New Methodology for Optimal Flight Control Using Differential Evolution Algorithms Applied on the Cessna Citation X Business Aircraft – Part 1. Design and Optimization

Yamina BOUGHARI[1], Georges GHAZI[1], Ruxandra Mihaela BOTEZ*[,1], Florian THEEL[1]

*Corresponding author
[1]ETS, Laboratory of Active Controls, Avionics and AeroServoElasticity LARCASE
1100 Notre Dame West, Montreal, Que., Canada, H3C-1K3
yamina.boughari.1@ens.etsmtl.ca, georges.ghazi.1@ens.etsmtl.ca,
Ruxandra.Botez@etsmtl.ca*, f.theel@gmail.com

DOI: 10.13111/2066-8201.2017.9.2.3

Received: 27 March 2017/ Accepted: 30 April 2017/ Published: June 2017

***Abstract**: Setting the appropriate controllers for aircraft stability and control augmentation systems are complicated and time consuming tasks. As in the Linear Quadratic Regulator method gains are found by selecting the appropriate weights or as in the Proportional Integrator Derivative control by tuning gains. A trial and error process is usually employed for the determination of weighting matrices, which is normally a time consuming procedure. Flight Control Law were optimized and designed by combining the Deferential Evolution algorithm, the Linear Quadratic Regulator method, and the Proportional Integral controller. The optimal controllers were used to reach satisfactory aircraft's dynamic and safe flight operations with respect to the augmentation systems' handling qualities, and design requirements for different flight conditions. Furthermore the design and the clearance of the controllers over the flight envelope were automated using a Graphical User Interface, which offers to the designer, the flexibility to change the design requirements. In the aim of reducing time, and costs of the Flight Control Law design, one fitness function has been used for both optimizations, and using design requirements as constraints. Consequently the Flight Control Law design process complexity was reduced by using the meta-heuristic algorithm.*

Key Words: *Flight Control; Linear Quadratic Regulator; Optimal Control; Heuristic Algorithm; Differential Evolution; Control Augmentation System; Stability Augmentation System; Proportional Integrator Derivative Tuning.*

NOMENCLATURE

$x(t)$	= State space parameter of the system
θ, φ	= Pitch, and roll angles
u, v, w	= Speeds along the *Ox, Oy, Oz* axes
p, q, r	= Angular speeds along the *Ox, Oy, Oz* axes
V	= Total Aircraft Speed

$\delta_e, \delta_a, \delta_r$	= Elevator, Aileron, and rudder deflections
ISE	= Integral Square Error
OS	= Overshoot range
Ts	= Settling Time
ess	= Steady State Error
P	= Positive Semi-Definite Matrix

CAS	= Control Augmentation System

DE	= Differential Evolution
LFR	= Linear Fractional Representation
LQR	= Linear Quadratic Regulator
SAS	= Stability Augmentation System
J	= LQR Cost Function
K	= Feedback Gain
ki	= Integral Gain
kp	= Proportional Gain
Kw	= Vertical speed Gain
Kq	= Pitch rate Gain
Q	= Weighting Matrix for the states
R	= Weighting Matrix for control input
ω_n	= Natural frequency
ζ	= Damping coefficient

1. INTRODUCTION

The certification authorities need to ensure that the Flight Control System (FCS) operates properly through the specified flight envelope, when the safety of the new generations of aircrafts, which are fully Flight By Wire (FBW) relay importantly on its FCS. The Flight Control Law (FCL) from design to clearance process is a time consuming process, and it costs, especially for civil aircrafts that need to achieve higher safety. This process aims to prove that the aircraft's robustness and flying requirements are satisfied.

The use of the aircraft flying qualities as requirements criteria in the flight control design is rarely, if ever carried out in the practice [1]. Usually the flight control design is achieved and implemented as a part of avionics system, when the flying qualities are a part of aerodynamics.

Flight control systems are designed to accomplish high aircraft performance with good or acceptable flying qualities within the flight envelope specified by the designer. However, in the real world the selection of a control law is commonly based on the experience of the engineers and the pilots in charge [2]. The flying qualities were considered for the first time in flight testing of the aircraft prototype, this process worked until the Fly By Wire technology were be implemented in the modern aircrafts, where the problem of the PIO appears and there were a loss of aircraft.

There are many ways in which the design of optimal flight control laws can be done using modern methods, such as the Linear Quadratic Regulation (LQR); the advantage of the LQR method is that it provides the smallest possible error to both its input and outputs while minimizing the control effort, where the error corresponds to the difference between the desired and the obtained value for system input and output. In case full states are measurable the LQR method ensures the obtaining of a stable controller for the nominal model, and provides cross-terms in the flight dynamics equations, and further, automatically leads to a robust control in the sense that the gain margin is infinite and the phase margin is greater than 60 deg.

This is shown in [3] where the LQR method has been used for the Stability Augmentation System (SAS) control, and applied on Hawker 800XP business aircraft, and to alleviate gust effects in [4] on bomber aircraft. The LQR method has also been used in a longitudinal attitude controller designed for B747 aircraft [5], and in adaptive control for remotely controlled aircraft [6].

In the same way a PID controller was tuned in [7], and in [8], for a linear model of a morphing wing relying on the engineer's experience, and validated on its nonlinear model. In order to overtake the time wasting during the trial and error method, many algorithms were developed in the last decades to optimize the controller performances. Using stochastic searching as an optimization algorithm is one of the most popular methods that have been used recently.

Both Genetic Algorithm (GA) and Particle Swarm Optimization (PSO), were used in the LQR optimization in [9], [10], [11], and [12]. Using the GA, the optimized LQR gains were used to improve the buck converter's voltage control [13], and the distillation column control in [14]; in both those instances, better results of the control performances were found than those based on experience. By using the GA and PSO algorithms; in [15] and [16] an inverted pendulum and double inverted pendulum were controlled successfully. In [17], the authors have used a shift function combined with Neural Network to improve a PID tuning algorithm for mobile robots. A social algorithm known as the 'small world phenomenon' was used in [18] to search for the shortest path that could be taken by an algorithm for PID parameters tuning. The tuning of PID parameters was based on Fuzzy Logic in [19] and [20]. In [21], [22], and [23] the authors used a PID controller based on genetic tuning. In [24- 29] the Differential Evolution and Genetic Algorithm were used to optimize robust flight controllers.

