



Control allocation to roll fly-by-wire aircraft with ailerons and roll spoilers

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Abstract: This paper compares two methods of control allocation to roll fly-by-wire aircraft, taking advantage of the flexibility given by fly-by-wire architecture, in order to compute adequate deflections of ailerons and roll spoilers that comply with requirements of stability, performance and handling qualities. As first method, consider a dead zone for roll spoilers, such that roll spoilers deflect only after certain deflection of ailerons. This is a conservative approach to deal with nonlinear behavior of roll spoilers around small deflections for example, but can expose ailerons to rate saturation when deflecting alone in scenarios with poor control power. As second method, consider that ailerons and roll spoilers work together whenever there is roll command. This approach alleviates the work of the ailerons, but it assumes a reliable model for design, which might be hard to develop. The study of the two methods covers real aspects for design, in order to implement in a Flight Control Computer (FCC): study of the bare-airframe (large-heavy transport/cargo aircraft adopted in this case), definition of objectives, control architecture, and linear design. It is possible to conclude that both methods are feasible to be implemented in FCC, complying with requirements of stability, performance and handling qualities. The results of second method are slightly better than first method, but requires a reliable model for design.

Keywords: *Nonlinear dynamics, Rate saturation, Control Allocation, Fly-by-wire Aircraft, Control Law*

INTRODUCTION

Fly-by-wire technology, in which pilot's commands are transmitted to flight control surfaces by digital signals, instead of mechanical cables, has been consolidated as a promising trend in aeronautical industry due to several benefits. The major benefits of fly-by-wire, if compared to conventional manual-controlled aircraft, is the ability to automatically manage and adjust the characteristics of the aircraft at each point in the flight envelope. This adaptive process is done by control laws, i.e., algorithms present in the Flight Control Computer (FCC), responsible for managing inputs from pilot and aircraft sensors and compute "adequate" deflections of flight control surfaces, in each flight condition. "Adequate" in this context usually refers to a design compromise involving multidisciplinary requirements, such as high levels of flight safety, performance, handling qualities and low levels of pilot workload.

In the context of aircraft lateral control (rolling axis), it is common to employ roll spoilers together with ailerons, working in collaborative way, in order to achieve requirements that ailerons only are not able to comply (low control power in some points of flight envelope for example). This is usually referred to as lateral control allocation (Holzapfel et al., 2006). Many related works to the theme control allocation, such as Bodson (2002), Durham et al. (2017), concentrate efforts to find the best combination of control surface deflections that comply with arbitrary moments prescribed by pilot's command in single cases of flight envelope. Other works such as Baggi (2020) apply control allocation to cope with failure tolerance. On the other hand, the contribution of this paper is to design and compare two methodologies of lateral control allocation for a transport aircraft involving aileron and roll spoilers, taking advantage of the flexibility given by fly-by-wire architecture. Alternatives for design are presented highlighting benefits and limitations. Next sections present the aircraft, design flight envelope, control objectives, architecture, gains computation, linear analysis and results.

AIRCRAFT MODEL

To perform a representative flight control laws design, it is necessary to have detailed information about the aircraft. Considering the level of details from report such as NASA (1970), the airframe of the aircraft Boeing 747-100 (four-fanjet intercontinental transport aircraft) was adopted for this study. Figure 1(a) presents a schematic view of the aircraft, with emphasis in the control surfaces. This paper focuses attention on flap settings equal to 30 deg. Directional (yaw) control is obtained from two rudder segments (upper and lower rudder, assumed to move together). Lateral control system consists of inboard ailerons (High Speed Ailerons), outboard ailerons (Low Speed Ailerons) and roll spoilers. For simplicity, it is assumed that: inboard and outboard ailerons deflect together; only four most outboard spoiler panels (1, 2, 3, 4, 9, 10, 11, 12) were considered to actuate as roll spoilers. Moreover, it is assumed that the ailerons, rudders, and roll spoilers are driven by hydraulic actuators, with a full authority fly-by-wire control system.

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A computational model for the aircraft (Figure 1(b)) was built using the software Simulink, described in Gripp et al. (2023), and it was validated comparing simulation results with data from report NASA (1970). The model inputs are Throttle, deflection of Actuators and Mass Properties (Mass and Center of Gravity, CG). The main outputs are aircraft velocity (V), Pressure Altitude (Alt), angular rates (p, q, r), accelerations at CG (a_x, a_y, a_z), Euler angles (ϕ, θ, ψ) and aerodynamic angles (α, β, γ).

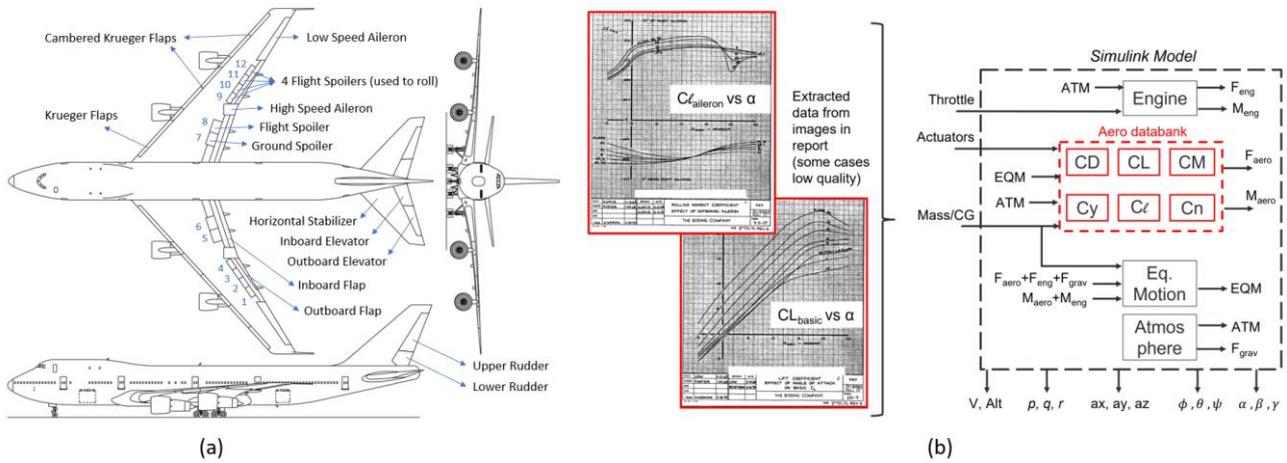


Figure 1 – (a) Views of Boeing 747-100. (b) Data extracted from report NASA (1970) to build aerodynamic model.

