

# Controller Design for a Digital Flight Control System DFCS

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## ABSTRACT

General Aviation has been traditionally hampered by the expense and time required to get a pilot's license and the instrument rating required for flight in less-than-ideal weather. Modern digital flight control technologies greatly improve handling qualities and flight safety compared to the even best naturally stable, un-augmented aircraft designs. Digital Flight Control System (DFCS) represents a control strategy which transforms a simplistic control surface commanding into a sophisticated motion control process. This paper discusses the design of two flight controllers for DFCS. One is based on the classical "best practice" design, the other features Total Energy Control System logic. Both control systems were subjected to simulations. The advantage of the TECS proved to be in excellent performance and moderate complexity of the resulting controller structure compared to classical control law design. TECS's expected ability to support proven analytical tools compatible with the airworthiness certification procedure makes it an ideal candidate for implementation on board of a General Aviation aircraft.

**Keywords:** Digital Flight Control System, digital signal processing, controller design, General Aviation, Total Energy Control System.

## 1. INTRODUCTION

The work was performed in support of the endeavor to provide reliable personal air travel platform that would take the advantage of using regional and local airports/airfields. This would lead among other point-to-point travel benefits also to relaxation of overloaded commercial aviation operations. Low-end General Aviation fleet is predominantly being perceived as a „good weather” base for low-cost pilot training and pleasure cross country flying that provides the pilots with a unique opportunity to experience the „real piloting”. Even the enthusiastic perception of „low cost” can not stand against terrestrial travel expenses, General Aviation still provides an edge, which when fully utilized, offers higher passenger safety and satisfaction.

The complexity of operating and navigating an airplane, and the dangers posed by weather, mechanical problems, and inevitable pilot carelessness advocate the rationality of a pilot workload reducing system [15]. Responsible piloting requires a constant

mental endeavor in monitoring the aircraft systems, prioritizing flight data and if necessary taking a corrective action under real-time constraints. This seriously contradicts with the human ability to successfully perform simultaneous data management processes in stressful conditions. The above observations are in fact more of a lead than an obstacle in pinpointing the direction for future General Aviation development. As General Aviation aircraft are mostly flown by a single pilot, this concept would benefit from an intelligent system or “Virtual Copilot” assisting in or supervising the aircraft’s safe operation. Aircraft with this capability might ultimately lead to trajectory based free-flight operations. However, will it pay for itself when put in a cost optimized small aircraft? The answer is in well designed automatic control system.

Operational state-of-the-art automatic flight control systems evolved in stepwise manner from legacy designs, inheriting their control philosophy along with basic functional limitations. This evolutionary process introduced advanced features to every new design generation, by increasing the level of sophistication and the complexity of onboard applications. Proposed digital flight control system framework is intended to simplify piloting, reduce pilot workload, and allow low-end general aviation aircraft to operate under deteriorated meteorological conditions. Despite controversies between perception of a modern manned aerial vehicle and limitations imposed by legacy airworthiness codes it has been shown that a pilot workload reducing system can be successfully operated on board of a low-end general aviation aircraft [1, 16, 17].

Flight control system is by the airworthiness code required to be highly reliable with critical elements having operational redundancy. A digital flight control integrates software and hardware, where reliability issues dictate the necessity of integration transparency [2]. With the system relying on secured networks of high data transfer rates, transparency of the system integration becomes a driving factor of a successful design. Authors discuss only the issues of algorithmic correctness and don't deal with problems of system's physical design limitations as bandwidth problems and time delays.

This paper is organized as follows. The next section provides an overview of classical controller design for flight path angle control. The section thereafter introduces Total Energy Control System (TECS). Both control design methodologies demonstrate its capabilities by the means of simulations. Final section describes the pilot-in-the-loop simulations.



