECS as a basis for simplified AFCS design is explored. This structural simplification is expected to reduce gaps between the pilot's mental model of the autopilot's behavior and the real system's behavior.

When one of the control outputs, namely the elevator or thrust, becomes saturated, TECS cannot track both FPA and airspeed references. Most often, for commercial jetliners, it is the thrust that becomes saturated due to a high absolute FPA reference. Lambregts proposed a Speed Priority and a Path Priority mode to manage energy during these maneuvers with saturated thrust, by breaking the FPA error path or the acceleration error path to the elevator control [1].

Since TECS is an integrated controller of FPA and airspeed, autothrottle or autothrust control is always active. The correctness of the system's functioning from the pilot's point of view is essential due to the tendency of pilots to disengage the system when it operates differently from their expectations. Simulation results attest that this problem shall not occur. Lambregts also proposed an integrated flight and thrust Mode Control Panel (MCP), including operational considerations [8].

The first aircraft on which this system was implemented is the NASA TSRV Boeing 737, where all primary objectives were met: increased fuel efficiency, decreased development cost, and safe design [9]. The TSRV test results were discussed in [10], focusing on the priority logic when thrust saturation occurs and the pilot-like control strategy, demonstrating the use of TECS as a single concept for integrating the autothrust/autothrottle and Path control functions for all autopilot modes.

In the first TECS implementation on the NASA TSRV, the controller was designed using ad-hoc techniques, manually adjusting the gains to achieve time domain performance. Subsequent developments suggested improvements to the original TECS design method. In 1991, a more systematic approach to designing the TECS controller was proposed, namely the constrained Parameter Optimization [11].

In 1999, TECS was designed using eigenstructure analysis and assignment method, applied to a linear model of the Aerospace Technologies Demonstrator (ATD) airplane [12]. Then, robust controller design methods were proposed, such as [13], where the H_∞ optimization theory was presented, using a TECS architecture to design the longitudinal controller.

Multivariable control design techniques can also be used, such as the Linear Quadratic Regulator (LQR), a full state feedback methodology as proposed by [14], and a modified version with a frequency-shaping approach as in [15]. As it yields feedback gains for all state variables, this technique is well-suited for designing controllers for inherently multivariable systems, such as longitudinal aircraft dynamics. But since LQR is a full state feedback technique, it cannot be used to design the TECS controller without changing its structure.

More recently, a modified TECS structure was designed using LQR [16]. The original TECS gains to be tuned are *Kep*, *Kei*, *Ktp*, and *Kti*. But when the LQR method is used, it also produces cross-feedback gains. The method yields the feedback variables to the thrust command $\dot{E}$ and $\dot{E}_{err}$, as in the original TECS, but also $\dot{L}$ and $\dot{L}_{err}$. Similarly, the feedback variables to the elevator command are $\dot{E}$, $\dot{E}_{err}$, $\dot{L}$, and $\dot{L}_{err}$. Hence, LQR yields 8 gains, while the original TECS structure yields only 4.

Since the original TECS design was introduced in 1983, numerous papers have been published exploring TECS's architecture. A work that serves as the object of study and comparison for this paper is [17], a design in which various aspects of real implementation are discussed, including nonlinear elements such as actuator saturation handling and mode-dependent logic switching.

In [2], the original TECS design was updated with the introduction of an automatic mode switching logic and a change of the elevator control channel structue. The updated design also introduced other nonlinear elements, such as the Control Authority Allocation (CAA).

TECS modularity was demonstrated in the work done by [18], in which the same autopilot architecture was used for a High Altitude Long Endurance (HALE) aircraft and a Cessna Citation passenger aircraft, with minimal adjustments.

This work's main contribution is a comparison of the implementation of [2] and [17] into a modern autopilot architecture, regarding the logical elements and nonlinearities introduced to handle thrust saturation. The design in [17] operates in 3 main TECS functioning modes: KINBYAPITCH mode, POTbyAPITCH mode and "dual" mode, while the design in [2] operates in 2 TECS modes: Path on Elevator Control Priority (PoECP) and Speed on Elevator Control Priority (SoECP). The focus of the implementation and comparison of both methods lies in the prioritization logic between FPA and airspeed and the integration with AFCS.

The case study is implemented using a nonlinear longitudinal model of the Research Civil Aircraft Model, or RCAM [19]. This work only addresses the longitudinal functions of AFCS, without discussing manual or augmented manual flight.

2 The Total Energy Control System (TECS)

The basic TECS control law derives from well-known energy principles in physics. The main concepts are derived from the Total Energy concept, defined as:

$$E = Wh + \frac{W}{2g}V^2 \tag{1}$$

Where W is the aircraft's weight, h is its altitude, V is the true airspeed, and g is the gravitational force.

TECS theory has been thoroughly explained in previous works. Therefore, this work will not delve deep into its theoretical foundation. For this work, it is enough to state its outcome: the thrust and elevator control equations:

$$T_{cmd} = \frac{K_{TI}}{s}\dot{E}e - K_{TP}\dot{E} \tag{2}$$

Where T_{cmd} is the thrust command. $\dot{E}$ is the Total Energy rate. $\dot{E}e$ is the Total Energy rate error. K_{TP} is the proportional gain and K_{TI} is the integral gain of the thrust channel of the controller.

The elevator control law is expressed as:

$$\delta_e = \frac{K_{EI}}{s}\dot{L}e - K_{EP}\dot{L} \tag{3}$$

Where δ_e is the elevator delta command. $\dot{L}$ is the Distribution of Energy rate. $\dot{L}e$ is the Distribution of Energy rate error. K_{EP} is the proportional gain and K_{EI} is the integral gain of the elevator channel of the controller.

3 RCAM Model

RCAM, or Research Civil Aircraft Model, is a six-degrees-of-freedom dynamic aircraft model developed by GARTEUR, or Group for Aeronautical Research and Technology in Europe [19]. It is a conventional twin-engine commercial jet, with similar weight and dimensions to a Boeing 757. It is a simple model, with fixed surfaces. The aerodynamic coefficients suggest the aircraft was modeled in full flaps configuration, at low altitude. The RCAM has been used for control systems benchmarking, such as in [20], where an energy-based control approach is employed in RCAM to demonstrate the stability and robustness of the method. Its choice for use in this paper is motivated by its simplicity, but good representation of a common jetliner in use nowadays.

In RCAM, the air density is a constant variable and not a function of altitude. Given that the focus is on the implementation of TECS into an AFCS system and the study of the logical elements that must be inserted into the system, and not the implementation of a fully functional and certifiable control law, the controllers are designed based on a single trim condition within the flight envelope, which represents a significant limitation from a control law design perspective. However, for comparative purposes, this simplified approach is sufficient. In a real implementation, the controller must be gain-scheduled throughout the entire flight envelope, using an aircraft model with a realistic data bank, considering realistic actuator dynamics, rates, system delays, notch filters, and any other nonlinearities deemed significant for the design. Some relevant properties of the RCAM model used in this work are shown in Table 2.

The model is implemented in MATLAB/SIMULINK environment. From the application of the Rigid-Body Equations of Motion, using the RCAM parameters and formulation available in [19], the derivatives of the state variables are calculated. In the implementation, a MATLAB function is used for this calculation, in which the function output is a vector with eight dimensions, containing the derivatives of relevant variables, including the state variables. An integrator is then inserted at the end of the function block output.

The input vector is given by:

$$U = [\delta_e \; \delta_T] \tag{4}$$

The model output variables are:

$$Y = [u \; w \; q \; \theta \; X \; Z \; V_s \; \alpha] \tag{5}$$

Table 2 RCAM model properties

Parameter	Value
Air density	1.15 $kg \cdot m^{-3}$
Gravity	9.81 $m \cdot s^{-2}$
Aircraft mass	120000 kg
Wing planform area	260 m^2
Tail planform area	64 m^2
Mean aerodynamic chord	6.6 m
Distance by AC of tail and body	24.8 m

The inputs are the elevator angle and thrust. In the output, there are 4 state variables of the bare-airframe: the x component of airspeed in body axis (u), the z component of airspeed in body axis (w), the pitch rate (q), and pitch (θ). The x component of the displacement in body axis (X), the z component of the displacement in body axis (Z), the airspeed in the stability axis (V_s), and the angle of attack (α) are not used as state variables, only as auxiliary variables for other implementation steps. This structure is presented in Figure 1.

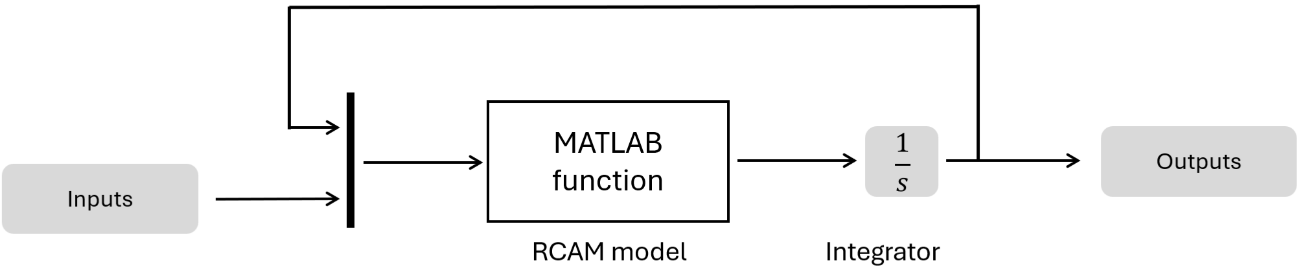

Fig. 1 RCAM implementation in SIMULINK.

