AIAA 96-4058

An MDO Approach to Control-Configured-Vehicle Design

M.R. Anderson and W.H. Mason
Virginia Polytechnic Institute and
State University, Blacksburg, VA

**6th AIAA/NASA/ISSMO
Symposium on Multidisciplinary
Analysis and Optimization**
September 4-6, 1996 / Bellevue, WA

AN MDO APPROACH TO CONTROL-CONFIGURED-VEHICLE DESIGN

M. R. Anderson* and W.H. Mason†
Department of Aerospace and Ocean Engineering
Virginia Polytechnic Institute and State University, Blacksburg, VA

Abstract

A new MDO method for Control-Configured-Vehicle (CCV) aircraft design is presented in this paper. The method allows CCV to be incorporated directly into a conceptual and preliminary configuration concept design Multidisciplinary Design Optimization (MDO) methodology, where freedom to change the configuration to exploit CCV is most readily available. To handle the CCV design objectives, the approach uses a fuzzy-logic algorithm to assign a risk metric based on the required flight control system complexity. This metric is then combined with traditional configuration metrics, such as weight and performance, to yield optimized aircraft configurations that directly include the effect of an active flight control system. Numerical results from a high-speed, civil transport aircraft design study are presented and clearly demonstrate how horizontal tail area and center-of-gravity location can be optimized with respect to flight control system complexity.

Introduction

In the mid 1970s, flight control research was focused on the concept of a Control Configured Vehicle (CCV).[1] The goal of CCV design was to improve aircraft performance through the use of active control. CCV concepts under study at the time included: improved handling qualities, flight envelope limiting, relaxed static stability, gust alleviation, maneuver load control, and active structural mode control.[1,2] Many of the concepts were flight tested and, in some cases, the CCV design concept allowed for modifications of existing aircraft. For example, CCV concepts were used on the L-1011 aircraft to increase the gross take-off weight while minimizing wing structural changes.[3]

A design methodology is needed to find the optimum combination of control system development cost and total aircraft system performance and cost. Kehrer, for example, describes how use of stability augmentation methods during preliminary design led to a 150 inch reduction in fuselage length for the Boeing 2707-300 Supersonic Transport (SST).[4] The shortened fuselage also led to reduced vertical tail size and gear length, with a weight savings of 6,000 lbs and a range increase of 225 nautical miles. The weight savings reported by the Boeing study came at the expense of an increase in control system development cost, however. The total cost of the Boeing SST flight and avionics systems were estimated to be double that of the Boeing 747. As a result, there was an assumption that the increased flight control system design complexity and cost (risk) was balanced by the performance improvements in the new design.

McRuer argues that the first CCV aircraft was the YB-49 flying wing.[5] The YB-49 was actually flight demonstrated at a 10% unstable static margin, using an automatic control system. The X-29 forward-swept-wing aircraft represents one of the more recent aircraft wherein the ability to use active control had a significant impact on the airframe configuration.[6] To achieve the performance benefits of the forward swept wing-canard configuration, the X-29 airplane was required to have a 35% unstable static margin. Even more recently, the F-117 and B-2 aircraft undoubtedly have poor bare-airframe stability characteristics but have reached production status because of active control. Each of these aircraft configurations would not be feasible had the impact of active control not been considered at the conceptual design stage.

The CCV concept fostered research on the impact of active control on aircraft configurations. During this early development period, the realization that aircraft performance gains were achievable using active control was an important motivation for multivariable control research.[7] Today, the use of a multivariable flight control system is accepted and even expected. However, to a large extent, a quantifiable impact of active control on the aircraft configuration design and layout has not been exploited. Design rules are certainly being used within airframe companies to include the benefit of active control on the configuration design. However, there appears to be no current systematic method through which the configuration can be optimized within the constraints of control system structure and control power.

Figure 1 illustrates the traditional and CCV design processes as described in Ref. [1]. The “traditional” design process includes flight control design on the outside of the primary configuration selection and optimization loop. This process is represented by Fig. 1(a). Basically, the airplane configuration is established through optimization amongst the aerodynamic, propulsion, and structures disciplines. The flight control design is not conducted until after the final aircraft configuration has been selected. Therefore, the

---

*Associate Professor, Senior Member AIAA.

†Professor, Associate Fellow AIAA.

design of the flight control system has no impact on the airplane configuration.

