AUTOMATIC LANDING CONTROL SYSTEM DESIGN USING QUANTITATIVE FEEDBACK THEORY

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Abstract. *The system's characteristics can vary throughout its operational envelope. This leads to a major challenge when designing a control system based on a nominal plant. Therefore, to design a controller that covers the system's full operational envelope, a gain scheduling technique is often used. An alternative is the Quantitative Feedback Theory, a robust control technique that is mainly characterized for considering, prior to the project, the plant modeling uncertainties, caused either by variations in the parameters of the system to be controlled or by external disturbances. This design technique is performed in the frequency domain and allows the usage of different requirements, such as: stability requirements, tracking-performance specifications, expected disturbance attenuation requirements. This paper presents the application of such method to an Automatic Landing Control System (ALCS) design for a medium weight passenger airplane. A set of different flight states in the flight envelope was chosen, aiming at developing a compensator and a pre-filter suitable for the ALCS. The validation of the design occurred through automatic landing maneuver simulations in some of these flight states and showed that Quantitative Feedback Theory is a promising landing control technique.*

Keywords*: Quantitative Feedback Theory, longitudinal control, lateral-directional control, automatic landing system*

1. INTRODUCTION

The conventional design approach of Flight Control System's (FCS) applications is based in gain scheduling techniques to obtain controllers capable of meeting requirements for the system's full operational envelope. In this scenario, robust control techniques are presented as an alternative, since the robust control design aims at finding a unique compensator and pre-filter capable of handling a degree of plant variability about a nominal plant.

The Quantitative Feedback Theory (QFT) (Horowitz, 1982) is a robust control technique that considers a range of system uncertainties since the beginning of the design. These uncertainties are caused by either variations in system parameters or by external disturbances. Hence, with this method, one obtains a robust controller that is also insensitive to disturbances. It also presents great flexibility, as it can use a system defined either by a transfer function or by experimental data.

QFT design is executed in a graphical form in the frequency domain and, therefore, presents the advantage of not using complex mathematical tools. It is based on a classical structure with two degrees of freedom presented in Fig. 1, in which G(s), the compensator, and F(s), the pre-filter, are linear time-invariant controllers.

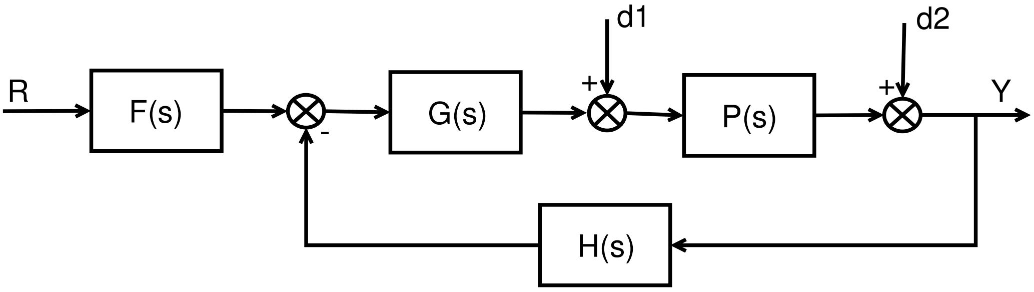

Figure 1. Fundamental QFT design structure.

QFT (Houpis and Rasmussen, 1999) design is executed through the following steps:

a. define a set of transfer functions P(s) that best describe system uncertainties;

b. determine the set of frequencies in which the system operates;

c. elect the nominal plat $P_0(s)$;

d. define system closed loop requirements and convert them into bounds in Nichols chart;

e. in the Nichols chart, design the compensator G(s) using a loop-shaping technique in order to guarantee that the open loop response L(s) = G(s)P(s) meets the requirement bounds previously defined;

f. in a bode diagram, design the pre-filter F(s), if the closed loop response does not meet the requirements using only G(s);

In order to perform the QFT design, a toolbox for MatLab (Borghesani, Chait and Yaniv, 2003) was used.

2. MODELLING

Taking into account that aircraft's equations of motion are nonlinear, to design an Automatic Landing Control System (ALCS), using linear compensator design methods, one must linearize these equations around a set of equilibrium points that fully describe the aircraft's dynamics. This set of linear models describes the aircraft's distinct operational points in which the plant's characteristics can widely vary.

