World Journal of Engineering Research and Technology
WJERT
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SJIF Impact Factor: 5.924

AIRCRAFT PITCH ANGLE CONTROL USING FEEDBACK PD AND FIRST-ORDER COMPENSATORS

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Article Received on 07/09/2023 **Article Revised on 28/09/2023** **Article Accepted on 19/10/2023**

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ABSTRACT

The purpose of this research paper is to investigate the use of feedback PD and first-order compensators to control an aircraft pitch with actuator and aircraft dynamics having fourth-order transfer function. The compensators are tuned using the MATLAB optimization toolbox with the selection of the appropriate performance index. The step time response of the control system using both compensators is compared with that using a conventional PID controller. The comparison reveals the best compensator among the three controller/compensators depending on the selection criteria.

KEYWORDS: Aircraft pitch control, feedback PD compensator, feedback first-order compensator, PID controller, compensator tuning.

INTRODUCTION

From safety point of view, flight control has vital importance in the design of aircrafts of all types. The selection of the controller type depends on the performance of the control system after tuning the controller in use. Compensators are considered as replacement for controllers that may be set in the feedforward or feedback paths of the control system. Pitch motion is one of the aircraft motions that have to be controlled accurately with high performance. We start with a literature survey about aircraft pitch control:

Edwards (1972) analyzed an electro-hydraulic aircraft control surface. He developed linear and nonlinear models and presented the transfer functions of the control system.[1] Yeshout, Morris, Bossert and Hallgren (2003) investigated the aircraft equations of motion, linearized them, and studied the classical feedback control and some special topics such as advanced control, algorithms and reversible and irreversible flight control systems. They presented a fourth order transfer function for an aircraft and a block diagram for the yaw damper.[2] Dydec, Annaswamy and Lavretsky (2010) examined the role of control in the X-15-3 aircraft using adaptive control. They derived the dynamic model of the X-15 aircraft and used a second-order transfer function for the hydraulic actuators with 0.7 damping ratio and used another first-order model for the hydraulic actuators. They presented the dynamic model of the adaptive controller with simulation results.[3] Gassetti and Ferrara (2012) derived a model for an airbrake electro-hydraulic smart actuator. They proposed and analyzed a proportional control with switching integrator and a second-order sliding mode control. They developed a fourth-order model for the actuator, second-order model for the electro-hydraulic valve and a third-order model for the LVDT, antialiasing filter and noise reduction low pass filter.[4] Gong et al. (2013) established a nonlinear model of a large aircraft and designed control laws for level change mode. They derived linear models for the pitch attitude leading to a third-order transfer function, angle of attack and airspeed with second-order transfer functions. They obtained a six-order transfer function for the closed-loop control system for the pitch attitude.[5]

Cooper (2014) studied the hydraulic actuators, electromechanical and electro-hydrostatic types used in aircrafts. He used a second-order model for the dynamics of the electro-hydraulic servo valve and a first-order model for the LR circuit of the vale torque motor.[6] Ahmed, Ouda, Kamel and Elhawagy (2015) investigated the design, simulation and control of an unmanned aerial vehicle. They derived the nonlinear model of the system and linearized it to provide a third-order transfer function model for the vehicle. They used PID and PI-D controllers to control the vehicle.[7] Sudha and Deepa (2016) investigated the use of a PID controller to control the pitch of an aircraft. They derived a linearized model and used a first-order model for the sensor and a fourth-order model for the actuator and aircraft dynamics. They tuned the PID controller using Ziegler-Nichols, Tyreus-Luyben and Astrom-Huggland methods.[8] Singh and Dahiya (2017) studied the elevator and aileron surfaces for controlling the aircraft longitudinal and roll movements. They derived the nonlinear model of the system and linearized it to design the used controller. They use a fuzzy-PID controller for the control of the longitudinal and roll of the aircraft.[9] Iskrenovic (2018) considered the use of a sliding mode control design based on linearization of the aircraft with pitch angle and elevator deflection as the controlled variables. He considered a fourth-order transfer function for the aircraft elevator.[10]

Mjahed (2019) applied neural network to the problem of flight control of an aircraft. He considered a longitudinal autopilot for a remotely piloted vehicle. He considered second-order models for the attitude, path, pitch angles, angle of attack and velocity. He presented the step time response of the control system for the path angle, attitude, and velocity using the neural controller.[11] Kayar (2020) in his study about stability analysis of a fighter jet (F-4C Phantom aircraft) derived models for the change in the angle of attack (second-order transfer function), the change in pitch (second-order transfer function), change in roll rate (first-order transfer function), change in roll angle (second-order transfer function) and change in yaw rate (second order transfer function). He derived the inner loop of the pitch displacement autopilot control system as a third-order transfer function and its outer loop as a fourth-order transfer function.[12]