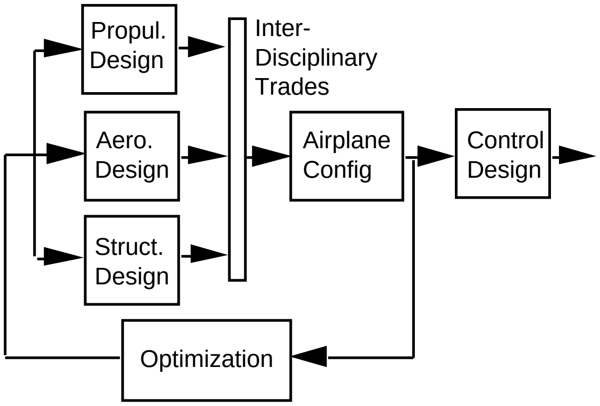

Figure 1(a) Traditional Aircraft Design Process

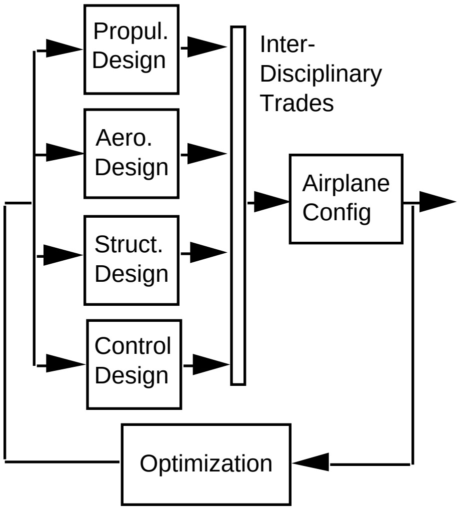

Figure 1(b) Control-Configured-Vehicle Design Process

The CCV design process is illustrated by Fig. 1(b). The CCV design concept includes active control system design in parallel with the other disciplines for configuration selection and optimization. Thus, flight control design directly affects configuration selection. However, the implication is that a complete control system design is carried out for each configuration iteration. Morris and Kroo, for example, include a “dynamic” quadratic model-following control cost function term along with several “non-dynamic” terms related to the configuration in their optimization strategy.[8] One of the primary drawbacks of this approach, and others like it, is that a complete control system is designed at each iteration step.[9,10] It is the authors' view that very few, if any, flight control design techniques are automated to the point that they can be embedded in an automated design procedure that does not allow human intervention.

Other researchers have attempted to optimize the flying qualities of the aircraft directly.[11] If the flying qualities of the bare airframe are optimized, then it is reasoned that the control system of the aircraft will be inexpensive to develop and build. However, this approach ignores the benefits of active control completely and is contrary to the objectives of CCV design. This approach attempts to eliminate the control system rather than benefit from it. As a result, statically unstable aircraft such as the F-16 and X-29 would not emerge from this approach.

The natural extension of CCV design is to link flight control considerations and configuration design such that the best configuration can be obtained through numerical optimization. This type of cross-disciplinary optimization is the basis for Multidisciplinary Design Optimization (MDO). An aircraft configuration MDO problem generally consists of separate modules which come from different traditional aeronautical disciplines such as structures, aerodynamics, and controls. The interaction between the structures and aerodynamics disciplines are at least clear conceptually - changes in geometric contours lead to lead changes in both fuel (drag) and structural weights.

Considerable work has been carried out at Virginia Tech developing MDO methods for use in the early phases of configuration design.[12] This research has led to improved understanding of both the MDO process and optimized vehicle design features. These efforts focus on variable complexity modeling, wherein the process uses several levels of fidelity of the different disciplines in the MDO process. Flight control system dynamics have not yet been included, but static control requirements such as engine-out, cross-wind landing, and the ability to rotate at takeoff and trim under approach conditions have been included.[13]

The controls component of an aircraft configuration MDO problem would most logically be a method that, given aerodynamic and structural properties of a candidate configuration, would result in some type of control system risk assessment. The control system risk might include such issues as development cost, complexity, reliability, and maintainability. A practical MDO method requires that the control system risk be assigned without actually designing the control system. An early example of this approach is given by Sliwa, who used parameters such as static margin to determine if a flight control system was needed for a particular configuration.[14]

One of the authors has recently proposed a method in which control system design risk is assessed using a set of rules driven by a fuzzy logic inference engine.[15] The rules are based on the experience of the control system designer and the result is a single, deterministic measure of design risk. This approach offers a significant benefit because the control system is not actually designed. Another benefit is that any previous experience regarding the control system implementation or operation can be included in the fuzzy logic rules.

This paper presents the formulation of an MDO problem which includes control system design. We provide the link between the benefits of relaxed static stability and critical handling qualities requirements. The method is demonstrated by applying the MDO aircraft configuration design approach to a high speed civil transport.

MDO Including CCV

The MDO procedure for conceptual design of an aircraft seeks to define the configuration that minimizes some representation of overall cost subject to consideration from numerous disciplines. Many variations have been used in detailed implementations. Often the overall metric is take-off gross weight, although the true objective is actual cost; typically, direct operating cost or life cycle cost.

In this work, we introduce the concept of control system design risk as a means of incorporating the effect of an active control system. In general, the objective function should be a measure of the weight and complexity of the complete configuration. In the overall design, the primary contributor to vehicle performance from CCV is the ability to control an airplane when the bare airframe characteristics would otherwise require larger control surfaces or balancing for stability. This idea is closely related to the concept of relaxed static stability.[2] With most stability limits removed, the control power needed becomes the primary consideration in sizing the surfaces. Typical control power requirements include nose wheel liftoff and nose down control authority at high angle of attack. References [16] and [17] provide good discussions of the static and dynamic requirements for consideration in design for active control of subsonic and supersonic transports, respectively.

The impact of CCV can be treated through the use of weighting functions applied to the components of an objective function that is made up of several pieces. This approach has been used previously, and good insight into the relative importance of different considerations has been obtained.[18] Alternately, one could apply CCV requirements as constraints in the design problem.

Including CCV in the MDO process requires evaluation of the design at the critical stability and control conditions, which may not occur at the design point. Thus, while the aerodynamic performance of an HSCT is heavily dependent on the cruise drag, including trim, the control power is likely to be critical at takeoff and landing. Therefore, the MDO problem formulation must account for design evaluation at multiple flight conditions. This is similar to the structural design problem, where the critical load conditions can occur well away from the design point.

