

# A Multidisciplinary Optimization Framework for Control-Configuration Integration in Aircraft Conceptual Design

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The emerging flight-by-wire and flight-by-light technologies increase the possibility of enabling and improving aircraft design with excellent handling qualities and performance across the flight envelope. As a result, it is desired to take into account the dynamic characteristics and automatic control capabilities at the early conceptual stage. In this paper, an integrated control-configured aircraft design sizing framework is presented. It makes use of multidisciplinary design optimization to overcome the challenges which the flight dynamics and control integration present when included with the traditional disciplines in an aircraft sizing process. A commercial aircraft design example demonstrates the capability of the proposed methodology. The approach brings higher freedom in design, leading to aircraft that exploit the benefits of control configuration. It also helps to reduce time and cost in the engineering development cycle.

## Nomenclature

$\bar{c}$	mean aerodynamic chord, ft
$\bar{r}$	reference signal
$\bar{u}$	control vector

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$\bar{x}$	state vector
$\bar{y}$	output vector
$A$	state matrix
$AR$	aspect ratio
$B$	input matrix
$C$	output matrix
$c$	chord length, ft
$CD$	drag coefficient
$CL$	lift coefficient
$ESF$	engine scaling factor
$f$	objective function
$HQL$	handling quality level
$I_{yy}$	pitching moment of inertia, slug- $ft^2$
$J$	compatibility constraint
$K$	feedback control gain
$M$	pitch moment
$MTOW$	maximum takeoff weight, lb
$n_z$	normal acceleration, g's/rad
$p$	roll rate, deg/sec
$q$	pitch rate, rad/sec
$r$	yaw rate, deg/sec
$S$	area, $ft^2$
$T$	engine thrust, lb
$t_{pk}$	response peak time, sec
$tc$	thickness to chord ratio
$TSFC$	thrust specific fuel consumption
$V$	aircraft velocity, ft/sec
$x$	local design variable
$y$	coupling design variable
$Z$	normal force
$z$	global design variable

#### *Subscripts*

$a$	aileron
$ce$	control effector
$cs$	control surface
$dr$	dutch roll
$e$	elevator

<i>eng</i>	engine
<i>ht</i>	horizontal tail
<i>i</i>	$i^{th}$ discipline
<i>ic</i>	inner chord
<i>oc</i>	outer chord
<i>r</i>	rudder
<i>ref</i>	reference value
<i>SL</i>	system level
<i>sp</i>	short period mode
<i>vt</i>	vertical tail
<i>w</i>	wing
<i>wo</i>	washout filter

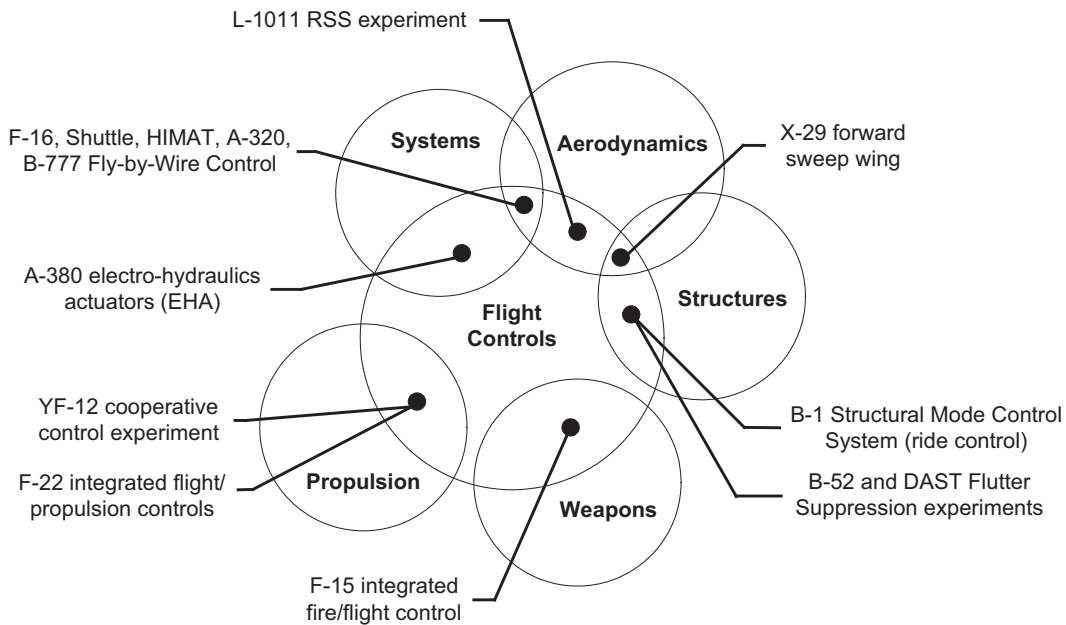
#### *Symbols*

$\alpha$	angle of attack, rad
$\beta$	sideslip angle, deg
$\delta$	deflection, deg
$\eta$	normalized control effector span location
$\Lambda$	sweep angle, deg
$\lambda$	taper ratio
$\omega$	frequency, rad/sec
$\phi$	bank angle, deg
$\tau$	time constant
$\varepsilon$	constraint tolerance value
$\zeta$	damping ratio

## I. Introduction

Flight dynamics and control (FD&C) has a significant impact on the aircraft performance and cost.<sup>1</sup> It is also an important discipline for flight safety and aircraft certification. Considerations of dynamic characteristics and control design are essential in the design of future aircraft. Furthermore, the use of control-augmented or control-configured vehicles could offer significant opportunities for expanded flight envelopes and enhanced performance, as demonstrated over the years with different research efforts as shown in Figure 1 adapted from Ref. 2.

In the traditional conceptual design process, the disciplinary analyses are performed sequentially. It is an iterative process in which interdisciplinary trades are used to size the aircraft. With the advances of new technologies such as flight-by-wire and flight-by-light



**Figure 1. Examples of flight control integration with traditional disciplines**

technologies, more emphasis is placed on the analysis of flight dynamics early at the conceptual stage.<sup>3,4</sup> It is of the authors' main interest to study the impact of the aircraft and control surface sizing on flight control capability and dynamic performance. From flight dynamics and control perspective, the classical control surface sizing at the conceptual design stage is primarily limited to the use of the so-called *volume coefficient*<sup>5</sup> which estimates the control surface size based on historical data by assuming the effectiveness of the tail in generating a moment about the center of gravity is proportional to the force (i.e. lift) produced by the tail and its moment arm.<sup>6</sup> Once these control surfaces are sized, limited trim, control, and stability characteristics can be found using single-degree-of-freedom equations.<sup>5,7</sup> In most advanced methods such equations are analyzed over some specific set of flight conditions.<sup>8,9</sup> More explicit considerations of flight dynamics and control are not taken into account until later in the preliminary design stages where much more detailed information about the aircraft has been established.

The challenge is, however, that the sequential process may lead to sub-optimal designs due to its inability to capture the interactions between the sizing of control surfaces, their control system, and their effect on the general dynamic behavior of the aircraft. It does not take into account (or take advantage of) the coupling effects between the sizing and the dynamic characteristics. Also, it imposes constraints on control surfaces and limitations on dynamic and control performance, which may be reflected in costly design modifications at later stages in the design chain.<sup>10</sup>

In order to address this challenge, a novel method for the concurrent design of the control system and the aircraft, including the control surface sizing, is presented in this paper. Using a multidisciplinary design optimization (MDO) approach, the control surface sizing with feedback flight control system development is integrated in the conceptual aircraft sizing process. Because more disciplinary aspects of the aircraft are considered simultaneously, better control-augmented aircraft designs can be obtained, based on specified mission parameters, including flight dynamics, handling quality and control related objectives over the entire aircraft mission profile.

## II. Integration Methodology Challenges

While the benefits of simultaneous considerations of flight dynamics and control in aircraft design have been considered since the 1970s,<sup>11</sup> very few efforts have been made over the years to integrate FD&C in the conceptual design phases. A number of challenges are given below.

First of all, the aircraft design has to guarantee satisfactory flight characteristics over the entire flight envelope. In order to ensure positive characteristics, proper control is required for each point within the envelope. The number of analyses required to cover the entire envelope becomes unaffordable at the conceptual stage.

Second, unlike many other disciplines involved in the conceptual design process, FD&C does not have an obvious figure-of-merit (FOM) that can be used for design optimization. For example, drag count is a continuous FOM used in aerodynamics where the disciplinary goal is to minimize such measurement. The challenge lies in the proper specification definition that considers the dynamics and control requirements and constraints simultaneously.

Third, in the current design process very few interactions between the control and aircraft design processes are taken into account. As a result, when the design has been frozen and information regarding the design matures, so better disciplinary information is known, any deficiencies in FD&C which could be avoided by considering such interactions suddenly become very expensive to fix; as they require changes to control surfaces, additional wind tunnel testing to place vortex generators, installation of redundant control systems, etc. The challenge lies in how to enable control-configuration interactions at the conceptual design stage not only to exploit the coupling benefits that arise from such integration but also to reduce any possible FD&C deficiencies as early as possible.

A final obstacle is how to deal with the increased data and computational complexity.

### III. Flight Dynamics and Control Integration Methodology

The proposed methodology makes use of multidisciplinary optimization to solve the design complexity paradigm while simultaneously designing the aircraft and the control system at different constraining conditions. Details of the proposed solution to flight dynamic and control integration challenges are presented in the following subsections.