The time invariant equations of motions are in the form $\dot{x} = Ax + Bu$, where $x = [v \quad \alpha \quad q \quad \theta \quad \beta \quad p \quad r \quad \phi \quad \psi]$ is the state vector, and $u = [\delta_e \quad N_1 \quad \delta_r \quad \delta_a]$ is the input vector. The longitudinal states are air speed, angle of attack, pitch rate and pitch angle, and the control signals are elevator deflection and engine percentage rate. The lateral directional states are bank angle, roll rate, yaw rate, roll angle and yaw angle, and the control signals are rudder and aileron deflections. Eighteen flight conditions were chosen in which different values of CG position, Mach number, mass and atmospheric pressure were used. Table 1 shows the percentage of variation of these parameters from their means.

Table 1. Operational points parameters' variations.

Parameter	**Variation**
CG position	± 26%
Mach number	± 17%
Mass	± 20%
Atmospheric pressure	± 33%

The same flap position was considered for all flight conditions.

According to the QFT method, one must define a nominal plant at the beginning of the design. This plant is used as reference in different stages of the compensator project. Table 2 shows the nominal plant's open-loop poles.

Table 2. Nominal plant's open-loop poles.

Mode	**Open-loop poles**	**Damping ratio**	**Frequency (rad/sec.)**
Short-period	-0.872±1.58i	0.48	1.80
Phugoidal	-0.023±0.28i	0.079	0.28
Dutch-roll	-0.159±1.24i	0.128	1.25
Roll	-2.200	1	2.20
Spiral	0.073	-1	0.07

3. SPECIFICATIONS

Military standards such as MIL-STD-1797A and MIL-DTL-9490E establish general flying and ground handling qualities as well as performance specifications for FCS design. Even though a small non-military aircraft is used in this paper, these standard's specifications were considered as they are also applicable to civil aircraft. The design specifications were defined for a Class II aircraft, in Category C flight phase with Level 1 flying handling qualities.

For short-period longitudinal control, time domain requirements were considered based on a step input command. To meet Level 1 flying qualities, the short-period damping ratio (ξ_{sp}) must be between 0.35 and 1.3.

For lateral/directional control (Yaw Damper and Roll Damper), time domain requirements were also considered. To meet Level 1 flying qualities, the Dutch Roll Mode damping ratio (ξ_{dr}) must be greater than 0.12 and the Roll Mode time constant less than 1.4 sec.

In approach landing phase, an adequate performance is obtained when the flight path control remains within ±2 degrees of glide slope angle or ±1 dot on ILS, and the airspeed control is less than 10 knots above approach speed, but not less than stall speed.

In touchdown landing phase, an adequate performance is obtained when the touchdown zone is within ±50 feet of aim point, laterally, and within -250 to +700 feet of aim point, longitudinally.

In normal operation, while flying in random and discrete turbulence environment, the FCS shall provide a safe level of operation and maintain mission accomplishment capabilities. Transients due to disturbances shall not exceed ±0.15g incremental normal acceleration at the center-of-gravity within the first 2 sec.

In addition, open-loop transmissions from the command input to the required output in each loop must present ±45° phase margin (PM) and ±6dB gain margin (GM). Finally, the phase margin frequency (cutoff frequency) must be within 0.1 and 20 rad/sec in order to prevent interaction with the aircraft's bending modes and slow control signals' response.

4. LOGITUDINAL AUTOMATIC LANDING SYSTEM DESIGN

The longitudinal automatic landing system consists of a short-period damper inner-loop wrapped around by, either a glide slope tracker loop, or an automatic flare loop. Also, an airspeed-command and hold loop involves a single loop closure, which involves the aircraft engine dynamics as the control.

4.1. QFT design for short-period damper loop

This loop is designed with the main purpose of providing a damping ratio for the short-period mode that satisfies Level 1 flying qualities. These flying qualities were converted into QFT tracking bounds. Also, considering the disturbance input, the project must guarantee this input rejection. Therefore, the design aims to find a compensator $G_1(s)$ and a pre-filter $F_1(s)$ that meet the performance requirements on tracking, stability and disturbance rejection.

Two outputs signals were controlled (Stevens and Lewis, 2003): pitch rate and pitch angle. However, the design was executed based on the QFT structure, instead of using gains in the feedback loop.

Even though all plants' short-period poles already satisfy Level 1 flying qualities requirements, based on previous experience, it is of great interest to obtain a greater damping. Hence, tow tracking bounds (T_{RU} and T_{RL}) were defined. They reflect the system dynamics, but present damping of 0.4 and 0.65. The objective of these bounds is to guarantee that the system's closed-loop response lies within them, as

$$T_{RL}(s) \leq \left| F_1(s) \frac{P(s)G_1(s)}{1 + P(s)G_1(s)H_1(s)} \right| \leq T_{RU}(s) \tag{1}$$

For robust stability, the following performance specification bound is applied:

$$\left| \frac{P(s)G_1(s)}{1 + P(s)G_1(s)} \right| \leq \mu = 1.02 \tag{2}$$

which corresponds to a gain margin of $GM = 20\log(1 + 1/\mu) = 6dB$ and a phase margin angle of $PM = 180° - \cos^{-}(0.5/\mu^2 - 1) = 58°$.