The inputs of the RCAM model saturate in accordance with table 3. Thrust input is non-dimensional.

Table 3 Input saturation values.

Input	Min Value	Max Value
Elevator angle	-0.4363 rad	0.1745 rad
Thrust	0.0087	0.1745

4 Design Plan

Since the focus of this work is on assessing feasibility and operational aspects of integrating the TECS architecture into a modern AFCS structure, rather than on developing improved control law design methods, a straightforward design approach was adopted, instead of more sophisticated and complex robust design techniques found in the literature. The design steps followed in this work are outlined as follows:

- Plant Linearization
- Pitch control innerloop design using pole placement;
- TECS outerloop design with constrained parameterized optimization.
- Frequency analysis of the whole control system.

4.1 Linearization

Before linearizing the model, the nonlinear model must be trimmed around the equilibrium point. The trimming process is the process of finding the input and state variables that keep the airplane at an equilibrium, with constant aerodynamic angles and angular rate components [21].

The plant is linearized using state-space representation, as in the equation below:

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) \\ y(t) &= Cx(t) + Du(t) \end{aligned} \tag{6}$$

In this work, the controllers are trimmed and designed at a single trim point, considering ISA+0 temperature, and a pressure altitude of 2000 ft, resulting in an air density of 1.15 $\frac{kg}{m^3}$.

4.2 Pitch Innerloop Design

The Pitch innerloop is designed using Classical Control Design theory, more specifically, root-locus plots and pole-placement, such as in [21]. The innerloop pitch controller was designed in this work with the idea that the innerloop can be designed independently of the TECS outerloop, as Lambregts' suggests a TECS controller should be [1]. For this reason, the pitch innerloop is the first controller to be designed.

Table 4 innerloop time domain requirements

Requirement	**Value**
Time constant	1 s
Overshoot	< 1%
Settling time	5 s

The pitch controller has the control structure presented in Figure 2.

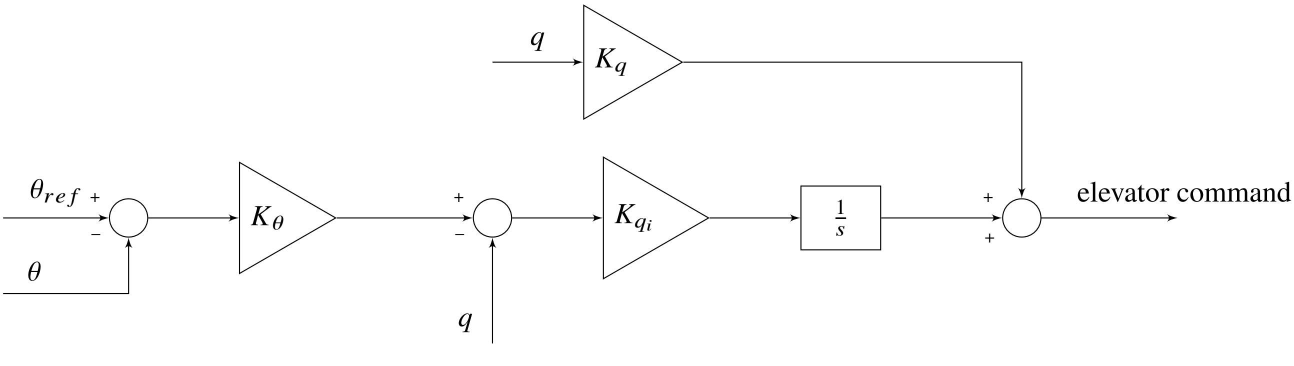

Fig. 2 Pitch rate controller structure

After the outerloop has been designed, it is essential to assess the influence of the innerloop gains on the overall plant response to ensure they do not compromise the performance or stability of the system. Finally, a frequency-domain analysis should be performed to evaluate the robustness of the closed-loop system. This includes breaking the control loop at the actuators and sensors interface with the bare-airframe dynamics and verifying if the frequency response has adequate gain and phase margins for each loop [15]. In this case, after the first iteration of outer and innerloop design, the frequency response of the system, with the loop broken at the pitch sensor, had a gain margin lower than the 6 db requirement, which meant a poor disturbance rejection in the pitch sensor, so the inner and outerloops had to be redesigned.

The pitch innerloop gains obtained after the redesign are in Table 5:

Table 5 Pitch innerloop gains

Parameter	**Value**
K_theta	1.1
Kq_i	-40
Kq	5

4.3 TECS design using parameterized optimization

This work compares the Lambregts' TECS architecture [2] with Kastner's and Gertjan's TECS architecture [17], by designing them separately, but using the same pitch innerloop controller, and optimizing each whole control system using the same criteria.

The design criteria used in this work follow the performance specifications established by the [19] RCAM benchmark. The most relevant aspects for evaluating controller performance are the FPA response, airspeed response, and the cross-coupling behavior between them.

According to the RCAM specifications:

- FPA and airspeed responses must exhibit rise times below 12 seconds and overshoots below 5%.
- Cross-coupling constraints include:
    - A maximum airspeed error of 2 knots for a 3° step in FPA.
    - A maximum FPA error of 0.5° for a 25-knot step in airspeed.

TECS gains are designed by simultaneously optimizing FPA and airspeed tracking performance. The technique used was the parameterized optimization, based on the method described in [22], and specifically tailored for this work. The function used for the optimization is the FMINSEARCH in MATLAB. The objective of the function is to find the optimal TECS gains to minimize the cost function given by equation 7:

$$J = \zeta \cdot \gamma_{ov} + \mu \cdot \gamma_{tr} + \eta \cdot \gamma_s + \chi \cdot V_{ov} + \epsilon \cdot V_{tr} + \kappa \cdot (\tau e - \tau t) + \psi_\gamma \cdot \gamma_{pk} + \psi_v \cdot V_{pk} \tag{7}$$

where γ is the FPA, V is the airspeed, the subscript "ov" is the overshoot, "tr" is rise time, "γ_s" is the FPA stabilization time, $\tau e - \tau t$ is the coupling term, in which τe is $\frac{Kep}{Kei}$ and τt is $\frac{Ktp}{Kti}$. γ_{pk} and V_{pk} are terms related to the relative size and number of peaks of the resulting step response, calculated using the "findpeaks" MATLAB function.

The cost function calculates the value of J after a combined step input of 3 degrees in FPA and 10 kn in airspeed. This way, the controller is simultaneously optimized for the FPA and airspeed responses. There is a performance tradeoff: A step response may have very little overshoot in the combined Path and airspeed step response, but generates an over-damped response for a pure Path step. So a higher Path overshoot is allowed in the combined optimization output. The cost is tailored for each architecture until the responses reach the desired criteria. This way, both TECS architectures are optimized and then their responses compared.

The TECS gains obtained are shown in the Table 6:

Table 6 TECS gains

Parameter	**Lambregts**	**Nir Kastner and Gertjan**
Ktp	0.8	1.2
Kti	0.51	0.5
Kep	0.95	0.85
Kei	0.5	0.35

4.4 Frequency analysis

The final step is to execute a frequency-domain robustness analysis by breaking the loop in the airplane actuators and sensors at the points where they interface with the RCAM bare-airframe dynamics [15]. The frequency performance criteria are a minimum of 6 dB of Gain Margin and 40º of Phase Margin.

5 Architecture Comparison

In this chapter, the updated TECS architectures of [2] and [17] are described and compared. TECS can be implemented in a way that it generates commands directly to the elevators, but short-period dynamics demand a pitch damper. Without an innerloop, TECS alone cannot improve the short-period and phugoid dynamics response. Therefore, TECS serves as an outerloop that consolidates acceleration and FPA references from the autopilot and generates a pitch reference command for the pitch innerloop.

A useful nomenclature is now introduced. TECS has 2 control channels. One is the Thrust Control Channel, which manages the Total Energy rate by producing a thrust command through the Full Authority Digital Engine Control (FADEC). The other is the Pitch Control Channel, which manages the Energy Distribution rate by producing a pitch command for the pitch innerloop. In the following subsections, the Thrust and Pitch control channels of both architectures are presented.

5.1 Thrust Control Channel

The thrust channel operates equally in both methods, calculating the thrust commands to the FADEC the same way as in the original TECS design. The Thrust channel schematic is represented in figure 3.

