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Optimal Control new Methodologies Validation on the Research Aircraft Flight Simulator of the Cessna Citation X Business Aircraft

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Abstract

In this paper the Cessna Citation X clearance criteria were evaluated for a new Flight Controller. This Flight Controller was designed and optimized using a combination of the Hinfinity method and the Differential Evolution algorithm, during a previous research. The linear stability, eigenvalue, and handling qualities criteria in addition of the nonlinear analysis criteria were investigated during this research to assess the business aircraft for flight control clearance and certification. The optimized gains provide a very good stability margins as the eigenvalue analysis shows that the aircraft has a high stability, and a very good flying qualities of the linear aircraft models are ensured in its entire flight envelope, its robustness is demonstrated with respect to uncertainties due to its mass and center of gravity variations.

Keywords:	Flight control clearance; Stability criteria; Aircraft handling qualities; Eigenvalues; Aircraft nonlinear analysis

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1. Introduction

The clearance of the flight control laws of a civil aircraft is a fastidious process, especially for modern aircrafts that need to achieve high performance as shown by in [1]. This process aims to prove that the selected stability, robustness and handling requirements are satisfied against any possible uncertainties. Because of the high number of data, the parameters variations and their uncertainties have to be provided for the clearance of the large flight envelope. To carry out this process, a detailed description of methods and procedures, which are used in industry, was given by Udo Korte [2]. The presence of uncertainties is related to many factors, such as the mass and Xcg variations, aerodynamics data values, control surfaces dynamics and delays, and Air Data measurements errors [3]. To demonstrate the effects of uncertainties, the clearance criteria are considered as robustness criteria from the Airbus team point of view, and were applied in linear, and nonlinear analysis. As well as in the simulation of HIRM+ generic model and HWEM the realistic model aircrafts as shown in [1]. A benchmark of high- fidelity generic civil aircraft was developed by Airbus for advanced flight control, and fault diagnosis research in [4]. In [5] a stochastic robust flight control was applied to the highly uncertain nonlinear HIRM aircraft model and compared its robustness of its flight control laws with other competitive flight control laws by using the Nichols plot. The research presented in [6], highlighted the importance of the clearance task, where it summarized five (5) new analysis techniques were applied to solve a benchmark clearance problem, researches and results of one of these 5 new techniques were presented extensively in [7], this technique is known as the clearance based optimization technique. Linear and nonlinear Cessna Citation X business aircraft benchmark was developed at Laboratory of Active Controls, Avionics and AeroServoElasticity LARCASE in [8]-[9] by using a Cessna Citation X Level D Research Aircraft Flight

Simulator designed and manufactured by CAE Inc. This benchmark programmed in Matlab/Simulink was used for advanced flight control design and clearance [10]-[11], for robust control analysis in [12]-[13], and for new identification methods designed and developed in [14]-[16].

The clearance analysis of linear and the nonlinear the Cessna Citation X business aircraft is addressed for the first time in this paper, which gives to the reader an excellent understanding of the criteria and visualization tools used in the assessment of the flight control laws. The aircraft linear model with actuators, and sensors dynamics is detailed, then a brief description of the clearance criteria theory is listed. Analysis of results and conclusions is further given.

2. Cessna Citation X aircraft actuators and sensors dynamic

The Cessna Citation X is the fastest civil aircraft in the world, as it operates at its speed upper limit given by Mach number of 0.935. [18] The longitudinal and lateral motions of this business aircraft are described, as well as its flight envelope and the flying qualities requirements.

The aircraft nonlinear model for the development and validation of the flight control system used the Cessna Citation X flight dynamics, and was detailed by Ghazi in [8], [9]. This model was built in Matlab/Simulink based on aerodynamics data extracted from a Cessna Citation X Level D Research Aircraft Flight Simulator designed and manufactured by CAE Inc. According to the Federal Administration Aviation (FAA, AC 120-40B) [19], the Level D is the highest certification level that can be delivered by the Certification Authorities for the flight dynamics. More than 100 flight tests were performed on the Citation X Level D Research Aircraft Flight Simulator within the aircraft flight envelope to validate linear model in [8], and tests were performed extensively in order to identify the Cessna Citaion X aircraft model in [14], [15], and the Engine model as in [16].

Using trim and linearization routines developed by Ghazi and Botez [8], and [9], the aircraft longitudinal and lateral equations of motions have been linearized for different flight conditions in terms of altitudes and speeds, and different aircraft configurations in terms of mass and center of gravity positions. In order to validate the different models obtained by linearization, several comparisons of these models with the linear model obtained by use of identification techniques as the ones proposed in [14-[16] were performed for different flight conditions and aircraft configurations. Results have shown that the obtained linear models were accurate and could be further used to estimate the local behaviour of the Cessna Citation X for any flight conditions.