For input disturbance-rejection specification, the following bound is applied

$$\left| F_1(s) \frac{P(s)}{1 + P(s)G_1(s)H_1(s)} \right| \leq 0.20 \tag{3}$$

which guarantees disturbances' attenuation by a factor of 0.80.

Figure 2 shows the performance bounds for the short-period damper loop together with the design of $G_1(s)$ controller. The closed round lines represent the robust stability bounds, while the two upper flat lines represent the disturbance-rejection bounds and the other two flat lines represent the tracking-performance bounds. It is possible to verify that tracking-performance bounds are not fully satisfied. In order to satisfy these bounds, a pre-filter design can be used instead of making changes in $G_1(s)$.

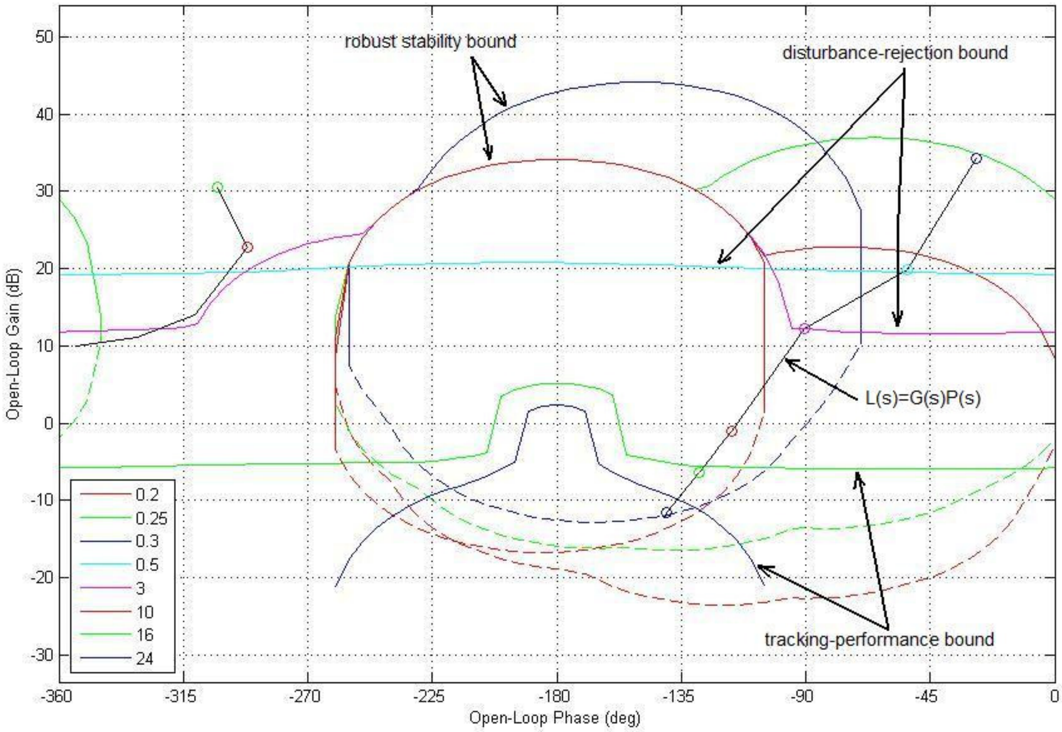

Figure 2. $G_1(s)$ QFT Design.

Figure 3 shows the tracking-performance bound as well as short-period damper loop together with the design of $G_1(s)$ and $F_1(s)$. As observed in the figure, the pre-filter leads to a design that meets the specifications.