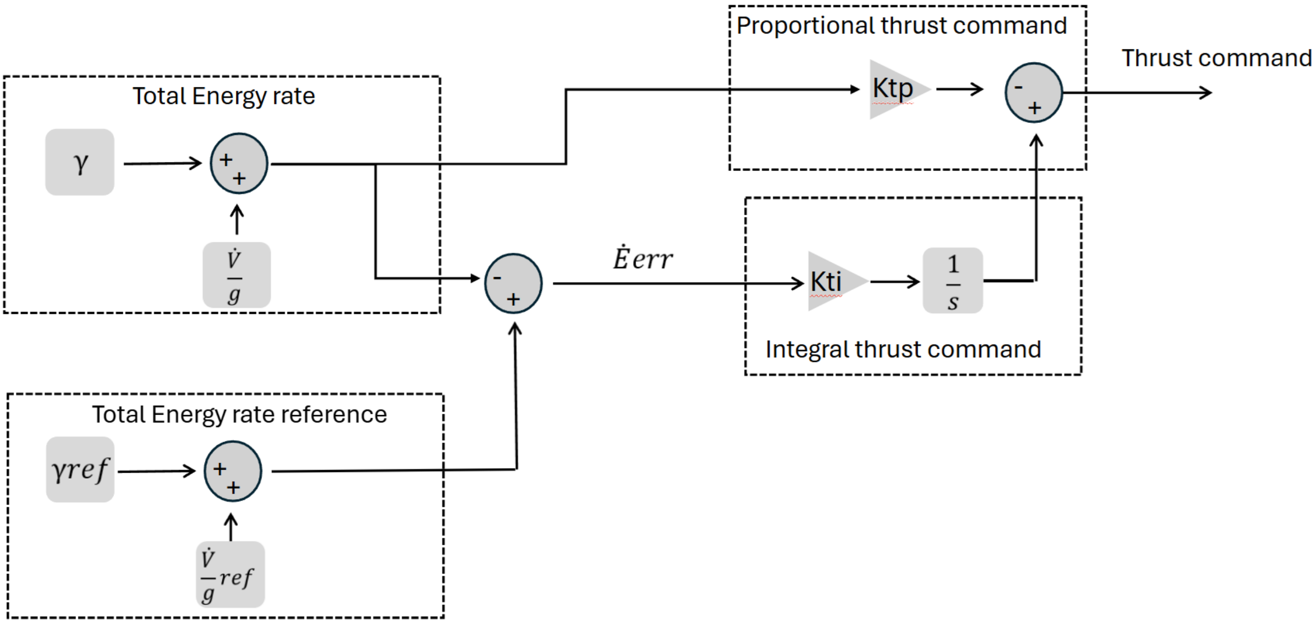

Fig. 3 TECS Thrust Control Channel schematic

Special care must be taken regarding the anti-windup mechanism of the integrator. The integrator saturation limit must be dynamic, and continually calculated according to the estimated maximum net thrust limit, plus the contribution of the proportional signal. In this work, this is how the saturation logic was implemented, but in later Lambregts‘ designs, the integrator was moved to the right of the sum block, and a differentiator function was introduced in the proportional thrust command, changing the order of integration. This is simpler, as the output can be limited solely by the maximum net thrust [2]. This logic was also implemented in [17].

5.2 Pitch Control Channel

The difference between the architectures lies primarily in the Pitch Control Channel, where TECS computes the pitch reference commands for the innerloop. In the original TECS design, the Distribution of Energy rate serves as the input to the Pitch Control Channel.

Since the maximum engine thrust is highly dependent on environmental and operational conditions, engine thrust is inherently limited. When an aircraft is climbing at maximum climb thrust, we can say that the thrust command is saturated. In such cases, TECS loses one control pathway, compromising control performance if no corrective action is taken. Because the energy rate that engines can deliver to the system is limited, TECS must prioritize either airspeed or FPA. A nonlinear logic must be introduced into the system: a prioritization method.

The concept of TECS modes is now introduced. A TECS mode is a functioning state of the TECS architecture. For example, in Lambregts’ updated design, there are 2 TECS modes, one in which airspeed is primarily controlled by the Pitch Control Channel and one in which FPA is controlled by the Pitch Control Channel. TECS modes can be associated with AFCS longitudinal modes, as is described in section 6.

5.3 Updated Lambregts Architecture

In the updated work of Lambregts, as mentioned, TECS has 2 modes of operation: Path on Elevator Control Priority (PoECP) and Speed on Elevator Control Priority (SoECP) [2].

The Pitch Control Channel differs from the original TECS in the following way: The Proportional Pitch command is calculated by making $Kep \cdot \gamma$, instead of $Kep \cdot \left(\gamma - \frac{\dot{V}}{g}\right)$.

In the original TECS, the Integral Pitch command is calculated by a function that integrates the Energy Distribution rate error input $\left((\gamma_{\text{ref}} - \gamma) - \left(\frac{\dot{V}_{\text{ref}}}{g} - \frac{\dot{V}}{g}\right)\right)$ and multiplies it by Kei. The updated TECS operates in two ways, depending on which mode is active. In the PoECP mode, the input to the Integral Pitch command function is $(\gamma_{\text{ref}} - \gamma)$. In the SoECP mode, the input is $\left(\frac{\dot{V}}{g} - \frac{\dot{V}_{\text{ref}}}{g}\right)$.

The switching logic between the SoECP and PoECP modes lies at the center of the challenges of integrating TECS into the AFCS. [2] proposes an automatic mode switching: While thrust is not limited, TECS works in PoECP mode, while Thrust remains in its maximum or minimum limits, SoECP is activated.

In Lambregts' work, TECS operates by automatically switching between SoECP and PoECP modes during normal operation, thereby inherently providing speed envelope control, except during Glide Slope mode, when FPA is prioritized over airspeed. For glide slope capture, which happens frequently when thrust is at idle [1], it is more important for the glide slope to be captured even if the airspeed oscillates away from the airspeed reference. In that case, inherent speed protection is lost, so the AFCS must implement an external speed envelope protection that automatically activates the SoECP mode, replacing the airspeed reference with the minimum or the maximum airspeed, plus a safety margin. Figure 4 shows the Pitch Control Channel architecture of [2].

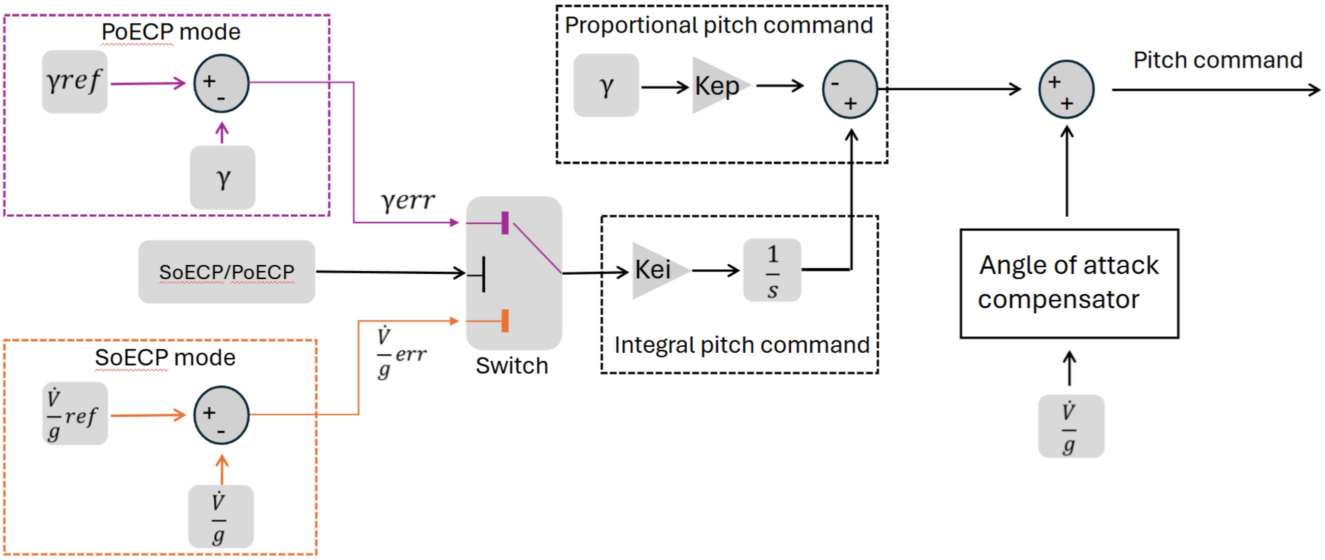

Fig. 4 Lambregts' TECS Pitch Control Channel architecture

The way the system operates as described above is the main operating mode of this TECS architecture. The system is always controlling the aircraft's speed. For that reason, the system cannot operate with autothrottle or autothrust off.

5.3.1 *Automatic Mode Switching*

In Lambregts' approach, the automatic mode-switching logic operates as follows: When the FPA reference exceeds an acceleration limit defined by the Control Authority Allocation (CAA) logic, and the engine thrust is saturated, the SoECP mode is engaged. Exceptions apply: When Glide Slope mode is active, mode switching is inhibited, and when speed protection is triggered, SoECP mode is enforced.

5.3.2 *Control Authority Allocation*

The SoECP mode needs a way of allocating the available energy rate to FPA or airspeed tracking. If left unchecked, a large speed increase command during climb may generate an undesired pitch-down command, and a large speed decrease command during descent may generate an undesired pitch-up command. Lambregts introduced the concept of Control Authority Allocation (CAA) [2]. CAA works by introducing a limit to the $\frac{\dot{V}_{\text{err}}}{g}$ TECS input. This limit is equal to $K_{\text{caa}} \cdot \dot{E}$, while K_{caa} is a number varying from 0 to 1, chosen depending on the designer's choice of energy allocation between Path or airspeed. With this limiter, the controller will never exert a pitch down command during a climb, or vice-versa, no matter how great the airspeed step input is. The lower the K_{caa} value, the lower the energy exchange rate from kinetic energy to potential energy, and higher values of K_{caa} indicate that this energy exchange rate will occur at a higher rate, allowing a more aggressive speed correction during thrust saturation.

Equation 8 shows how CAA logic calculates the acceleration error input limit:

$$CAA = K_{caa} \cdot \dot{E} \tag{8}$$

where $K_{\text{caa}} \in [0, 1]$ defines the energy allocated to airspeed error regulation during SoECP mode.