So the main contributions of this paper firstly, is to apply an evolutionary algorithm such as the Differential Evolution (DE) algorithm to optimize the Flight Control Laws, by combining the LQR modern control method for Stability Augmentation and the classical PI control method for the Control Augmentation System in one objective function, and secondly to consider some of the design specifications and flying qualities requirements as constraints in the design problem. Finally, to ease the design engineer's work, the whole process is automated using a Graphical User Interface, to overcome to the time consuming process due to its iterative nature

2. AIRCRAFT CONTROL ARCHITECTURE

The main idea of this study is to use the Differential Evolution Algorithm to search for the appropriate weighting matrices Q and R, where the LQR method is based on them; the optimal controller used as SAS is further obtained by solving the well known Ricatti equation. Then a second optimization follows to find the optimal CAS by using the PI method. The linear longitudinal and lateral models of Cessna Citation X aircraft dynamics are given by using the state space matrices, also actuators and sensors dynamics are given.

The SAS is used to stabilize the system response accordingly to the flying qualities requirements, and the CAS is used as tracking controller as shown in the aircraft closed loop architecture given in Figure 1.

In the following sections, useful theories that will be utilized in this work are presented: the Cessna Citation X dynamics, the differential evolution algorithm, and the LQR methods.

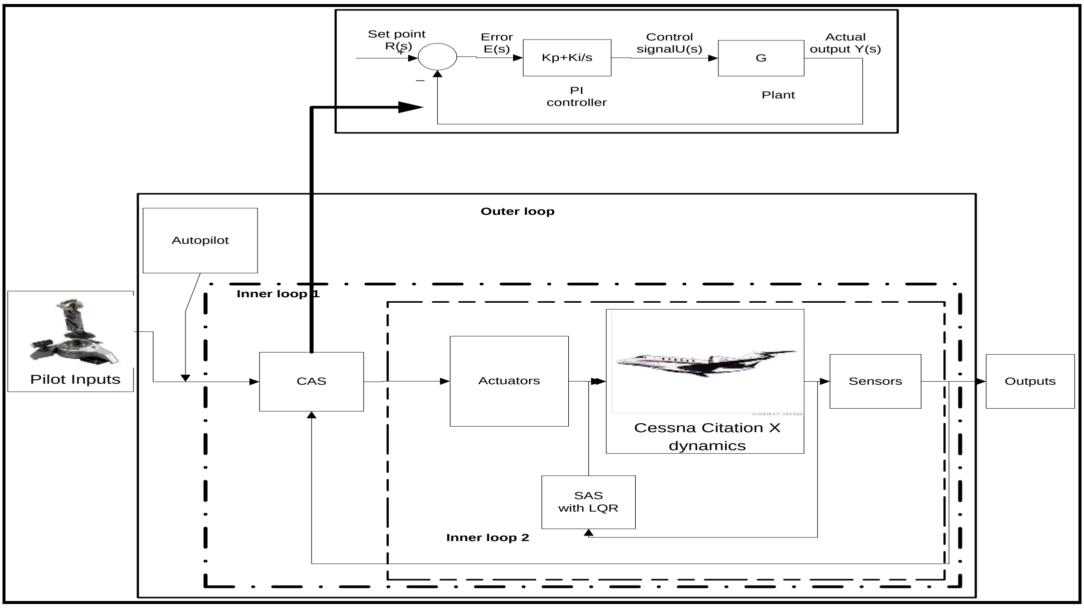

Figure 1. Closed loop representation of the Cessna Citation X business aircraft

3. CESSNA CITATION X AIRCRAFT

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. The longitudinal and lateral motions of this business aircraft are described, as well as its 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 [30]. 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), the Level D is the highest certification level that can be delivered by the Certification Authorities for the flight dynamics.

The linearization routines developed by Ghazi and Botez in [31] were used to linearized , the aircraft longitudinal and lateral equations of motions for different aircraft configurations in terms of mass and center of gravity positions, and for different flight conditions in terms of altitudes and speeds, several comparisons of these models with the linear model obtained by use of identification techniques as proposed in [32] were performed.

3.1 Aircraft dynamics

The aircraft's rotation and translation axes are illustrated in Figure 2.

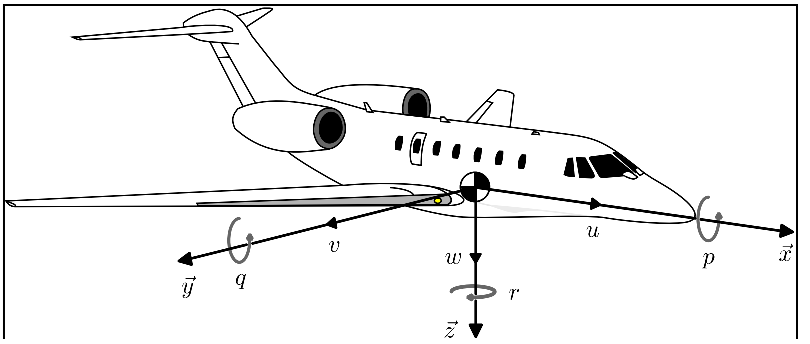

Figure 2. Representation of Cessna Citation X aircraft's rotation (body) axes

The motion of an aircraft can be represented with a nonlinear model, [33]. To design a controller for any aircraft, a linearization of the nonlinear aircraft model for flight conditions within the flight envelope given by the designer is required as a first step. Following the decoupling of the linearized aircraft motion into longitudinal and lateral motions, and their dynamics are given in the form of the state space matrices as follows:

$$\dot{x} = \mathrm{A}x + \mathrm{B}u \tag{1}$$

The aircraft's longitudinal dynamics are given by using the elevator as input as follows:

$$\dot{x}_{long} = \mathrm{A_{long}}x_{long} + \mathrm{B_{long}}u_{long}$$

$$\mathrm{A_{Long}} = \begin{pmatrix} \mathrm{X_u} & \mathrm{X_w} & \mathrm{X_q} & -\mathrm{g}\cos\theta \\ \mathrm{Z_u} & \mathrm{Z_w} & \mathrm{Z_q} & 0 \\ \mathrm{M_u + M_{\dot{w}}Z_u} & \mathrm{M_w + M_{\dot{w}}Z_w} & \mathrm{M_q + M_{\dot{w}}u_0} & 0 \\ 0 & 0 & 1 & 0 \end{pmatrix}, \mathrm{B_{Long}} = \begin{pmatrix} \mathrm{X_{\delta_e}} \\ \mathrm{Z_{\delta_e}} \\ \mathrm{M_{\delta_e} + M_{\dot{w}}Z_{\delta_e}} \\ 0 \end{pmatrix} \tag{2}$$

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

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

The aircraft's lateral dynamics are given by using the aileron and the rudder as inputs:

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

$$\mathrm{A_{Lat}} = \begin{pmatrix} \mathrm{Y_\beta/u_0} & \mathrm{Y_p/u_0} & -(1-\mathrm{Y_r/u_0}) & \mathrm{g}\cos\theta_0/\mathrm{u_0} \\ \mathrm{L_\beta} & \mathrm{L_p} & \mathrm{L_r} & 0 \\ \mathrm{N_\beta} & \mathrm{N_p} & \mathrm{N_r} & 0 \\ 0 & 1 & 0 & 0 \end{pmatrix}, \mathrm{B_{Lat}} = \begin{pmatrix} \mathrm{Y_{\delta_a}/u_0} & \mathrm{Y_{\delta_r}/u_0} \\ \mathrm{L_{\delta_a}} & \mathrm{L_{\delta_r}} \\ \mathrm{N_{\delta_a}} & \mathrm{N_{\delta_r}} \\ 0 & 0 \end{pmatrix} \tag{4}$$

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

$$x_{lat}(t) = (\beta \quad p \quad r \quad \phi)^T \qquad \text{and} \qquad u_{lat}(t) = (\delta_a \delta_r)^T \tag{5}$$

The Cessna Citation X linear model is obtained for 72 flight conditions based on the Aircraft Flight Research Simulator tests performed at the LARCASE laboratory [32]. The linearized model is interpolated using the bilinear method [34] as represented in Figure 3.

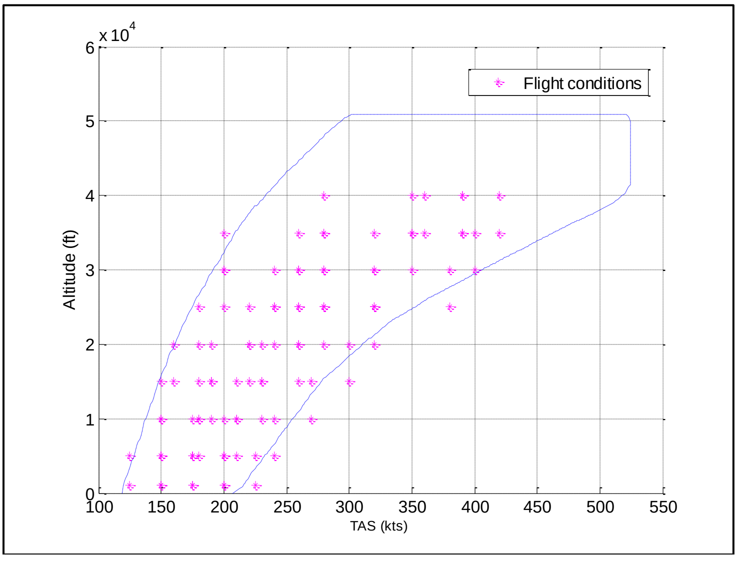

Figure 3. Flight points obtained by LFR models

3.2 Design specifications and requirements

The aircraft Flight Control System required airworthiness and handling qualities requirements that should be considered in the Flight Control Law design. These criteria are intended for satisfactory flight performance, and safety. In this research some of the flying qualities and time response specifications have been considered in the optimization problem for the flight controller design. Table 1 presents the desired flying qualities, and temporal criteria expressed in terms of damping [33], overshoot, steady state error, time constant, and settling time required for the longitudinal and lateral modes; the criteria were provided in the U.S "Military specification for the Flying Qualities of Piloted Airplanes MIL-STD-1797A". Two modes are associated with an aircraft's longitudinal motion: the short period, and the long period, known as phugoïd mode. Three modes are observed in the lateral aircraft motion: 1) the Dutch roll mode, 2) the spiral mode, and 3) the roll mode.

Table 1. Aircraft flying qualities and temporal criteria

Criteria	**Type**	**Limits**
Overshoot	Temporal	$OS<30\%$
Steady state error	Temporal	$ess\leq 2\%$
Settling time	Temporal	$Ts\leq 4$s
Short period damping	Modal	$0.3 \leq \zeta_{sp} \leq 2$
Phugoid damping	Modal	$0.04 \leq \zeta_{ph}$
Dutch roll damping	Modal	$0.3 \leq \zeta_{dr} \leq 2$
Roll time constant	Temporal	$Tr<1.4$ sec

4. DIFFERENTIAL EVOLUTION

The Differential Evolution (DE) algorithm was developed in 1995 by Price and Storn [35, 36], and has been used in global optimization in many domains. The DE algorithm is a meta-heuristic optimization algorithm that uses real values (which do not need any encoding and decoding operations) to represent problem parameters. The key concept of DE is its use of a differential operator to generate the mutant vector which allows population diversity. Flow charts given in Figure 4 summarize the DE algorithm used to search for the optimal LQR and PI gains.