Megyesi, Breda and Schrotter (2021) investigated an adaptive control algorithm for the control of a fixed wing unmanned aerial vehicle. They designed and simulated an adaptive PID controller. They obtained the transfer function of the unmanned aircraft relating the angular velocity of the longitudinal inclination and the rudder deflection at speeds of 60, 90 and 120 km/h. All the models were of the second-order type (1/2 transfer function). They used a first-order model for the actuator transfer function.[13] Idir, Bensofia, Khattab and Canale (2022) proposed an optimal reduced order fractional PID controller for an aircraft pitch angle control. They used a third-order transfer function for the aircraft pitch, used a number of fractional order approximation methods and compared the step time response and Bode plot for the pitch angle.[14] Gomi et al. (2023) adopted a coupled fluid-rigid body simulation for the takeoff, hovering and yawing flight of an electric vertical takeoff and landing aircraft eVTOL. They used an integral model for the climbing, roll rate, yaw rate and pitch rate. They used a PD controller to control the velocity of the aircraft with proportional gain between 300 and 20,000 and derivative gain between 100 and 10,000.[15]

Aircraft Pitch Control System

The control loop of aircraft pitch control consists of an actuator driving an elevator to set the aircraft pitch angle through the aircraft dynamics. The actuator receives a command from a controller with error detector. The pitch angle is measured and fed back to the error detector. Fig.1 shows a block diagram for reference input tracking of the aircraft pitch.[16] The control loop in Fig.1 presents the use of a feedback compensator having various designs controlling the performance of the control loop in both time and frequency domain.

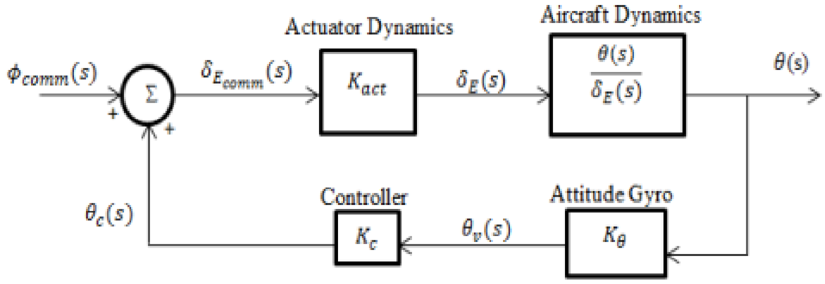

Figure 1: Typical aircraft pitch control system.[16]

The dynamics of the aircraft pitch change depends on the modeling assumptions and the model type (nonlinear or linear). A transfer function for the actuator and aircraft dynamics was given by Sudha and Deepa as a fourth order transfer function given as[8]

$$G(s) = (110s + 243.8) / (s^4 + 12.7s^3 + 43.64s^2 + 127.94s) \quad (1)$$

The transfer function in Eq.1 represents an unstable system that upon receiving a step input it will not reach a steady-state value. This represents a challenge for the controller or compensator used to control the aircraft pitch. It has to stabilize the aircraft first and secondly it has to provide good dynamic performance. The authors used a PID controller to achieve those purposes. Here, we are going to use different approach to control the aircraft pitch. We present a feedback PD compensator and a feedforward first-order compensator.

Using a Feedback PD Compensator

The feedback PD compensator was introduced by Professor Galal Hassaan to the world of automatic control in 2014 to control second order processes[17] and third order processes.[18] A feedback PD compensator has a transfer function, $G_c(s)$ given by:

$$G_c(s) = K_{pc} + K_d s \quad (2)$$

Where: K_{pc} = proportional gain of the compensator.

K_d = derivative gain of the compensator.

The dynamics of the pitch control loop of the aircraft is improved by tuning the compensator by adjusting its gain parameters in an optimal way to decrease an error based performance index. The optimization toolbox of the MATLAB program is used for this purpose.[19] The performance index used is ITSE.[20] The tuned compensator parameters are:

$$K_{pc} = 0.9907 \quad \text{and} \quad K_d = 1.2321 \tag{3}$$

The step time response for reference input tracking is obtained through the derivation of the closed-loop transfer function of the pitch control system using Fig.1, Eqs.1, 2 and 3. The step time response of the control system using the feedback PD compensator and the forward PID controller of reference[8] was plotted using the '*step*' command of MATLAB[21] and shown in Fig.2.