#### A. Multidisciplinary Design Integration

With recent advances in the field of multidisciplinary optimization (MDO),<sup>12</sup> it is possible to transform the traditional vertical design process into a horizontal process, enabling concurrent analysis and design. Therefore, it is possible to address the FD&C integration/interaction challenge, and take advantage of the concurrent structure to increase freedom in the design space. Among many different MDO strategies, Collaborative Optimization (CO)<sup>13</sup> shown in Figure 2 has been found to be one suitable alternative to include flight dynamics and control in the design process. CO is a bi-level optimization scheme that decouples the design process by providing the common design variables and disciplinary coupling interactions all at once in an upper level, eliminating the need for an *a priori* process that accumulates all the disciplinary data required to perform FD&C analyses.

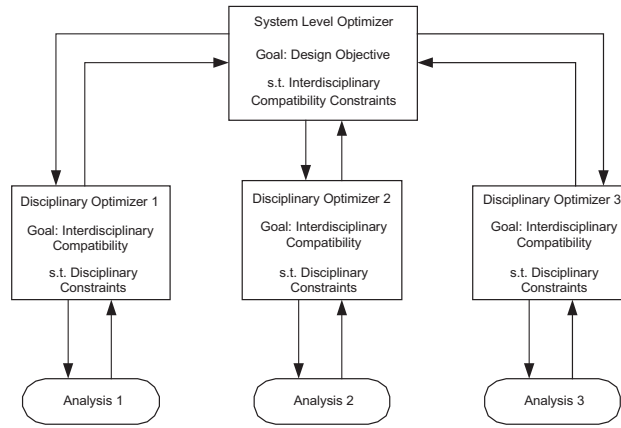


Figure 2. Collaborative Optimization Method

At the system-level (SL), the Collaborative Optimization objective function is stated as:

$$\begin{aligned} \min_{z_{SL}, y_{SL}} \quad & f(z_{SL}, y_{SL}) \\ \text{s.t.} \quad & J_i^*(z_{SL}, z_i^*, y_{SL}, y_i^*(x_i^*, y_j^*, z_i^*)) \leq \varepsilon \quad i, j = 1, \dots, n \quad j \neq i \end{aligned} \quad (1)$$

where  $f$  represents the system level objective function.  $J_i^*$  represents the compatibility

constraint for the  $i^{th}$  subsystem (of the total  $n$  subsystems) optimization problem, and  $\varepsilon$  is a constraint tolerance value. Variables shared by all subsystems are defined as global variables ( $z$ ). Variables calculated by a subsystem and required by another are defined as coupling variables ( $y$ ). Variables with superscript star indicate optimal values for the subsystem level optimization. Note that the system level constraint assures simultaneous coordination of the coupled disciplinary values. When using local optimization schemes the MDO mathematical foundation leads to a unique ‘multidisciplinary feasible point’, which is the optimal solution for all disciplines.

The lower level objective function is formulated such that it minimizes the interdisciplinary discrepancy while meeting local disciplinary constraints. At the disciplinary level, the  $i^{th}$  subsystem optimization is stated as:

$$\begin{aligned} \min_{z_i, y_i, y_j, x_i} \quad & J_i = \sum (z_{SL_i} - z_i)^2 + \sum (y_{SL_j} - y_j)^2 + \sum (y_{SL_i} - y_i)^2 \\ \text{s.t.} \quad & g_i(x_i, z_i, y_i(x_i, y_j, z_i)) \leq 0 \end{aligned} \quad (2)$$

where  $x_i$  are local subsystem design variables,  $y_i$  are subsystem coupling outputs variables,  $y_j$  are subsystem coupling input variables,  $z_i$  are the system level variables required by the sub-system discipline analysis, and  $g_i$  is the specific disciplinary constraint.

FD&C concurrent evaluation becomes available thanks to the nature of the adopted MDO approach. The flight dynamics and control analysis requires parameters from other disciplines, such as lift, drag, stability derivatives, and inertias. Under the bi-level design structure, these parameters are defined as coupling variables and are provided simultaneously to all disciplines from the system level (see Figure 3). This way, the traditional approach of interdisciplinary trades is avoided. Compatibility between the provided system level information and the calculated disciplinary analysis results is handled by the lower level optimization formulation.

In addition, the MDO bi-level decomposition provides independent and concurrent local disciplinary optimizations processes that can be taken advantage of for control design and to distribute the computational effort when the design process requires analysis at different flight conditions, as shown in Figure 4.

## B. FD&C Design-Constraining Flight Conditions

In this paper, the critical flight conditions analyses, both symmetric and asymmetric, are defined based on their interdisciplinary effect on the longitudinal and lateral-directional control

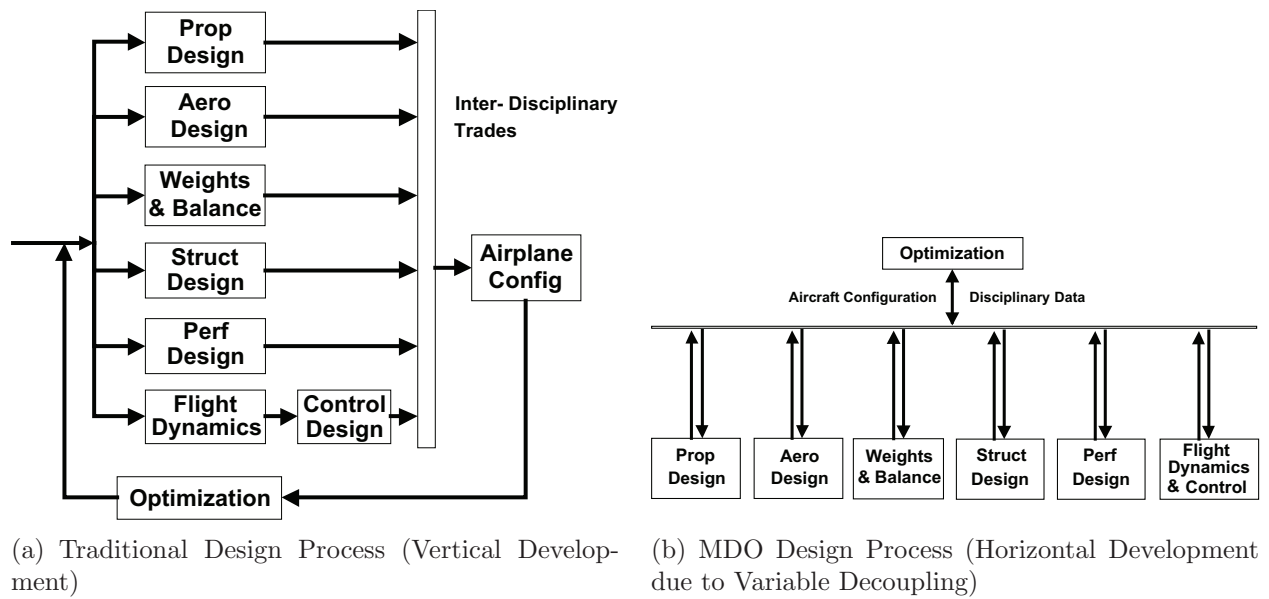


Figure 3. Flight Dynamics and Control Decoupling

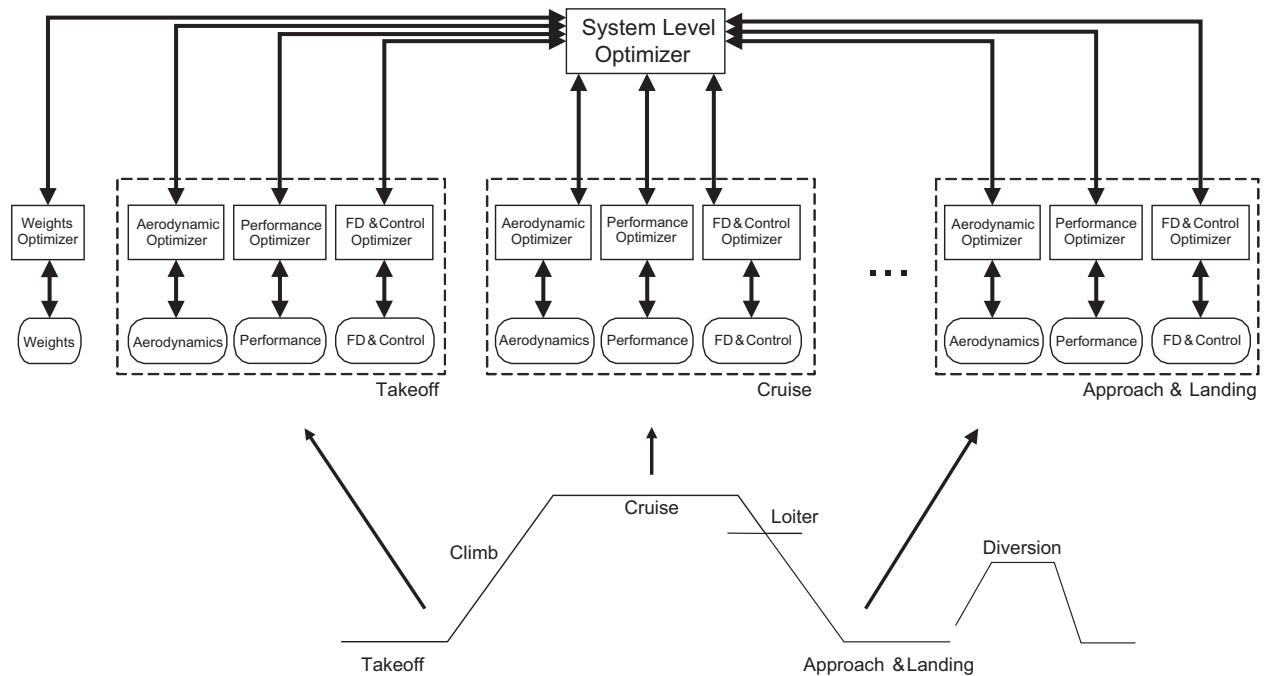


Figure 4. Mission Segments Disciplinary Decomposition



surfaces sizing as presented in Table 1. They contain static, maneuver, inertia coupling and dynamic considerations along the flight envelope and are valid for a large range of aircraft configuration and concepts.<sup>8,14–16</sup> Only primary design conditions are considered. Critical control failure cases are neglected since they represent secondary requirements and can be covered in great extent by open-loop and closed-loop dynamic requirements.