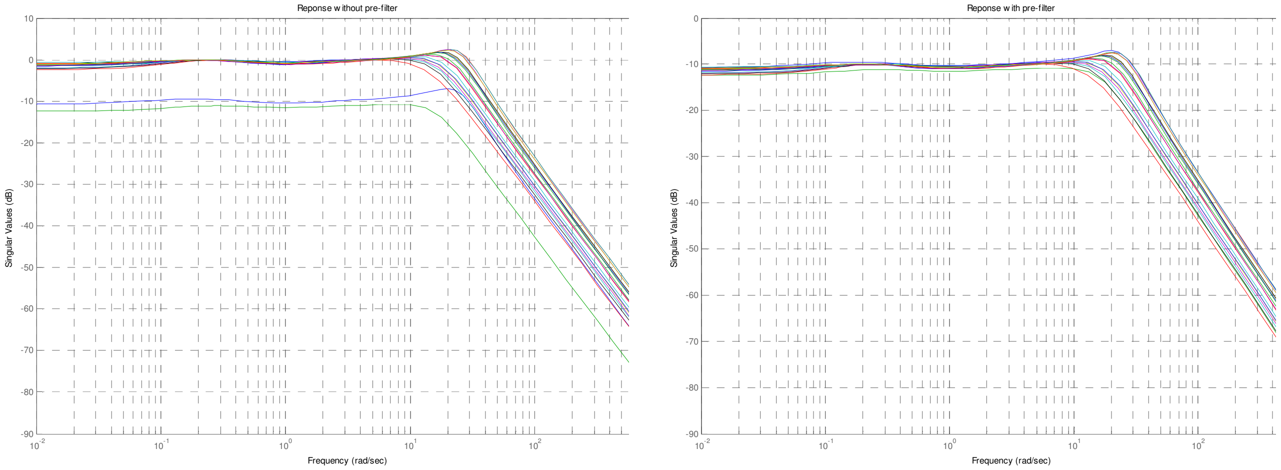

Figure 3. $F_1(s)$ QFT Design.

Figure 4 shows the system response when the pilot inputs a doublet on the elevator. With the QFT design, it can be observed an improvement in aircraft handling qualities.

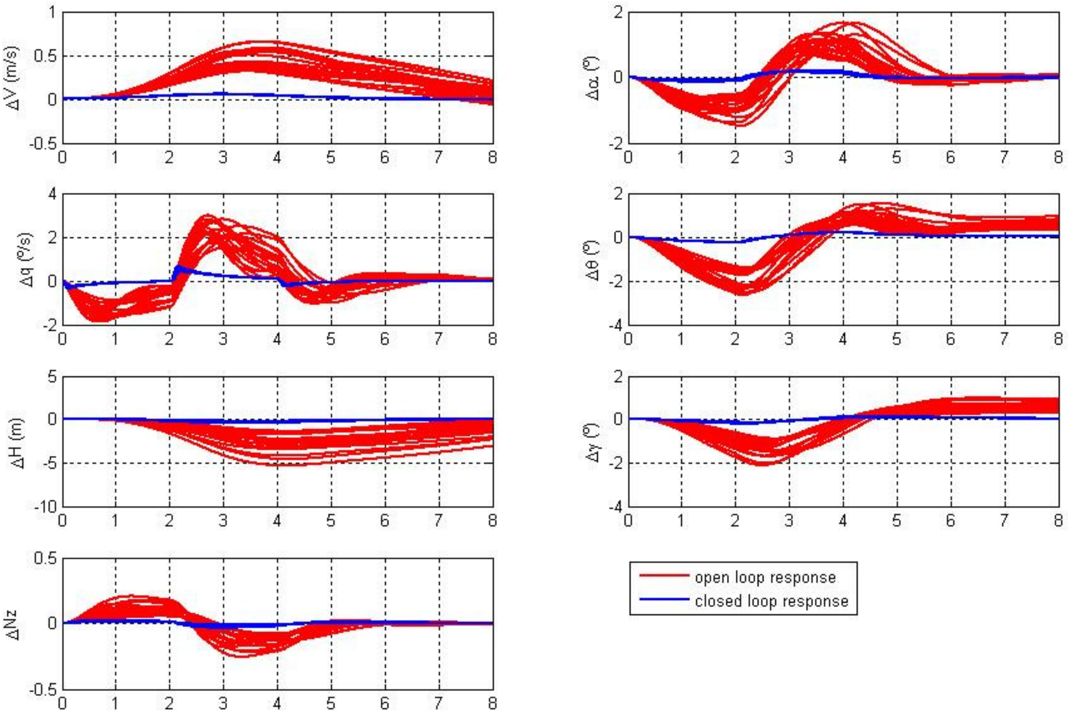

Figure 4. System response for a doublet input.

4.2. QFT design for glide slope tracker

The glide slope tracker is a simple regulator loop, since it is desired that glide slope deviation approaches zero. This deviation is calculated according to the equation $\dot{d}_{GLIDE} = v_A \sin(\gamma - \gamma_R)$, where d_{GLIDE} is a distance measurement between the desired approach trajectory and the current aircraft trajectory, v_A, is the approach speed, and γ_R is the flight path angle of the reference trajectory.