DESIGN FLIGHT ENVELOPE

Considering the aerodynamic database for Boeing 747-100, linear models of the aircraft at different Mach, flight altitude, weight, and center of gravity (CG) combinations were estimated in selected (trim) conditions for design (Figure 2). Eighteen different Mach and altitude combinations were considered (Figure 2(a)), and at each of those design points, up to five different weight and CG combinations (Figure 2(b)), as well as angle of attack (α) covering a range from -5 to 20 deg, for a total of over 220 models. All these models are for Flaps equal to 30 deg and gear-up configurations.

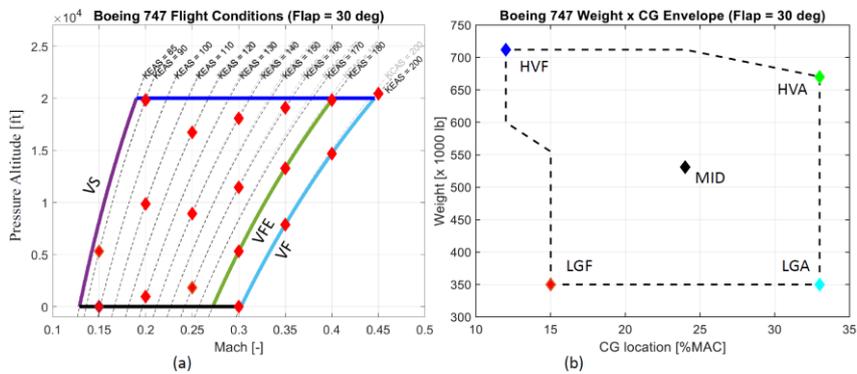


Figure 2 - Aircraft flight conditions for design (a) and Weight/CG envelope (b).

LATERAL-DIRECTIONAL CONTROL LAWS

Control allocation characteristics

The behavior of rolling moment for aileron is usually linear as function of its deflection, but the rolling moment due to roll spoiler usually is not linear as function of deflection. Additionally, significant uncertainties around roll spoiler neutral position might be present in aircraft model. The challenge of control allocation in this context is to compute deflections of aileron and roll spoiler that comply with requirements of stability, performance, and handling qualities. Moreover, the global rolling moment generated by combinations of aileron and roll spoilers must be linear as function of pilot command, resulting smooth and predictable turns. Finally, it is desirable to use roll spoiler only when it is necessary (for example in abrupt turns), since spoiler deflections results loss of lift and addition of drag as consequence, disturbing longitudinal dynamics.

Method 1: Aileron + Roll spoiler with dead zone

One possible approach, called *Method 1* in this work, is to deflect only ailerons for small roll commands (cases of small corrections), but deflect ailerons together with spoilers in case of large roll commands (cases which require more agility). Moreover, in linear design, for sake of simplification, it is adopted a unique entity for lateral command

(Artificial Aileron), which will be converted into actual deflections for aileron and roll spoilers during nonlinear design phase (Figure 3(a)). The benefits of this approach are: 1) to avoid deflection of spoiler when it is not necessary; 2) simplify the roll control surface, by reducing the number of states for optimization of LQR (linear-quadratic regulator) during control gains computation. However, the limitations of Method 1 are: 1) since deflections of aileron and roll spoiler are related (same set of controller gains), there is limited flexibility to adjust separately the deflections of aileron and roll spoiler; 2) when aileron is deflecting alone in the range of spoiler dead zone there is a risk for aileron rate saturation, which a known contributor factor for Pilot-Induced Oscillations (PIO).

Method 2: Aileron + Roll spoiler without dead zone

Another possible approach, called *Method 2* in this work, assumes the availability of a reliable aircraft model for design, specially capturing the nonlinearities of spoiler around neutral positions. With this approach, ailerons and roll spoilers deflect whenever there is lateral command. Roll spoiler can be tuned to provide initial moment with agility and reduce deflection in steady state. Following this approach, aileron and roll spoilers are designed separately. The benefits of this approach are: 1) roll spoilers always alleviate the workload of ailerons (reducing risk of rate saturation); 2) there is significant flexibility to adjust separately the deflections of aileron and roll spoiler tuning separately the gains of each control surface. However, the limitations of Method 2 are: 1) there are more gains for control design. Using LQR approach, it is necessary to prioritize certain states for optimization and convergence; 2) it is assumed that the airframe model has a good representation of system dynamics.

Figure 3 illustrates the process to convert *Artificial Aileron* deflections into actual Aileron and Roll Spoiler deflections. Note the dead zone of roll spoiler gearing (Figure 3(a)) and the steeper inclination of Aileron gearing to compensate the roll command in the range that aileron works alone.

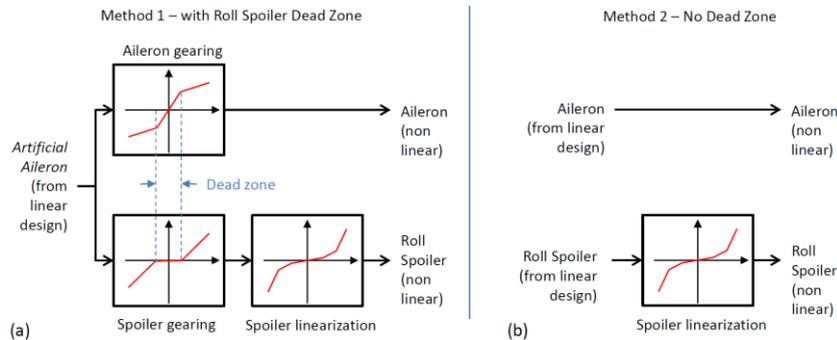


Figure 3 - Simplified strategies for control allocation involving aileron and roll spoilers.

Control objectives and design criteria

This work adopted as case study two versions of regulators for ϕ' (Euler roll angle rate) and β (sideslip angle), for the aircraft presented in previous section, using different methods of control allocation for roll spoilers and ailerons. The selection of the regulated variables ϕ' and β is a natural one, since these are the variables that either a pilot or an autopilot shall control in order to achieve the desired trajectory path in terms of lateral-directional dynamics. The control architectures analyzed in this study are adaptations of usual controllers referred to in literature as “p-beta” (controllers for roll rate and angle of sideslip), such as presented in the references Berger et al. (2013), Gripp (2015). Related longitudinal control laws for same aircraft are described in the reference Moreira et al. (2022).