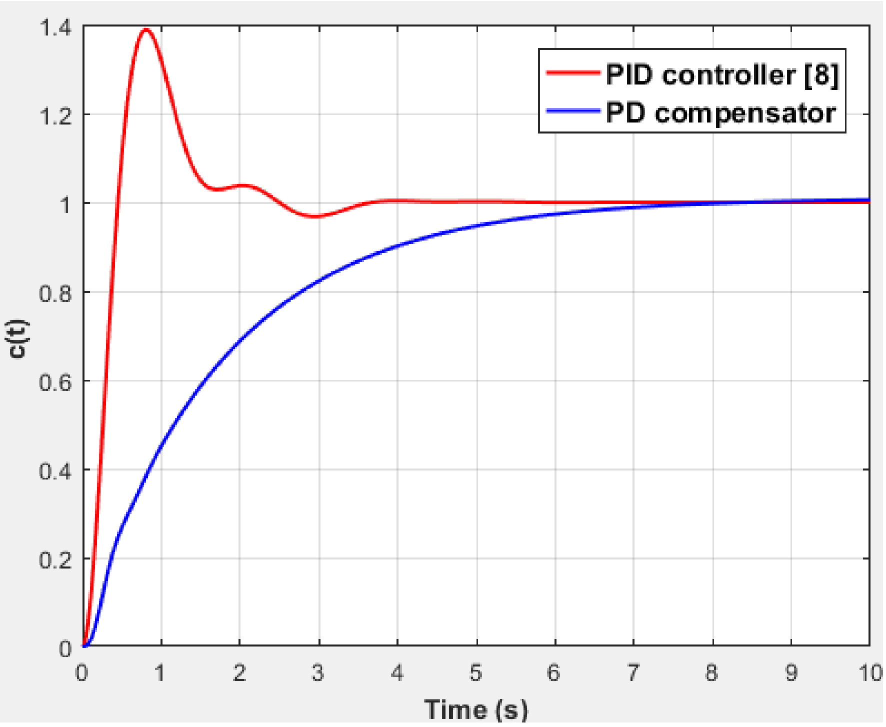

Figure 2: Step response tracking using feedback PD compensator for the aircraft pitch control.

The frequency based characteristics of the control system is obtained using the '*margin*' command of MATLAB.[22] The control loop of the pitch control of the aircraft using the feedback PD compensator has the following time and frequency based specifications:

- Maximum percentage overshoot: 0 (compared with 38.82 % for the PID controller).
- Settling time: 6.4 s (compared with 3.26 s for the PID controller).
- Steady-state error: 0.0025 (compared with 0 for the PID controller).
- Gain margin: ∞ for both feedback PD compensator and PID controller.
- Phase margin: 44.9 degrees (compared with 41.2 degrees for the PID controller).

Using a Feedback First Order Compensator

The feedback first order compensator was introduced by Professor Galal Hassaan in 2014 to control a highly oscillating second order process.[23] The block diagram of the feedback first order compensator is shown in Fig.3.[24] The compensator has two elements. A feedforward element of a transfer function $G_{c1}(s)$ and a feedback element of a transfer function $G_{c2}(s)$. The compensator has the transfer functions:

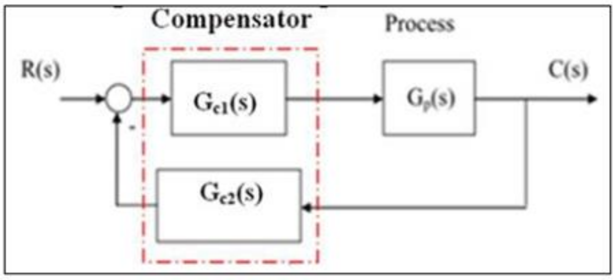

Figure 3: Structure of the first order compensator.[25]

$$G_{c1}(s) = K_{pc} \quad (4)$$

$$(s) = K_c(1 + T_z s) \,/\, (1+T_p s)] \quad (5)$$

Where; K_{pc} = Proportional gain of the feedforward part.

K_c = Gain of the feedback part.

T_z = Time constant of the compensator zero.

T_p = Time constant of the compensator pole.

The compensator has four gain parameters to be tuned to achieve an optimal performance of the aircraft pitch control problem. The best performance index used in the optimization process leading to the compensator tuning was the ITSE (Integral of Time multiplied by Square Error). The tuned compensator parameters are:

$$K_{pc} = 2.4173,\ K_c = 0.8411$$

$$Tz = 1.2067,\ Tp = 0.1788 \quad (6)$$

The step time response for reference input tracking is obtained through the derivation of the closed-loop transfer function of the pitch control system using Fig.1, Eqs.1, 4 and 5. The step time response of the control system using the feedback first-order compensator and the forward PID controller of reference[8] was plotted using the '*step*' command of MATLAB[21] and the tuned compensator parameters in Eq.6 and shown in Fig.4.

The control loop of the pitch control of the aircraft using the feedback first-order compensator has the following time and frequency based specifications:

- Maximum percentage overshoot: 0 (compared with 38.82 % for the PID controller).
- Settling time: 7.5 s (compared with 3.26 s for the PID controller).
- Steady-state error: 0.0083 (compared with 0 for the PID controller).
- Gain margin: 13.7 dB (compared with ∞ for the PID controller).
- Phase margin: 43 degrees (compared with 41.2 degrees for the PID controller).