Equation (6) consists of pitch controller function Eq. (7) and transfer function which meets response of aircraft pitch to the change of elevator deflection (involving pitch damper).

$$G_{AP\_theta}(s) = K_{ip} + \frac{K_{ii}}{s} = K_t \left( \frac{s + z_r}{s} \right) \quad (7)$$

where:

- $K_{ip}$  - proportional gain of pitch controller,
- $K_{ii}$  - integration gain of pitch controller.

Design criteria [4, 5] indicate how to shape frequency characteristics of Eq. (6) to obtain proper handling qualities (figure 3). Very good dynamic properties of pitch control system are assured by phase margin  $\Delta\varphi=50$  [deg] or over and gain margin  $\Delta A=12$  [dB] or over. Minimal acceptable values are  $\Delta\varphi=30$  [deg] and  $\Delta A=8$  [dB].

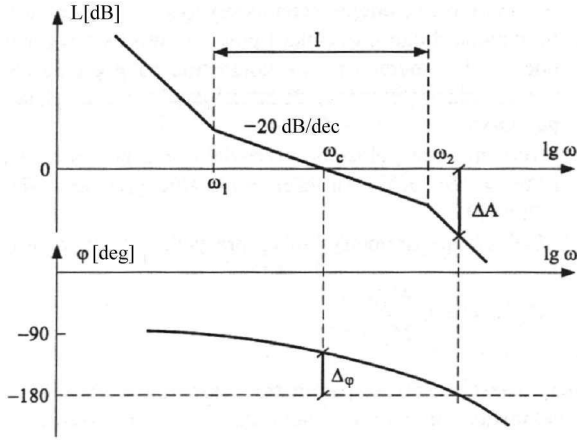


Figure 3. Recommended frequency characteristics of pitch control system [4].

Assuming function Eq. (6) we can estimate values of pitch controller parameters to meet these criteria. Value of  $z_r$  should be ten times smaller than value of  $z_2$  (this assumption is correct for small aircraft) [4]. Gain  $K_t$  is calculated from the Eq. (8). Calculated values of  $K_t$  and  $z_r$  assures crossover frequency  $\omega_c$  at slope of characteristics  $-20$  [dB/decade] and defines lower boundary of bandwidth at  $\omega_r=z_r$ . Upper boundary of  $-20$  [dB/decade] slope is defined by parameter  $z_2$  associated directly with aircraft dynamics.

$$K_t = (0.9 \div 1) \cdot \frac{\omega_0^2}{A_v} \quad (8)$$

Flight path control system bases on pitch control subsystem Eq. (9) (figures 1 and 2). Open loop flight path control system can be written as Eq. (10) where  $G_{AP\_gamma}(s)$  represents dynamics of flight path regulator Eq. (11).

$$G_v(s) = \frac{K_t \cdot (s + z_R) \cdot A_v(s + z_2)}{s^2 \cdot (s^2 + 2d_z \omega_0 s + \omega_0^2) + k_t \cdot (s + z_R) \cdot A_v(s + z_2)} \quad (9)$$

$$G_{o\gamma}(s) = G_{AP\_gamma}(s) \cdot G_v(s) \quad (10)$$

$$G_{AP\_gamma}(s) = K_{gp} + \frac{K_{gi}}{s} = K_g \left( \frac{s + z_g}{s} \right) \quad (11)$$

where:

- $K_{gp}$  - proportional gain of flight path controller,
- $K_{gi}$  - integration gain of flight path controller.

Values of  $K_g$  and  $z_g$  should be selected to minimize time lag and overshoot. Practically  $z_g$  can be calculated as  $(z_2 - z_r)/2$  and  $K_g$  selected to ensure intersection of gain characteristics with the frequency axis at  $-20$ [dB/decade] slope. Calculated values of  $z_g$  and  $K_g$  should assure proper amplitude and phase margins.