Considering that the reference input of this loop is zero, tracking-performance bounds and pre-filter are not used in this design. Also, since the glide slope tracker uses the short-period damper loop as its inner-loop, a disturbance rejection bound is not used either, as the inner-loop compensator design already meets the disturbance rejection specification. Therefore, the design aims at finding a compensator $G_2(s)$ that meets only the requirements on robust stability. The same gain and phase margins used in the short-period damper loop were used here, leading to a stability margin of 1.02. Table 3 presents the designed controller for glide slope tracker.

4.3. QFT design for airspeed command and hold loop

The airspeed command and hold loop was designed in a similar manner as the short-period damper loop. The design aims to find a compensator $G_3(s)$ and a pre-filter $F_3(s)$ that meet the performance requirements on tracking, stability and disturbance rejection. A stability margin of 1.02 was used, which led to the same gain and phase margins used in short-period damper loop. Concerning the tracking performance, the requirements are a rise time between 13 and 20 sec and an overshoot less than 10%. Also, for input disturbance-rejection specification, an attenuation factor of 0.80 was used. After the design of $G_3(s)$, the tracking performance bound was not satisfied and a pre-filter design was needed

Figure 5 illustrates the system response. Through simulation analysis, it is verified that an airspeed command and hold loop design is required to minimize airspeed variation during glide slope tracking. Also, it is observed that a zero steady-state error is not obtained for all operation points with the designed $G_3(s)$ and $F_3(s)$. A higher order controller would be needed. However, considering that the maximum airspeed steady-state error is 0.38 m/s and it is within section 3 specifications, a re-design was not necessary.

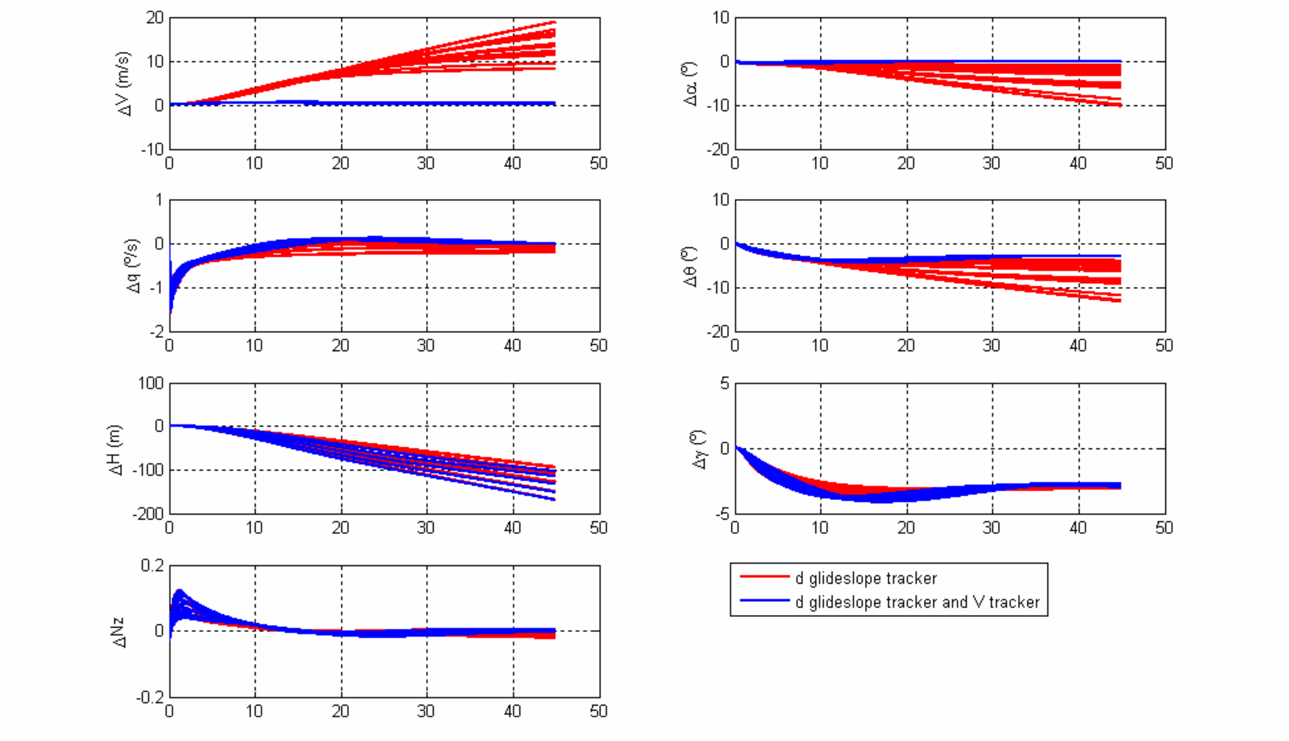

Figure 5. System response when tracking glide slope for $\gamma_R = -3°$.