2.1. Aircraft dynamics

The aircraft's dynamics is represented firstly by nonlinear equations representing the equations of motion in the three axis (x, y, z) as given in [19], and secondly these nonlinear equations are linearized, the longitudinal and lateral motions are decoupled for each equilibrium point, which means that the longitudinal motion dynamics can be represented for each flight condition or equilibrium point under the form of the following state space equation, using the elevator as deflection angle input:

$$\dot{x}_{lat} = \mathrm{A_{long}}\, x_{long} + \mathrm{B_{long}} \mathrm{u_{long}} \quad (1)$$

$$\mathrm{A_{Long}} = \begin{pmatrix} X_u & X_w & X_q & -g\cos\theta \\ Z_u & Z_w & Z_q & 0 \\ M_u + M_{\dot{w}} Z_u & M_w + M_{\dot{w}} Z_w & M_q + M_{\dot{w}} u_0 & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix},$$

$$\mathrm{B_{Long}} = \begin{pmatrix} X_{\delta_e} \\ Z_{\delta_e} \\ M_{\delta_e} + M_{\dot{w}} Z_{\delta_e} \\ 0 \end{pmatrix} \quad (2)$$

where the state vector $x_{long}(t)$ and the control vector $u_{long}(t)$ are given by:

$$x_{long}(t) = (\mathrm{u} \quad \mathrm{w} \quad \mathrm{q} \quad \theta)^{\mathrm{T}} \text{ and } u_{long}(t) = \delta_e \quad (3)$$

In the same way the aircraft's lateral motion dynamics is also given by the state space equation, using the aileron and the rudder as deflection angle inputs:

$$\dot{x}_{lat} = \mathrm{A_{lat}}\, x_{lat} + \mathrm{B_{lat}} \mathrm{u_{lat}} \quad (4)$$

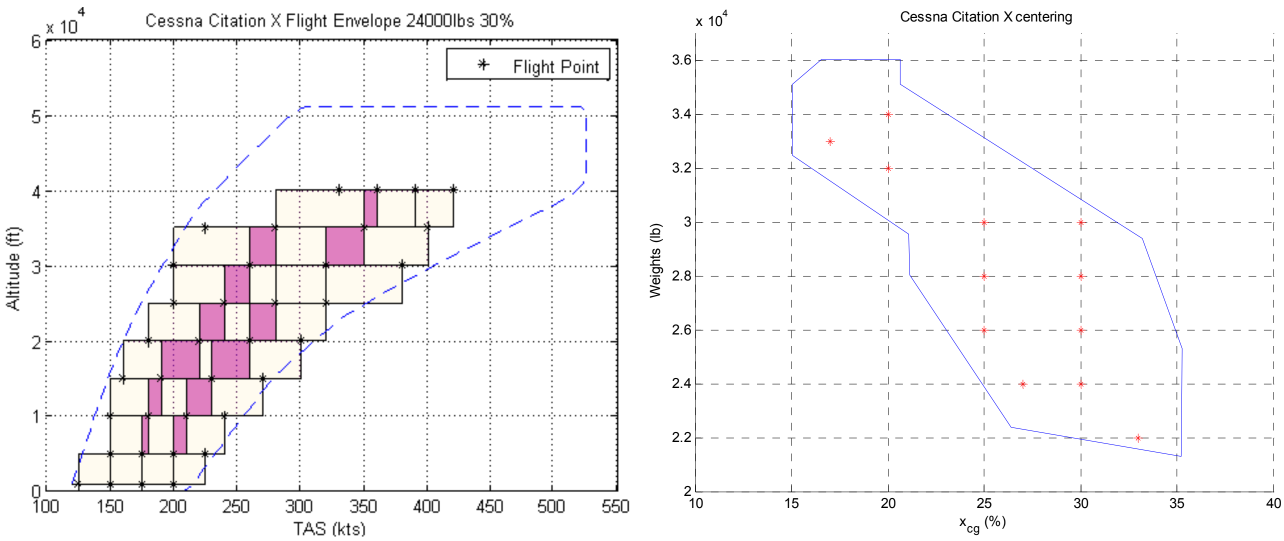
$$\mathrm{A_{Lat}} = \begin{pmatrix} Y_\beta/u_0 & Y_p/u_0 & -(1 - Y_r/u_0) & g\cos\theta_0/u_0 \\ L_\beta & L_p & L_r & 0 \\ N_\beta & N_p & N_r & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix},$$

$$\mathrm{B_{Lat}} = \begin{pmatrix} Y_{\delta_a}/u_0 & Y_{\delta_r}/u_0 \\ L_{\delta_a} & L_{\delta_r} \\ N_{\delta_a} & N_{\delta_r} \\ 0 & 0 \end{pmatrix} \quad (5)$$

where the state vector $x_{lat}(t)$ and the control vector $u_{lat}(t)$are given by:

$$x_{lat}(t) = (\beta \quad \mathrm{p} \quad \mathrm{r} \quad \phi)^{\mathrm{T}} \quad \text{and}$$

$$u_{lat}(t) = (\delta_a \delta_r)^{\mathrm{T}} \quad (6)$$



(a) (b)

Figure 1. (a) Flight envelope with LFR regions; (b) Weight versus Xcg envelope

Table 1: Actuators dynamics characteristics

Actuator	Frequency ω [rad/sec]	Damping ζ	Angle [$^\circ$]	Rates [$^\circ$/s]
Elevators	60	0.7	$\pm$20	$\pm$30
Rudder	60	0.7	$\pm$20	$\pm$30
Ailerons	60	0.7	$\pm$60	$\pm$30

The linearized model of the Cessna Citation X is obtained for 36 flight conditions using the Cessna Citation X Aircraft Flight Research Simulator tests performed at our laboratory LARCASE. The linearized model is further decomposed using the Linear Fractional Representation (LFR) method as explained in [20]; the bilinear interpolation method is used to present by 26 regions of the flight envelope by LFR models as shown in Figure 1(a). Thus, 72 flight points represented by state space models are obtained for each Xcg and weight configuration for a total of 12 Xcg and weight configurations shown in Figure 1 (b).