**Table 1. Longitudinal and Lateral-Directional Design-Constraining Conditions**

Control Effector Analysis	Applicable Flight Conditions	Critical CG Location	Applicable Requirement	Aircraft Configuration
<b>Longitudinal</b>				
1-g Trim	All	Fwd, Aft	FAR/JAR 25.161C	Dependent on Flight Condition
Approach 1-g Trim	Approach	Fwd	FAR/JAR 25.161C	Full Flaps
Landing 1-g Trim	Landing	Fwd	FAR/JAR 25.161C	Full Flaps, Landing Gear Down
Go-Around 1-g Trim	Climb	Aft	FAR/JAR 25.161C	Full Flaps, Landing Gear Down
Manoeuvre Load	All	Fwd	FAR/JAR 25.255	Dependent on Flight Condition
Go-Around maneuver	Approach	Fwd	FAR/JAR 25.255	Full Flaps
Rotation on Takeoff	Takeoff	Fwd	FAR/JAR 25.143	Takeoff Flaps, Landing Gear Down, in ground effect
Rotation on Landing	Landing	Aft	FAR/JAR 25.143	Full Flaps, Landing Gear Down, in ground effect
Dynamic Mode Oscillation	All	Fwd, Aft	FAR/JAR 25.181A	Dependent on Flight Condition
<b>Lateral</b>				
Steady Sideslip	All	-	FAR/JAR 25.177	Dependent of Flight Condition
One Engine Inoperative Trim	All	-	FAR/JAR 25.161	Dependent of Flight Condition
Time to Bank	All	-	FAR/JAR 25.147	Dependent of Flight Condition
Inertia Coupling (Pitch due to Velocity Axis Roll)	Cruise	-	FAR/JAR 25.143	Dependent of Flight Condition
Yaw Due to Loaded Roll Pullout	Cruise	-	FAR/JAR 25.143	Dependent of Flight Condition
Coordinated Velocity Axis Roll	Cruise	-	FAR/JAR 25.143	Dependent of Flight Condition
Dutch Roll Oscillation	All	-	FAR/JAR 25.181B	Dependent of Flight Condition
Roll Subsidence	All	-	FAR/JAR 25.181B	Dependent of Flight Condition
Spiral Divergence	All	-	FAR/JAR 25.181B	Dependent of Flight Condition
Closed-Loop Stability	All	-	FAR/JAR 25.177	Dependent of Flight Condition

Longitudinal static considerations are aimed to maintain steady 1-g level flight, which can become highly demanding for the control effectors at low speeds in both forward (fwd) and aftward (aft) CG limits, and with complex high lift devices (where the aerodynamic pitching moment is large) as is the case in the approach and go-around flight phases. Maneuver considerations include load and rotation capabilities. In the first one the control effectors should be able to achieve load factors between the maximum and minimum operational limits in a pull-up from a dive over the flight envelope. This scenario becomes critical with the maximum takeoff weight and fwd CG, and in the go-around maneuver where the control effectors should be able to provide  $8 \text{ deg/sec}^2$  pitch acceleration starting from an approach trim condition. Rotation capabilities consider the ability of the control effectors to gener-

ate enough pitch moment to lift/de-rotate the nose wheel off/on the ground in takeoff and landing respectively. This scenario becomes critical for takeoff at maximum gross weight with fwd CG, and with complex high-lift systems and high CG locations for landing. A pitch acceleration of  $7 \text{ deg/sec}^2$  for dry, prepared runways is specified for takeoff, it is higher than the minimum requirement as specified by FAR 25.331C, to provide an ample margin of control for future aircraft variants. Longitudinal dynamic response considerations are included as well for both the un-augmented (open-loop) and augmented (closed loop) aircraft. With a control-augmented aircraft the closed-loop dynamic criteria assessment serves primarily for the evaluation of control laws. However, consideration of these conditions during the conceptual sizing stage ensures the aircraft is properly designed for adequate dynamic characteristics where control-augmentation is used to avoid excessive system demands.

For the lateral-directional dynamics, the static considerations include steady sideslip and one-engine-inoperative (OEI) considerations. For the steady sideslip the lateral control surfaces should provide adequate roll and yaw power to perform steady sideslip maneuver at a 10-degree sideslip angle. This situation becomes critical during crosswind landing, when the sideslip angle is the greatest because of low airspeed. Similarly, the roll and yaw control effectors must be able to cope with asymmetric propulsion failure and maintain a steady straight flight with a 5 degree bank angle. This requirement becomes most demanding when operating at very low speed, specifically at takeoff where the weight and inertia are higher. A lateral-directional dynamic consideration is related to the time to bank response to full roll control input where the maneuver result must meet the performance requirements prescribed by Ref. 17. Similar to the longitudinal case, critical dynamic characteristics are considered where the dynamic mode response for both the un-augmented (open-loop) and augmented (closed loop) aircraft is assessed.

Three inertia coupling effects are included as well. The first one considers the pitch due to velocity axis roll, where the control effectors (elevators) should provide sufficient nose-down pitch authority to compensate for the nose-up moment as a result of inertia cross-coupling during high angle-of-attack stability axis roll maneuvers. Similarly, the control effectors (rudder) should possess adequate authority to overcome the yawing moment as a result of inertia coupling during a rolling pullout maneuver. In addition, the control effectors (rudder and ailerons) should be able to maintain a zero sideslip conditions when performing a coordinated stability-axis roll.

Note that many of the above critical conditions for the control effectors match the traditional design mission profile flight phases which greatly simplify the flight condition analyses. However, if necessary other off-mission design conditions can be calculated and taken into consideration in the design process.

### C. FD&C Design Constraints and Requirements

Control power, which describes the efficiency of a control system in producing a range of steady equilibrium or maneuvering states<sup>18</sup> is defined as the common figure-of-merit to be used in FD&C. It is quantified in terms of control deflection making it a continuous measurement useful for optimization. Specific sets of flight condition analyses will become critical, as the aircraft geometry varies during sizing. To ensure adequate flight control characteristics, the aircraft has to provide sufficient, yet not excessive, control power to meet the requirements of the prescribed flight analyses. For such reason, the FD&C disciplinary constraints in 2 are specified in terms of such FOM, along with complementary open and closed loop dynamic requirements. The additional open-loop constraints take care of dynamic response specifications, such as limits of oscillation, damping ratios, natural frequency requirements, and control force gradients, which are defined from military specifications (such as Ref. 17), or certification guidelines (such as FAR or JAR). The closed-loop constraints are mainly aimed to meet with control design requirements in order to achieve internal stability of the control system, reject external disturbances, and assure adequate handling qualities (HQ) requirements for both the longitudinal and lateral-directional modes. The assessment of HQ is closely related to dynamic considerations of the augmented closed-loop aircraft. Different handling qualities quantification procedures exist. For the longitudinal case, the method such as the one proposed in Ref. 19 is very useful for an optimization procedure. It directly quantifies dynamic modes responses with HQ.

For example, if the aircraft dynamics is considered to be uncoupled into longitudinal and lateral modes, the short period mode handling quality can be assessed by using a control anticipation parameter (CAP). This parameter quantifies the response necessary to make precise adjustments to the flight path in terms of instantaneous angular pitching acceleration per unit of steady state normal acceleration.<sup>20</sup> Furthermore, a generic control anticipation parameter (GCAP) extends the CAP application to both un-augmented and control augmented aircraft.<sup>21</sup> The GCAP parameter is defined as:

$$GCAP = \frac{\dot{q}(0)}{n_z(t_{pk})} \left( 1 + \exp \left( \frac{-\zeta_{sp}\pi}{\sqrt{1-\zeta_{sp}^2}} \right) \right) \quad (3)$$

$$0 < \zeta_{sp} < 1$$

where  $n_z(t_{pk})$  is the normal acceleration at the peak time in response to a control step input. Specified GCAP bounds correlate the qualitative HQ levels to the aircraft step input dynamic response. In the case of the Phugoid mode, handling quality is related to the mode damping and time to double amplitude to ensure long enough time to stabilize the aircraft following a disturbance. Lateral HQ include roll and bank oscillations responses, a sideslip excursion and a ‘Phi-to-Beta’ ( $\phi/\beta$ ) ratio criteria specifications.<sup>17,19</sup>

## D. Control System Design

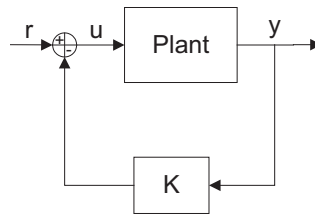
While some research has been done to select the most appropriate control system at the design stage before any detailed analysis is performed (see e.g. Ref. 22), the proposed methods do not perform the actual control design, therefore limiting their capability in the scope of control-configured aircraft design. Among the different control systems, the stability augmentation systems (SAS) have the strongest relationship with the design of the airplane, since their use can directly affect the aircraft layout characteristics. For this reason the control design goal at the conceptual design stage is to provide adequate stability augmentation systems to meet the close-loop and handling quality specifications over the flight envelope for both longitudinal and lateral dynamics. The aircraft plant is defined as a strictly proper linear time invariant (LTI) system without disturbances and sensor noise. An output feedback controller, Figure 5, is used to provide the necessary stability augmentation. The feedback control is formulated as:

$$\begin{aligned}\dot{\bar{x}} &= A\bar{x} + B\bar{u} \\ \bar{y} &= C\bar{x} \\ \bar{u} &= \bar{r} - K\bar{y}\end{aligned}\tag{4}$$

$$\text{where : } K = \begin{bmatrix} k_{11} & \dots & k_{1d} \\ \vdots & \ddots & \vdots \\ k_{c1} & \dots & k_{cd} \end{bmatrix}$$

where  $\bar{x}$  is the aircraft states,  $\bar{y}$  is the plant output,  $\bar{u}$  is the control variables,  $\bar{r}$  is the reference signal,  $c$  is the number of control variables  $\bar{u}$ , and  $d$  is the number of outputs  $\bar{y}$ , and  $A, B, C$  are the state, control and output matrices respectively. The closed-loop system is then:

$$\begin{aligned}\bar{y} &= C(sI - A_c)^{-1} Br \\ \text{where : } A_c &= A - BKC\end{aligned}\tag{5}$$



**Figure 5. Generalized Control Process**

Stability is assured by selecting adequate control gains such that the closed loop system

lies in the negative real axis. It is assumed the aircraft dynamics follow “traditional” mode responses for both longitudinal and lateral dynamics so the sign of the gains can be selected beforehand to guarantee stabilization. The control design itself is done as part of the MDO lower-level optimization, where control gains are specified as local optimization variables  $x$  in (2), while closed-loop stability and control constraints assure proper stabilization and performance.