4.1 DE Initialization phase

In this phase, the number of iterations or generations is fixed, the dimension of the problem is then determined according to the fitness function parameters number. Next, a vector is formed by the parameters to be optimized; at each generation, the i^{th} vector is described as:

$$\vec{X}_{iG} = \left[x_{1,iG}, x_{2,iG}, x_{3,iG}, \dots, x_{D,iG}\right] \tag{6}$$

The population is initialized at random in its search space, where each parameter is limited by a lower and upper value. These boundaries are represented in vectors given by equations (6) and (7):

$$\vec{X}_{imin} = \left[x_{1,imin}, x_{2,imin}, x_{3,imin}, \dots, x_{D,imin}\right] \tag{7}$$

$$\vec{X}_{imax} = \left[x_{1,imax}, x_{2,imax}, x_{3,imax}, \dots, x_{D,imax}\right] \tag{8}$$

The j^{th}component of the i^{th} vector is initialized as:

$$x_{j,i,0} = x_{j,min} + rand_{i,j}[0,1].\left(x_{j,max} - x_{j,min}\right) \tag{9}$$

where $0 \leq rand_{i,j}[0,1] \leq 1$.

Once the initialization phase is completed, the next step is the mutation operation.

4.2 DE Mutation

In DE algorithm, the "Mutation" is when different vectors change their parameters between them. So the "donor vector" is obtained from the differential mutation operation. Each "donor" vector is created from its corresponding i^{th} "target" vector.

In the current population a sampling of three different vectors $\vec{X}_{r_1^i,G}$,$\vec{X}_{r_2^i,G}$,$\vec{X}_{r_3^i,G}$ at random is performed.

For each "mutant" vector $\vec{X}_{r_i^i,G}$, three different indices $r_1^i, r_2^i,$ and r_3^i, are chosen from the range $[1, NP]$ at random, where *NP* is the population number. Then the difference between two different vectors is weighted by a scalar F selected at random to finally obtain the "donor" vector V_{iG}, [27] as defined in equation (9):

$$V_{IG} = \vec{X}_{r_1^i,G} + F * \left(\vec{X}_{r_2^i,G} - \vec{X}_{r_3^i G}\right) \tag{10}$$

4.3 DE Crossover

In the operation of the "crossover", a "trial" vector $\vec{U}_{IG}$ results from the operation of exchanging components between the "donor" and the "target" vectors, which improve the population diversity:

$$\vec{\mathrm{U}}_{\mathrm{IG}} = [\mathrm{u}_{1,\mathrm{iG}}, \mathrm{u}_{2,\mathrm{iG}}, \mathrm{u}_{3,\mathrm{iG}}, \dots, \mathrm{u}_{\mathrm{D},\mathrm{iG}}] \quad (11)$$

There exist two crossover types: the exponential and the binomial. Two integers n and L are chosen arbitrarily in the exponential crossover from the interval $[1, D]$, where D represents the dimension, which is the number of parameters subject to optimization [27], and then the trial vector is given as follows:

$$\mathrm{u}_{\mathrm{j,iG}} = \mathrm{v}_{\mathrm{j,iG}} \ \text{ for } \mathrm{j} = \langle \mathrm{n} \rangle_{\mathrm{D}}, \langle \mathrm{n}+1 \rangle_{\mathrm{D}}, \dots., \langle \mathrm{n}+\mathrm{L}-1 \rangle_{\mathrm{D}} \quad (12)$$

Else

$$\mathrm{u}_{\mathrm{j,iG}} = \mathrm{x}_{\mathrm{j,iG}}\text{, and} \quad \mathrm{j} \in [1, \mathrm{D}] \quad (13)$$

where $\langle . \rangle$ refers to the modulo function with modulus D.

While in the binomial crossover the trial vector is given as:

$$u_{j,iG} = v_{j,iG} \ \text{ if } \quad rand_{i,j}[0,1] \leq \mathrm{Cr} \ \text{ or } \ j = j_{rand} \quad (14)$$

Else

$$u_{j,iG} = x_{j,iG} \quad (15)$$

After the population diversity has been assured with the crossover step, a selection operation is performed as detailed in the next phase.

4.4 DE selection

The operation of “selection” determined if the “target” or “trial” vectors survive in the next generation or not, and thus maintain a constant population size. The selection operation is outlined as:

$$\vec{\mathrm{X}}_{\mathrm{i,G+1}} = \vec{\mathrm{U}}_{\mathrm{i,G}} \ \text{ if } \ \mathrm{f}(\vec{\mathrm{U}}_{\mathrm{i,G}}) \leq \mathrm{f}(\vec{\mathrm{X}}_{\mathrm{i,G}}) \quad (16)$$

Else

$$\vec{\mathrm{X}}_{\mathrm{i,G+1}} = \vec{\mathrm{X}}_{\mathrm{i,G}} \ \text{ if } \ \mathrm{f}(\vec{\mathrm{U}}_{\mathrm{i,G}}) > \mathrm{f}(\vec{\mathrm{X}}_{\mathrm{i,G}}) \quad (17)$$

Where $\mathrm{f}(\vec{\mathrm{X}}_{\mathrm{i,G}})$ is the objective function or the “fitness” to be converged using an iteration process.

4.5 Iteration

The operations (Initialization, mutation, crossover and selection) listed above are repeated until the termination criteria have been met.

These criteria are related to the maximum number of generations and to the convergence of fitness functions.

5. LINEAR QUADRATIC REGULATION (LQR)

The LQR control algorithm is one of many optimal controls methods described in [37], [38] and used in an optimal way to stabilize the controlled system in [39], [40].