Aerodynamic Modeling for MDO With CCV

The number of configurations and flight conditions requiring aerodynamic analysis during optimization studies is very large, and the computational cost and time required to make the analyses is an important consideration in developing an MDO methodology. In our work establishing this new MDO CCV method, the APAS program[19-20] has been chosen to obtain aerodynamic modeling information about the baseline configuration. However, our approach allows the user to replace APAS results with other aerodynamic results, new analytical and empirical estimation methods, and/or wind tunnel and flight test data to improve accuracy and efficiency.

APAS is a collection of linear theory, panel-type methods that is widely used to estimate stability and control characteristics. In earlier work, we investigated its accuracy by making comparisons to data for supersonic transports and found it to be generally accurate.[21] However, using a panel-type method such as APAS directly during an MDO study would require too much computing time, as well as an automated and robust geometric paneling method.

To reduce computation time, the variable complexity modeling approach is used in our aerodynamic estimation method.[12] This approach uses very fast aerodynamic models based on refined DATCOM-type methods, adjusted to agree with more accurate results at key design points during the optimization cycle. If the configuration geometry departs significantly from the baseline geometry, the model has to be readjusted.

Some of the DATCOM-type methods have been extended using analytic approximations beyond those previously available.[22] Thus, APAS is typically only used to estimate aerodynamics of the baseline and final configurations. Using analytic approximations also allows sensitivities to be computed analytically rather than numerically.

Flight Control System Risk Assessment

A fuzzy logic approach similar to Ref. [15] is used to assign a numerical risk value from the aerodynamic parameters determined for the configuration. At this point, the risk value is based upon the required control system structure or complexity. Other considerations such as reliability and hardware cost will not be addressed in this paper but they can also influence and be influenced by the control system complexity.

To obtain a measure of relative control system complexity, four separate control system configurations were studied for the longitudinal axis. These control system architectures are listed in Table 1, along with a linguistic representation of their relative complexity. For example, a single-loop stability augmentation system (SAS) is consider a "medium" complexity design because this configuration is well-known and relatively easy to design. The most advanced configuration under consideration includes a proportional+integral control structure and an angle-of-attack feedback to the aircraft flaps. This multi-loop configuration is considered a "very high" complexity flight control system.

Table 1 Control System Relative Complexity

Complexity Level	Control System Description
Low	Bare airframe with static prefilter for pilot command shaping.
Medium	Single-loop SAS including pitch rate, angle-of-attack, or accelerometer feedback.
High	Proportional+Integral controller.
Very High	Proportional+Integral controller with augmented flap schedule.

Since a numerical risk value is required for optimization, each level of complexity is assigned a range of possible values. Using an artificial scale ranging from 0 to 100, each level of complexity is given a range of 25. For example, a "low" complexity control system configuration is assigned the range from 0 to 25, a "medium" complexity control system is given the range of 25 to 50 and so on. These numerical ranges can be represented using fuzzy logic membership functions as shown in Fig. 2. For reference, the "medium" complexity membership function is shaded in Fig. 2.

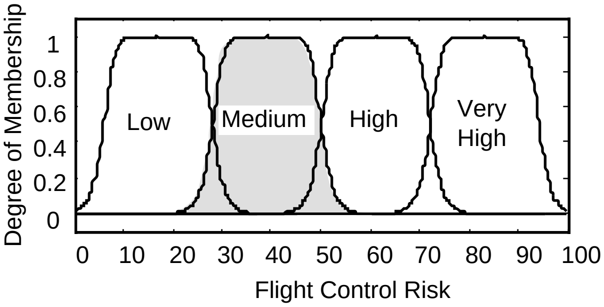

Figure 2 Control System Risk Membership Functions

To illustrate the idea using our current longitudinal-axis rulebase, the XB-70 in a cruising flight condition yields a control system design risk value of about 40. This risk value clearly falls in the "medium" category according to the membership functions shown in Fig. 2. Reference [23] describes the XB-70 longitudinal control system. The control system senses pitch rate, normal acceleration, and Mach number and controls the elevons and canard. It includes a second-order stick shaping filter and a first-order lead network for Mach stabilization. All of the feedback gains are static with the exception of one gain scheduled with altitude and one scheduled with Mach number.

In contrast, Ref. [6] gives a description of the X-29 flight control system. The longitudinal control system of the X-29 controls three surfaces: canard, strake, and symmetric flap. It includes four feedback variables in the longitudinal axis. During cruise, nearly all of the feedback gains are scheduled with Mach number and altitude. The control system structure consists of a proportional+integral feedback element with several complimentary filters adding up to about an eighth order control system. Using our current longitudinal-axis rulebase, this aircraft receives a risk value of 78 in cruise. A risk value of 78 is clearly in the "very high" risk category in Fig. 2.

It should be clear that the risk values assigned for the XB-70 and X-29 are at least representative of the flight control system complexity for each aircraft. Therefore, while we do not have a direct measure of the actual cost to develop these systems, it would be reasonable to assume that the actual costs are closely tied to the complexity of the control system architecture.

As an example of rule base development using root locus analysis, consider the MIL-STD-1797 Short Term Pitch Response requirement for the cruise flight configuration (Category B).[24] This specification can be checked using a short-period mode approximation. The short-period mode transfer function from elevator deflection (δ_e) input to pitch rate (q) output is typically given by the equation,

$$\frac{q(s)}{\delta_e(s)} = \frac{K_\theta(\tau_{\theta 2}s + 1)}{s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2}$$

where ω_{sp} is the short-period natural frequency, ζ_{sp} is the short-period damping ratio, and $\tau_{\theta 2}$ is the pitch numerator time constant. The Level 1 part of this specification states that the short-period damping ratio must lie in the range from 0.3 to 2.0. In addition, the product $\omega_{sp}\tau_{\theta 2}$ must also be greater than unity. These requirements can be represented on the complex plane as shown Fig. 3.