## IV. Application Example

### A. Aircraft Mission and Optimization Goal

This section illustrates the proposed framework process in the case of a narrow-body 130-passenger airliner sizing, with twin wing engines, and conventional aft tail. Its mission profile is specified in Figure 6, in line with industry standards for similarly sized aircraft. The design goal (MDO system level goal, eq. (1)) is to find a feasible aircraft that maximizes specific air range ( $\max_{z_{SL}, y_{SL}} Range$ ) while meeting individual disciplinary requirements as shown in the mission profile. A fixed fuel weight is specified as 40000 lb, while the payload weight is specified as 32175 lb based on 130 passengers, crew of 2, and 5 attendants. The subsystem level disciplinary optimization process follow the formulation presented in eq. (2).

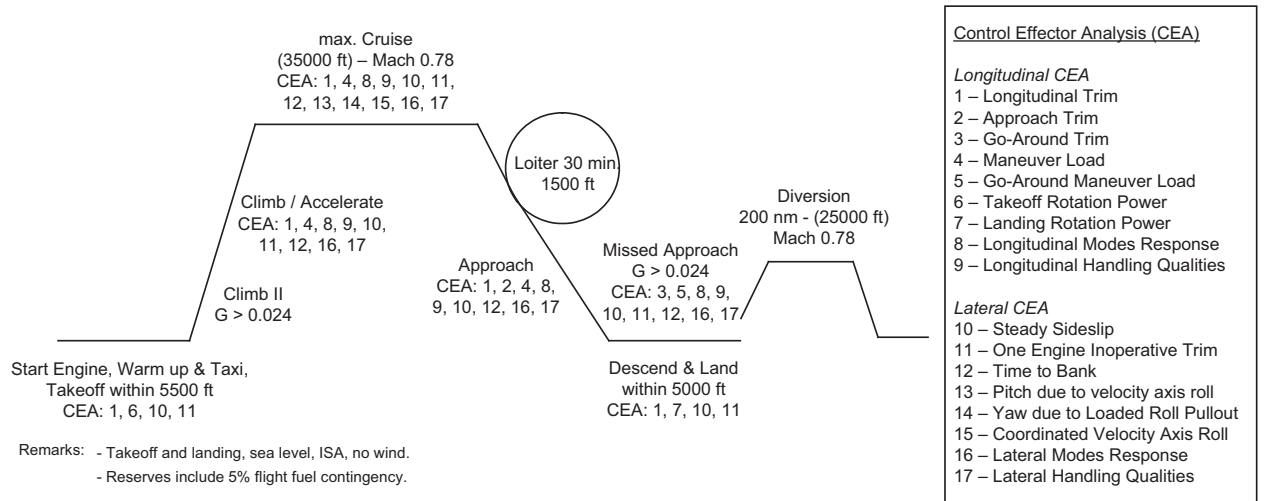
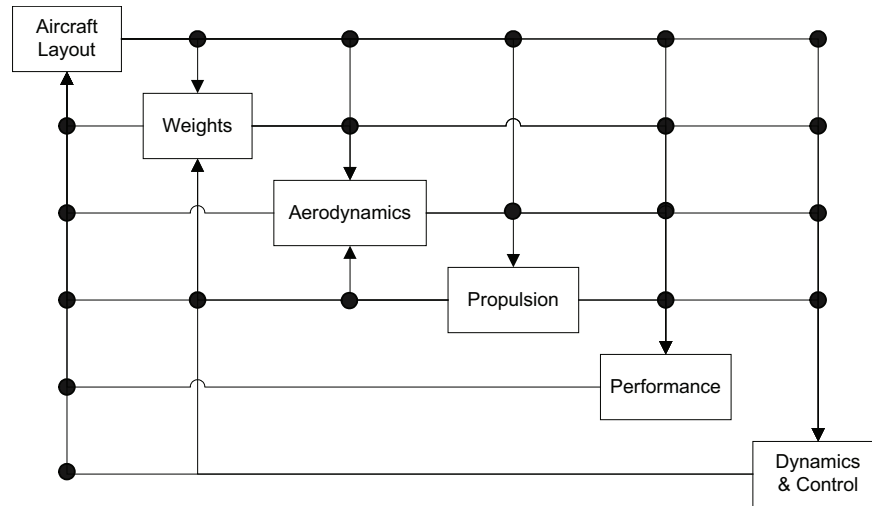


Figure 6. Mission Profile and Longitudinal Control Effectors Analysis Considered

### B. Disciplinary Analyses

The design process of this example is composed of five coupled disciplines, namely: weights, aerodynamics, propulsion, performance, and dynamics & control. They are coupled as shown

in the n-square diagram presented in Figure 7. Details of each discipline are described below.



**Figure 7. Design Example Disciplinary Couplings**

- Weights: The aircraft takeoff weight is calculated from main component weights that are estimated using statistical methods.<sup>6,23</sup> The maximum permissible center of gravity (CG) range for the configuration is calculated from each aircraft component permissible CG limits, based on their own geometry, physical and functional considerations.<sup>24</sup> Similarly, the aircraft inertias are calculated from a build-up based on each component inertias calculated from the mean CG location for each component.
- Aerodynamics: Aircraft lift, drag and stability derivatives are calculated based on standard aerodynamic calculation used at the conceptual stage. Induced, parasite and wave drag calculations are considered. The induced drag is calculated from parametric technology models whereas parasite-drag is calculated using a detailed component build-up<sup>25</sup> taking into consideration viscous separation and components mutual interference effects. Transonic wave drag is modeled based on Lock's empirical approximation, using the Korn equation extended by Mason to include sweep.<sup>26</sup> To provide greater flexibility and accuracy in the calculation of aerodynamic characteristics, downwash effects, and stability derivatives, a combination of semi-empirical formulae<sup>27,28</sup> and a non-planar multiple lifting surface panel method are implemented.
- Performance: Takeoff and landing distances, rate of climb, and range are calculated based either on analytical expressions or numerical simulations. For example, take-off distance is calculated based on a numerical simulation, while specific air range is

calculated based on Breguet's equation. Landing field length is calculated assuming a landing weight of 90% MTOW.

- Propulsion: Propulsion characteristics, such as engine weight, thrust and specific fuel consumption for a given altitude and Mach number, are calculated based on engine scaling of a baseline PW-2037 high bypass turbofan engine.
- Flight Dynamics and Control: For the present analysis it is assumed that all aircraft states are measurable without noise. Longitudinal and lateral design open-loop, and closed-loop analyses are performed at each flight mission segment as shown on Figure 6. Control design is performed for all in-flight phases (climb, cruise, and landing approach) of the mission profile.

### C. Control Systems Design

In this example, the stability augmentation system uses standard cascaded SISO gains for the longitudinal and lateral-directional modes as shown in Figure 8.

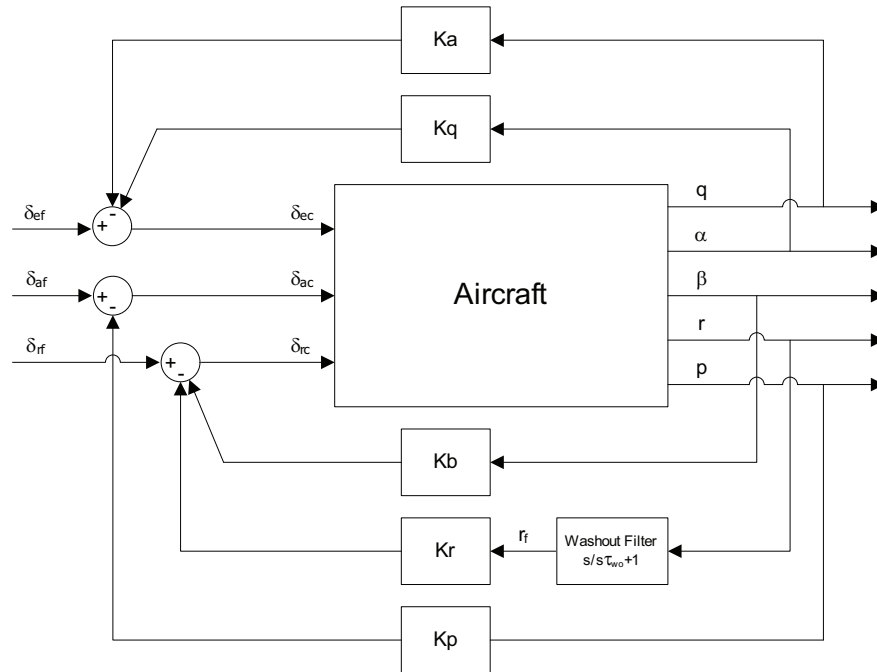


Figure 8. Designed Stability Augmentation System

#### *Longitudinal Stability Augmentation*

Among the longitudinal modes the short period response is of prime concern due to its rapid response and its correlation with handling qualities evaluation. For this reason, efforts