4.4. QFT design for automatic flare loop

The automatic flare loop presents the same inner-loop used in the glide slope tracker. Since the inner-loop compensator design already meets the disturbance rejection specification, a disturbance rejection bound is not used in the automatic flare design.

The automatic flare loop is a simple tracker, since it aims to track the trajectory given by $h_{REF}(t)=h_o e^{-\frac{t}{\tau}}$, where h_o is the aircraft altitude above ground at the beginning of the flare, and τ is a time constant calculated according to the distance between the glide slope transmitter and the touchdown point. For this design, a time constant of 3.33 sec. was chosen. The tracking specifications were determined based on this trajectory, which lead to a rise time between 6 and 8 sec., and an overshoot less than 10 %. Also, a stability margin of 1.02 was used, which lead to the same gain and phase margins used in short-period damper loop.

Using the tracking performance bounds and the stability margins, a controller $G_4(s)$ and a pre-filter $F_4(s)$ were designed.

5. LATERAL DIRECTIONAL AUTOMATIC LANDING SYSTEM DESIGN

The lateral directional automatic landing system consists of a Yaw Damper inner-loop wrapped around by a localizer tracker loop. Also, a Roll Damper loop involves a single loop closure.

5.1. QFT design for yaw damper loop

The purpose of this loop design is similar to the short-period damper loop: provide a Dutch Roll Mode damping ratio that satisfies Level 1 flying qualities, guarantee disturbance input rejection and obtain a stability margin of 1.02. Therefore, the design aims to find a compensator $G_5(s)$ and a pre-filter $F_5(s)$ that meet the performance requirements on tracking, stability and disturbance rejection.

All plants' short-period poles already satisfy Level 1 flying qualities requirements. However, based on previous experience (Ebrahimi and Coleman, 1990), it is of great interest to obtain a greater damping. Tow tracking bounds were defined: T_{RU} and T_{RL}. They reflect the system dynamics, but present damping between 0.3 and 0.5.

A first-order high-pass filter (washout filter) was considered in the feedback path to differentiate the feedback signal so that it vanishes during steady-state conditions. This filter is necessary as the yaw rate has a constant non-zero value that the yaw rate feedback will try to oppose.

Figure 6 illustrates the system response. Through simulation analysis it is verified that a roll damper loop design is required to attenuate the effect that the unstable spiral mode has on system dynamics.