2.2. Actuators and sensors dynamics

The actuators dynamics are provided from the literature [8], and are given as second order transfer function – their damping and frequencies are mentioned in Table 1:

$$\frac{\omega^2}{s^2+2\zeta\omega s+\omega^2} \tag{7}$$

2.3. Flight controller

The flight controller is designed, and optimized using a combination of the Hinfinity control method and the Differential Evolution algorithm, where the objective function used in the previous research combined both time domain performance criteria and frequency-domain robustness criterion, which led to good level aircraft flying qualities specifications and reduce considerably the time computing, this method is given in detailed by Boughari et all [11] and [21].

3. Clearance criteria

3.1. Linear stability and eigenvalue analyses

The aim of the aircraft clearance and certification is to prove that the aircraft is stable over its full flight envelope with sufficient margin stabilities, in the presence of uncertainties as shown in [6]. An overview of 5 new techniques for analysing the stability and robustness was considered by the industry in [6]. The basic theory of the linear stability was given in [22], while methodologies and results on these new techniques were presented in [23], [24], [25], and [26]. The weight functions method was applied on the business Hawker 800 XP, and on the HIRM aircrafts to assess their stability in [27] and [28]. In this paper linear stability margins for the pitch, and roll open – loop frequency responses were investigated for the Cessna Citation X business aircraft using Bode and Nichols plots.

The unstable eigenvalues either of the unaugmented aircraft or augmented closed-loop system must be identified for the worst cases [29]. During this research, the open loop eigenvalues are identified by using "the robustness stability", and analysed using the GUI developed by the COFCLUO project [30]. In addition the closed loop eigenvalues are investigated by using zero poles map.

3.2. Linear, nonlinear handling qualities and nonlinear analyses

The linear handling analysis is presented in time domain and frequency domain criteria [31].

The time domain criteria are given by :

1. Pitch acceleration peak time, pitch rate peak time, pitch rate overshoot/dropback, roll mode time constant, and time to bank.

The frequency domain responses and results, which are the most used to assess the linear handling criteria are defined [31-32]:

2. Pitch/bank attitude frequency response.
3. The pitch/bank average phase rate, and the absolute amplitude should assess the resistance to Pilot Induced Oscillation (PIO).
4. Frequency and damping of short period mode, dutch roll and Flight Control System (FCS) modes [31]-[32] and their relationships with flight tests data parameters were given in [33].
5. Closed-loop pitch axis bandwidth (Neal Smith), the open-loop pitch axis bandwidth (Hoh), and phase and gain margin criterion (Roger).

A civil aircraft should have good handling requirements in addition of the stability ones. The aircraft certification and assessment has to give the proof that the aircraft is capable to accomplish the flight easily with excellent handling qualities given by level 1, which is defined as the highest by the American military specification F-8785C [32] among 3 levels of flying qualities. Also the nonlinear analysis has to investigate problems encountered in the linear analysis, and to evaluate the aircraft stability, handling and control in the presence of nonlinearities.

3.3. Pitch control and rapid roll

The aircraft manoeuvres are usually evaluated in modern flight control according to [1], which means that the load factor and angle of attack are proportional to the pitch command (stick deflection). By using different inputs types (pull/push, step, and ramp), the required aircraft response trajectory should not exceed a given limit in the nominal aircraft model including added uncertainties.

The rapid roll control mode is a very important criterion to be checked for the nominal aircraft model or in presence of uncertainties. The maximum roll rates/overshoots, roll angle overshoot, maximum sideslip generated during roll, and the load factor have to be verified.