are concentrated in designing the stability augmentation system (SAS) of this mode. The longitudinal short period flight dynamics equations can be formulated as:<sup>29</sup>

$$\begin{bmatrix} \dot{\alpha} \\ \dot{q} \end{bmatrix} = \begin{bmatrix} Z_{\alpha}/V & 1 \\ M_{\alpha} + M_{\dot{\alpha}}Z_{\alpha}/V & M_q + M_{\dot{\alpha}} \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} + \begin{bmatrix} Z_{\alpha}/V \\ M_{\delta} + M_{\dot{\alpha}}Z_{\delta}/V \end{bmatrix} [\delta_e] \quad (6)$$

where  $\alpha$  and  $q$  are the angle of attack and pitch rate respectively,  $\begin{bmatrix} M_{\alpha} & Z_{\alpha} & M_{\dot{\alpha}} & M_q \end{bmatrix}$  and  $\begin{bmatrix} M_{\delta_e} & Z_{\delta_e} \end{bmatrix}$  are the dimensional stability derivatives and control derivatives respectively; their formulation include the inertia terms, i.e.  $M_{\alpha} = \frac{qS_{ref}\bar{c}}{I_{yy}} \frac{\partial C_m}{\partial \alpha}$ .

Every dynamic state is affected by the elevator deflection control input signal. The control system is designed to achieve Level I handling qualities performance while meeting natural damping and frequency limit characteristics. The output feedback gains can be expressed as:

$$\{\bar{u}\} = \delta_e = \delta_{er} - \begin{bmatrix} k_{\alpha} & k_q \end{bmatrix} \begin{bmatrix} \alpha \\ q \end{bmatrix} \quad (7)$$

#### *Lateral-Directional Stability Augmentation*

The lateral flight control system provides lateral/directional stabilization. It consists of a roll feedback and yaw damper implemented to improve the Dutch roll damping. The washout filter time constant in the yaw damper depends on the washout corner frequency  $\omega_{wo}$  as:

$$\frac{1}{\tau_{wo}} = \omega_{wo} = k_{wo}\omega_{ndr} \quad (8)$$

where  $k_{wo}$  is a control design variable representing a percentage of the Dutch roll natural frequency value.

The open-loop lateral dynamics equations are omitted but they follow the standard LTI form state space form given as:  $\{\dot{\bar{x}}\} = [A]\{\bar{x}\} + [B]\{\bar{u}\}$  where  $\{\bar{x}\} = \begin{bmatrix} \beta & p & \phi & r \end{bmatrix}^T$  and  $\{\bar{u}\} = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix}^T$ . The lateral output feedback gains can be expressed as:

$$\{\bar{u}\} = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix}^T = \begin{bmatrix} \delta_a & \delta_r \end{bmatrix}_r^T - \begin{bmatrix} 0 \\ -k_r\omega_{wo} \end{bmatrix} x_5 + \begin{bmatrix} 0 & k_p & 0 & 0 \\ k_{\beta} & 0 & 0 & k_r\omega_{wo} \end{bmatrix} \begin{bmatrix} \beta \\ p \\ \phi \\ r \end{bmatrix} \quad (9)$$

where  $x_5$  is an additional state that arise from the inclusion of the washout filter in the



state space representation. Note that as described in III, the closed loop system stability is guaranteed by selecting adequate control gain direction and values.

#### D. Design Variables and Constraints

Table 2 lists the design variables and their bounds used for the optimization. At the system level, 102 design variables are taken into consideration, from which 18 are global design variables and 84 are coupling design variables. The global design variables specify the general aircraft geometric configuration. Coupling variables include four flight condition independent terms (engine scaling factor, MTOW, fuel and engine weights), while the rest are distributed over the different flight conditions. Local variables are specified only to the flight dynamic and control discipline and correspond to the controller design gains (both longitudinal and lateral). Additional aircraft characteristics are provided as fixed parameters to the optimization problem. The nose gear location is assumed to be at 80% of the nose length:  $xLG_{nose} = 0.8 * L_{nose}$ . The main landing gear location is calculated assuming that 8% of the maximum takeoff weight is applied on the forward wheels to provide sufficient weight on the nose wheel to permit acceptable traction for steering with the CG at its aft limit:  $xLG_{main} = (xCG_{aft} - 0.08 * x_{nLG})/0.92$ . The optimization constraints used at the subsystem level are shown in Table 3. They are split based on the analyzed disciplines and flight phase. The aerodynamic constraints are specified to avoid negative aerodynamic compressibility effects. The flight dynamic and control discipline include control power, and flight condition-dependent open and closed loop dynamic constraints. The control power limits are set below the maximum control deflection, to provide allowance for additional control power requirements, such as active control and turbulence disturbance rejection, and a margin of safety for uncertainties on the stability and control derivative calculations. The normalized extension along the main control span ( $\eta_{ic}$  to  $\eta_{oc}$ ), chord extension  $c_{ce}/c_{cs}$ , and maximum deflections of the control flapped surfaces are shown in Table 4. The deflections limits are specified to avoid non-linear or undesirable aerodynamic behavior of the flapped surface.

#### E. Test Cases, Optimizer and Accuracy

Two illustrative cases are implemented to determine the relative merits of the proposed methodology. The first case optimizes the aircraft with the proposed FD&C integration. The second case makes use of the same MDO architecture as the first one (disciplines are decoupled and decomposed) but it performs a traditional aircraft design sizing process where no considerations of FD&C are made except for the use of tail volume coefficients to constrain the horizontal and vertical tail areas. Both cases are optimized from the same initial design point as shown in Table 2. To maintain uniformity in the calculations, a Sequential

**Table 2. Variables names, units, bound and initial points**

Variable Name	Variable Type	Lower Bound	Upper Bound	Initial Design
Wing reference area ( $S_w$ ), $ft^2$	Global	1000	1400	1200
Wing aspect ratio ( $AR_w$ )	Global	7	11	9
Wing taper ratio ( $\lambda_w$ )	Global	0.1	0.4	0.2
Wing LE sweep angle ( $\Lambda_w$ ), deg	Global	25	35	30
Wing average thickness/chord ratio ( $tc_w$ )	Global	0.08	0.12	0.1
Wing dihedral angle ( $\Gamma_w$ ), deg	Global	-2	8	6
Wing location along fuselage ( $xrLE_w$ )	Global	0.3	0.5	0.4
Horizontal Tail area ( $S_{ht}$ ), $ft^2$	Global	200	350	300
Horizontal Tail aspect ratio ( $AR_{ht}$ )	Global	3	5	4
Horizontal Tail taper ration ( $\lambda_{ht}$ )	Global	0.3	0.6	0.4
Horizontal Tail LE sweep angle ( $\Lambda_{ht}$ ), deg	Global	25	40	35
Horizontal Tail thickness/chord ratio ( $tc_{ht}$ )	Global	0.07	0.11	0.09
Horizontal Tail dihedral angle ( $\Gamma_{ht}$ ), deg	Global	-2	3	0
Vertical Tail area ( $S_{vt}$ ), $ft^2$	Global	200	400	350
Vertical Tail aspect ratio ( $AR_{vt}$ )	Global	1.4	1.8	1.6
Vertical Tail taper ratio ( $\lambda_{vt}$ )	Global	0.3	0.6	0.4
Vertical Tail LE sweep angle ( $\Lambda_{vt}$ ), deg	Global	25	40	40
Vertical Tail thickness/chord ratio ( $tc_{vt}$ )	Global	0.09	0.12	0.11
Engine Scaling Factor ( $ESF$ )	Global	0.8	1.2	1
Maximum takeoff weight ( $MTOW$ ), lb	Coupling	100000	155000	123200
Engine weight ( $W_{eng}$ ), lb	Coupling	5664	8670	7160
Specific fuel consumption ( $TSFC$ ), lb/hr/lb	Coupling	0.20	0.80	0.50
Engine Thrust ( $T$ ), lb	Coupling	20000	35000	31000
Maximum Clean Lift Coefficient ( $CL_{max}$ )	Coupling	1.30	1.50	1.47
Lift to Drag Ratio ( $LD$ )	Coupling	6.00	15.00	9.00
Drag Coefficient ( $CD$ )	Coupling	0.05	0.50	0.20
Stability Derivative ( $Cz_\alpha$ )	Coupling	4.00	6.50	5.50
Stability Derivative ( $Cm_\alpha$ )	Coupling	-2.00	2.00	-1.20
Stability Derivative ( $CL_q$ )	Coupling	2.00	11.00	7.00
Stability Derivative ( $Cm_q$ )	Coupling	-40.00	-10.00	-20.00
Stability Derivative ( $Cm_{\dot{\alpha}}$ )	Coupling	-8.00	-0.10	-5.70
Stability Derivative ( $Cz_{\delta_e}$ )	Coupling	0.05	0.50	0.33
Stability Derivative ( $Cm_{\delta_e}$ )	Coupling	-2.00	-0.10	-1.00
Stability Derivative ( $Cy_\beta$ )	Coupling	-1.50	-0.50	-1.17
Stability Derivative ( $Cl_\beta$ )	Coupling	-0.30	-0.10	-0.26
Stability Derivative ( $Cn_\beta$ )	Coupling	0.05	0.25	0.19
Stability Derivative ( $Cl_p$ )	Coupling	-0.60	-0.30	-0.47
Stability Derivative ( $Cn_p$ )	Coupling	-0.30	-0.10	-0.25
Stability Derivative ( $Cl_r$ )	Coupling	0.25	0.85	0.57
Stability Derivative ( $Cn_r$ )	Coupling	-0.40	-0.05	-0.19
Stability Derivative ( $Cl_{\delta_a}$ )	Coupling	0.04	0.08	0.06
Stability Derivative ( $Cn_{\delta_a}$ )	Coupling	-0.04	-0.01	-0.03
Stability Derivative ( $Cy_{\delta_r}$ )	Coupling	0.10	0.30	0.26
Stability Derivative ( $Cl_{\delta_r}$ )	Coupling	0.00	0.02	0.01
Stability Derivative ( $Cn_{\delta_r}$ )	Coupling	-0.10	-0.01	-0.08
Control gain ( $k_\alpha$ )	Local	-0.01	-50	0
Control gain ( $k_q$ )	Local	-0.01	-50	0
Control gain ( $k_p$ )	Local	0.01	0	50
Control gain ( $k_\beta$ )	Local	0.01	0	50
Control gain ( $k_r$ )	Local	-0.01	-50	0
Control variable ( $k_{wo}$ )	Local	0.3	0.2	0.4