The LQR used as a control method in this context implies that a cost function must be determined in order to balance between the actuators’ effort and the aircraft’s responses. The weighting matrices Q and R need to be selected. Q represents the weighted state space matrix, R represents the weighted control inputs’ matrix, $x(t)$ and $u(t)$ denote the state space and input matrices of the aircraft. These matrices are selected to minimize the cost function J given by the following equation:

$$\mathrm{J} = \frac{1}{2}\int_{0}^{\infty} [x^{\mathrm{T}}(\mathrm{t})Qx(\mathrm{t}) + u^{\mathrm{T}}(\mathrm{t})Ru(\mathrm{t})]\, \mathrm{dt} \tag{18}$$

The Q matrix is of $m\times m$ and the R matrix is of $n\times n$ dimensions, as follows:

$$Q = \begin{bmatrix} q_{11} & \cdots & q_{1m} \\ \vdots & \ddots & \vdots \\ q_{m1} & \cdots & q_{mm} \end{bmatrix}, R = \begin{bmatrix} r_{11} & \cdots & r_{1n} \\ \vdots & \ddots & \vdots \\ r_{n1} & \cdots & r_{nn} \end{bmatrix}$$

These Q and R matrices are used to determine the positive matrix P which is semi-definite by use of the Ricatti equation [37]:

$$PA + A^{\mathrm{T}}P - PBR^{-1}B^{\mathrm{T}}P + Q = 0 \tag{19}$$

From equation (19) the gain vector K is then found by using the next equation:

$$K = \mathrm{R}^{-1}B^{\mathrm{T}}P \tag{20}$$

The control vector is then determined as follows:

$$u = -K(Q, R)x(\mathrm{t}) \tag{21}$$

5.1 DE algorithm for solving the LQR-PI problem

The optimal controller is found using the following algorithm given by the flow charts in Figure 4 mentioned bellow:

Set the population number *NP*; formed by the parameters of the weighting matrices Q and R (only the diagonal parameters are considered), and the PI gains, $\mathrm{k_i}, \mathrm{k_p}$; from the initial vector:

$$\vec{\mathrm{X}}_{\mathrm{IG}} = \left[q_{1,iG}, q_{2,iG}, q_{3,iG}, \dots, q_{m,iG}, r_{1,iG,\dots}, r_{n,iG}, k_i, k_p\right] \tag{22}$$

Each of these parameters belongs to an interval with lower and upper bounds. The optimal controller is found by first choosing the appropriate Q, R, , k_i and, $k_p$parameters and then performed a system time domain simulation to obtain the characteristics of a system's response.

The iteration process continues if the satisfactory characteristics are not reached, until one of the stopping conditions is achieved.

5.2 Objective function

One objective function was used for both LQR and PI algorithms to give the desired time response specifications of the closed loop system, and to be minimized in order to obtain the optimal solution, in which one fitness function.

The settling time T_s, the natural frequency ω_n, the damping ζ, the overshoot OS and the Integral Square Error (ISE) are shown in the next equation giving the expression of fitness by equation (23):

$$\mathrm{fitness} = 10 * (\mathrm{ISE}) + 10 * (\mathrm{OS}) + 10 * (\mathrm{Ts}) + 10(\omega_{\mathrm{n}}) + 10 * (\xi) \tag{23}$$