A comprehensive set of Stability (S), Performance (P) and Handling qualities (H) criteria was chosen to drive the design of control laws, summarized in Table 1. Following the definitions of flight envelopes presented in FAA (2012), Normal Flight Envelope (NFE) is defined by load factors within 0.8 to 1.3g. At the extreme, Limit Flight Envelope (LFE) is defined by load factors within 0 to 2g (Flap down), angle of attack (α) below the α for maximum lift. To achieve a reasonable compromise involving stability, performance, and handling qualities (multidisciplinary criteria with conflicts), the approach adopted in this work was to extract as much as possible performance and handling qualities from aircraft model, respecting minimum levels of stability.

Table 1 – Selected design criteria (Class III aircraft: large-heavy transport/cargo).

Type	Criteria Name	Target	Reference	Rational
S	Phase Margin (NFE)	> 45 deg	USAF (1975)	Broken loop at sensors/actuators
S	Phase Margin (LFE)	> 35 deg	USAF (1975)	Broken loop at sensors/actuators
S	Gain Margin (NFE)	> 6 dB	USAF (1975)	Broken loop at sensors/actuators
S	Gain Margin (LFE)	> 4.5 dB	USAF (1975)	Broken loop at sensors/actuators
S	Dutch Roll Damping (NFE)	> 0.4	USAF (2006)	Level 1, Flight Phase Category A
S	Dutch Roll Damping (LFE)	> 0.3	USAF (2006)	Level 1, better than Phase Cat. A
P	Overshoot for ϕ' step input (NFE)	< 10 %	USAF (2006)	As low as possible. Usual guide
P	Roll Time constant (NFE)	< 1.4 sec	USAF (2006)	Level 1, Flight Phase Cat. A or B

P	Roll Time Delay (NFE)	< 0.1 sec	USAF (2006)	Level 1
H	Innocenti Roll Tracking (NFE)	Template	Innocenti, Thurkal (1991)	Level 1, No Cat. I PIO
H	Bandwidth/Phase Delay (NFE)	Template	Mitchel and Hoh (1999)	Level 1, No Cat. I PIO
H	Gibson Phase Rate (NFE)	Template	Gibson (1999)	Level 1, No Cat. I PIO
H	Sideslip excursion (NFE)	Template	USAF (2006)	Level 1, Flight Phase Category B

Common Parameters for both methods

For the system modeled, the properties of the actuators are summarized in the Table 2, such as cross-over frequency (ω_c) and damping ratio (ζ), considering a representation as second-order systems.

Table 2 – Actuators' properties, adapted from NASA (1970), Silva (2009).

Actuator	ω_c [rad/s]	ζ [-]	Negative Limit [deg]	Positive Limit [deg]	Rate Limits [deg/s]
Aileron	31.4	0.7	-25 (up)	+20 (down)	± 50
Roll Spoiler	31.4	0.7	0 (closed)	+45 (up)	± 75
Rudder	31.4	0.7	-25 (yaw to right)	+25 (yaw to left)	± 50

The properties of the sensors are summarized in the Table 3, such as cross-over frequency (ω_c) and damping ratio (ζ), considering a representation as second-order systems for some sensors (r_b , yaw rate in body axis; p_b , roll rate in body axis; N_y , lateral acceleration). Additionally, each sensor signal has a Transport delay, to account for sampling skew and bus transport delays. Moreover, the computation delay upstream of each actuator is set to 10 ms, assuming that the Flight Control Compute runs at 100 Hz.

Table 3 – Sensors' properties, adapted from NASA (1970), Silva (2009).

Signal	Meaning	ω_c [rad/s]	ζ [-]	Transport Delay [ms]
ϕ	Euler roll angle	-	-	30
r_b	Yaw Rate in body axis	50.3	0.7	27
p_b	Roll Rate in body axis	50.3	0.7	27
N_y	Lateral Acceleration at CG	50.3	0.7	27
β	Angle of sideslip	-	-	85

According to references, such as Stevens and Lewis (1992), it is possible to demonstrate the relation between estimates (subscript "est") for roll rate (p) and yaw rate (r) involving stability axis (subscript "s") and body axis (subscript "b"), for certain trimmed angle of attack (α_{tr}), given by Equations (1) and (2). Other relevant estimate adopted in this work is for derivative of Euler roll angle (ϕ'_{est}). The linearized version for small perturbations around trim condition is presented in Eq. (3), where θ is the pitch angle, q is pitch rate, subscript "tr" represents trimmed condition.

$$p_{s\ est} = \cos(\alpha_{tr}) p_b + \sin(\alpha_{tr}) r_b \quad (1)$$

$$r_{s\ est} = -\sin(\alpha_{tr}) p_b + \cos(\alpha_{tr}) r_b \quad (2)$$

$$\phi'_{est} = p_b + \cos(\phi_{tr}) \tan(\theta_{tr}) r_b + \tan(\theta_{tr}) (q_b \cos(\phi_{tr}) - r_b \sin(\phi_{tr})) \phi \quad (3)$$

Measurements of sideslip and sideslip rate, necessary to feedback module, are processed by a complementary filter, taking advantage of high frequency content estimated from inertial measurements and low frequency content from direct sideslip sensor (air data). The purpose of the complementary filter is to filter turbulence from air data to prevent the control surfaces from responding to the high frequencies, without destabilizing the loop with a simple low-bandwidth filter (lag). Based on definitions from Duke et al. (1988), since there is no direct measurement for sideslip rate, the estimate of sideslip rate ($\beta'_{inertial\ est}$) can be reconstructed from inertial measurements according to Eq. (4) (g is the gravity acceleration, V_T is the true airspeed). It is assumed trim β close to zero, lateral-directional model decoupled from longitudinal one (negligible variation of θ).

$$\beta'_{inertial\ est} = -r_{s\ est} + (g/V_T) (N_y + \cos(\phi_{tr}) \cos(\theta_{tr}) \phi) \quad (4)$$