**Table 3. Constraints for the Optimization Problem**

Discipline	Flight Phase	Constraint Name	Value
Geometry	-	Wing span, ft	$\leq 260$
Geometry	-	Wing LE sweep, deg	$\leq$ H.T. LE sweep
Geometry	-	Wing LE edge sweep, deg	$\leq$ V.T. LE edge sweep
Weights	-	Avail. wing fuel volume, $ft^3$	$\leq$ Req. block fuel volume
Weights	-	CG fwd position % MAC	$\geq 0.05$
Weights	-	CG aft position % MAC	$\leq 0.55$
Aerodynamics	Climb, Cruise, Approach, Go-Around	Wing Mach divergent drag number	$\geq$ Mach number
Aerodynamics	Climb, Cruise, Approach, Go-Around	H.T. Mach divergent drag number	$\geq$ Mach number
Aerodynamics	Climb, Cruise, Approach, Go-Around	V.T. Mach divergent drag number	$\geq$ Mach number
Performance	Takeoff	Takeoff field Length, ft	$\leq 5500$ . ft
Performance	Climb	Engine-out climb gradient	$\geq 0.024$
Performance	Go-Around	Missed approach climb gradient	$\geq 0.024$
Performance	Landing	Landing field Length, ft	$\leq 5000$ . ft
Propulsion	All Flight phases	Drag to Thrust Ratio	$\leq 0.88$
FD&C	Climb, Cruise, Approach, Go-Around	Static Margin	$\geq 0.05$
FD&C	Takeoff	Rotation elevator power, deg	$\leq 15$
FD&C	Landing	Rotation elevator power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	1-g Trim elevator power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Maneuver elevator power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Pitch - Vel. Axis Roll elevator power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Steady Sideslip aileron power, deg	$\leq 20$
FD&C	Climb, Cruise, Approach, Go-Around	Steady Sideslip rudder power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Steady Sideslip roll angle, deg	$\leq 5$
FD&C	Climb, Cruise, Approach, Go-Around	Engine-out Trim aileron power, deg	$\leq 20$
FD&C	Climb, Cruise, Approach, Go-Around	Engine-out Trim rudder power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Yaw - Loaded Roll Pullout, rudder power, deg	$\leq 15$
FD&C	Climb, Cruise, Approach, Go-Around	Coord. Vel. Axis Roll, aileron power, deg	$\leq 20$
FD&C	Climb, Cruise, Approach, Go-Around	Coord. Vel. Axis Roll, rudder power, deg	$\leq 15$
FD&C	Climb, Cruise	Open-Loop short period damping ratio	$\geq 0.2, \leq 2.0$
FD&C	Approach	Open-Loop short period damping ratio	$\geq 0.35, \leq 2.0$
FD&C	Climb, Cruise, Approach	Open-Loop short period natural frequency	$\geq 1$
FD&C	Climb, Cruise	Open-Loop short period GCAP for HQL I	$\geq 0.038, \leq 10$
FD&C	Approach, Go-Around	Open-Loop short period GCAP for HQL I	$\geq 0.096, \leq 10$
FD&C	Climb, Cruise, Approach, Go-Around	Open-Loop dutch roll damping	$\geq 0.02$
FD&C	Climb, Cruise, Approach, Go-Around	Open-Loop dutch roll natural frequency	$\geq 0.5$
FD&C	Climb, Cruise, Approach, Go-Around	Open-Loop time to roll, sec	$\leq 3$
FD&C	Climb, Cruise, Approach, Go-Around	Open-Loop time to double spiral, sec	$\geq 8$
FD&C	Climb, Cruise	Closed-Loop short period damping ratio	$\geq 0.3, \leq 2.0$
FD&C	Approach, Go-Around	Closed-Loop short period damping ratio	$\geq 0.5, \leq 1.3$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop short period natural frequency	$\geq 1$
FD&C	Climb, Cruise	Closed-Loop GCAP for HQL I	$\geq 0.3, \leq 3.3$
FD&C	Approach, Go-Around	Closed-Loop GCAP for HQL I	$\geq 0.16, \leq 3.6$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop dutch roll damping	$\geq 0.08$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop dutch roll natural frequency	$\geq 0.5$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop time to roll, sec	$\leq 1.4$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop time to double spiral, sec	$\geq 12$
FD&C	Climb, Cruise, Approach, Go-Around	Closed-Loop System Eigenvalues	$\leq 0$

**Table 4. Control Effector Flapped Surface Characteristics**

<b>Control Effector/Parameters</b>	$\eta_{ic}$	$\eta_{oc}$	$c_{ce}/c_{cs}$	max. Deflection, deg
Elevator	0.25	0.95	30%	$\pm 25$
Ailerons	0.72	0.90	20%	$\pm 25$
Rudder	0.10	1.00	26%	$\pm 15$

Quadratic Programming (SQP) optimization algorithm<sup>30</sup> is used at both the system and the disciplinary levels. Proper scaling of the design variables, objectives and constraints is enforced for the gradient-based optimizer to handle discrepancies along the feasible/near-feasible descent direction when disciplinary constraints force incompatibilities among the different subsystems. Objective function gradients are evaluated using finite differences. Tolerances for the optimization procedure are defined on the order of  $10^{-6}$  based on initial studies to have a good compromise between the number of analysis calls at system and subsystem levels and the optimal objective function. Convergence of the optimization procedure is reached when the search direction, maximum constraint violation and first-order optimality measure are less than the specified tolerances.

## V. Results

### A. Optimized Designs and Comparisons

Table 5 shows selected variables and performance values for the multidisciplinary feasible solution obtained from both the integrated and traditional design test cases. The geometric configuration for both test cases is shown in Figure 9. While similar wing characteristics are obtained for both designs, the horizontal and vertical tail geometry is significantly different as seen in Figure 10. The concurrent consideration of flight dynamics and simultaneous design of stability and control augmentation systems, leads to significant geometric changes over the traditional design approach. The horizontal tail area is reduced to promote lower static margins and improved aerodynamic efficiency. Similarly, the horizontal tail sweep increases to avoid flow separation at high Mach numbers, hence it aggravates changes in wing pitching moment. In addition, the increase in horizontal tail sweep delays the stall angle and produces a more benign non-linear lift/stall behaviour. Furthermore, the wing apex location is slightly moved forward along with a horizontal tail area reduction. This affects the center of gravity of the aircraft and reduces its static margin. At the same time, the designed control system assures the required level of stability is achieved. The wing dihedral is increased significantly to improve roll stability characteristics. In terms of performance, both test cases meet the specified performance requirements. The reduction in exposed surface area for the integrated aircraft design causes higher lift to drag values at all flight conditions, as shown

in Table 5. An air-range improvement of 510 nm is reached as compared to the traditional design approach.

**Table 5. Traditional and Integrated FD&C Optimization Results**

Variable Name	Traditional	Integrated FD&C
Wing reference area ( $S_w$ ), $ft^2$	1400	1400
Wing aspect ratio ( $AR_w$ )	11.00	11.00
Wing taper ratio ( $\lambda_w$ )	0.382	0.187
Wing LE sweep angle ( $\Lambda_w$ ), deg	25.00	25.00
Wing average thickness/chord ratio ( $tc_w$ )	0.117	0.105
Wing dihedral angle ( $\Gamma_w$ ), deg	2.000	4.839
Wing location along fuselage ( $xrLE_w$ )	0.39	0.35
Horizontal Tail area ( $S_{ht}$ ), $ft^2$	328.43	250.35
Horizontal Tail aspect ratio ( $AR_{ht}$ )	4.88	3.07
Horizontal Tail taper ratio ( $\lambda_{ht}$ )	0.561	0.525
Horizontal Tail LE sweep angle ( $\Lambda_{ht}$ ), deg	28.10	40.00
Horizontal Tail thickness/chord ratio ( $tc_{ht}$ )	0.088	0.073
Horizontal Tail dihedral angle ( $\Gamma_{ht}$ ), deg	0.00	-1.97
Vertical Tail area ( $S_{vt}$ ), $ft^2$	250.04	250.01
Vertical Tail aspect ratio ( $AR_{vt}$ )	1.8	1.4
Vertical Tail taper ration ( $\lambda_{vt}$ )	0.40	0.60
Vertical Tail LE sweep angle ( $\Lambda_{vt}$ ), deg	31.17	40.00
Vertical Tail thickness/chord ratio ( $tc_{vt}$ )	0.090	0.090
Engine Scaling Factor ( $ESF$ )	0.8	0.8
Maximum takeoff weight ( $MTOW$ ), lb	120186	120413
Engine weight ( $W_{eng}$ ), lb	5664	5664
Specific fuel consumption ( $TSFC$ ) @ Cruise, lb/hr/lb	0.5034	0.5034
Engine Thrust ( $T$ ) @ Takeoff, lb	25056	25056
Maximum Clean Lift Coefficient ( $CL_{max}$ ) @ Cruise	1.483	1.501
Lift to Drag Ratio ( $LD$ ) @ Cruise	17.050	17.653
Drag Coefficient ( $CD$ ) @ Cruise	0.020	0.019
Lift to Drag Ratio ( $LD$ ) @ Approach	9.681	10.311
Drag Coefficient ( $CD$ ) @ Approach	0.183	0.143
Range, nm	5278.3	5788.7
Takeoff Field Length, ft	4284.1	4261.9
Landing Field Length, ft	3953.5	3945.2
Engine-out climb gradient	0.0681	0.0673
Missed approach climb gradient	0.0846	0.0906
Static Margin @ Cruise	0.3679	0.2424
Static Margin @ Approach	0.2528	0.1992