4. Analysis of results

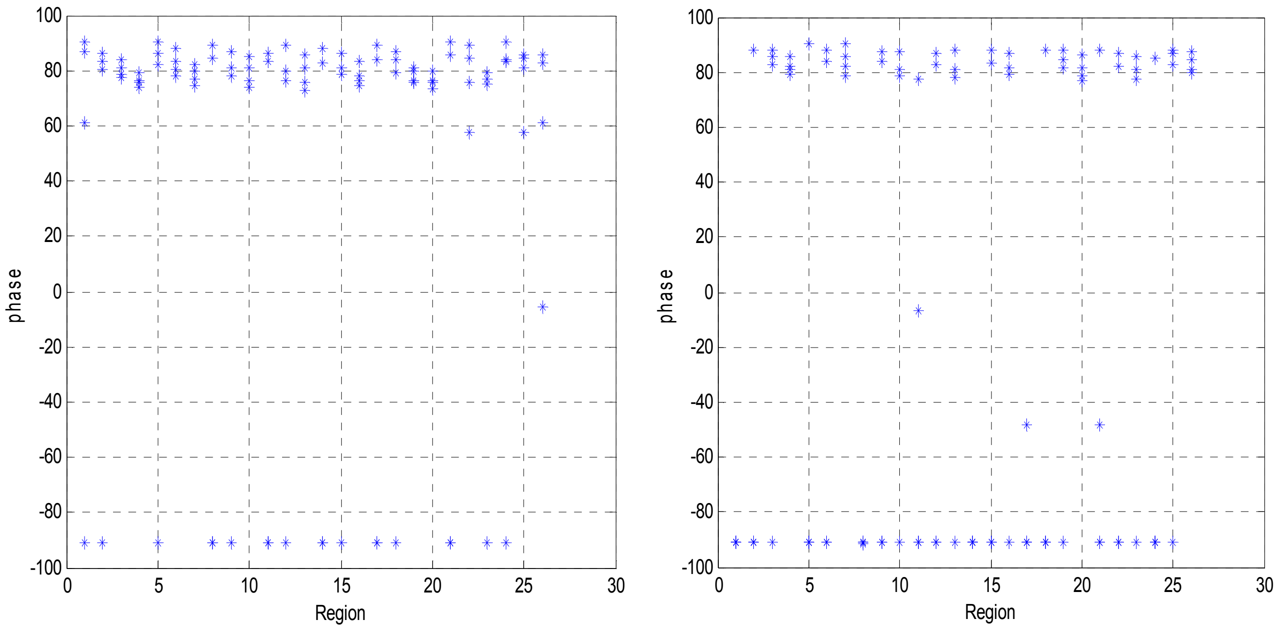
Closed loop simulations of the Cessna Citation X longitudinal and lateral aircraft linear and nonlinear models, were performed for the whole flight envelope. The results presented below were obtained for 12 X_{CG} and weight configurations, by using of 72 flight conditions obtained from both the Cessna Citation X flight simulator, and by using the interpolation method.

4.1. Stability analysis

The phase margin for 26 regions (where each region is obtained for a number of 4 flight conditions) representing the entire flight envelope as shown in Figure 2. It can be noticed that the phase margin of almost the entire envelope is between 60 deg, and 90 deg, which is stable. If the results obtained for different weight and Xcg conditions are compared, we can see that they decreases for some flight conditions of heavy Gross Weights, high True Air Speeds (TAS), and Altitudes (h) above 35000 feet and 300 knots, and for those beyond the flight envelope limits. Detailed Bode and Nichols plots are shown in Figure 3, where the gain margin for almost the entire envelope is higher than 6 dB, which leads to the conclusion that good stability margins are ensured by the new optimized controller.

4.2. Eigenvalue analysis

The aircraft open loop eigenvalues are analyzed using the Lyapunov function given by the "Stabilty and Robustness" toolbox developed during COFCLUO project developed in Europe in 2011, for a given weight and Xcg condition as shown in Figure 4. It can be deduced that the behaviour of the aircraft is "naturally stable" except for the region of very high altitudes and True Air Speeds (TAS), which is already shown by the stability margins results given in the Figure 2 and Figure 3, and also for other worst combination of parameters (altitude h and TAS). The closed loop eigenvalues are presented by pole zero maps and are shown in Figure 5(b), where all flight conditions are given in the left half plan of the pole- zero map, which means that the new controller stabilizes the aircraft.



(a) The 1st weight and Xcg condition (b) The 12th weight and Xcg

Figure 2. Minimum phase margin versus flight conditions per region for all angle of attack (up to 14 deg)

4.3. Handling qualities analysis

The aircraft longitudinal and lateral motions are stabilized with the H-infinity controller. For both controls the pitch angle rate q, and the roll angle ϕ, the resulting response for pitch rate control are shown in Figure 5: the flying qualities level 1 are satisfied as they have the damping ratio, and natural frequency within the limits given by [32] for both lateral and longitudinal motions, and the imposed time domain performance, given by the Integral Square Error (ISE) less than 2%, and overshoot (OS) of less than 30%, which means that the optimized gains are very satisfactory, they ensure a very good flying qualities of level 1. The results in Table 2 show the percentage of the cleared flight envelope according to the Flying qualities level 1, by using the new optimized controller in both the pitch and roll angle controls.