Correct performance of flight path controller requires application of airspeed controller (figure 4). Classical PI regulator can be applied to meet the above mentioned request, resulting in Eq. (12). Values of  $K_{up}$  and  $K_{ui}$  depends highly of engine/engines types and theirs dynamics.

$$G_{AP\_u}(s) = K_{up} + \frac{K_{ui}}{s} \quad (12)$$

where:

- $K_{up}$  - proportional gain of airspeed controller,
- $K_{ui}$  - integration gain of airspeed controller.

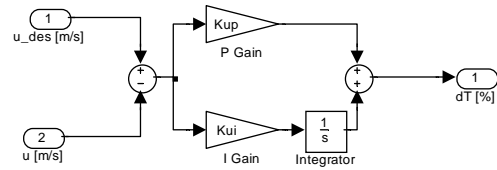


Figure 4. Structure of flight path controller.

### 3. TECS FLIGHT PATH CONTROL

It is industry's belief that a control system with a direct stabilized control of airspeed and flight path will be a major step in making personal air transport more accessible to broad public [2, 7]. This opinion motivated the experimental implementation of a flight control concept known as the Total Energy Control System (TECS).

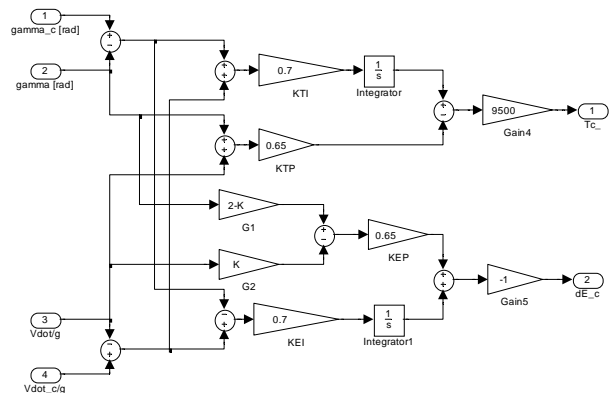


Figure 5. Structure of TECS controller.

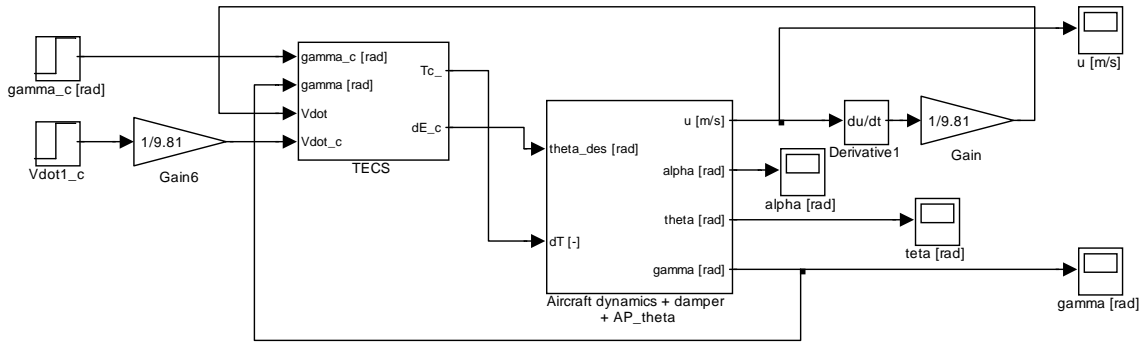


Figure 6. Structure of flight path control system based on TECS controller.

TECS mimics an intuitive human piloting strategy for longitudinal aircraft motion. It was derived from a point mass approximation of the aircraft dynamics and its control logic uses energy states of the system Eq. (13). Control inputs command airspeed and flight path angle variables. In TECS, the amount of total energy is being influenced by inputs through different thrust settings Eq. (14), whereas the changes of pitch attitude lead to energy Eq. (15). Subscript  $e$  refers to error in control variable.

$$E_T = E_{kinetic} + E_{potential} \quad (13)$$

$$T_{cmd} = \left( K_{TP} + \frac{K_{TI}}{s} \right) \cdot \dot{E}_e \quad (14)$$

$$\theta_{cmd} = \left( K_{EP} + \frac{K_{EI}}{s} \right) \cdot \dot{L}_e \quad (15)$$