A second order complementary filter is adopted to estimate sideslip and sideslip rate because this kind of filter eliminates effects due to biases of derivative input and offers better high frequency attenuation if compared to first-order filter. The complementary filtered sideslip (β_{CF}) and sideslip rate (β'_{CF}) are built up such that:

$$\beta_{CF} = (s/(s^2 + 2\zeta_{CF} \omega_{nCF} s + \omega_{nCF}^2)) \beta'_{inertial\ est} + ((2\zeta_{CF} \omega_{nCF} s + \omega_{nCF}^2)/(s^2 + 2\zeta_{CF} \omega_{nCF} s + \omega_{nCF}^2)) \beta_{sns} \quad (5)$$

$$\beta'_{CF} = ((s^2 + 2\zeta_{CF} \omega_{nCF} s)/(s^2 + 2\zeta_{CF} \omega_{nCF} s + \omega_{nCF}^2)) \beta'_{inertial\ est} + ((\omega_{nCF}^2 s)/(s^2 + 2\zeta_{CF} \omega_{nCF} s + \omega_{nCF}^2)) \beta_{sns} \quad (6)$$

where $\beta'_{inertial\ est}$ is described in Eq. (4), β_{sns} is the measured sideslip (air data), w_{nCF} is the complementary filter frequency (tuned to 0.1 rad/s in this design), ζ_{CF} is the complementary filter damping ratio (tuned to 0.5 in this design), and s is the Laplace variable (frequency domain).

Although aeroservoelastic (ASE) analysis is out of scope of this work, the effects of filters in control laws such as delays and distortion in command response were considered in this design. According to references such as Cohen et al. (1976), first structural mode of Boeing 747 is approximately around 2 Hz. For simplicity, a notch filter and a low-pass filter (roll-off) downstream were considered in the paths without inherent high-frequency attenuation, providing aeroservoelastic stability, which requires 9 dB of gain margin from control law structural coupling. The designed transfer function of the notch filter with roll-off downstream (G_{ASE}) is presented in the Equation (7), where the parameters of the notch filter are $\zeta_{num} = 0.40$, $\zeta_{den} = 0.50$, $w_{nASE} = 2\pi \cdot 2$ rad/s, and the parameters of the roll-off filter are $\zeta_{RO} = 0.60$ and $w_{nRO} = 2\pi \cdot 4$ rad/s.

$$G_{ASE} = ((s^2 + 2\zeta_{num} w_{nASE} s + w_{nASE}^2) / (s^2 + 2\zeta_{den} w_{nASE} s + w_{nASE}^2)) (w_{nRO}^2 / (s^2 + 2\zeta_{RO} w_{nRO} s + w_{nRO}^2)) \quad (7)$$

Designed parameters for each method

Figure 4 presents the architectures in each method of control law. Both methods adopt structures with two degrees of freedom for each axis (roll and yaw): “Feedback” blocks contain control structures with focus in stability and “Set Point” blocks have focus on tuning pilot command to have high level of handling qualities. The inputs of the models are ϕ'_{cmd} (pilot command for roll angle rate, using sidestick) and β_{cmd} (pilot command for sideslip, using rudder pedals).

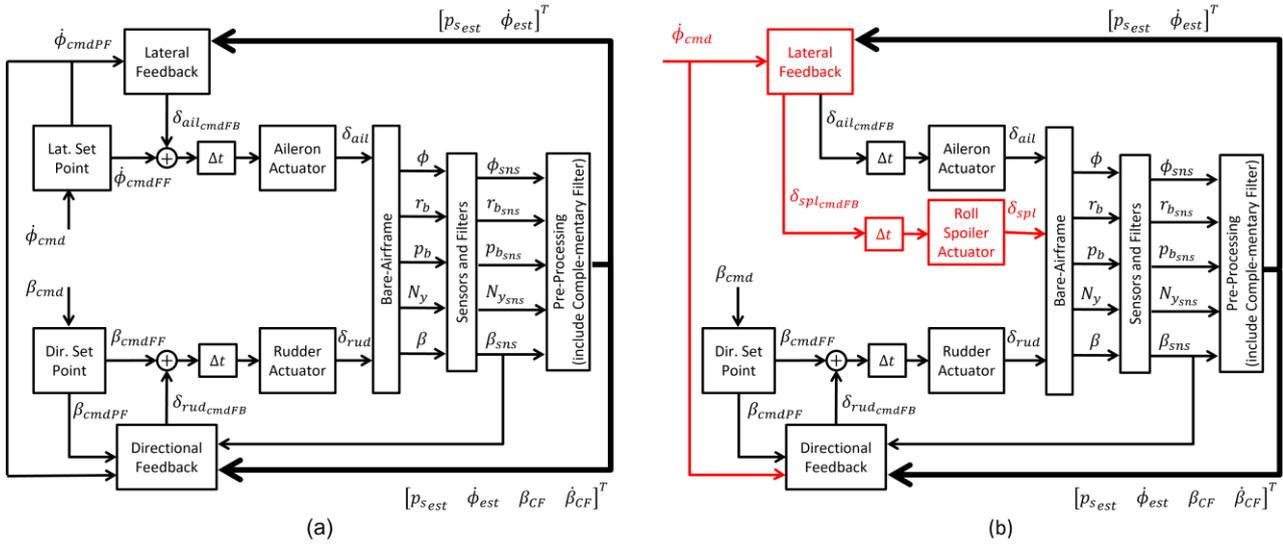


Figure 4 – Linear design architecture for $\phi' - \beta$ regulator. (a) Method 1. (b) Method 2 (differences highlighted).