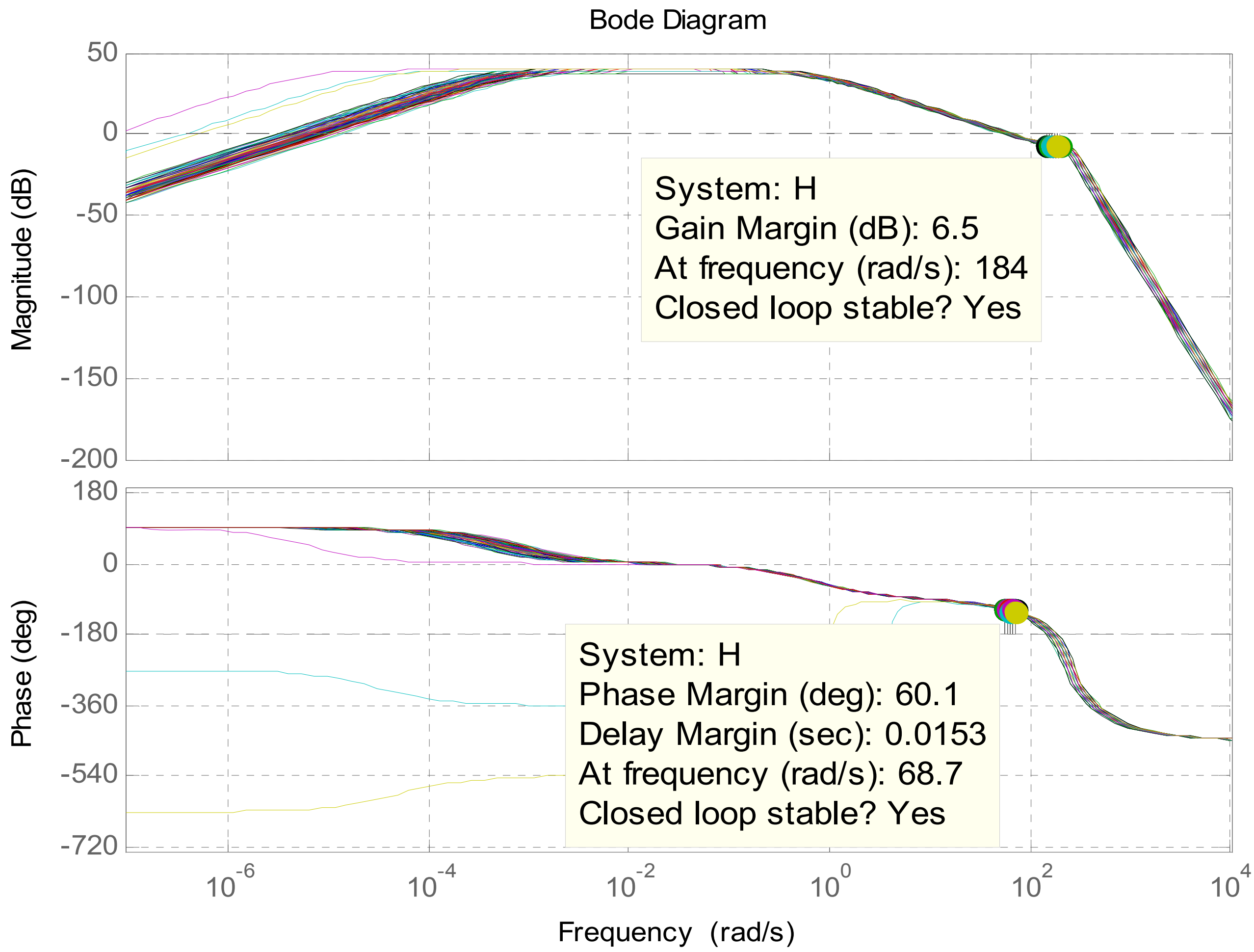
Table 2: Flight points with the good handling qualities over the flight envelope

Controls	Flight points with the good handling qualities using the DE algorithm
Pitch rate q	860/864 (99.5%)
Roll angle φ	851/864 (98.5%)