The TECS control strategy allows thrust and elevator control coordination in a decoupled response, causing the flight path angle command having a negligible influence on speed fluctuation and vice versa. The core feedback integral  $K_{TI}$ ,  $K_{EI}$  and proportional  $K_{TP}$ ,  $K_{EP}$  gains are designed to yield identical dynamics for energy rate error  $\dot{E}_e$  and energy distribution rate error  $\dot{L}_e$  for either a flight path angle command or a longitudinal acceleration command.

For the case of a decoupled longitudinal motion, the TECS core algorithm influences system's phugoid dynamics. In order for the system to cope with fast aircraft dynamics, in the likely form of a short period rotational motion, an innerloop design is generally being implemented. TECS has been successfully implemented on a NASA B737 technology demonstration plane, followed by application onboard of Condor UAV project [7]. More recently published results describe successfully simulated TECS based designs for medium size transport aircraft type [2, 10].

#### 4. OFF LINE SIMULATIONS

The controllers' performance has been demonstrated in series of simulations using linearized models of aircraft dynamics and nonlinear actuators.

Typical flight regimes and related configurations have been investigated. In off-line simulation, these featured: take-off, climbing, cruise at two different airspeeds and final approach.

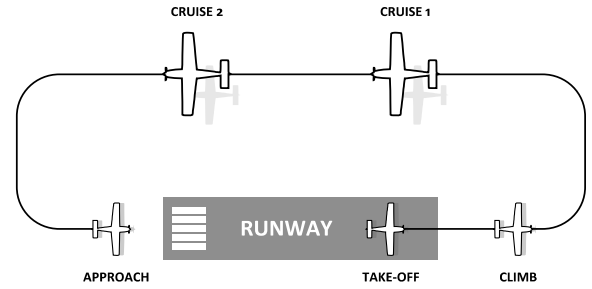


Figure 7. Simulated flight regimes.

Results of flight path stabilization in classically designed flight control system as well as in TECS based DFCS are presented in figures 8 and 9. It can be seen that the response of TECS system is practically insensitive to changes in flight conditions (constant regulation parameters). All responses of "classical" flight control system are similar in shape but they have different values of overshoots. It is good visible in zoomed flight path angle graph in figure 9. We can also see that response of "classical" flight control system is a little faster than TECS's.

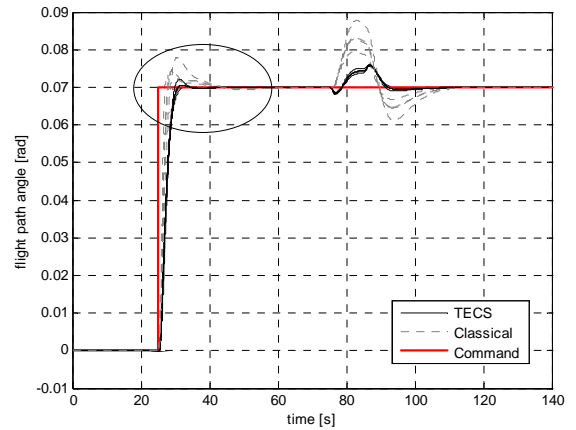


Figure 8. Results of flight path stabilization in classically designed DFCS and TECS based.

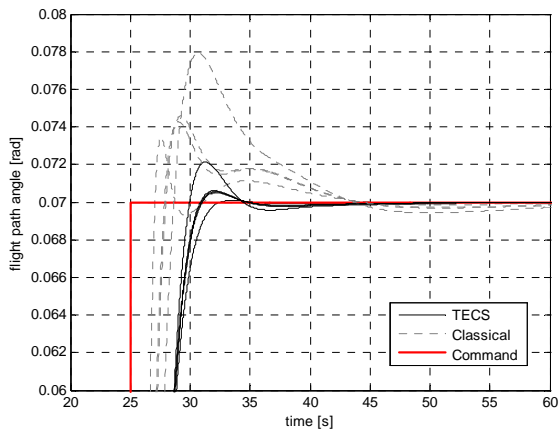


Figure 9. Zoomed results of flight path stabilization.