5.3.3 *Angle of Attack Compensator*

Lambregts introduced the idea of an Angle of Attack Compensator to account for the fact that as airspeed increases, the angle of attack increases, and so the pitch command must compensate for the change in angle of attack due to acceleration. Figure 5 shows this structure:

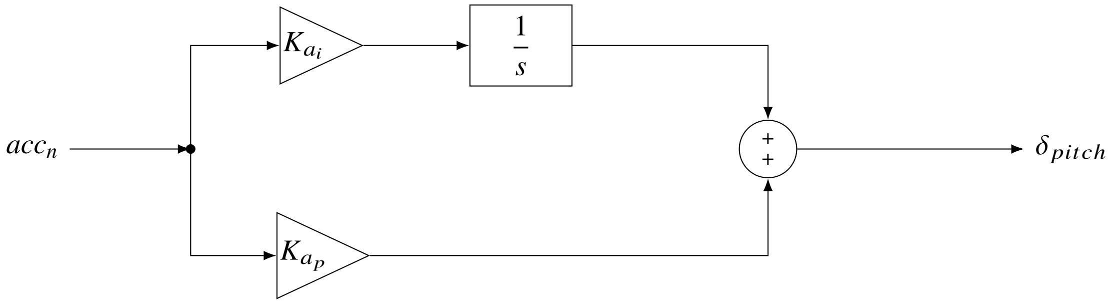

Fig. 5 Angle of Attack compensator structure.

Where acc_n is the normalized acceleration and δ_{pitch} is the compensation in pitch command. In Lambregts' work, only the Kai integral gain is present. Simulation results show that introducing an additional proportional gain, Kap, increases the compensator's performance.

5.4 Nir Kaster's and Gertjan Looye's Architecture

The Thrust Control Channel works similarly in both architectures, as mentioned. In [17], TECS has 4 different modes, denominated, using their work's terminology: Dual, KINbyAPITCH, KINByATHR, and POTbyAPITCH.

The terminology is related to the inputs available for control and the target controlled variable. When both pitch angle command and thrust command inputs are available for TECS, and it is controlling both Path and airspeed, it is in Dual mode. When one of the command inputs is unavailable for TECS, a prioritization is defined between Path, or POT (Potential Energy), and Speed, or KIN (Kinetic Energy). The prioritization is done via the activation of one of the other modes. For example, when thrust is saturated in the maximum climb thrust, it is unavailable as one of the TECS control inputs. KINbyAPITCH is a mode in which airspeed is the priority, and it is controlled by the pitch angle alone, while thrust command is unavailable. POTbyAPITCH is a mode in which the aircraft's FPA is the priority, and it is controlled by pitch angle alone. KINByATHR is a mode in which pitch angle control is unavailable for TECS, a mode that is useful for augmented manual control, but not a feature of the autopilot; hence, this mode is not analyzed in this work.

In "dual" mode, the functioning is the same as in the original TECS, in which the Energy Distribution rate and Energy Distribution rate error are the inputs to the Proportional Pitch command function and the Integral Pitch command function, respectively.

In POTbyAPITCH mode, the system is similar to Lambregts' PoECP mode, in which γ is the input to the Proportional Pitch command function and $(\gamma_{ref} - \gamma)$ is the input to the Integral Pitch command function. The difference is that, while in Lambregts' TECS, the Proportional Pitch command function's input is always γ, regardless of mode, in Gertjan's and Kastner's TECS architecture, the Proportional Pitch command function also switches input according to the active mode.

In KINbyAPITCH mode, $\frac{\dot{V}}{g}$ is the input to the Proportional Pitch command function and $(\frac{\dot{V}}{g} - \frac{\dot{V_{ref}}}{g})$ is the input to the Integral Pitch command function. This architecture is presented in Figure 6

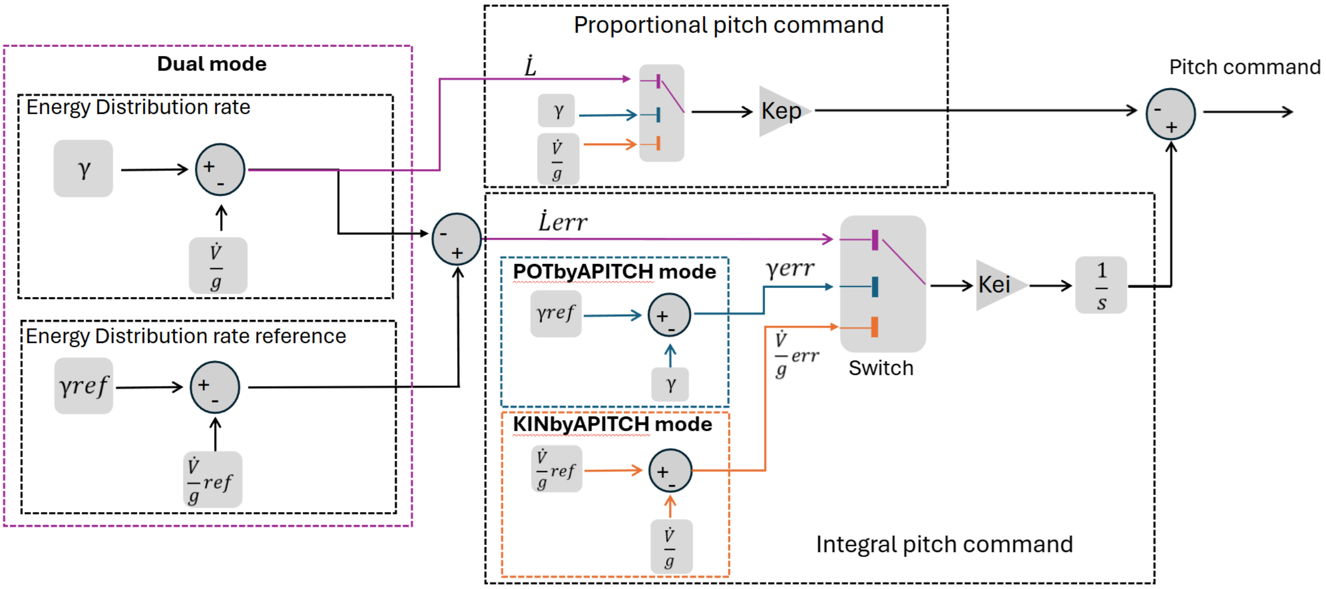

Fig. 6 Gertjan and Kastner TECS Pitch Control Channel

As in [2], a pitch command limiter was also introduced, to use in conjunction with the KINbyAPITCH mode [17]. But in the simulations, the CAA method was used for the comparison.

5.5 Comparison Comments

Both architectures have strong and weak points. Lambregts' updated TECS is a simpler design, and Kastner's and Gertjan's TECS have a slightly better performance, in some scenarios, considering FPA tracking, as can be seen in section 7, due to their strategy of using the energy distribution in both pitch and thrust paths in the "dual" mode.

Under a realistic operational concept, the usefulness of the "dual" mode proposed in [17] is limited. This mode introduces behaviors that are difficult to accommodate. In the context of the AFCS modes described in section 6, for example, in level flight, a commanded change in airspeed in the "dual" mode results in a pitch-down command followed by a pitch-up command, thus introducing a disturbance in altitude control when operating in Altitude Hold mode, as can be seen in Figure 9. A similar effect occurs when the "dual" mode is used in altitude change modes such as FPA, Vertical Speed, and Glide slope. This behavior is particularly problematic when pilots are operating in heavily ATC-controlled environments that require procedures such as Standard Instrument Departures (SID) and Standard Terminal Arrival

Routes (STAR), or other ATC impositions, where compliance with prescribed vertical trajectories takes precedence over airspeed.

For this reason, a TECS mode in which the flight path is controlled by the elevator is essential. Given this requirement and the marginal performance benefits offered by the “dual” mode, its inclusion unnecessarily increases system complexity. Consequently, Lambregts’ design in [2] is more suitable for the objective of this work, which is to reduce AFCS complexity.

However, the automatic switching logic proposed in [2] requires a flight deck philosophy that contradicts the previously discussed principle that, frequently, vertical trajectory control should take precedence over airspeed. In [23], a simplified Mode Control Panel (MCP) concept is presented, in which this automatic switching logic is integrated into all vertical modes. In the framework of [23], when operating in corresponding modes of Flight Path Angle or Vertical Speed, if thrust becomes saturated during the maneuver, the AFCS maintains the selected vertical mode, while TECS automatically transitions to Speed on Elevator Control Priority, prioritizing airspeed over the commanded flight path.

Introducing mode switching during climb or descent maneuvers leads to signal discontinuities and nonlinearities in the control law, which are difficult to address both in control design and within the constraints of software certification (e.g., DO-178C). Furthermore, this behavior must be considered in light of the pilot’s mental model of the system. In particular, it raises design questions regarding whether such mode transitions should be transparent or explicitly annunciated to the pilots in the Flight Mode Annunciator (FMA), and how the pilot is expected to respond in a switching failure event. literature in human factors in aviation indicate that complex mode structures and implicit transitions contribute to mode confusion, and therefore recommends minimizing the number of modes, simplifying transition logic, and ensuring clear mode annunciation [24], [25].