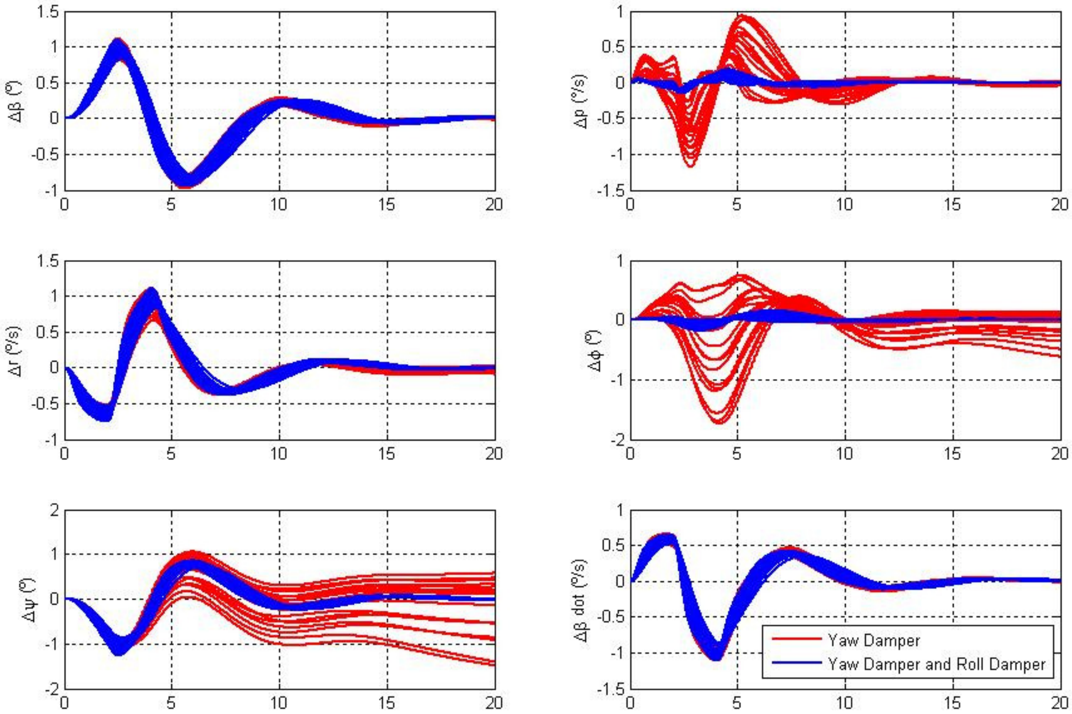

Figure 6. System response for a doublet input in aileron.

5.2. QFT design for roll damper loop

The main purpose of this loop design is to meet the stability margin of 1.02, as the spiral mode is very fast, but unstable. Considering that the roll mode presents a time constant less than 1.4 sec for all operation points, Level 1 flying qualities are met and no tracking performance bounds and pre-filter were used in this design. Specifications concerning roll rate time delay, and the time to double bank angle amplitude of the Spiral Mode, were not converted into QFT bounds, as it was preferred to verify them through simulation.

An input disturbance-rejection specification was used in this design with an attenuation factor of 0.80. System simulation can be observed in Fig. 6. With the Roll damper, the steady-state error in roll and yaw angles is greatly attenuated since the spiral mode is now stabilized.

5.3. QFT design for localizer tracker

Similar to the glide slope tracker, the localizer tracker is a simple regulator loop, since it is desired that localizer deviation approaches zero. This deviation is calculated according to the equation $\dot{d}_{LOC} = v_A \sin(\psi + \beta - \psi_R)$, where d_{LOC} is a distance measurement between the desired lateral approach trajectory and the current aircraft lateral trajectory, v_A is the approach speed.

Considering that the reference input of this loop is zero, tracking-performance bounds and pre-filter are not used in this design. Also, since the localizer tracker uses the yaw damper loop as its inner-loop, a disturbance rejection bound is not used either, as the inner-loop compensator design already meets the disturbance rejection specification. Therefore, the design aims to find a compensator $G_7(s)$ that meets only the requirements on robust stability. The same gain and phase margins used in previous loop's designs were used here, leading to a stability margin of 1.02. Table 3 presents the designed controller for localizer tracker.

Figure 7 illustrates the system response. It can be verified that system response meets performance requirements described in section 3.