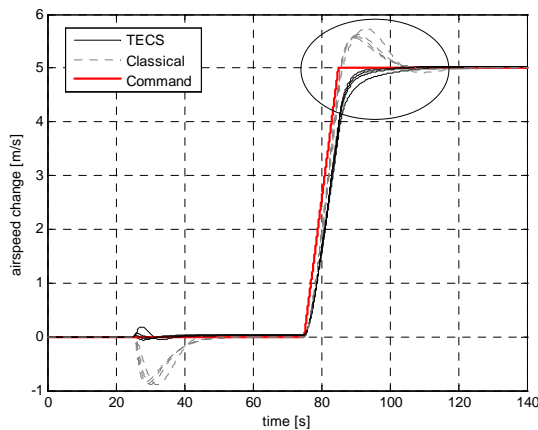


Figure 10. Changes in airspeed corresponding to flight path changes from shown in figure 8.

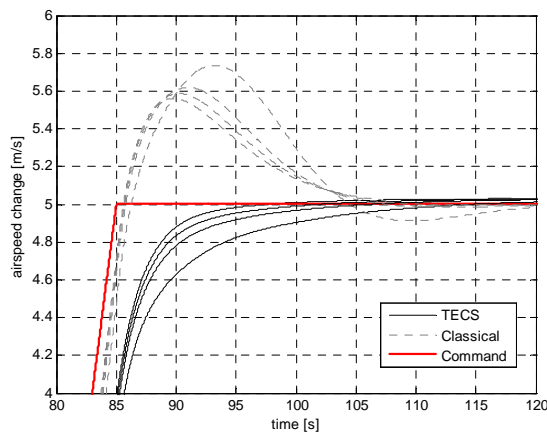


Figure 11. Zoomed graph of airspeed response due to flight path change.

Airspeed is stabilized with very good precision in DFCS based on TECS solution (figure 10). These responses feature minimal overshoot and short time of regulation. Classically designed regulator causes overshoots in airspeed up to almost 20% over commanded value as seen in figure 11. Classical flight path control system has hierarchical structure that makes its tuning

process more straightforward. Unfortunately this type of controller design requires adaptation/scheduling of flight path regulator parameters for different flight conditions. TECS flight path controller proved to be sufficiently robust to various flight conditions changes. Despite TECS's superb performance in simulations, it has been found to require quite a challenging tuning process.

## 5. PILOT IN THE LOOP SIMULATIONS

Successful implementation of control laws on board of aircraft requires detailed analysis of controller structure and selection of regulator parameters for various flight conditions. Control laws should be analyzed with the use of handling qualities criteria, so aspects of pilot and passengers comfort and safety are taken into consideration. In the initial step an analytical level of the design should be verified during off-line simulations, proceeding further to more realistic real-time simulations. Pilot in the loop experiments should be as much similar to the real flight conditions as possible. Furthermore, experiments with unconventional control laws tend exhibit the need for specialized research simulator environments. Authors of this paper work on such system and they intend to use in future experiments. Structure of planned flight simulator is presented in figure 12.