For this reason, in the next section, where a mapping between TECS and AFCS modes is proposed, the Lambregts’ automatic mode switching logic is not adopted, further simplifying the design. Automatic switching is activated only by a dedicated speed envelope protection function, which transitions TECS from Path-on-Elevator to Speed-on-Elevator.

For a general view of the whole control system, including the proposed TECS architecture, the autopilot logic, the innerloops, and the aircraft dynamics, a simplified schematic is presented in Figure 7.

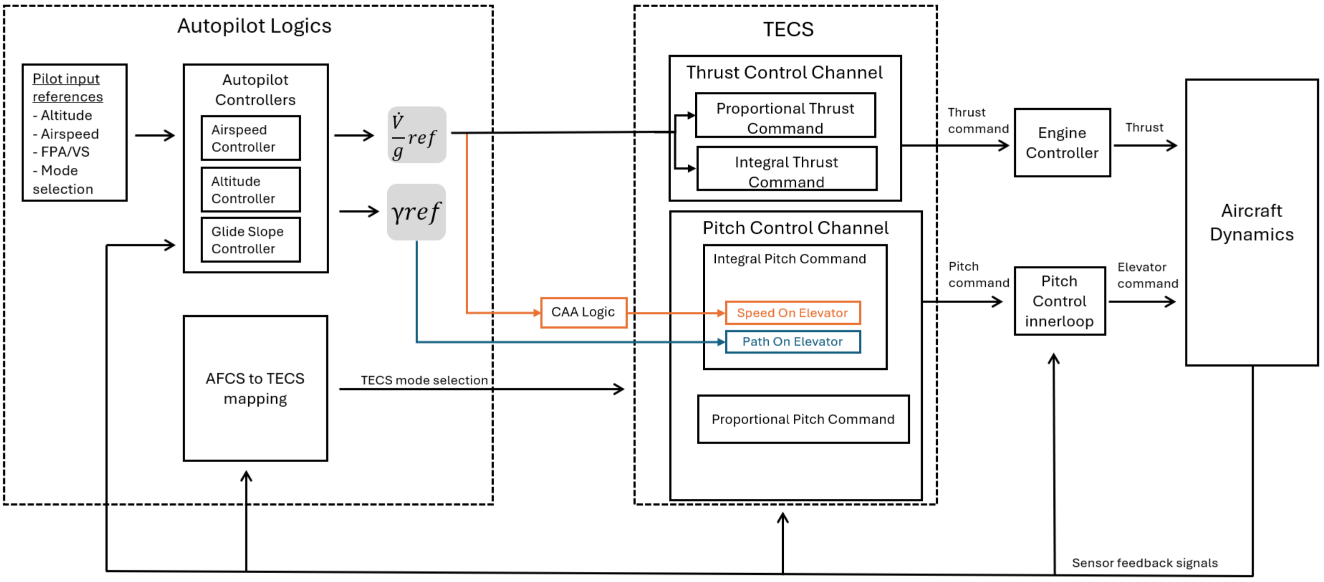

Fig. 7 Simplified complete control system structure.

6 Mode Mapping

This work proposes the implementation of standard longitudinal AFCS modes, including Flight Level Change (FLCH), Altitude Hold (ALT HOLD), and Glide Slope (GS), within the TECS framework. To achieve a complete autopilot design, a functional mapping is established between the AFCS modes and corresponding TECS modes. A simplified version of Lambregts' architecture in [2] was selected, which intentionally omits automatic mode switching, as discussed in Section 5.5.

To maintain existing cockpit operational concepts and training requirements, conventional AFCS nomenclature is retained in the pilot interface. The TECS modes are defined as Speed-on-Elevator (SoE) and Path-on-Elevator (PoE), to avoid proprietary terminology. The proposed correlation, alongside the associated FPA and airspeed references, is summarized in Table 7, while modes related specifically to take-off and landing phases are excluded from this analysis.

Table 7 Proposed correlation between AFCS modes and TECS modes

AFCS Mode	TECS mode	Control Priority	FPA Reference
FLCH	SoE	Speed	Max/Min (operational limits)
ALT HOLD	PoE	Path	Closed-loop (altitude error)
FPA/VS	PoE	Path	Fixed
GS	PoE	Path	Closed-loop (vertical deviation)

In Flight Level Change (FLCH) mode, TECS operates in Speed-on-Elevator mode, prioritizing airspeed control. The FPA reference is driven to a predefined operational limit (max or min), tailored to exceed the current aircraft's achievable performance. As a result, thrust reaches saturation. This reflects conventional FLCH behavior, in which airspeed is controlled via pitch, while thrust is saturated, in idle for a descent, or according to the maximum thrust rating currently active (e.g. Climb Thrust), for climb.

For Altitude Hold (ALT HOLD), Flight Path Angle (FPA), Vertical Speed (VS), and Glide Slope (GS) modes, TECS operates in Path-on-Elevator mode, ensuring that the commanded FPA or vertical trajectory is maintained through pitch control. In these modes, the FPA reference is either internally generated (e.g., from altitude error) or manually commanded by the pilot, depending on the mode. Vertical Speed (VS) mode is similar to FPA mode, only differing on a conversion factor that converts reference Vertical Speed to reference FPA. FPA reference changes throughout the maneuver to achieve the target Vertical Speed. The Path-On-Elevator mode ensures that trajectory tracking takes precedence, consistent with operational requirements during the approach phase. Additionally, this mode enables the use of the Angle-of-Attack Compensator [2], which mitigates the effect of airspeed commands on the vertical trajectory, as illustrated in Figure 9. In these conditions, it is essential to provide the pilot with a clear indication when thrust saturation occurs and airspeed deviates from its reference. If the airspeed reaches predefined minimum or maximum limits, a speed envelope protection function is triggered, and TECS transitions to Speed-on-Elevator mode.

The transition from a climb or descent mode to ALT HOLD mode is traditionally managed by a dedicated mode (e.g., ALT SEL), in which the autopilot is specifically tuned for the target altitude capture phase. Within the TECS framework, this intermediate mode can be eliminated, and the transition can instead be treated only as a pilot cue indicating convergence to the target altitude. This can be achieved by progressively reducing the FPA reference to zero through a proportional control law (Or another altitude control law chosen by the designer) acting on the altitude error. Because the FPA reference is also an input to the thrust control channel, this transition strategy remains effective in FLCH mode. In the implementation presented herein, TECS operates in Speed-on-Elevator mode during transition phases, switching to Path-on-Elevator mode only once the target altitude is reached, the FPA error converges to zero, and the aircraft stabilizes in level flight.

Airspeed reference is not presented in table 7 because, similarly to all AFCS modes, the speed reference is either pilot-selected or managed by the FMS. It can be argued that, while Path-on-Elevator mode is active, the autothrust/autothrottle function may be disengaged at the pilot's discretion. However, for the sake of simplicity, this work assumes that TECS airspeed control is always active.

Compared to a conventional AFCS, the system operates similarly from the pilot's perspective. However, the autothrottle/autothrust function is simplified, as only a single operational mode is considered, in which the inputs are the FPA reference and the linear acceleration reference. Special cases, such as take-off and go-around, are not addressed in this work.

From the system's perspective, the simplification lies in the interface between AFCS and TECS. TECS requires from the AFCS only the FPA reference, γ, the normalized acceleration reference, $\frac{\dot{V}}{g}$, and a discrete signal selecting the active mode (Speed-on-Elevator or Path-on-Elevator), regardless of whether these signals originate from pilot-selected modes, FMS functions, or other autopilot logic. Typically, when the FMS manages the aircraft's vertical trajectory, it is treated as a separate mode (e.g., VNAV), with the control function implemented within the FMS computer [1]. In the proposed architecture, however, these functions provide the AFCS only with the trajectory deviation. This reduced complexity is beneficial for the pilot's system comprehension and the accuracy of his mental model.

7 Results

The nonlinear simulation results for the architectures proposed in [2] and [17] are presented in the following figures for selected TECS modes. All simulations are initialized with the aircraft trimmed at a constant airspeed of 155.7 kn and an altitude of 1000 m (3280 ft). The objective of these simulations is to assess the response of TECS operating in dual mode, in which both FPA error and airspeed error are inputs to the Pitch Control Channel, under different maneuvers, and to compare its behavior with other TECS modes in the context of AFCS integration. The controllers were designed using the RCAM model linearized at a single operating point. Therefore, no gain scheduling was implemented. This limits the assessment of robustness. However, since the simulations are performed using the nonlinear model, the evaluation of performance for the considered scenarios, from a comparative perspective, remains valid.

7.1 FPA step response (3 degrees) with constant speed

Figure 8 presents the response to a 3° step command in flight path angle at constant airspeed, starting from the trimmed condition. This scenario corresponds to a climb in FPA mode without thrust saturation. The simulation based on [2] is conducted with TECS operating in Path-on-Elevator mode, whereas the architecture in [17] is evaluated in dual mode.