One can see from the complex plane representation shown in Fig. 3 that to meet the Level 1 flying qualities specification, the short-period poles must lie inside the shaded region in Fig. 3. The outline of this region can be quantified using fuzzy membership functions. For example, the membership functions for short period damping ratio are shown in Fig. 4. The membership functions shown in Fig 4 divide the short-period damping ratio into regions where it is either "within specification" ($0.3 < \zeta_{sp} < 2.0$), "above specification" ($\zeta_{sp} > 2.0$), or "below specification" ($\zeta_{sp} < 0.3$).

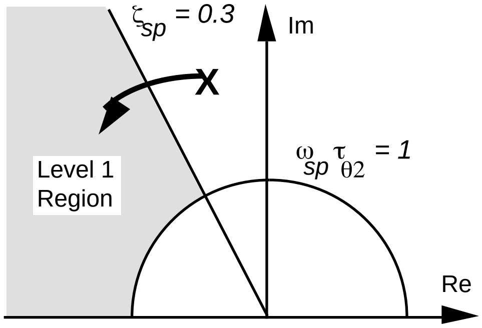

Figure 3 Short-Term Pitch Response Requirement

To illustrate how the fuzzy logic rules are constructed, Fig. 3 also shows the pole locations for an aircraft configuration that has deficient short period damping. The bare airframe poles are indicated by the 'X' marks in Fig. 3. For this configuration, it is possible to improve the short period damping by introducing a pitch damper, which consists of pitch rate feedback to the aircraft elevator. The pitch damper will move the short-period poles into the desired Level 1 region as shown by the curved arrow in Fig. 3.

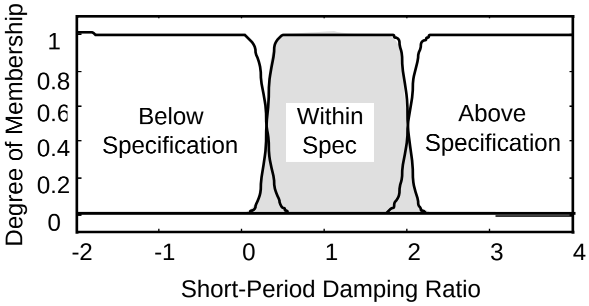

Figure 4 Membership Functions for Short-Period Damping Ratio

A fuzzy logic rule that represents the pole locations shown in Fig. 3 is,

IF the short-period poles are "complex and stable"
AND $\omega_{sp}\tau_{\theta 2}$ *is "within specification"*
AND ζ_{sp} *is "below specification"*
THEN the control system complexity is "medium"

The result of this rule, when fired, is to assign a control system design risk metric in the range of "medium" complexity or a value between 25 and 50 from Fig. 2. As shown in Table 1, a pitch damper or other single-loop SAS is associated with a "medium" complexity range similar to the XB-70. Thus, the flight control development costs associated with this configuration will be equivalent to the XB-70. When combined with other rules, the defuzzification process of each rule will lead to a unique risk value for the configuration. Fifteen rules are required to completely specify the Level 1 Short Term Response flying qualities specification for cruise flight conditions.

In the design examples that follow, three sets of rules are used to assess flight control design risk in the powered approach flight condition (Class III, Category C). The rulebases represent MIL-STD-1797 flying qualities requirements for Short Term Pitch Response, Control Anticipation Parameter, and Transient Peak Ratio. These rulebases consist of fifty-four, fifty-four, and fifteen rules, respectively. The final risk value is the largest predicted by each rulebase. Consequently, the final risk value is determined by the specification that would require the most complicated control system.

Model MDO Design Problem

We now demonstrate our MDO CCV procedure with a model problem. The baseline we used for our model design problem aircraft is the McDonnell Douglas D3230-2.2-5E Advanced Supersonic Cruise Aircraft Configuration (ASCAC).[25] This design reached the stage where considerable work had been done for NASA, including an extensive series of wind tunnel tests. Table 2 lists the aircraft geometric parameters that were used for the reference ASCAC model. The one-quarter chord point of the wing mean aerodynamic chord (fuselage station 184 ft) was chosen as a reference point for the center of gravity location x_{cg}. For the design problem the all-moving horizontal tail area will be varied but the planform shape will remain identical to the baseline.

Table 2 ASCAC Geometric Parameters

Aircraft weight, W	750,000 lbs
Wing reference area, S_w	10,000 ft^2
Wing span, b	135 ft
Wing MAC, $\bar{c}$	65 ft
Horizontal tail reference area, S_{ho}	781 ft^2
Moment of Inertia, I_{xx}	1.79×10^7 slug.ft^2
Moment of Inertia, I_{yy}	6.30×10^7 slug.ft^2
Moment of Inertia, I_{zz}	8.00×10^7 slug.ft^2

Two design variables are considered in our model problem, the normalized center-of-gravity shift $\Delta x_{cg}/\bar{c}$ and normalized horizontal tail area, given by S_h/S_{ho}. These variables represent a center-of-gravity increment with respect to the mean aerodynamic chord and the ratio of horizontal tail area to the nominal area, respectively. Note that, using the common aerodynamicist’s axis system, a negative center-of-gravity shift moves the aircraft center-of-gravity *forward* with respect to its nominal location. Nominal values for design parameters are $\Delta x_{cg}/\bar{c} = 0$ and $S_h/S_{ho} = 1$.