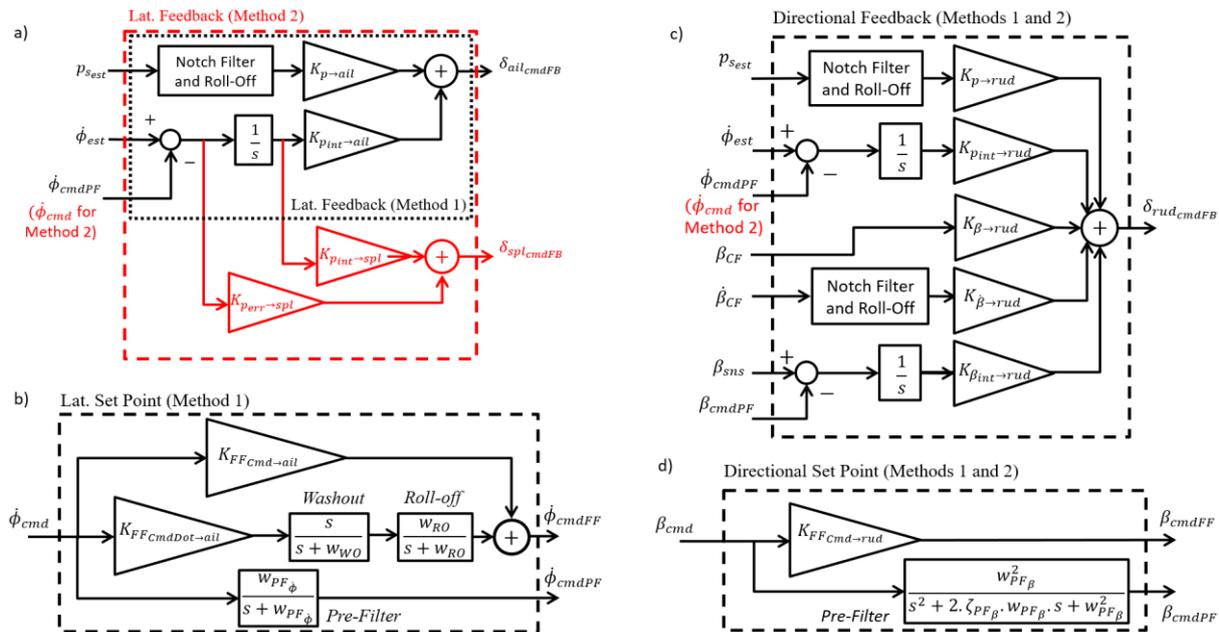


Figure 5 – Structures from Figure 4 in detail. a) Lateral Feedback, b) Lateral Set Point, c) Directional Feedback, d) Directional Set Point. Differences relative to Method 2 highlighted in red color.

In the sequence, particular portions of each method are presented and compared. In terms of lateral (roll) control, Figure 5(b) presents the Lateral Set Point of the Method 1, required to tailor the pilot command to the aircraft capacity, in order to extract satisfactory handling qualities (those filters were not necessary in Method 2). The gains $K_{FFCmd \rightarrow ail}$ and $K_{FFCmdDot \rightarrow ail}$ were tuned manually for each flight condition. The filter parameters for washout $\omega_{WO}=10$ rad/s, roll-off $\omega_{RO}=20$ rad/s and pre-filter $\omega_{PF\phi}=20$ rad/s were selected to comply with design criteria (Table 1).

Figure 5 represents in a compact view the Lateral Feedback for Method 1 (Figure 4(a)) and Method 2 (Figure 4(b)). The feedback command for Total Aileron ($\delta_{ailcmdFB}$) is given by a Proportional-Integral controller. For Method 1, the proportional and integral gains to aileron (respectively $K_{p \rightarrow ail}$, $K_{pint \rightarrow ail}$) were designed in a preliminary design phase using a linear-quadratic regulator (LQR) design method using target zeros, as employed by Berger et al. (2013), with additional fine tuning. For Method 2, besides the structure presented for Method 1, two additional paths were considered to compute roll spoiler deflections ($\delta_{splcmdFB}$, separated from $\delta_{ailcmdFB}$). The preliminary concept of this design was to share the rolling control efforts, such that ailerons and roll spoilers would apply as much as possible commands to have a quick rolling response in the beginning of the maneuver (larger error between ϕ'_{est} and ϕ'_{cmd} , modulated by gain $K_{perr \rightarrow spl}$), and rolling steady-state would be controlled mainly by aileron deflections (small portion of roll spoilers in steady-state only if necessary, modulated by $K_{pint \rightarrow spl}$). All the gains for Lateral Feedback by Method 2 ($K_{p \rightarrow ail}, K_{pint \rightarrow ail}, K_{pint \rightarrow spl}, K_{perr \rightarrow spl}$) were redesigned manually.

In terms of directional (yaw) control, Figure 5(d) presents the Directional Set Point adopted in both methods, whose concept is to improve the directional time response. The gain $K_{FFCmd \rightarrow rud}$ was designed for each flight condition, finding a reasonable compromise with $K_{FFCmd \rightarrow rud} = 1.5$ for Method 1 and $K_{FFCmd \rightarrow rud} = 1.0$ for Method 2. The selected parameters for the sideslip pre-filter (second order low-pass filter) are $\omega_{PF\beta} = 12$ rad/s and $\zeta_{PF\beta} = 1$. Figure 5(c) presents the Directional Feedback adopted in both methods. The feedback rudder command ($\delta_{rudcmdFB}$) is given by the sum of a Proportional-Integral-Derivative controller for sideslip and two extra paths (proportional and integral) in terms of $p_{s,est}$ and ϕ' -integral of error. The proportional, integral and derivative gains to rudder (respectively $K_{\beta \rightarrow rud}$, $K_{\beta int \rightarrow rud}$, $K_{\beta' \rightarrow rud}$) were designed according to linear-quadratic regulator (LQR) design method using target zeros, as employed by Berger et al. (2013), with additional fine tuning. The paths modulated manually by gains $K_{p \rightarrow rud}$ and $K_{pint \rightarrow rud}$ were added to improve aspects of turn coordination (Sideslip excursion criteria, from Table 1). Finally, it was necessary to add Notch-Filters in all the paths without inherent high-frequency attenuation.