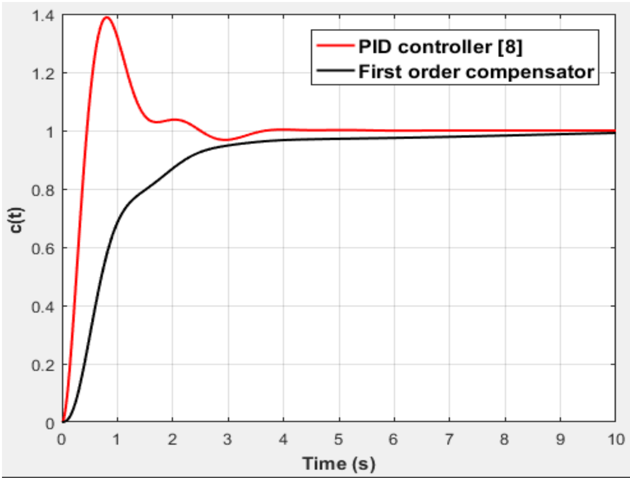

Figure 4: Step response tracking using feedback first-order compensator for the aircraft pitch control.

Step Time Response and Characteristics Comparison

- The step time response of the control system using feedback PD compensator, feedback first order compensator and conventional PID controller is compared in Fig.5.

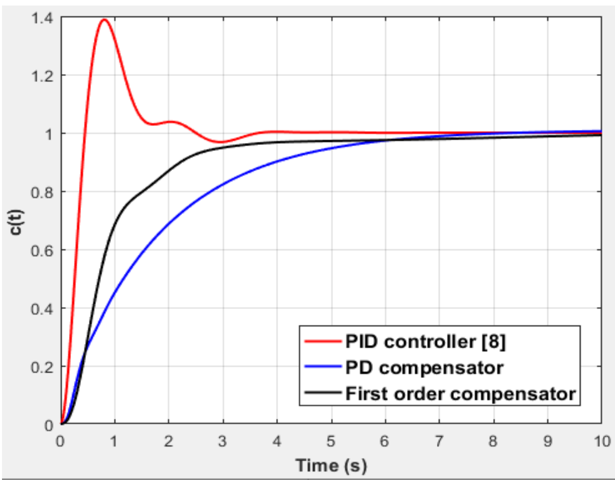

Figure 5: Step time response of the aircraft pitch control system for reference input tracking using feedback PD and feedback first order compensators.

- The proposed compensators to control the aircraft pitch has time-based and frequency-based characteristics given in Table 1 compared with that of the conventional PID controller.

Table 1: **Time-based and frequency-based characteristics of the pitch control system using PD and first order compensators and conventional PID controller.**

Characteristics	**Feedback PD compensator**	**Feedback first order compensator**	**PID controller**
Maximum percentage overshoot (%)	0	0	38.82
Settling time (s)	6.4	7.5	3.26
Steady-state error	0.0025	0.0083	0
Gain margin (dB)	∞	13.7	∞
Phase margin (degrees)	44.9	43	41.20

- **According to Table 1**
➢ The gain margin of the control system is > 6 dB.
➢ The phase margin (PM) is in the range: $41.2 \leq PM \leq 44.9$ degrees.
- According to Ogata, a control system having those ranges for gain and phase margins has good performance.[25]

CONCLUSION

- The objective of the paper was to investigate the use and tuning of PD and first order feedback compensators controllers when used to control an aircraft pitch angle.
- A two-parameter feedback PD compensator was tuned using the MATLAB optimization toolbox using an ITSE performance index.
- The tuning process of the feedback PD compensator revealed:

➢ A complete elimination of the kick associated with the step time response practiced with the use of conventional PID controllers.
➢ A settling time almost twice that when using a tuned conventional PID controller.
➢ A steady-state error of 0.0025 compared with zero steady-state error when using a conventional PID controller.
➢ A Phase Margin 1.09 that when using a tuned conventional PID controller (better stability with the feedback PD compensator).

- A four-parameter feedback first order compensator was tuned using the MATLAB optimization toolbox using an ITSE performance index.
- The tuning process of the feedback first-order compensator revealed:
  - Complete elimination of the kick associated with the step input of the control system.
  - A settling time 2.3 times that when using a tuned conventional PID controller.
  - A steady-state error of 0.0083 compared with zero steady-state error when using a conventional PID controller.
  - A gain margin of 13.7 dB. Even though it is less than that of the other PD compensator and PID controller it is accepted level for accepted control system performance.
  - A Phase Margin 1.04 that when using a tuned conventional PID controller.
- If the criterion of controller or compensator selection is the maximum percentage overshoot, then the feedback PD compensator is the best selection.
- If the criterion of controller selection is the settling time, then the PID controller is the best selection. However, the kick is a real problem that may cause inconvenience flight.

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