Since the mass distribution details were not available, the inertia coefficients were estimated using approximate methods by Roskam.[26] The weight of the horizontal tail is usually less than 5% of the total weight of the airplane. Therefore, in this initial study, we neglected the horizontal tail size variation affect on the center of gravity location and the inertia coefficients.

The variable complexity modeling approach described above was used to estimate stability and control derivatives for this aircraft. First, three APAS runs for the baseline wing-body and horizontal tail in isolation were made. Then, six runs for the wing-body-tail with differing tail sizes were made. The paneled wing-body-tail is shown in Fig. 5. All aerodynamic data required to determine the lift, drag, pitching moment, and pitch damping coefficients as functions of $\Delta x_{cg}/\bar{c}$, S_h/S_{ho}, angle-of-attack, and control surface deflection could be obtained from these results. Then, following the variable complexity design approach, we used our extended-DATCOM methods to obtain the aerodynamic model for configurations around the configuration for which APAS calculations were made. Thus, a complete model for the aerodynamic characteristic changes due to variations in the center-of-gravity and horizontal tail area was obtained.

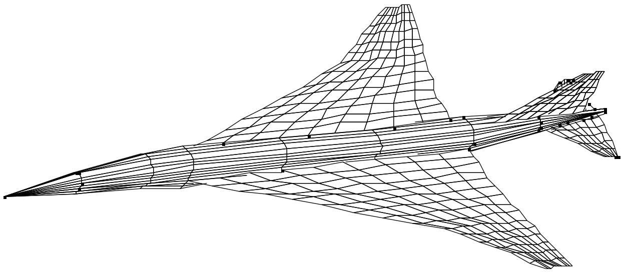

Figure 5 APAS Model for the ASCAC Airplane

We want to solve the MDO problem that minimizes the composite cost function,

$$J = C_D + \mu R$$

where C_D is the trimmed aircraft drag coefficient in cruising flight (Mach 2.2 and 60,000 ft) and R is the flight control system design risk in the powered approach configuration. The best design should emerge by considering both technologies together in the conceptual design phase. The parameter μ is used to weight the powered-approach control system design risk relative to the trimmed drag coefficient in cruise. An example suggesting a process for selecting μ will be presented below.

Note that for convenience we are minimizing drag. The cost function can easily be changed without loss of generality. In previous work including structural design optimization, we minimized takeoff gross weight and drag is weighted indirectly from the fuel weight required to complete a mission.[12] Thus, for the first demonstration of our MDO CCV method we consider point performance metrics. The approach can readily be extended to include more disciplines and a complete mission metric, which is ultimately cost.

Horizontal Tail Sizing

The first MDO CCV problem we consider is the one-dimensional case where only the normalized tail area is used as a design variable. The center-of-gravity shift is fixed at its nominal value of $\Delta x_{cg}/\bar{c} = 0$. We then determine the optimal tail size that minimizes the cost function *J*, defined above. The normalized tail size is allowed to vary from 0.5 to 3.

Figure 6 shows the optimal horizontal tail area as a function of the weighting parameter μ. This figure shows that the optimal tail area increases as the weighting parameter increases. The trend is consistent with our expectations. For a small weighting value, the cruise drag coefficient dominates the cost function and a small tail area results because the solution is "aero dominated."

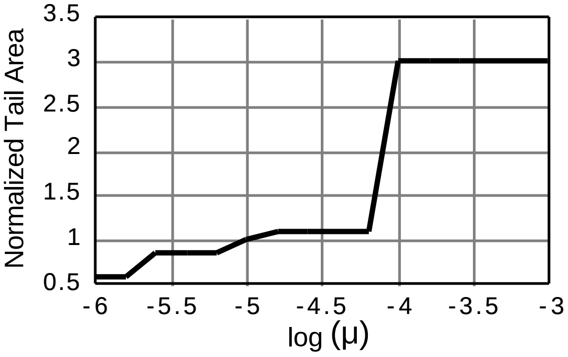

Figure 6 Optimized Tail Area with Zero c.g. Shift

A much larger tail area results when the weighting parameter μ is large. A large weighting means that the value of risk R dominates the cost function during optimization. This situation leads to large horizontal tail solutions that are "control dominated."

Figure 7 shows the resulting drag coefficient and risk values for each of the optimal tail areas from Fig. 6. Again, the trends follow the expected behavior. When the solution is "aero dominated", the tail area is small and the drag coefficient is also small. However, Fig. 7 also shows that the control risk R is very large for the "aero dominated" solution. Recall that risk values near 60 indicate "high" design risk.

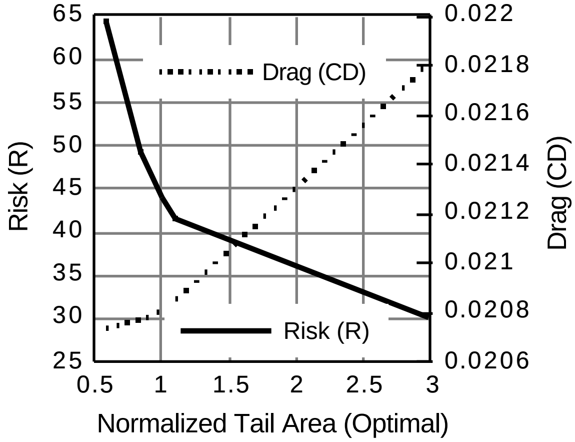

Figure 7 Risk and Drag for Optimized Tail Areas

The "control dominated" solution yields large tail areas and large trimmed drag coefficients as illustrated in Fig. 7. Note that the aerodynamic penalty associated with the "control dominated" solution is an increase in drag coefficient of nearly 0.0010. This penalty comes from increasing the tail area by a factor of three.