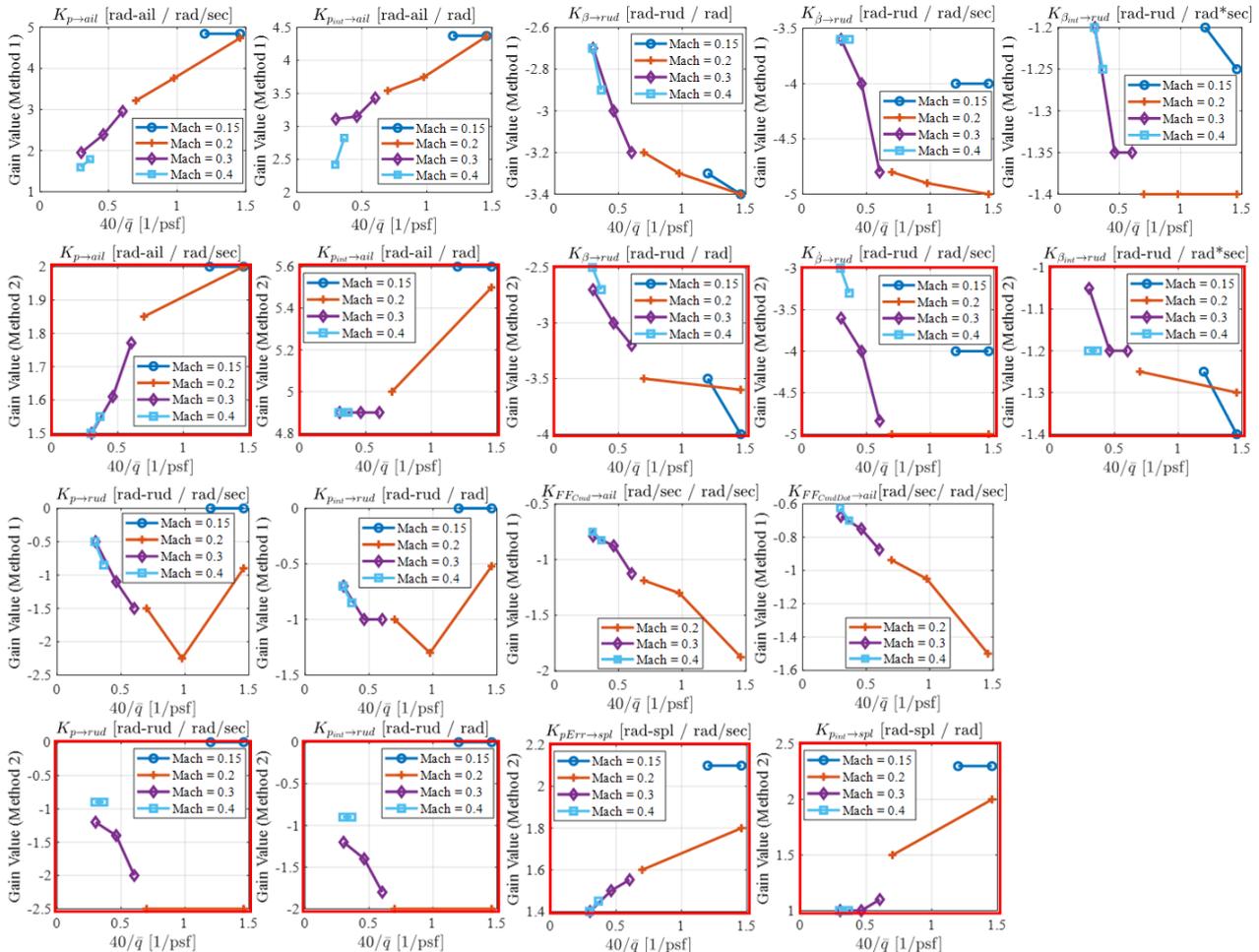


Figure 6 – Design gains for Method 1 and Method 2 (highlighted in red color).

RESULTS

For each selected case from Flight Envelope (Figure 2), the gains of the controllers were designed according to Methods 1 and 2, following the structures presented in Figure 4 in order to comply with the design criteria (Table 1). Figure 6 presents the designed gains for Lateral and Directional Feedback (cases of Method 2 highlighted in red color). It is important to note that most of gains present certain increasing or decreasing trend for each Mach, when plotted versus inverse of dynamic pressure (\bar{q}). This behavior is useful for gain scheduling using look-up tables.

Figure 7 presents a comparison of closed-loop Dutch roll poles for Method 1 and Method 2 (highlighted in red color), considering flight cases from Figure 2, with load factor around 1g (NFE) and extreme load factors (LFE, $-5 \leq \alpha \leq 20\text{deg}$). All combinations comply with the proposed damping levels (Table 1), presenting similar dispersion along flight envelope.

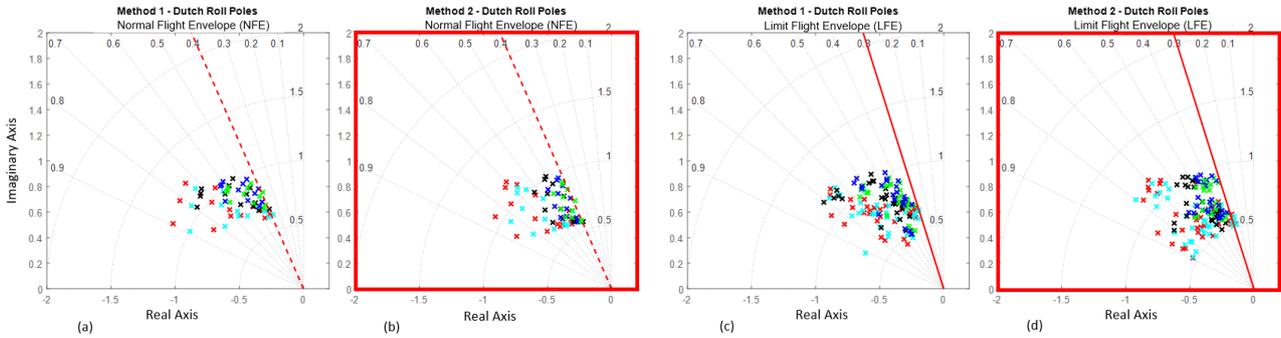


Figure 7 – Closed-Loop Dutch Roll Poles.(a) Met.1/NFE; (b) Met.2/NFE; (c) Met.1/LFE; (d) Met.2/LFE.

In the sequence, Figure 8 presents Nichols plots with control loop broken at main sensors (β and p) and actuators (δ_{ail} and δ_{spi}). For each case it is presented a comparison of Method 1 and Method 2 (highlighted in red color), considering flight cases from Figure 2 in Limit Flight Envelope (LFE, $-5 \leq \alpha \leq 20\text{deg}$), in order to check robust stability. All combinations comply with the proposed stability margins (Table 1). Similar checks for Nichols plots were performed successfully to other sensors (ϕ , r , N_y) and rudder (δ_{rud}) as well. It is important to note that stability margins for aileron are significant larger in Method 2 if compared to Method 1. It occurs because Method 2 assumed in linear design ailerons and roll spoilers separately, thus those control surfaces share the rolling efforts. On the other hand, Method 1 considered an *Artificial Aileron* that represents the consolidated efforts of aileron and roll spoilers. The particular deflections for ailerons and roll spoilers shall be divided in nonlinear design phase.