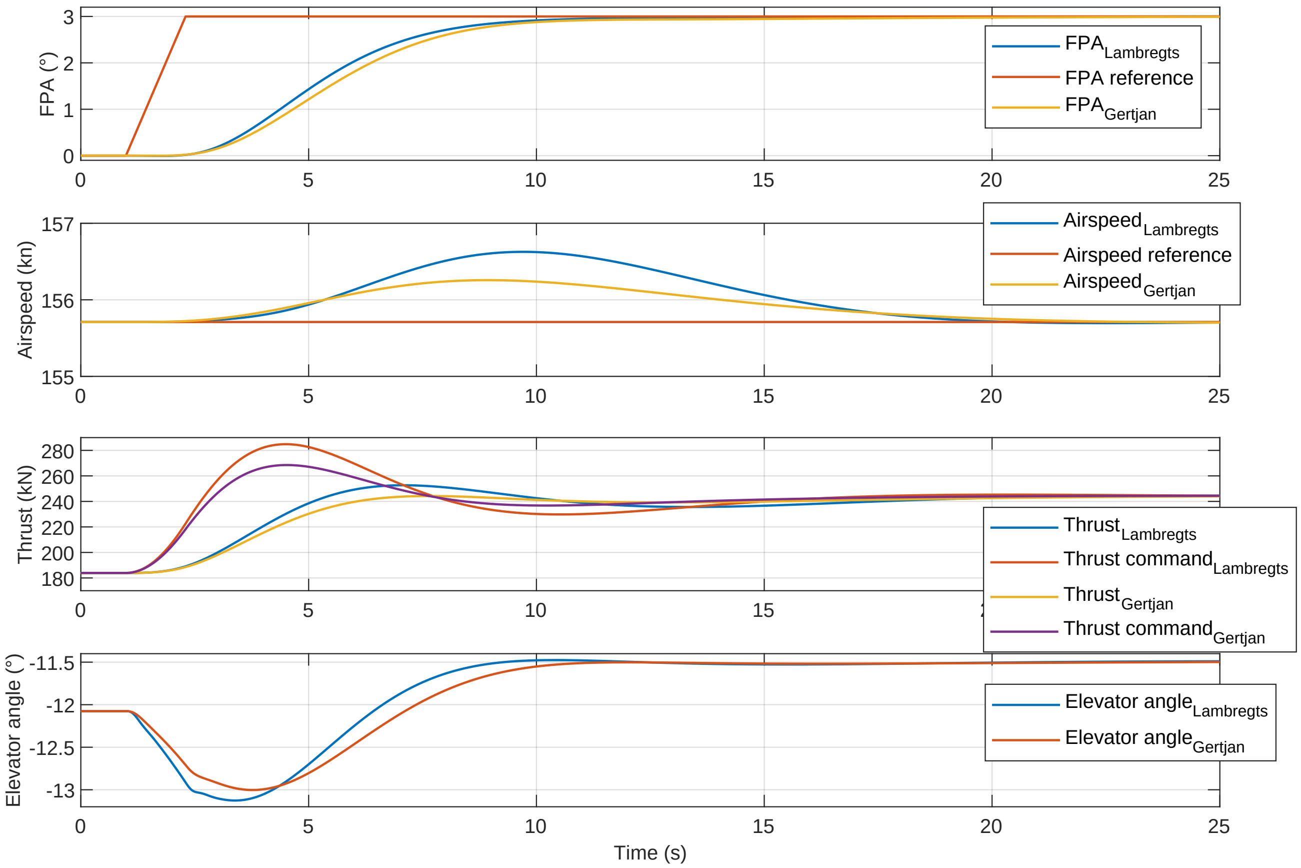

Fig. 8 3° FPA step response at constant speed.

Figure 8 shows that the airspeed deviation for both [2] and [17] remains within the 2-knot requirement. The approach in [17] exhibits smaller speed deviations and a smoother thrust response, at the expense of slightly slower flight path angle tracking. Therefore, under non-saturated thrust conditions, the performance of both architectures is comparable.

7.2 Airspeed step response (25 kn) with constant FPA

Figure 9 presents the response to a 25 kn step change in airspeed, with the flight path angle reference held constant at 0°. This scenario resembles a speed increase in ALT HOLD mode. However, the ALT HOLD function is not engaged. Instead, only the flight path angle reference is tracked, and altitude is not controlled.

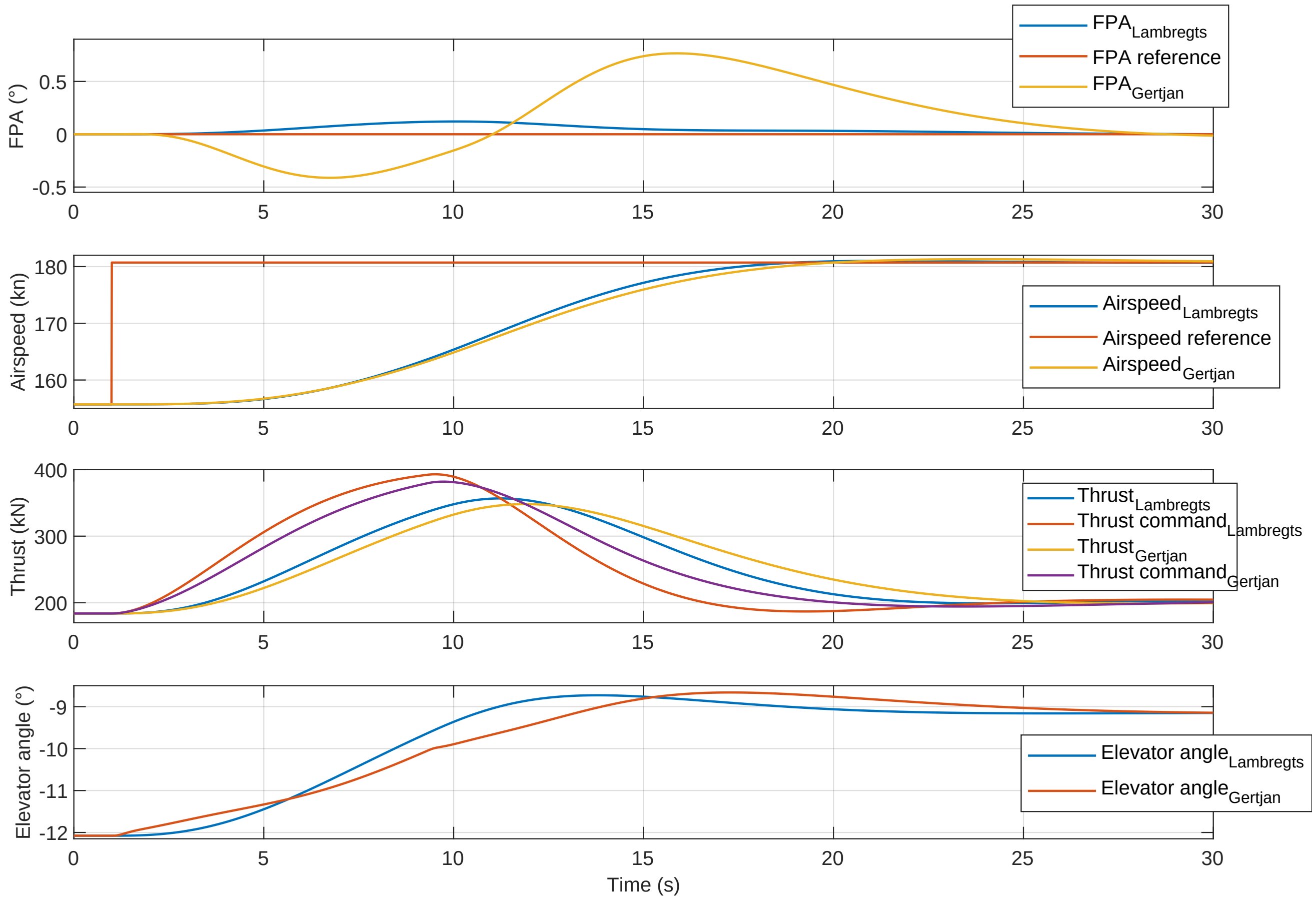

Fig. 9 **25 kn speed step at constant gamma.**

Figure 9 illustrates the significant FPA deviation exhibited by the implementation of [17] in dual mode, which exceeds the 0.5° deviation criterion. This is expected from TECS operating in dual mode, as the feedback of normalized acceleration error into the Pitch Control Channel naturally induces deviations in FPA during speed change maneuvers. In contrast, [2] demonstrates improved performance, owing not only to the use of Path priority control, but also to the the inclusion of the Angle of Attack Compensator. These results indicate that a TECS mode with Path priority is more appropriate for the Altitude Hold mode.

7.3 Speed step during climb with saturated thrust

To evaluate prioritization under thrust saturation, the model incorporates a variable maximum thrust limit. This limit is set such that the aircraft achieves a maximum climb flight path angle of approximately 4 degrees at an airspeed of 170 knots. A climb scenario with saturated thrust is then simulated, representative of FLCH operation, during which a step change in airspeed is commanded. TECS is maintained in dual mode throughout the maneuver, resulting in steady-state errors in both FPA and airspeed due to energy balance constraints, as shown in Figure 10.