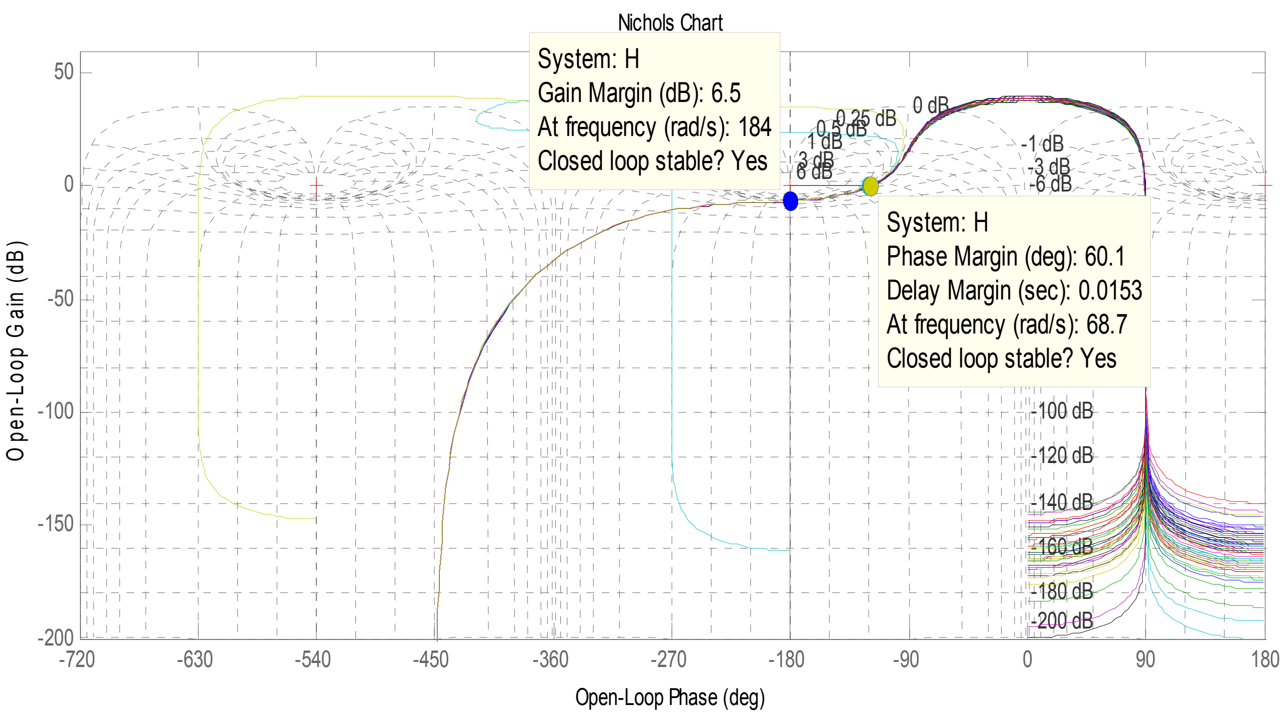
4.4. Nonlinear analysis

Finally, to prove the efficiency of the optimized controller, its robustness against uncertainties, and the effects of nonlinearities, a nonlinear validation was performed using the Cessna Citation X aircraft's non-linear model developed to simulate a real aircraft dynamics. A simulation of a pitch angle rate q and roll angle ϕ controls responses were performed, and the results were shown respectively in Figure 6, and Figure 7 for the altitude of 2000 ft, TAS of 230 knots and load of 26000 lb, and varying mass. It can be seen that the pitch angle rate q and roll angle ϕ hold responses remained stable during the simulation despite the mass variation, and that all the performance criteria were reached.

Figures 8 (a) and (b) show robustness results for the nonlinear model of the Cessna Citation X with $H\infty$ controller by taking into account the nonlinear dynamics, actuators, sensors, saturations and signal processing times. A total of 160 tests were performed by generating uncertainties of +/- 5% on the mass and the center (position of center of gravity) with respect to a nominal condition for which the controller was obtained. The selection of the nominal flight condition and uncertainties were random. The results revealed that the pitch rate, and roll angle controls were stable with respect to the mass, and center of gravity position variations; the variations were stable and further included in the acceptable range.



(a) Bode diagram



(b) Nichols diagram

Figure 3. Bode diagram and Nichols for the 2nd Xcg condition

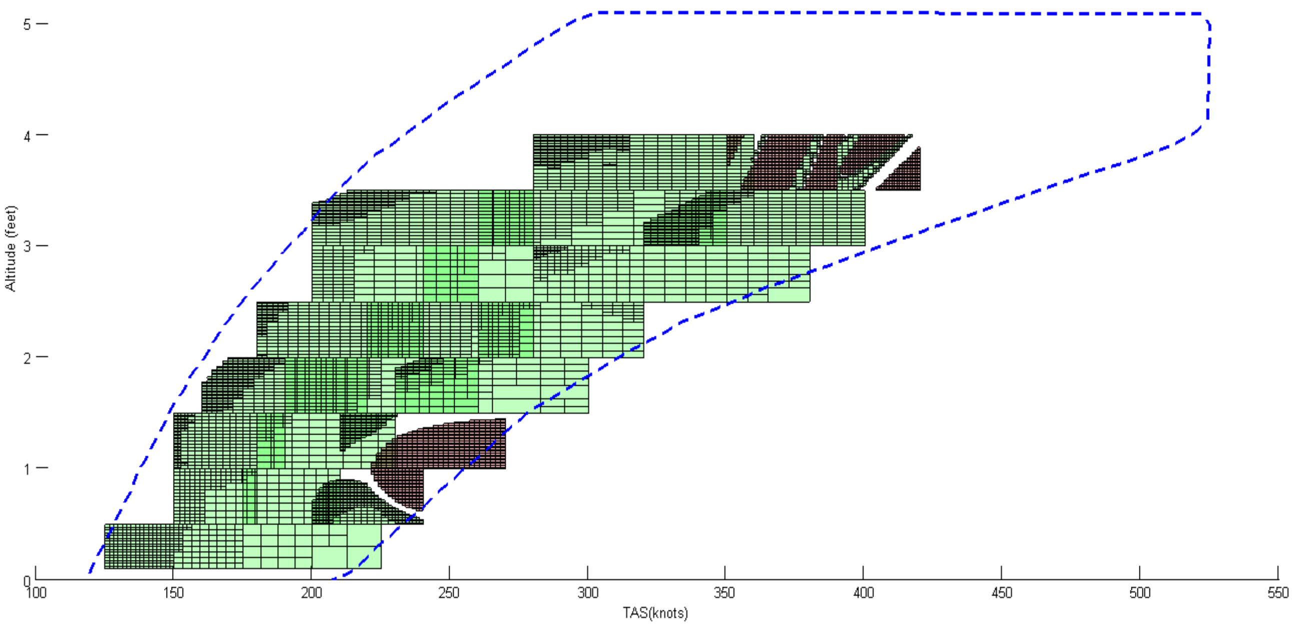


Figure 4. Aircraft stability analysis using Lyapunov function.