It is also very interesting to recognize that the nominal horizontal tail area ($S_h/S_{ho} = 1$) provides a very reasonable tradeoff in control risk and aerodynamic penalty. From Fig. 7, one can see that the control risk increases significantly for normalized tail areas below unity. On the other hand, the trimmed drag coefficient increases dramatically for tail areas above unity. As a result, the nominal solution appears to offer a very reasonable compromise between the two conflicting objectives. Our MDO CCV method is in agreement with the results of the much more detailed Douglas design study.

Tail Area and Center-of-Gravity Optimization

The second MDO problem uses both the horizontal tail area and the center-of-gravity position design variables in the optimization. The normalized tail area is allowed to vary from 0.5 to 3.0 again and the center-of-gravity position is allowed to move $\pm 0.2\bar{c}$ from the baseline position. Fig. 8 shows the trimmed drag coefficient for the ASCAC aircraft estimated using APAS and the DATCOM extensions. As expected, the drag coefficients in Fig. 8 increase with larger tail areas and more forward center-of-gravity locations. However, the effect of center-of-gravity position appears to be more pronounced than the effect of tail area changes. This trend occurs because the control surface deflection required to trim the aircraft increases as the center-of-gravity moves forward. The benefit of relaxed static stability can be seen on this graph because the trimmed drag coefficient is significantly reduced in the aft center-of-gravity positions. The nominal point is shown by the 'X' in Fig. 8, where $S_h/S_{ho} = 1$ and $\Delta x_{cg}/\bar{c} = 0$.

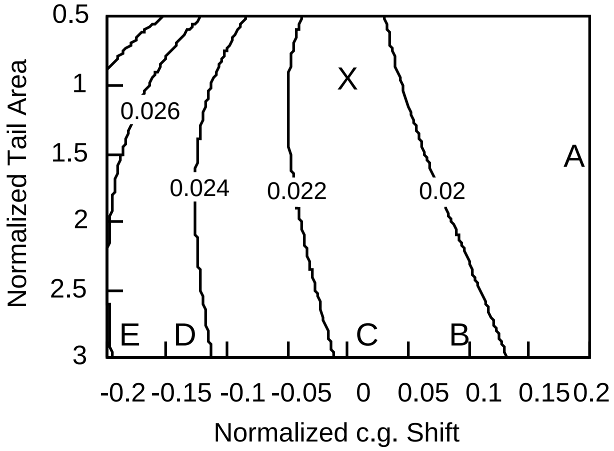

Figure 8 Contours of Constant Trimmed Drag Coefficient

Figure 9 shows a contour plot of the control system design risk metric for the ASCAC aircraft in a powered approach flight condition. This plot illustrates the effect of the two design variables on control system design risk and, again, the nominal reference point is indicated by an 'X'.

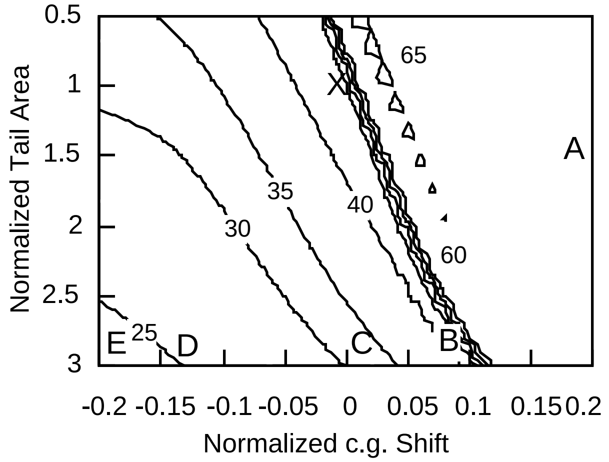

Figure 9 Contours of Constant Control Risk

Figure 9 demonstrates that the aircraft variants with smallest tail areas and most aft center-of-gravity locations yield the highest control system design risk. This trend is expected since aft center-of-gravity shifts will tend to destabilize the short-period mode. The ridge at about 0-10% aft center-of-gravity shift, where design risk jumps from 40 to 60, essentially shows where the aircraft shifts from a statically stable configuration to a statically unstable configuration. It is noteworthy that the nominal configuration is very close to this stability ridge but just slightly on the statically stable side. Conversely, it is not surprising to find that the lowest control system design risk occurs when the tail area is the largest and the center-of-gravity is shifted farthest forward. Note that although the control system design risk is low here, takeoff rotation and trim to high lift is not considered in this problem, and may impose system penalties.[13]

The fuzzy logic rulebase also yields information about the control system architecture required for each parameter variation. From Fig. 9, we can identify three distinct regions of control risk values. In the lower left corner, where the risk values are less than 30, the rule that fires with the highest strength (antecedents resulting in highest degree of membership) indicates that the aircraft requires a pitch rate damper. In other words, the aircraft has deficient short-period damping ratio. In the region just to the left of the ridge, where risk values range from 30 to 40, the rule that fires with the highest strength indicates that the aircraft requires a pitch damper and vertical acceleration feedback signals like the XB-70. This two-loop feedback architecture is still considered a medium risk control system. Finally, those parameter variations above the ridge, in the top right corner of Fig. 9, require a proportional+integral control system architecture. This architecture is very similar to the X-29 longitudinal control system and earns a "high" design risk.