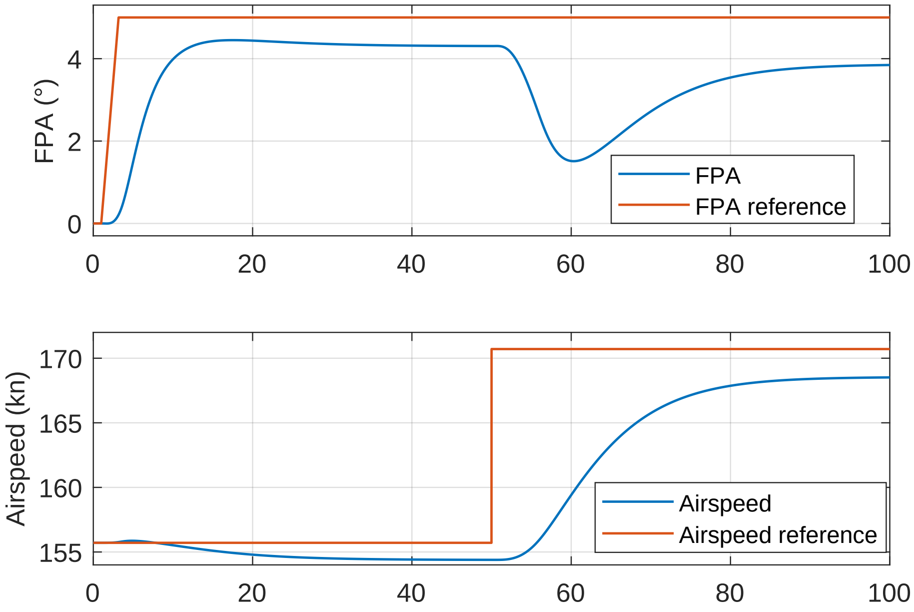

Fig. 10 Speed step during climb — TECS dual mode.

Although some speed protection occurs via airspeed feedback to the Pitch Control Channel, the pilot loses control over which variable is prioritized. In this case, a mode switch should occur at this stage to prioritize either airspeed or FPA.

Airspeed prioritization and Control Authority Limitation

During maneuvers with saturated thrust, airspeed prioritization is achieved by activating the Speed-on-Elevator mode (Lambregts' SoECP or Gertjan's KINbyAPITCH) in conjunction with the Control Authority Allocation (CAA) logic.

Figure 11 compares the system response of the design in [2] under the same maneuver conditions as in Subsection 7.3, but with TECS operating in SoECP mode, for Kcaa = 0.5 and Kcaa = 0.9. The response of [17] is omitted, as it is similar when operating in the equivalent mode (KINbyAPITCH).

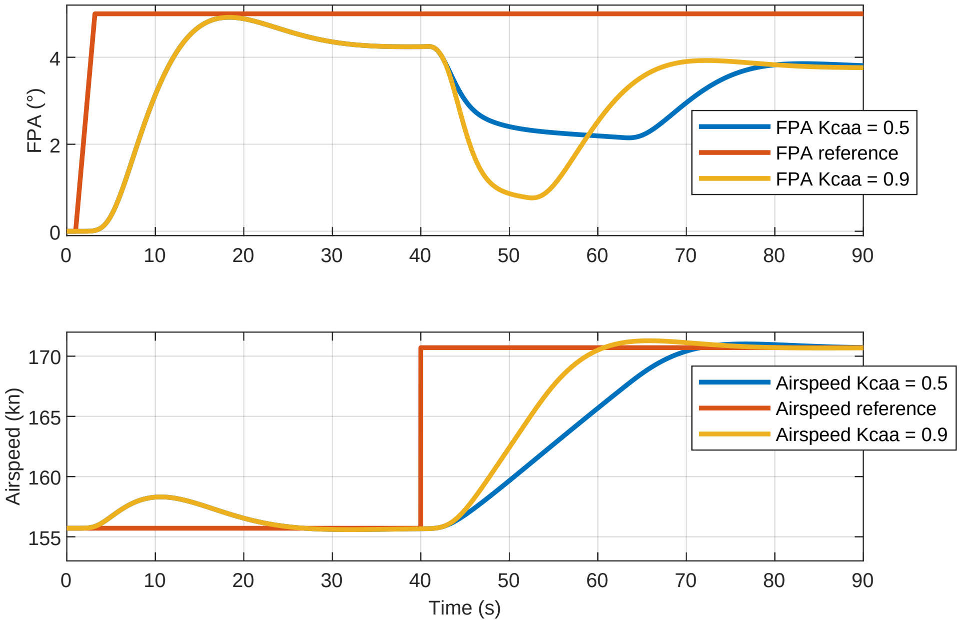

Fig. 11 Speed step during climb — Kcaa = 0.5 X Kcaa = 0.9

As shown, with a lower Kcaa value, airspeed convergence is slower. With higher Kcaa values, airspeed convergence is faster. Kcaa = 0.5 means that 50 % of the available energy is directed to airspeed change, which means that the aircraft reduces FPA to roughly 50 % of the previous value.

7.4 AFCS modes

Using the AFCS–TECS integration strategy presented in Section 6, along with the mode mapping defined in Table 7, the FLCH, FPA, and GS modes are evaluated under the same thrust saturation conditions described in Subsection 7.3.

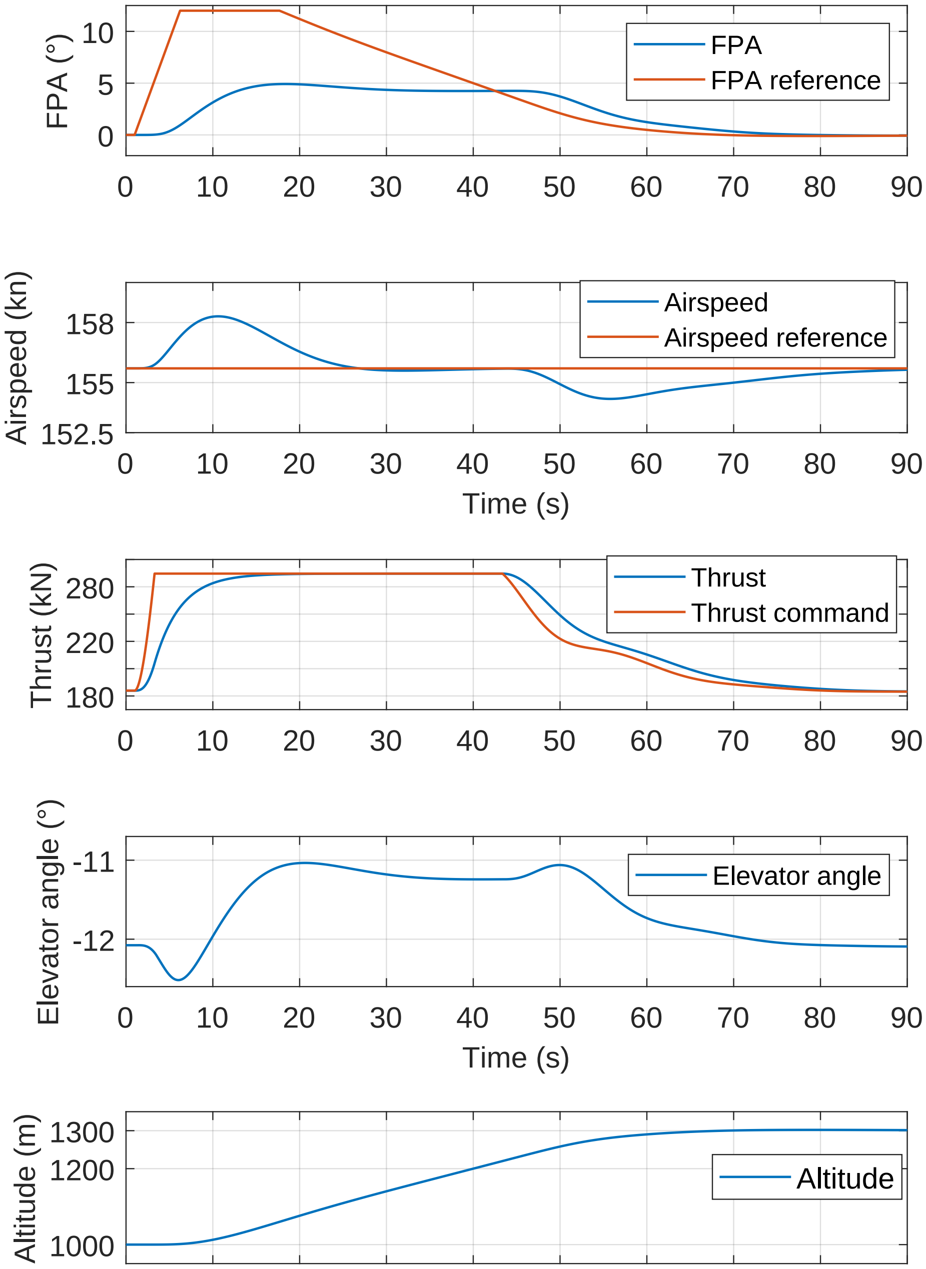

Fig. 12 Change flight level - FLCH mode - TECS Speed-On-Elevator mode

Figure 12 shows a climb simulation from 1000 m (3281 ft) to 1300 m (4265 ft), in the FLCH mode. FPA reference is set as 12°, which is unachievable for the aircraft given its current performance condition, so thrust become saturated. Throughout the maneuver, Speed-On-Elevator mode is activated. No mode TECS switching is necessary until target altitude is reached.