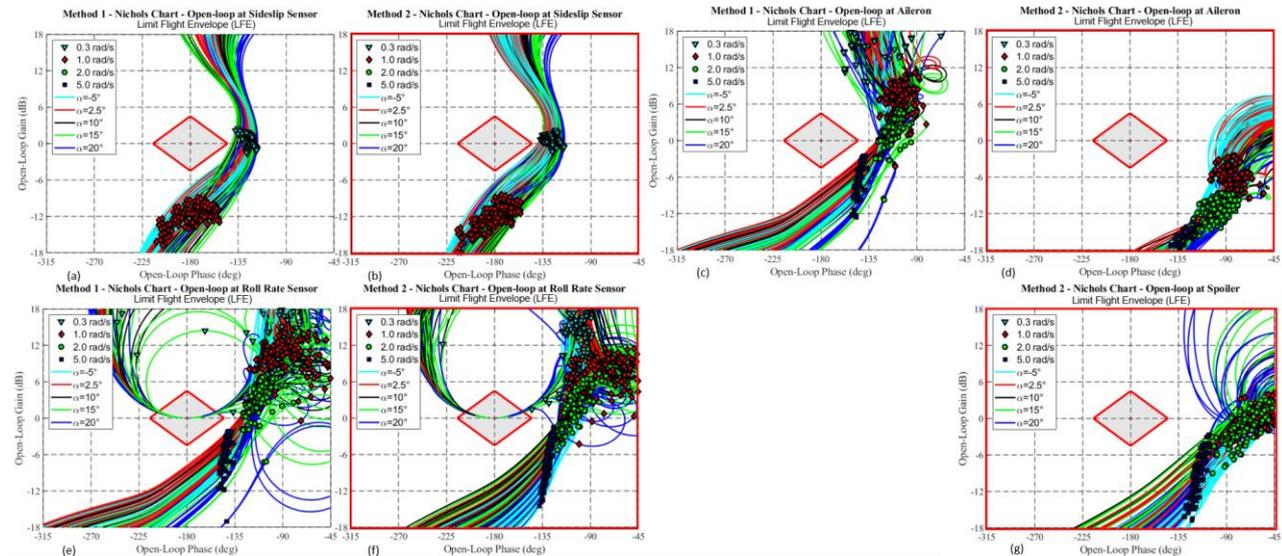


Figure 8 – Nichols plots for Methods 1 and 2 (highlighted in red color) with loop broken at: (a)/(b) β (sideslip sensor); (c)/(d) Total Aileron; (e)/(f) p (roll rate sensor); (g) Roll spoiler.

Some useful criteria were adopted to drive the design in order to predict Category I PIO (Pilot-Induced Oscillations) in the context of linear design, following good practices of aeronautical industry (NATO, 2000). Figure 9 summarizes the results for the following templates: (a) Innocenti-Gibson Lateral Tracking, (b) Roll Attitude Bandwidth vs Phase Delay, (c) Gibson Phase Rate. For both Methods 1 and 2 it was possible to accommodate the design cases (NFE) inside the boundaries defined for each criterion indicating good or acceptable handling qualities (Level 1, not PIO prone).

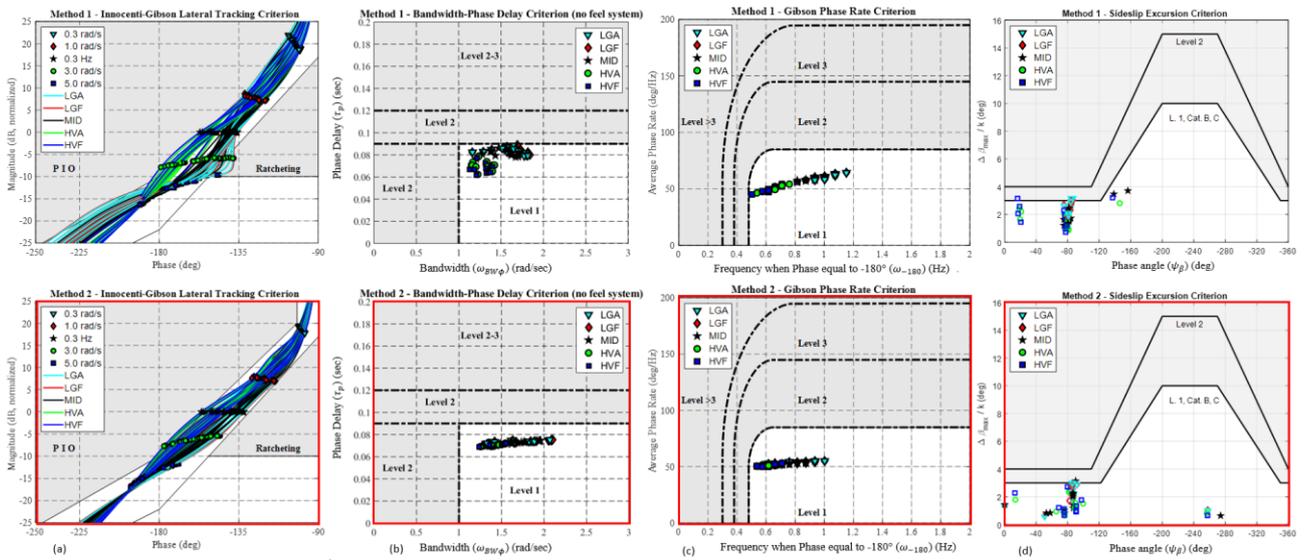


Figure 9 – Results of handling qualities criteria for Method 1 (top) and Method 2 (bottom). (a) Innocenti-Gibson Lateral Tracking. (b) Bandwidth vs Phase Delay. (c) Gibson Phase Rate. (d) Sideslip excursion.

Figure 10 presents an overview of results comparing time responses for Methods 1 and 2 due to an input of $\phi' = 3 \text{ deg/sec}$ (pilot command). The amplitude of command is low enough to adopt linear models for comparison (dynamics in the vicinity of trim condition), but large enough to illustrate the differences between two methods. The results are illustrated for one flight condition (Mach number equal to 0.3, Equivalent Airspeed equal to 160kt), but design of control laws was performed for the whole flight envelope of Flaps 30deg, with similar results. For Method 1, as expected, roll spoilers deflect only after certain dead zone. For Method 2, aileron and roll spoilers deflect whenever required (no dead zone). As result, for Method 1, while aileron do not achieve the dead zone, its deflection achieves higher rates because it is working alone (aileron exposed to possible rate saturation). The roll spoilers start deflecting only after the dead zone, alleviating the aileron rates. On the other hand, for Method 2, ailerons and roll spoilers work with low rates of deflection all the time, sharing the rolling efforts. In general, the roll performance obtained for Method 2 is better if compared to Method 1 (same bank angle is achieved earlier by fractions of seconds), since the aileron and roll spoilers are designed separately in order to extract better performance, without compromising other design criteria. In simple terms for Method 2, the roll spoiler works as a “kicker” in the beginning of the command (“washout-like” command), helping the ailerons to achieve enough roll response as soon as required. In steady state, the roll spoiler deflection converges to small deflections. Finally, for all cases the yaw response is similar, achieving deflections of rudder and sideslip angles with similar magnitudes.