Recall that the parameter μ is used to weight the powered-approach control system design risk relative to the trimmed drag coefficient in cruise. Returning to Figs. 8 and 9, one would expect that when μ is small, the optimal solution would be the minimum drag configuration. This solution is indicated by point 'A' in Figs. 8 and 9. It essentially defines the "aero dominated" design wherein the control system design risk is not taken into account. From Fig. 9, one should clearly see that the control system design risk at point 'A' is over 60 which places this configuration in the "high" risk category.

Conversely, point 'E' shown in Figs. 8 and 9 indicates the optimal solution for the case when μ is large. This solution represents the "control dominated" solution because the objective function is dominated by the risk value R. As mentioned previously, the lowest control system design risk configuration has the largest tail area and the forward center-of-gravity shift. However, this configuration yields a (cruise) trimmed drag coefficient of 0.0260 which is nearly 0.0070 larger than the "aero dominated" solution, and would be considered unacceptable.

Table 3 gives the optimal configuration solutions for several values of μ in between the "aero" and "control" dominated solutions. The solutions are each assigned a letter that is shown in Figs. 8 and 9 as well. From these solutions, a picture of the optimization history emerges. As the risk weighting parameter μ is increased from point 'A' to 'B', the solution jumps to the smallest center-of-gravity shift needed to stabilize the aircraft. Therefore, the point 'B' solution occurs at the largest admissible tail area and the smallest center-of-gravity shift relative to the "aero dominated" solution point 'A'. This result is consistent with the fact that the trimmed drag coefficient is influenced more by center-of-gravity shift than by tail area.

Table 3 MDO Results for Varied Risk Weighting

Point	$\log\mu$	S_h/S_{ho}	$\Delta x_{cg}/\bar{c}$	R	C_D
A	-5.0	1.5	0.2	64	0.0190
B	-4.0	3.0	0.09	39	0.0205
C	-3.5	3.0	0.0	30	0.0218
D	-3.0	3.0	-0.15	25	0.0249
E	-2.0	3.0	-0.2	24	0.0261

Once at point 'B', the optimal solutions continue to result in a tail area ratio at the upper limit. As the control risk weighting μ increases, points 'C' and 'D' show a tradeoff in control risk and drag coefficient. Each increase in μ leads to lower control risk and a more stable aircraft. Finally, at point 'E', the "control dominated" solution is obtained with the largest tail area and the most forward center-of-gravity shift.

Conclusions

Flight control system requirements can be included in MDO aircraft configuration problems using concepts motivated by early CCV research. The control system "risk" or development cost can be assessed using a fuzzy-logic rulebase. The rules can be developed directly from flying qualities and control system specifications. For MDO applications, the resulting risk metric can be used in the optimization cost function or as a constraint.

Aerodynamic information needed for control system assessment is best generated using a combinations of modeling methods. In this work, the APAS program is used to define models across a course grid of the parameter space. Analytical extensions of DATCOM methods are used for information in between APAS models. The combination of these methods yields improved computational efficiency.

The results shown in this paper confirm that optimized aircraft configurations will be significantly altered by the inclusion of flight control requirements following the CCV design philosophy. This MDO approach produces numerical values for not only the risk level that is needed, but also the performance that is gained or lost.

There are many areas where the current research can be extended and modified to solve new CCV MDO problems. Vertical tail sizing is just one example of the many other aircraft design problems that could be addressed using the combined CCV MDO approach. Also, the definition of control system design risk included only control system complexity in this paper. Other considerations such as reliability, component cost, and maintainability could be included in the fuzzy logic rulebase. Static control power requirements such as nose-wheel lift-off and engine-out landing could also be used in addition to flying qualities specifications. These extensions will bring even more of the practical issues faced by aircraft designers into the structured formulation offered by the CCV MDO approach.

Acknowledgment

This effort is sponsored by NASA Langley Research Center, Dynamics and Control Branch, under Grant NAG-1-1573. Mr. Martin R. Waszak is the technical monitor. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of NASA Langley Research Center or any other agency of the U.S. Government. The authors would also like to acknowledge the work done on this project by Mr. A. Suchkov and Mr. V.L. Razgonyaev while they were graduate students at Virginia Tech.

References

[1] Holloway, R.B., "Introduction of CCV Technology Into Airplane Design," Aircraft Design Integration and Optimization, AGARD CP-147, 43rd Flight Mechanics Panel Meeting, Oct. 1973.

[2] Anderson, D.C., Berger, R.L, and Hess, J.R., "Maneuver Load Control and Relaxed Static Stability Applied to a Contemporary Fighter Aircraft," *Journal of Aircraft*, Vol. 10, No. 2, Feb. 1973, pp. 112-120.

[3] O'Connell, R.F., "Design, Development and Implementation of an Active Control System for Load Alleviation for a Commercial Transport Airplane," AGARD-R-683, 49th Structures and Materials Panel Meeting, Oct. 1979.