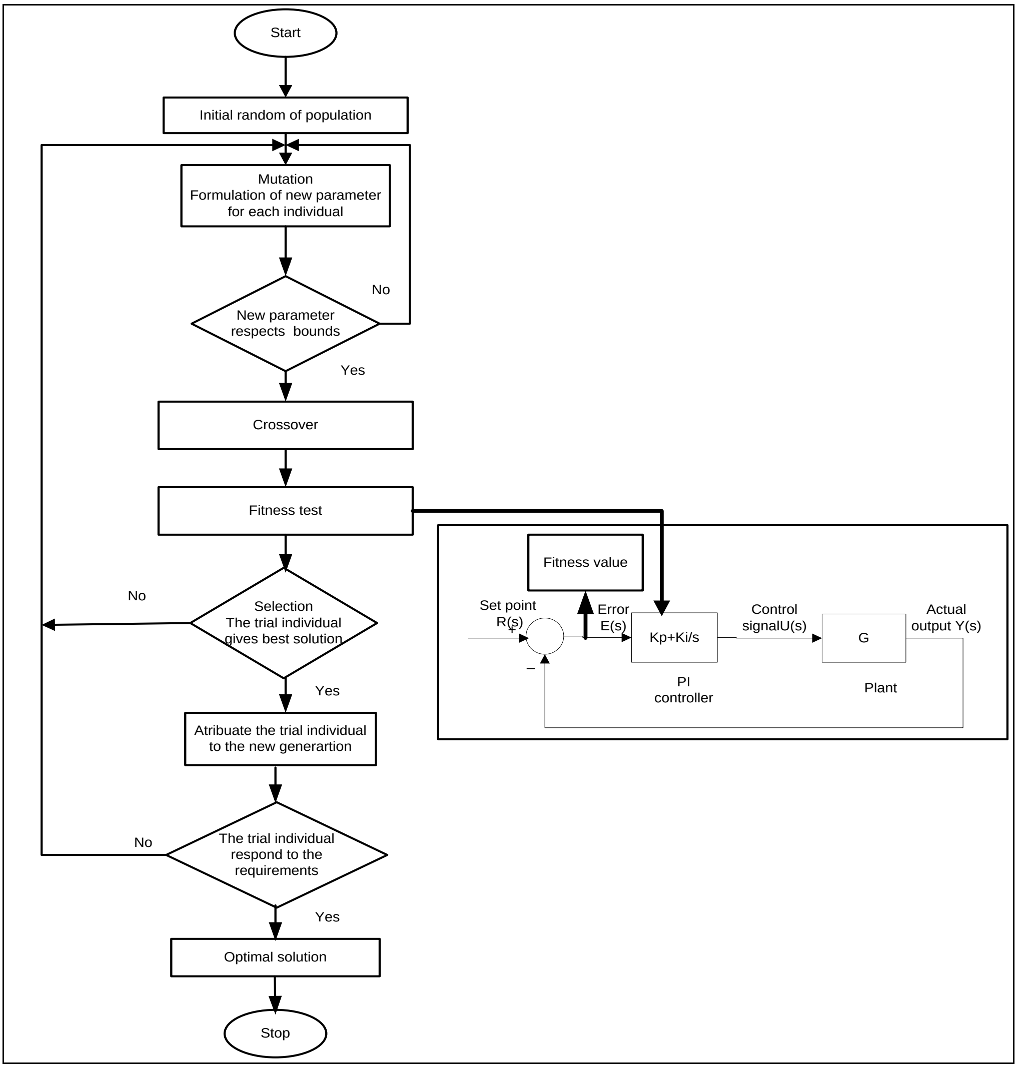

Figure 4. LQR weighting matrices and PI tuning optimization using DE algorithm

6. SIMULATION AND RESULTS ANALYSIS

Simulations were performed firstly on the linearized model (longitudinal and lateral) of Cessna Citation X business aircraft, for which its flight dynamics model is represented using state space matrices for multiple flight conditions.

Then, the Stability Augmentation System (SAS) is established using the LQR design approach, and is applied on the aircraft to enhance its response.

Furthermore, the tracking reference signals are ensured by using the PI controller as Control Augmentation System (CAS).

This process was automated using a Graphical User Interface as shown in Figure 5, which facilitate to the design engineer the manipulation of some parameters such as the design requirements (flying qualities, time response specifications), the parameter to be controlled (pitch rate q, pitch angle θ, and roll rate p), and to visualize the responses for the entire flight envelope.

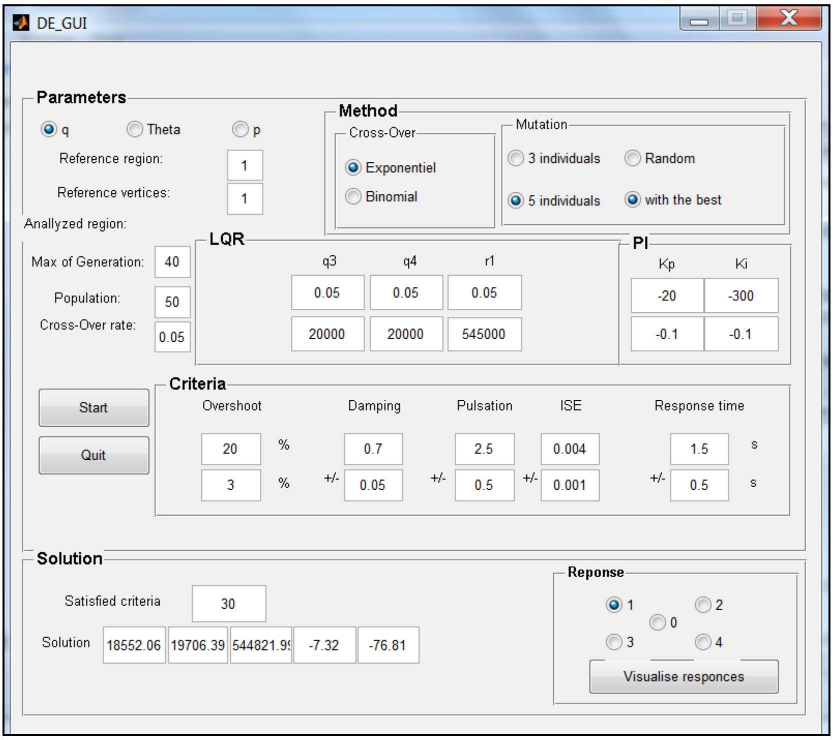

Figure 5. GUI used in the controller design and optimization

After the obtaining of optimal weighting matrices, the SAS and the CAS were computed for each flight condition, and aircraft configuration. The results obtained by the algorithm were given under the form of a set of gains for each inner loop (pitch angle control loop, pitch rate control loop, etc.). These gains were next exported into the Matlab's curve Fitting Toolbox in order to compute an interpolation model. Figure 6 shows an example of interpolation of the feedback gains K_q and K_w with respect to the altitude h and airspeed V_{TAS} for the 4th X_{CG} location 30%. In Figure 6, the data points represent the results obtained with the algorithm, and the surface represents the interpolated model for K_q (Figure 6.a) and for K_w (Figure 6.b).

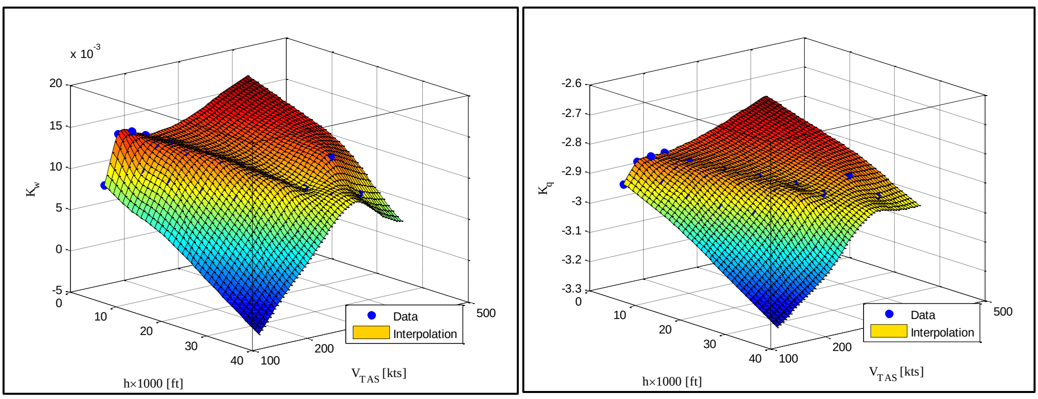

Figure 6.a Figure 6.b

Figure 6. Gains scheduling with respect to the altitude and airspeed

This process was repeated for all the gains for each loop and for each aircraft mass and center of gravity position. The results were next formatted into different 4-D Lookup Tables in order to allow the linear interpolation for any altitude, airspeed, mass and center of gravity position. The results presented in Figure 6 show the smoothness of the scheduling gains. Article PART 2 presents the results obtained for each loop.