Table 6 shows a control power requirement comparison between the two design cases, where bold values designate parameters which did not meet the required specifications (Table 3). The integrated design shows reduced static margins due to the horizontal area reduction. The design requires larger elevator deflection for takeoff rotation as compared to the traditional aircraft, but it still within limits of the specified deflection constraint. Trim requirements are similar for both designs. However, the integrated design requires less control power for trim at the approach condition, where the CG is critical at its maximum fwd

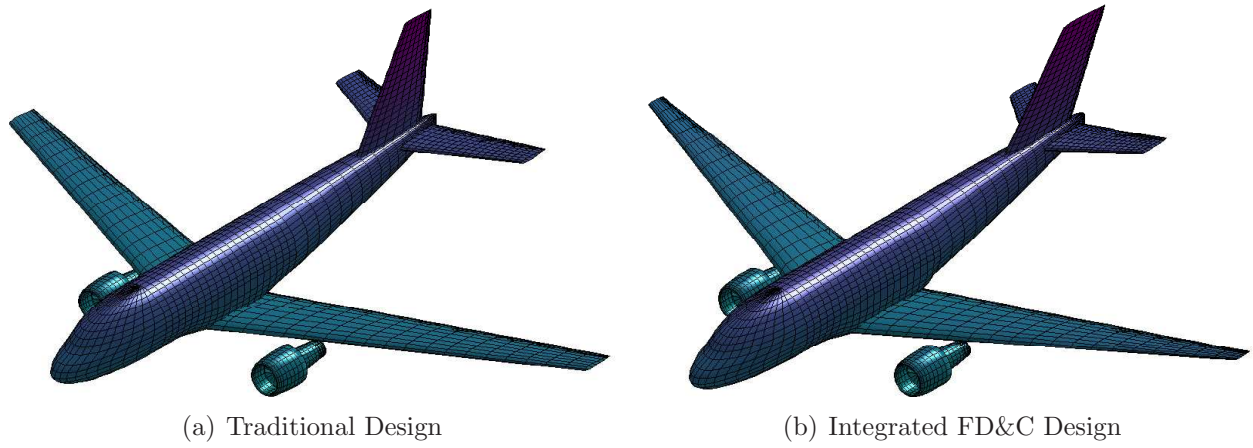


Figure 9. Test Cases Optimal Configurations

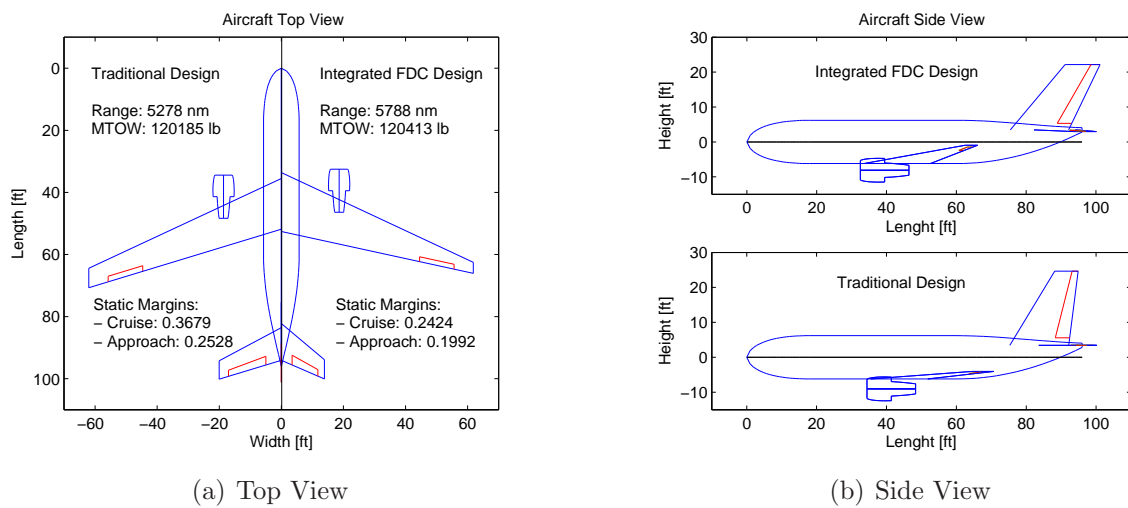


Figure 10. Aircraft Configuration Comparison

position. Therefore, it provides a larger control power margin for other tasks such as gust disturbance rejection. For the lateral control power requirements, a significant difference can be seen between the two test cases. The traditional aircraft design approach cannot capture the flight dynamics coupling effects with the general airframe geometric characteristics or take advantage of control-augmentation, leading to poor control power performance. For example, the aileron control power required for sideslip and the rudder control power required for engine-out trim exceeds the maximum allowable deflections at the approach condition. In this case, the aircraft is not able to maintain proper heading tracking when it lands with crosswinds or cope with an asymmetric propulsion failure. These characteristics are not considered directly in the traditional design process. The benefits of the integrated approach become evident since all control power requirements are met from the initial design phase. Furthermore, the required control deflections are lower than the allowable limits providing ample margin of safety to deal with external disturbance rejection or to cope with an increased control effort due to failures. Additional open-loop dynamic results for both aircraft cases are shown in Table 7.

**Table 6. Control Power Requirements Comparison**

Parameter	Traditional	Integrated FD&C
Static Margin @ Cruise	0.3679	0.2424
Static Margin @ Approach	0.2528	0.1992
Takeoff Rotation elevator power, deg	-6.2738	-14.0386
1-g Trim elevator power, deg @ Cruise	4.3247	4.3042
1-g Trim elevator power, deg @ Approach	19.6754	15.0588
Maneuver elevator power, deg @ Cruise	-12.7531	-12.6707
Pitch - Vel. Axis Roll elevator power, deg @ Cruise	1.5796	2.7342
Pitch - Vel. Axis Roll elevator power, deg @ Approach	4.0268	6.4436
Steady Sideslip aileron power, deg @ Approach	<b>26.7672</b>	20.0638
Steady Sideslip rudder power, deg @ Approach	2.1798	6.5533
Steady Sideslip roll angle, deg @ Approach	4.1680	4.2251
Engine-out Trim aileron power, deg @ Approach	15.6064	18.5121
Engine-out Trim rudder power, deg @ Approach	<b>-28.1814</b>	-15.0702
Yaw - Loaded Roll Pullout, rudder power, deg @ Approach	-3.5798	-2.6306
Coordinated Velocity Axis Roll, aileron power, deg @ Approach	<b>23.3895</b>	16.5668
Coordinated Velocity Axis Roll rudder power, deg @ Approach	<b>-47.8037</b>	-13.0146

## B. Integrated FD&C Design Dynamic Behaviour

Table 8 shows the optimal control gains and closed-loop characteristics of the integrated design. Aircraft flight dynamic characteristics are demonstrated using a simulation of the aircraft dynamics for cruise and landing approach representative conditions with and without the augmentation system. Longitudinal dynamic characteristics are shown in Figure 11



**Table 7. Open-Loop Dynamic Properties Comparison**

Parameter	Traditional	Integrated FD&C
Open-Loop short period damping ratio @ Cruise	0.3000	0.2874
Open-Loop short period damping ratio @ Approach	0.5272	0.4740
Open-Loop short period natural frequency @ Cruise	2.6409	2.1990
Open-Loop short period natural frequency @ Approach	1.5546	1.3677
Open-Loop short period GCAP @ Cruise	0.5152	0.3540
Open-Loop short period GCAP @ Approach	0.4042	0.3294
Open-Loop dutch roll damping @ Cruise	0.1227	0.1247
Open-Loop dutch roll damping @ Approach	0.1098	0.0777
Open-Loop dutch roll natural frequency @ Cruise	0.8072	0.5024
Open-Loop dutch roll natural frequency @ Approach	1.2906	1.2164
Open-Loop time to roll, sec @ Cruise	0.2725	0.2878
Open-Loop time to roll, sec @ Approach	0.4659	0.5842
Open-Loop spiral time to double, sec @ Cruise	1030.9	32.239
Open-Loop spiral time to double, sec @ Approach	19.5277	11.2838

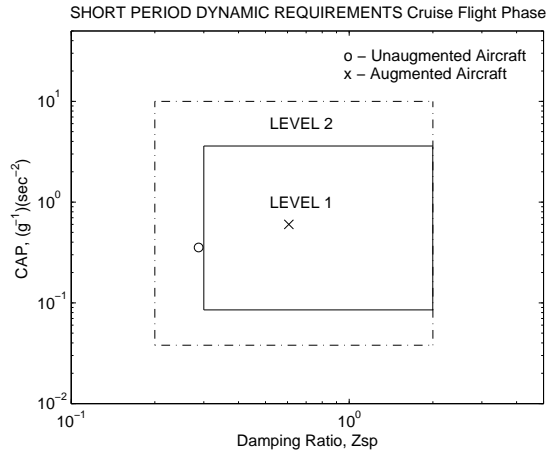
and Figure 12 for the cruise and approach flight phases respectively. On both flight phases, the aircraft shows Level I handling quality for both the bare-airframe and stability augmented system (Figure 11(a), and Figure 12(a)). Other flight conditions present a similar behaviour. The response to an elevator step input by the augmented system is adequate, with fast damping of the disturbance as shown in Figure 11(b) and Figure 12(b).