[4] Kehrer, W.T., "Design Evolution of the Boeing 2707-300 Supersonic Transport," AGARD CP-147, Aircraft Design Integration and Optimization, 43rd Flight Mechanics Panel Meeting, Oct. 1973.

[5] McRuer, D. and Graham, D., "Eighty Years of Flight Control: Triumphs and Pitfalls of the Systems Approach," *Journal of Guidance, Control, and Dynamics*, Vol. 4, No. 4, July-Aug. 1981, pp. 353-362.

[6] Clarke, R., Burken, J.J., Bosworth J.T., and Bauer, J.E., "X-29 Flight Control System: Lessons Learned," AGARD CP-560, Active Control Technology: Applications and Lessons Learned, Flight Mechanics Symposium, May 1994.

[7] Holloway, R.B., Burris, P.M., and Johannes, R.P., "Aircraft Performance Benefits for Modern Control Systems Technology," *Journal of Aircraft*, Vol. 7, No. 6, Nov.-Dec. 1970, pp. 550-553.

[8] Morris, S.J. and Kroo, I., "Aircraft Design Optimization with Dynamic Performance Constraints," *Journal of Aircraft*, Vol. 27, No. 12, Dec. 1990, pp. 1060-1067.

[9] Livne, E., Friedmann, P.P., and Schmit, L.A., "Integrated Aeroservoelastic Wing Synthesis by Nonlinear Programming /Approximation Concepts," *Journal of Guidance, Control, and Dynamics*, Vol. 15, No. 4, July-Aug. 1992, pp. 985-993.

[10] Niewhoener, R.J. and Kaminer, I., "Linear Matrix Inequalities in Integrated Aircraft/Controller Design," American Control Conference, Seattle, WA, June 1995, pp. 177-181.

[11] Soban, D.S., Biezad, D.J., and Gelhausen, P., "Computer Optimization of Aircraft Handling Qualities During Preliminary Design," IEEE International Conference on Systems, Man, and Cybernetics, Vancouver BC, Canada, Oct. 1995, pp. 2670-2675.

[12] Dudley, J., Huang, X., MacMillin, P. E. , Grossman, B., Haftka, R. T., and Mason, W. H, “Multidisciplinary Optimization of the High-Speed Civil Transport,” Paper 95-0124, 33rd AIAA Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 1995.

[13] MacMillin, P.E., Dudley, J., Mason, W. H., Grossman, B., and Haftka, R.T ., “Trim, Control and Landing Gear Effects in Variable-Complexity HSCT Design,” Paper 94-4381, 5th AIAA /USAF /NASA Symposium on Multidsciplinary Analysis and Optimzation, Panama City, Fl., Sept. 1994.

[14] Sliwa, S.M., “Impact of Longitudinal Flying Qualities Upon the Design of a Transport with Active Controls,” Paper No. 80-1570, AIAA Guidance, Navigation, and Control Conference, Aug. 1980.

[15] Anderson, M.R., Suchkov, A., Einthoven, P., and Waszak, M.R., "Flight Control System Design Risk Assessment," Paper No. 95-3197, AIAA Guidance, Navigation, and Control Conference, Baltimore, MD, Aug. 1995, pp. 225-233.

[16] Hofman, L., and Clement, W. F., “Vehicle Design Considerations for Active Control Application to Subsonic Transport Aircraft,” NASA CR-2408, Aug. 1974.

[17] McCarty, C. A., Feather, J. B., Dykman, J. R., Page, M. A., and Hodgkinson, J., “Design and Analysis Issues of Integrated Control Systems for High-Speed Civil Transports, “ NASA CR-186022, May 1992.

[18] Malone, B., and Mason, W.H., “Aircraft Concept Optimization Using the Global Sensitivity Analysis and Parametric Multiobjective Figures of Merit,” AIAA Paper 92-4221, Aug. 1992.

[19] Bonner, E., Clever, W., and Dunn, K., “Aerodynamic Preliminary Analysis System II-Part I, Theory”, NASA CR-165627 , Apr. 1981.

[20] Sova, G., and Divan, P., “Aerodynamic Preliminary Analysis System II-Part II, User's Manual”, North American Aircraft Operations, Rockwell International, Los Angeles, CA, 1988.

[21] Razgonyaev, V.L., and Mason, W.H., “An Evaluation of Aerodynamic Prediction Methods Applied to the XB-70 for Use in High Speed Aircraft Stability and Control System Design,” AIAA Paper No. 95-0759, 33rd Aerospace Sciences Meeting and Exhibit, Reno, NV, Jan. 1995.

[22] Razgonyaev, V.L., and Mason, W.H., “Refined Lift and Side Force Wing-Body-Tail Interference Coefficients for Aircraft and Missile Aerodynamics,” Paper No. 95-3451, AIAA Atmospheric Flight Mechanics Conference, Baltimore, MD, Aug. 1995.

[23] Heffley, R.K. and Jewell, W.F., "Aircraft Handling Qualities Data," NASA CR-2144, May 1972.

[24] Military Standard, Flying Qualities of Piloted Aircraft, MIL-STD-1797, March 1987.

[25] Radkey, R.L., Welge, H.R., and Felix, J.E., “Aerodynamic Characteristics of a Mach 2.2 Advanced Supersonic Cruise Aircraft Configuration at Mach Numbers from 0.5 to 2.4,” NASA CR-145094, Feb. 1977.

[26] Roskam, J., *Airplane Design, Part V: Component Weight Estimation*, Roskam Aviation and Engineering Corporation, Ottawa, KA, 1985.