7. CONCLUSIONS

In this research, some of the FCL design requirements were considered in the FCL optimization problem; these requirements were based on a selected set of flying quality criteria, and desired temporal ones chosen from the designer experience usually used in aircraft control design in the Aeronautical Industry.
A multi-objectives optimization was presented. First the SAS design was optimized by combining the Differential Evolution algorithm (DE) with the LQR method, and secondly the DE was used to tune the PI gains for the CAS design in one objective function.
Due to the complexity of the FCL design and its iterative nature a Graphical User Interface was developed to carry on the optimization, and the clearance of the FCL in the entire envelope. This computing tool offered the flexibility to change the design requirements if needed before a new optimization.
Using more Complex handling quality and airworthiness requirements in the optimization problem could be a subject of future research.

ACKNOWLEDGEMENTS

This research was carrying out at the LARCASE (Laboratory of active controls, avionics and aeroservoelasticity research). We express our gratitude to the CAE Inc. team, and especially to Mr. Ken Dustin for their support in the development of the Aircraft Research Flight Simulator at the LARCASE laboratory. Also thanks are due to the research grants approved by the Canadian Foundation of Innovation (CFI) and MDEIE. We also wish to thank to Mrs. Odette Lacasse and to Mr. Oscar Carranza at ETS for their support related to the flight simulator research and development.

REFERENCES

[1] M. B. Tischler, *Advances in aircraft flight control*, CRC Press, 1996 Jun 28, pp. 750, ISBN 9780748404797.
[2] R. Pratt, *Flight control systems: practical issues in design and implementation*, No. 57. Iet. 2000, pp. 382.
[3] Y. Boughari and R. M. Botez, Optimal flight control on the hawker 800 XP business aircraft, in *IECON 2012 - 38th Annual Conference on IEEE Industrial Electronics Society*, 2012, pp. 5471-5476.
[4] R. M. Botez, I. Boustani, N. Vayani, P. Bigras, and T. Wong, Optimal control laws for gust alleviation, *Canadian Aeronautics and Space Journal*, vol. **47**, pp. 1-6, 2001.
[5] Z. Guilong, Y. Lingyu, Z. Jing and H. Chan, *Longitudinal attitude controller design for aircraft landing with disturbance using ADRC/LQR*, Piscataway, NJ, USA, 2013, pp. 330-5.
[6] I. S. Mukherjee and J. K. Pieper, Adaptive LQR gain sheduling applied to an experimental OHS aircraft, in *AIAA Guidance, Navigation, and Control Conference and Exhibit 2000, August 14, 2000 - August 17, 2000*, Dever, CO, United States, 2000.
[7] T. L. Grigorie, A. V. Popov, R. M. Botez, M. Mamou, and Y. Mebarki, On-off and proportional-integral controller for a morphing wing. Part 1: Actuation mechanism and control design, *Proceeding of the IMechE, Part G: Journal of Aerospace Engineering* 2012, Vol. **226**, pp. 131-145.
[8] T. L. Grigorie, A. V. Popov, R. M. Botez, M. Mamou and Y. Mebarki, On-off and proportional-integral controller for a morphing wing. Part 2: Control validation - Numerical simulations and experimental tests, *Proceeding of the IMechE, Part G: Journal of Aerospace Engineering*, pp. 146-162.

[9] J. Chen and C.-J. Zhang, Control of triple inverted pendulum based on LQR coefficients optimization, *Computer Engineering and Applications*, vol. **45**, pp. 245-8, 2009.

[10] S. A. Ghoreishi and M.-A. Nekoui, Optimal weighting matrices design for LQR controller based on Genetic Algorithm and PSO, in *2011 International Conference on Material Science and Information Technology, MSIT2011, September 16, 2011 - September 18, 2011*, Singapore, Singapore, 2012, pp. 7546-7553.

[11] Y.-F. Guo, Z.-D. Xu, Q. Tu, and C.-S. Ran, Optimal analysis for weight matrices in LQR algorithm based on genetic algorithm, *Journal of Vibration and Shock*, vol. **29**, pp. 217-220, 2010.

[12] X. Zeng, L. Jing, Z. Yao, and Y. Guo, A PSO-based LQR controller for accelerator PWM power supply, in *2nd International Conference on Mechatronics and Intelligent Materials 2012, MIM 2012, May 18, 2012 - May 19, 2012*, GuiLin, China, 2012, pp. 71-75.

[13] M. B. Poodeh, S. Eshtehardiha, A. Kiyoumarsi, and M. Ataei, Optimizing LQR and pole placement to control buck converter by genetic algorithm, in *International Conference on Control, Automation and Systems, ICCAS '07*, 2007, pp. 2195-2200.

[14] K. O. Jones and W. Hengue, *Distillation column control using genetic algorithms for LQR design*, in International Conference on Computer Systems and Technologies and Workshop for PhD Students in Computing, CompSysTech'09, June 18, 2009 - June 19, 2009, Ruse, Bulgaria, 2009, pp. IIIA.191-IIIA.196.

[15] C. Wongsathan and C. Sirima, Application of GA to design LQR controller for an inverted pendulum system, in *2008 IEEE International Conference on Robotics and Biomimetics, ROBIO 2008, February 21, 2009 - February 26, 2009*, Bangkok, Thailand, 2008, pp. 951-954.

[16] X. Xiong and Z. Wan, The simulation of double inverted pendulum control based on particle swarm optimization LQR algorithm, in *2010 IEEE International Conference on Software Engineering and Service Sciences, ICSESS 2010, July 16, 2010 - July 18, 2010*, Beijing, China, 2010, pp. 253-256.

[17] W. Zhi, Q. Luo, and J. Liu, An improved PID tuning algorithm for mobile robots, in *Electronic Commerce, Web Application and Communication, ECWAC 2012*, March 17-18, 2012, Wuhan, China, 2012, pp. 345-353.