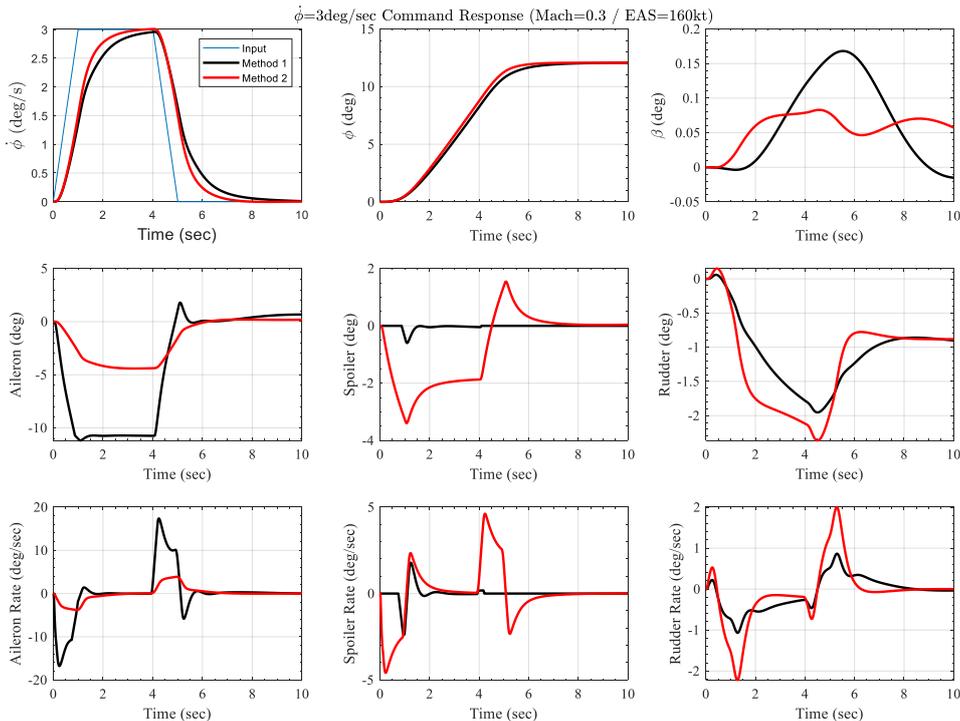


Figure 10 – Time Responses for $\phi' = 3 \text{ deg/sec}$ command (Mach=0.3, EAS=160kt, $N_z=1g$, Weight/CG=medium).

The main conclusions of this work are summarized in the Table 4.

Table 4 – Conclusions of this work comparing two methods of roll control allocation.

Item for comparison	Method 1 Aileron + Roll spoiler (with dead zone)	Method 2 Aileron + Roll Spoiler (no dead zone)
Assumption or Limitation	Nonlinearities of roll spoiler not well modeled or known, specially around zero deflection	Behavior of roll spoiler reasonably modeled or known
Behavior for small commands	Only aileron deflects (below roll spoiler dead zone)	Aileron and Roll Spoiler always deflect (Roll spoiler as "kicker" in the beginning of the command)
Behavior for large commands	Aileron works alone below dead zone and together with roll spoiler above dead zone	Aileron and Roll Spoiler always deflect (Roll spoiler as "kicker" in the beginning of the command)
Structure of linear control law	Proportional-Integral Controller for Artificial Aileron that mimics the real aileron and roll spoiler in linear model	Proportional-Integral Controller for real Aileron and Proportional to error - Integral Controller for real roll spoilers
Structure of nonlinear control law	Necessary additional design to translate Artificial Aileron into real deflections of aileron and roll spoilers (out of scope of this work)	Control allocation defined in linear design is directly adapted to nonlinear implementation
Flexibility of design (linear model)	Low, because real deflections for aileron and roll spoiler are already linked by <i>Artificial Aileron</i>	High, because real deflections for aileron and roll spoiler can be tuned separately
Compliance to design criteria	Yes, however it is exposed to potential rate saturation of aileron below roll spoiler dead zone (while aileron works alone)	Yes, usually with slightly better results in terms of performance, stability margins and handling qualities
Effects in longitudinal axis	Negligible when ailerons work alone	Possible additional drag and disturbance introduced by spoilers
Feasibility to industrial implementation	Yes	Yes

CONCLUSIONS

This work presented two practical methods to deal with lateral control allocation for fly-by-wire aircraft employing aileron and roll spoilers. This study highlighted benefits and limitations of each method with focus in performance and handling qualities, respecting minimum levels of stability. In one hand, Method 1 employs a dead zone for roll spoilers as a conservative approach, in order to minimize usage of roll spoilers when not necessary, avoiding side effects such as disturbance in longitudinal axis, additional drag due to spoilers, introduction of possible unknown nonlinearities. The penalization is that for rapid lateral maneuvers, ailerons might be exposed temporarily to rate saturation when working alone in the range of roll spoiler dead zone, a known cause for occurrences of PIO (Pilot-Induced Oscillations). On the other hand, Method 2 employs roll spoilers together with ailerons all the time, in order to alleviate the ailerons efforts and minimize risks of rate saturation, as well as it helps to achieve compliance with performance requirements when aileron alone is not able to achieve. This approach depends on a representative model for bare-airframe, especially mapping nonlinearities of roll spoilers, which can demand much effort to obtain. Therefore, the conclusion is that there is a trade-off involving the level of confidence in the bare-airframe model to capture the most relevant characteristics of ailerons and roll spoilers and the tolerable degradation in performance. Depending on the aircraft case, a solution involving both approaches could be employed, trying to extract the benefits of each one in different flight phases or missions.

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