**Table 8. Integrated FD&C Closed-Loop Characteristics**

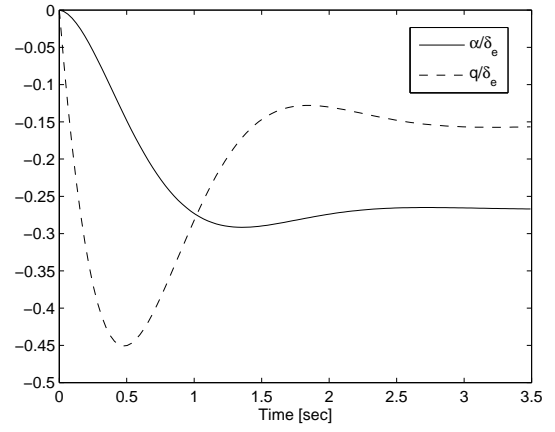
Parameter	Cruise	Approach
$k_\alpha$	-0.510	-1.000
$k_q$	-0.610	-1.000
$k_p$	1.201	1.301
$k_\beta$	1.021	0.001
$k_r$	-0.891	-0.591
$k_{wo}$	0.300	0.300
Closed-Loop short period damping ratio	0.6066	0.5755
Closed-Loop short period natural frequency	2.8929	1.8735
Closed-Loop short period GCAP	0.6004	0.5926
Closed-Loop dutch roll damping	0.1604	0.1726
Closed-Loop dutch roll natural frequency	0.9438	0.9591
Closed-Loop time to roll, sec	0.1164	0.3256

In a similar way, the response of the augmented aircraft to an aileron and rudder doublet control inputs are shown in Figure 13 and Figure 14 for the cruise and approach flight phases, respectively. It can be seen that the found lateral control augmentation system provide adequate control in both the roll rate and yaw rates, where the augmented system quickly damps out the commanded oscillations without significant overshoot.



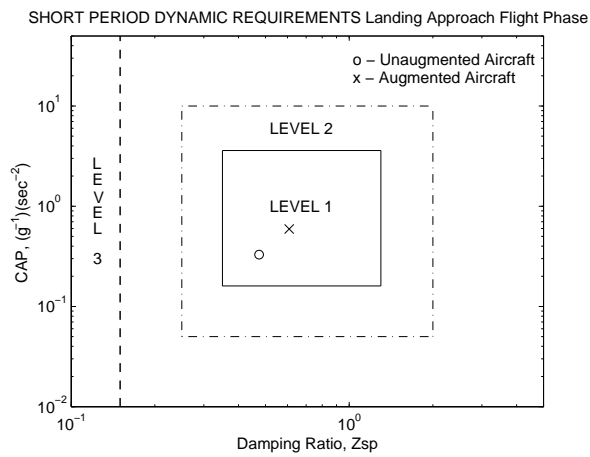


(a) Short-Period Handling Qualities

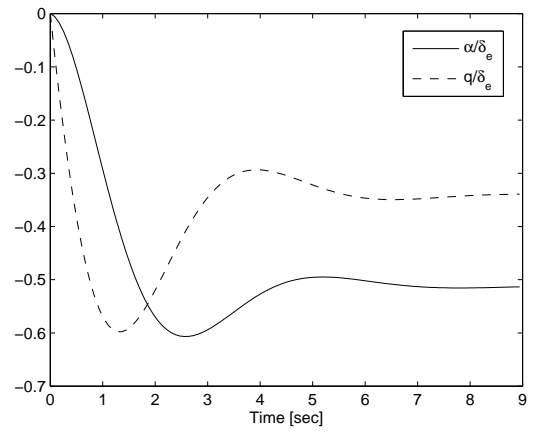


(b) Closed-Loop Response to Control Step

**Figure 11. Cruise Longitudinal Dynamics Characteristics**



(a) Short-Period Handling Qualities



(b) Closed-Loop Response to Control Step

**Figure 12. Landing Approach Longitudinal Dynamics Characteristics**

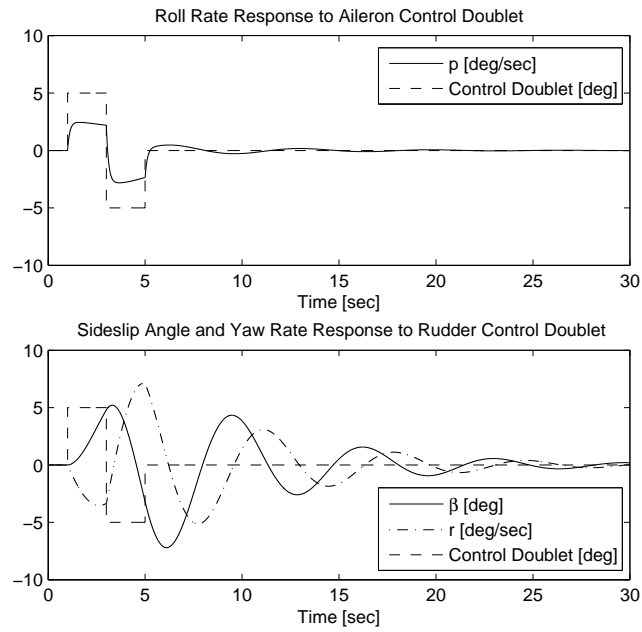


Figure 13. Cruise Closed-Loop Lateral Dynamics Response to Controls Doublet

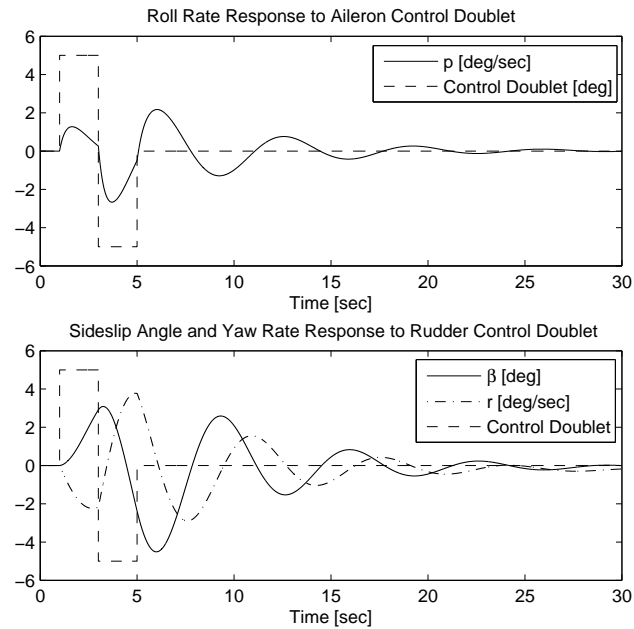


Figure 14. Landing Approach Closed-Loop Lateral Dynamics Response to Controls Doublet

### C. Size Variation Effect on Integrated Methodology

The proposed integrated methodology was further applied over a broader set of aircraft sizes for the given configuration example. The aircraft size was varied to accommodate from 70 to 200 passengers. Variables and parameters such as payload and fuel weight were scaled in accordance with the variation of passengers. The effect of the methodology as compared to the traditional sizing process is shown on Figure 15. The integrated approach leads to increase range as compared to the traditional process for all the aircraft size variations analyzed. As before, the integrated designs have reduced total control surface areas while the wing is shifted forward to take advantage of reduced static stability. By taking advantage of control-configuration interactions the design layout is altered to improve performance while meeting the specified disciplinary requirements.

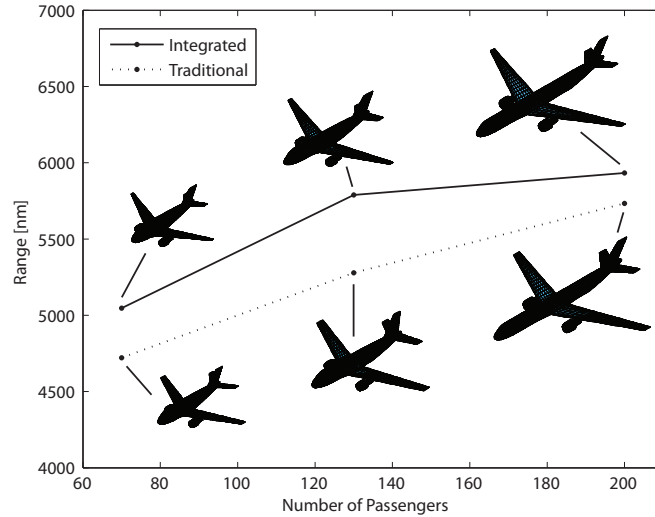


Figure 15. Methodology Effect on Aircraft Size Variation

## VI. Conclusions

A methodology to address the challenges of integrating flight dynamics and control in the aircraft design sizing process has been presented. It enabled control-configuration considerations in the conceptual sizing process, while simultaneously designing proper control augmentation systems. The application of this approach to the design of a commercial aircraft was successful in producing solutions with better performance and flying characteristics than the traditional sizing process over a broad range of aircraft sizes. Furthermore, the methodology could potentially mitigate some of the problems that arise at the later

stages of the design process as compliance with the most general flight dynamic certification requirements is assured from the conceptual stage, reducing time and cost in the engineering development cycle.

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