[18] L. Xiaohu, D. Haifeng, Z. Jian, and W. Sunan, A PID parameters tuning algorithm inspired by the small world phenomenon, Chapter on '*Advanced Intelligent Computing Theories and Applications. With Aspects of Theoretical and Methodological Issues*', Volume **5226** of the series Lecture Notes in Computer Science, Berlin, Germany, 2008, pp. 817-24.

[19] H-S Hwang, J. N. Choi, W-H Lee, J.-K. Kim, A tuning algorithm for the PID controller utilizing fuzzy theory, *International Joint Conference on Neural Networks IJCNN '99, Piscataway, NJ, USA*, 1999, pp. 2210-2215.

[20] R. Bandyopadhyay and D. Patranabis, A new auto-tuning algorithm for PID controllers using dead-beat format, *ISA Transactions*, vol. **40**, pp. 255-66, 2001.

[21] M. S. Saad, H. Jamaluddin, and I. Z. M. Darus, PID Controller Tuning Using Evolutionary Algorithms, *WSEAS Transactions on Systems and Control*, vol. **7**, pp. 139-149, 2012.

[22] Y. Mitsukura, T. Yamamoto, and M. Kaneda, A genetic tuning algorithm of PID parameters, Systems, Man, and Cybernetics, *IEEE International Conference on Computational Cybernetics and Simulation*, Vol. **5**, New York, NY, USA, 1997, pp. 923-928.

[23] H. Han, A. Luo, and Y. Yang, Nonlinear PID controller based on genetic tuning algorithm, *Control and Decision*, vol. **20**, pp. 448-454, 2005.

[24] Y. Boughari, R.M. Botez, G. Ghazi, F. Theel, Evolutionary Algorithms for Robust Cessna Citation X Flight Control, Paper No. 2014-01-2166. *SAE 2014 Aerospace Systems and Technology Conference*, Cincinnati, Ohio, USA, 2014, September 23-25, doi:10.4271/2014-01-2166.

[25] Y. Boughari, R.M. Botez, , G. Ghazi, F. Theel, Flight Control Clearance of the Cessna Citation X using Evolutionary Algorithms, *Proceedings of the Institution of Mechanical Engineers* (*IMechE*), *Part G: Aerospace Engineering*, 2016 Apr. 11, doi: 10.1177/0954410016640821.

[27] Y. Boughari, R.M. Botez, F. Theel et G. Ghazi. 2014. *Optimal Flight Control on Cessna Citation X Aircraft Using Differential Evolution*. In IASTED International Conference on Modelling, Identification and Control, MIC. (Innsbruck, Austria, Feb.17-19, 2014), p. 189-198. Coll. Proceedings of the IASTED International Conference on Modelling, Identification and Control: Acta Press. < http://dx.doi.org/10.2316/P.2014.809-052 >.

[28] G.Ghazi, R.M. Botez, *New Robust Control Analysis Methodology for Lynx Helicopter and Cessna Citation X Aircraft Using Guardian Maps, Genetic Algorithms and LQR Theories Combinations*, AHS 70th Annual Forum & Technology Display Proceedings, Montreal, Quebec, Canada, 2014, May 20-22.

[29] G.Ghazi, R.M. Botez, *Lateral Controller Design for the Cessna Citation X with Handling Qualities and Robustness Requirements*, 62nd Canadian Aeronautical Society Institute CASI Aeronautics Conference and AGM & 3rd GARDN Conference Proceeding, Montreal, Que., Canada, 2015, May 19-21.

[30] G. Ghazi, *Développement d'une plateforme de simulation et d'un pilote automatique-application aux Cessna Citation X et Hawker 800XP.*, Master University of Quebec-École Polytechnique de Montréal.

[31] G. Ghazi and R. Botez, Development of a High-Fidelity Simulation Model for a Research Environment, *SAE Technical Paper* 0148-7191, 2015.

[32] C. Hamel, A. Sassi, R. Botez, C. Dartigues, Cessna Citation X aircraft global model identification from fight tests, *SAE International Journal of Aerospace* vol. **6**(1), pp. 106-114, 2013.

[33] R. C. Nelson, *Flight Stability & Automatic Control*, ISBN-13: 978-0070462731, ISBN-10: 0070462739 1997.

[34] C. Poussot-Vassal and C. Roos, *Flexible aircraft reduced-order LPV model generation from a set of large-scale LTI models*, in American Control Conference (ACC), 2011, pp. 745-750.

[35] K. V. Price, *Differential evolution: a fast and simple numerical optimizer*, in Fuzzy Information Processing Society, 1996. NAFIPS., 1996 Biennial Conference of the North American Fuzzy Information Processing Society NAFIPS, 1996, pp. 524-527.

[36] R. Storn and K. Price, Minimizing the real functions of the ICEC' 96 contest by differential evolution, in *Proceedings of IEEE International Conference on Evolutionary Computation*, 1996, pp. 842-844.

[37] P. Dorato, C. T. Abdallah, V, Cerone, *Linear-Quadratic control: an Introduction*, Englewood Cliffs, N.J.: Prentice-Hall c1995.

[38] P. Albertos, A. Sala, *Multivariable Control Systems, 2014* [on line]. Available: http://f3.tiera.ru/2/E_Engineering/Albertos%20P.,%20Sala%20A.%20Multivariable%20Control%20Systems..%20An%20Engineering%20Approach%20(Springer,2002)(ISBN%201852337389)(358s)_E_.pdf

[39] C. S. Lee, W. L. Chan, S. S. Jan, and F. B. Hslao, A linear-quadratic-Gaussian approach for automatic flight control of fixed-wing unmanned air vehicles, *Aeronautical Journal*, vol. **115**, pp. 29-41, 2011.

[40] A. Turoczi, *Flight control system of an experimental unmanned quad-rotor helicopter*, in 10th International Symposium of Hungarian Researchers on Computational Intelligence and Informatics, CINTI 2009, November 12- 14, 2009, Budapest, Hungary, 2009, pp. 777-789.