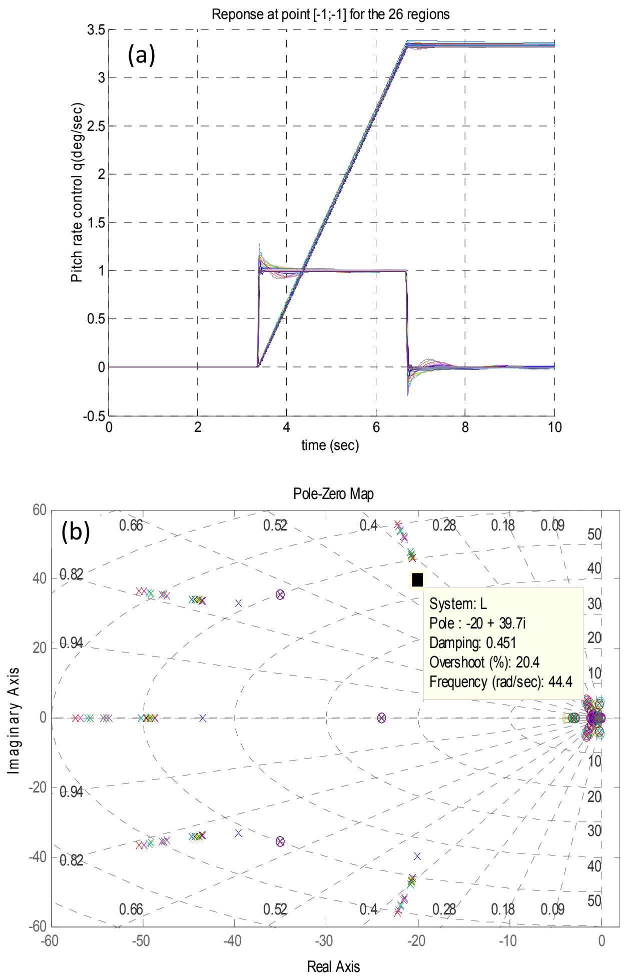


Figure 5. (a) Time response for the pitch rate q (b) the resulting pitch angle and pole, zero map

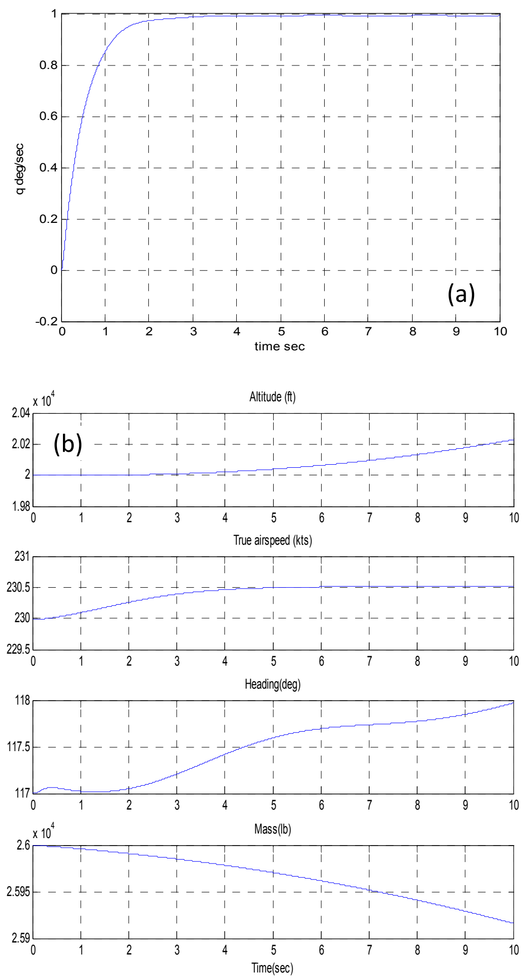


Figure 6. (a) Pitch angle rate q hold control responses (b) the resulting altitude, true airspeed, heading and mass variation responses of the nonlinear aircraft model