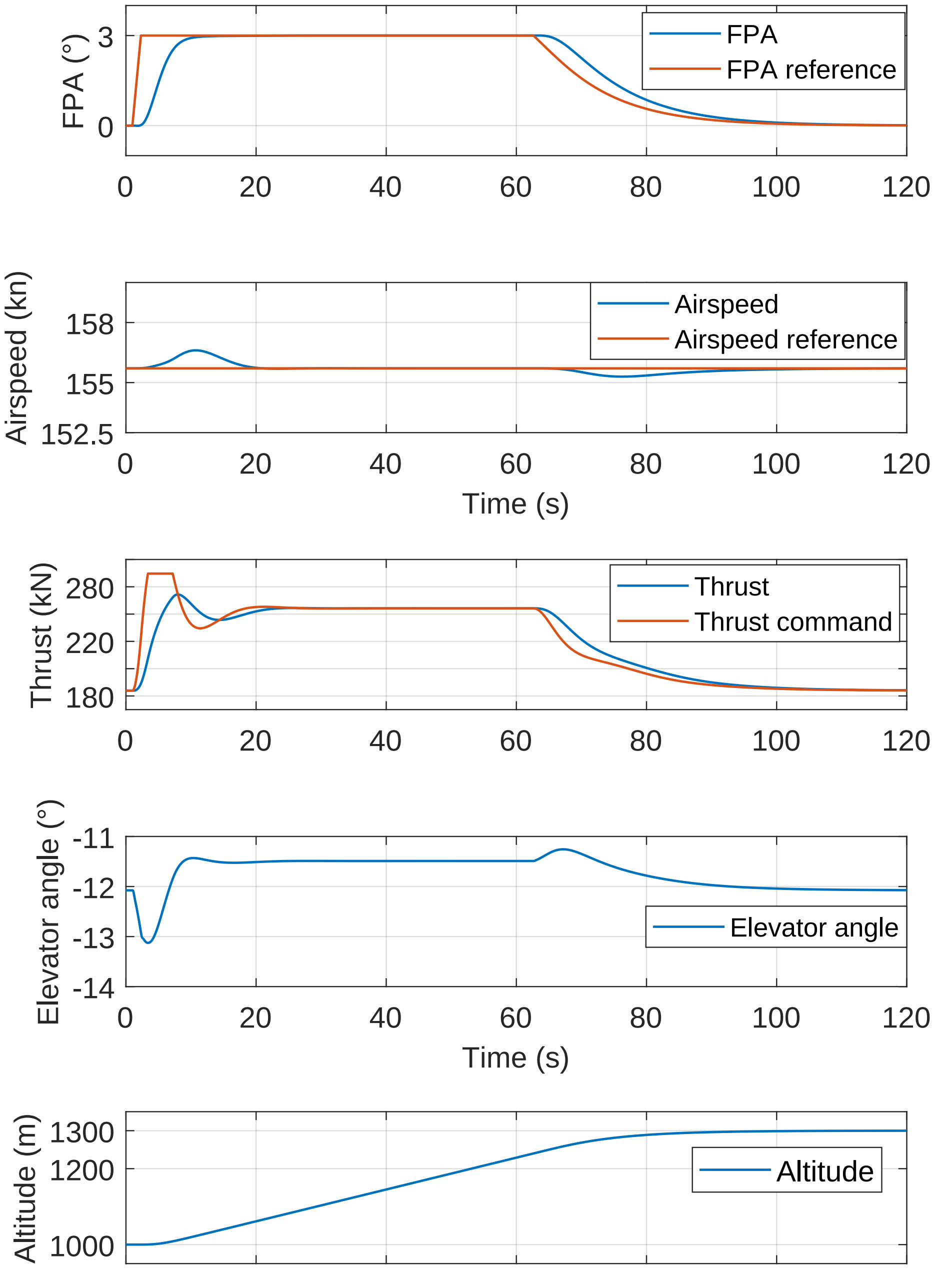

Fig. 13 Change flight level - FPA mode - TECS Path-On-Elevator mode

Figure 13 shows the same climb conditions of Figure 12, but the maneuver is executed in FPA mode. FPA reference is 3°, which is achievable by the aircraft, then thrust is not saturated. Without any mode switching, the FPA reference diminishes proportionally until target altitude is captured.

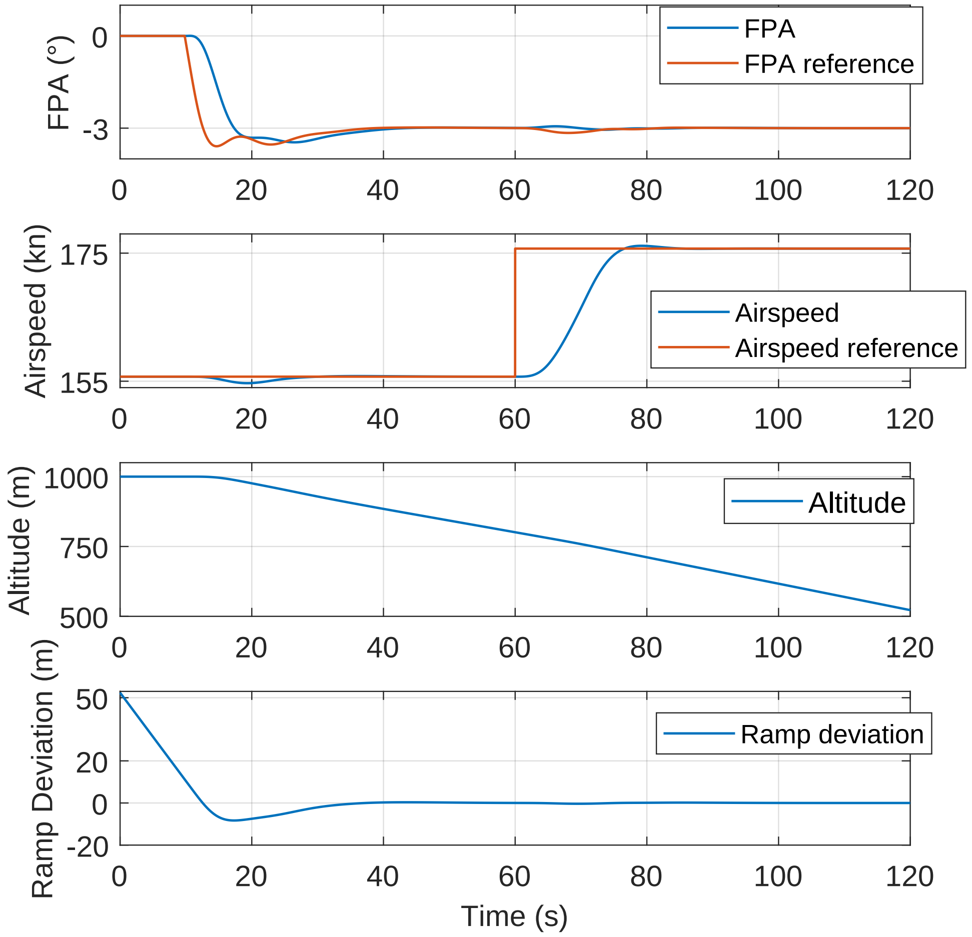

Fig. 14 Glide slope capture - GS mode - TECS Path-On-Elevator mode

Figure 14 illustrates a glide slope capture maneuver, with the GS mode. At the start of the simulation, the glide slope is above the aircraft. As the aircraft intercepts the glide slope path, the deviation becomes negative, resulting in a pitch-down command to capture it. Even though a step increase in airspeed is commanded during the maneuver, the aircraft maintains the glide slope without noticeable deviation. GS mode pairs with TECS Path-On-Elevator mode.

8 Conclusions

Simulation results reinforce the potential of TECS as a viable framework for simplifying both AFCS design and the pilot's mental model of autopilot behavior. In this work, two TECS-based implementations were implemented and compared: the updated method by Lambregts and the approach by Nir Kastner and Gertjan. The comparison focuses primarily on how each method handles prioritization between FPA and airspeed control.

The approach in [17] introduces additional TECS modes to support prioritization, resulting in more complex mode-switching logic. In contrast, the updated method by Lambregts adopts a simpler structure, with only two TECS modes. A comparative analysis of the prioritization strategies indicates that the Lambregts architecture provides a better balance between implementation simplicity and operational performance, while the approach by Kastner and Looye offers other advantages, such as smoother thrust response in specific FPA tracking scenarios under non-saturated thrust conditions when operating in dual mode. An even more simplified version of Lambregts' approach was selected to implement the mode mapping between TECS and AFCS, however omitting the automatic mode switching logic. Lambregts' automatic switching logic supports an AFCS system with inherent speed protection, but its usefulness in a scenario where Path takes precedence over airspeed is limited.

The implementation of the mapping between AFCS modes (e.g., FLCH and ALT HOLD) and the corresponding TECS modes (Speed-on-Elevator and Path-on-Elevator) shows promise in reducing autopilot complexity by eliminating functional overlap between the Flight Control Computer, the Autothrottle/Autothrust computer, and the navigation computer (FMS), while preserving the conventional flight deck operational philosophy.

Finally, although TECS is designed as an aircraft-independent outerloop, practical implementation revealed that adjustments to TECS gains were necessary after the first design iteration. This highlights that TECS indeed influences the innerloop dynamics and can possibly make the system unstable. In [2], Lambregts addresses this issue by designing the pitch innerloop using short-period model inversion, thereby contributing to the aircraft-independence of the TECS outerloop design.

For future work extensions, the proposed architecture must include modes for take-off, go-around, and landing, implemented in a high-fidelity model of a real aircraft and evaluated under challenging atmospheric conditions, including turbulence and wind shear, to validate the system's robustness to atmospheric perturbations. Additionally, the proposed AFCS-TECS integration structure requires further validation in realistic operational scenarios, with a corresponding MCP and FMA to ensure its practical viability and effectiveness, considering human factors analysis.

Declaration of Use of Artificial Intelligence

Artificial intelligence was used for proofreading and translation of parts of the text.

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