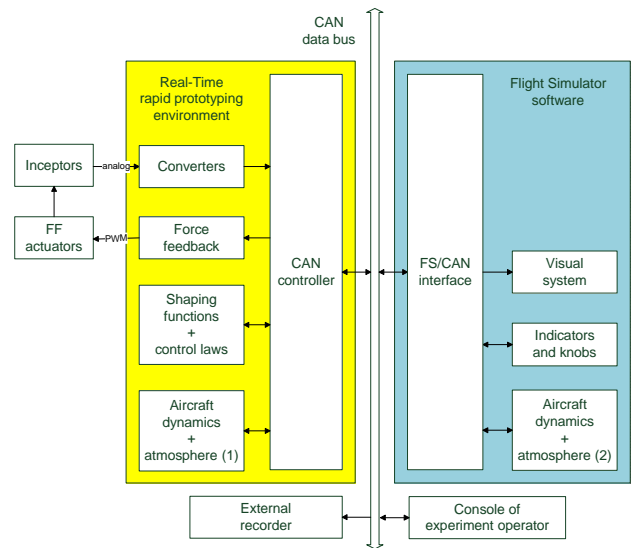


Figure 12. Block scheme of experimental flight simulator.

Flight simulator presented in figure 12 bases on CAN data bus. There are four elements connected directly to CAN. First of them is rapid prototyping environment which enables building of real-time models, e.g. control laws, aircraft dynamics, atmosphere disturbances, inceptor's shaping functions, force feedback, etc. Flight simulator software and FS/CAN interface constitutes second block. This block is responsible for visualization of surroundings, indicators and knobs operations as well as for simulation of in-build aircraft dynamics and atmosphere influences. The operator can select what kind of aircraft dynamics and atmosphere model should be used for simulation purposes. There is an option of switching between a model from rapid prototyping card and model from software module. Third and fourth blocks connected directly to CAN are experiment operator's console and data recorder. This solution

enables connecting additional equipment to the simulator. Particular software or rapid prototyping modules can be replaced by real parts of aircraft control system. Additional actuators [13], indicators or other hardware modules equipped with CAN interface and CANaerospace protocol can be connected directly to the bus and can work in the loop (hardware in the loop simulation).

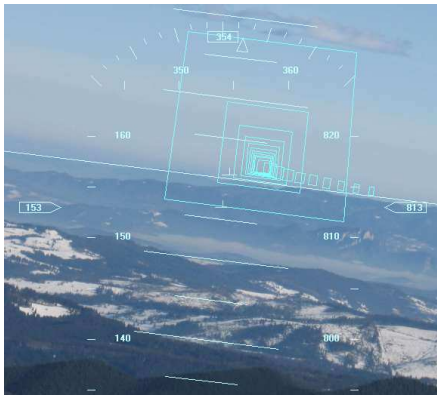


Figure 13. Experiment with visualization of flight-path for purposes of future experiment.

## 6. CONCLUSIONS

The anticipated future growth of the General Aviation market arises from the social needs for individual transportation. TECS based DFCS provides the essential ingredient for delivering an easier to handle, safer, operationally attractive and environmentally friendly airplane to the General Aviation community. Serious considerations, except the technological and certification challenges behind a digital flight control system, are given to the viability of the design and its implementation costs. It has been shown on a number of examples from military and commercial transport aviation that the technology is available and mature.

TECS represents an elegant way of controlling the longitudinal aircraft motion and thanks to its compact and clear design it is authors' preferred choice over classical controllers. Nevertheless, the total energy control system's design supports proven analytical tools in line with the airworthiness certification procedure making it transparent to implementation processes. Future work on DFCS will focus on rigorous testing of TECS based controller in pilot-in-the-loop simulations. As manual control modes are frequently the likely cause of pilot induced oscillations (PIO) phenomena, future research will be directed towards clearing the system from unwanted PIO occurrence [14]. Finally the issue of robustness of the resulting controller would need to be addressed by utilization of advanced techniques able to cope with system's nonlinearities. The effects of time delays, lost or damaged control data remain beyond the scope of this paper, but represent topics which are of high interest to the community and remain to be seriously investigated.

## 7. ACKNOWLEDGMENT

This work has been supported by the "Security-Oriented Research in Information Technology" research project CEZ MŠMT, MSM 0021630528 and supported from Polish

scientific funds within the framework of development project in years 2007-2010.

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