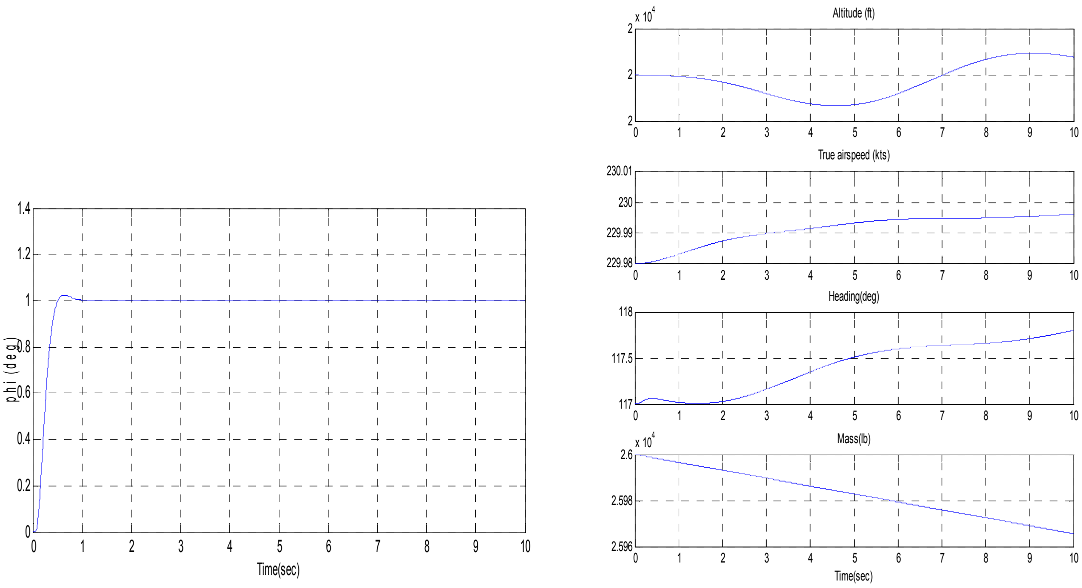
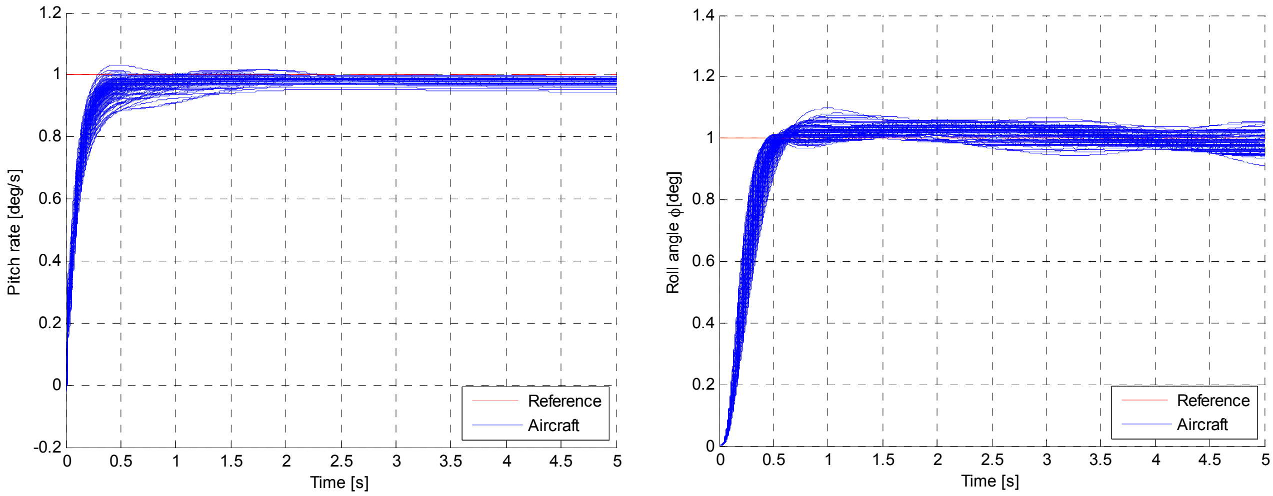


Figure 7. Roll angle φ control responses of the nonlinear aircraft model



(a) (b)

Figure 8. Pitch rate q (a) and Roll (b) response using mass and Xcg variation

5. Conclusion

In this paper, the clearance criteria for the new flight controller of Cessna Citation X business aircraft were evaluated, which is a part of the certification process. The clearance addressed how flight limitations were derived for the Cessna Citation X business aircraft from the worst cases parameters combinations, such as True airspeed (TAS) and altitude (h), and they could be visualized and analysed to give precise information on the direction, which the aircraft was allowed to fly. These limitations were clearly shown by the eigenvalues analysis, where the stability of the aircraft could be analyzed in its flight envelope limits. The flight control laws design optimization provided gains that have ensured very good stability margins in terms of phases and gains, these gains also provided to the aircraft very good flying qualities of Level 1. Regarding the manoeuvres such as the pitch and roll hold, their stability and robustness in presence of uncertainties dues to the mass and center of gravity variations were tested on the nonlinear aircraft model, and the obtained results were found to be very good.

The new optimized controller had ensured its stability and robustness against mass variations to the Cessna Citation X business aircraft which has led to safe control flight operations.

Nomenclature

A,B,C,D	State Space matrices
p, q, r	Angular Speeds along *Ox, Oy, Oz* axis
u, v, w	Linear Speeds along the *Ox, Oy, Oz* axis
u(t)	Control Vector
x(t)	State Space Vector
V	True Aircraft Speed
X, Z, Y	Aircraft Aerodynamic Forces
OS	Overshoot
Ts	Settling Time
δ_e, δ_a δ_r	Elevator, Aileron, and Rudder deflections
ϑ, β, ϕ	Pitch angle, Sideslip angle, and Roll angle
ω_n	Natural Frequency
ζ	Damping Coefficient

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