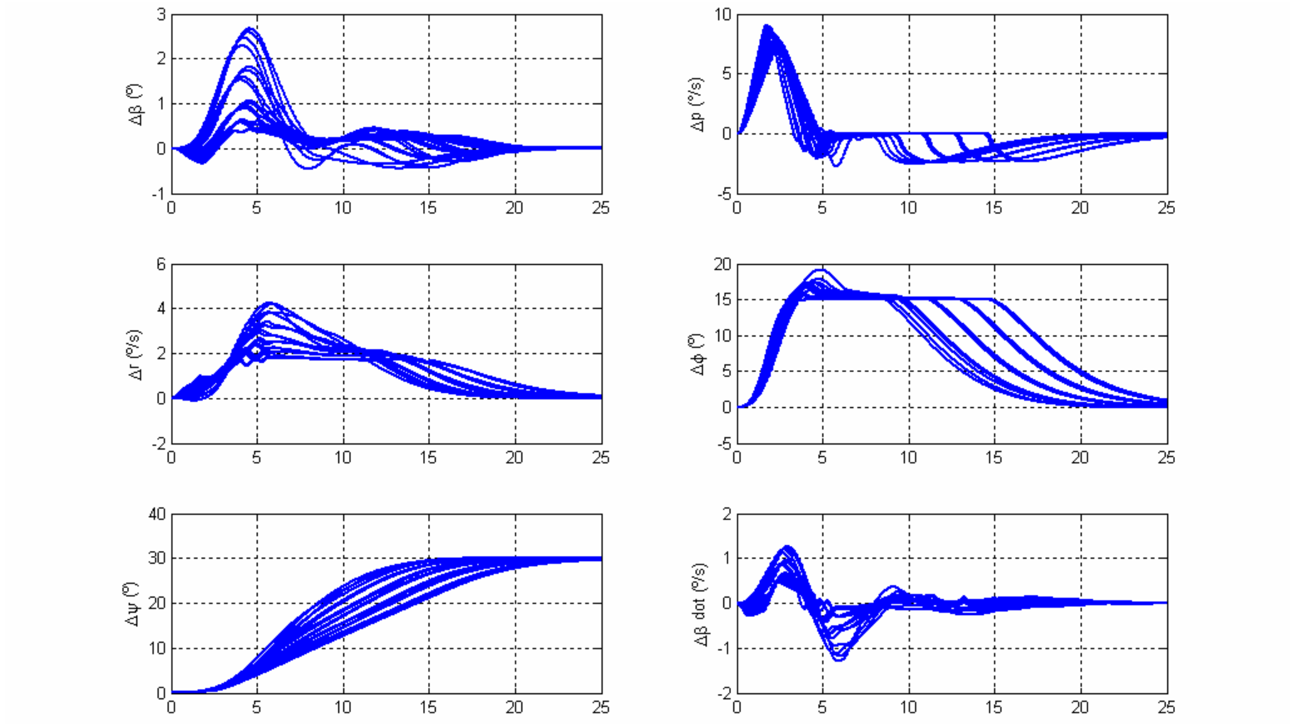

Figure 7. System response when tracking localizer for $\Psi_R = 30°$.

6. RESULTS

Table 3 presents all the controllers obtained with the robust QFT method. This technique was employed aiming at finding a unique controller, capable of meeting section 3 specifications for a large envelope control, and therefore, eliminating the need for gain scheduling.

Table 3. Controllers obtained with the QFT design.

Designs	**Controller and Pre-filter**
short-period damper loop	$G_1(s) = 5$ and $F_1(s) = 0.32$
glide slope tracker	$G_2(s) = \frac{-0.3544 s^2 - 0.211 s - 0.02664}{s^2 + 18.96 s + 0.02664}$
airspeed command and hold loop	$G_3(s) = \frac{872 s + 527.5}{s + 21.28}$ and $F_3(s) = \frac{0.02272}{s^2 + 0.3065 s + 0.02092}$
automatic flare loop	$G_4(s) = \frac{3.179 s^2 + 1.867 s + 0.2343}{s^2 + 88.94 s + 0.125}$ and $F_4(s) = \frac{1.215 s + 1.205}{s + 0.3844}$
yaw damper loop	$G_5(s) = \frac{17.42}{s + 0.6968}$ and $F_1(s) = 0.21$
roll damper loop	$G_6(s) = 5.3$

localizer tracker	$G_7(s) = \frac{0.077894\ s}{s + 3.763}$

In order to verify the final gain and phase margins, each control loop was opened while the others remained closed and its frequency response was obtained. Each frequency response was presented in a Nicholes chart where a closed region, delimitating the ± 6 dB and ± 45° margins, was also presented. The result of this process is shown in Tab. 4. It can be verified that only in the d_{GLIDE} loop the 45° margin was not obtained for all operation points.

Table 4. Minimum Gain and Phase Margins considering all operation points.

Open loop at:	**Minimum GM (dB)**	**Minimum PM (°)**
Bank Angle Rate	17	55
Roll Angle	27	87
Roll Rate	Inf.	60
d loc	25	71
Pitch Angle	27	48
Pitch Rate	18	45
d glide	29	41
V	Inf.	76
Rudder position	17	55
Aileron position	Inf.	57
Elevator Position	Inf.	45
Nk1	Inf.	76

Also, through this analysis, the cutoff frequencies were obtained. Even thought they were within the requirements presented in section 3, aileron and rudder position cutoff frequencies were high and compromised system performance.

Table 5 shows the obtained result for damping ratio. It can be observed that they are in accordance with the specifications.

Table 5. Damping Ratio considering all operation points.

Mode	Minimum	Maximum
Short-period	0.412	0.583
Dutch Roll	0.467	0.533

Concerning normal acceleration variations when the aircraft is flying under moderate turbulence, it was verified that the specification was not met for all operation points and further design effort is necessary. One reason for this problem are the elevated cutoff frequencies obtained.

Through system simulation and frequency response analysis, it has been demonstrated that the QFT technique is suitable for FCS applications, such as ALCS, as it presents benefits as a robust control technique. It has also been verified that, the required specifications for robust stability and robust tracking were fulfilled for the set of eighteen flight conditions, since these requirements were defined as goals early in the project execution. However, this method results in different designs every time it is executed and an improvement to this technique would be to create an optimization algorithm to be executed after a preliminary design. This optimization would guarantee that the optimum controller was obtained, despite of the designer's previous experience.

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