CONDUIT—A NEW MULTIDISCIPLINARY INTEGRATION ENVIRONMENT FOR FLIGHT CONTROL DEVELOPMENT

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Abstract*

A state-of-the-art computational facility for aircraft flight control design, evaluation, and integration called CONDUIT (Control Designer's Unified Interface) has been developed. This paper describes the CONDUIT tool and case study applications to complex rotary- and fixed-wing fly-by-wire flight control problems. Control system analysis and design optimization methods are presented, including definition of design specifications and system models within CONDUIT, and the multi-objective function optimization (CONSOL-OPTCAD) used to tune the selected design parameters. Design examples are based on flight test programs for which extensive data are available for validation. CONDUIT is used to analyze baseline control laws against pertinent military handling qualities and control system specifications. In both case studies, CONDUIT successfully exploits trade-offs between forward loop and feedback dynamics to significantly improve the expected handling qualities and minimize the required actuator authority. The CONDUIT system provides a new environment for integrated control system analysis and design, and has potential for significantly reducing the time and cost of control system flight test optimization.

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Introduction

The design, integration, and flight test development of flight control systems for modern fixed- and rotary-wing aircraft presents a challenging multidisciplinary task that factors significantly in the overall time and cost of aircraft development.[1] Comprehensive specifications such as those embodied in ADS-33C (rotorcraft),[2] MIL-STD-1797A (fixed-wing),[3] MIL-F-9490D (general control system characteristics),[4] and sophisticated time- and frequency-domain evaluation techniques are applied to ensure desired performance and handling qualities and to minimize flight test tuning of highly augmented modern combat aircraft. The overlap of flexible airframe modes and high-bandwidth control laws drives the requirement for incorporating increasingly higher-order analytical and identification-derived simulation models[5] and automated gain selection techniques in the control system design process.[6]

The control law design and evaluation for a single design point is made very laborious as a result of the numerous (often competing) design specifications and constraints. This process must be repeated for the tens (or even hundreds) of configuration design points that are evaluated for a full flight envelope control system. Further, the control system design engineer must continually update and integrate improvements in the mathematical models as hardware test data become available.[1] Often, design specification changes are also introduced during the course of aircraft development, which as with the other changes require control law

retuning across the flight envelope. Since current tools generally do not facilitate the study of the trade-offs between competing specifications, hardware characteristics, and performance metrics, the final design may not make the best use of available control authority for modern control-configured vehicles. The failure to consider such trade-offs can compromise control system performance and handling qualities. Clearly, sophisticated interactive computational tools are needed to integrate the many aspects of the flight control design process.

The U.S. Army Aeroflightdynamics Directorate in conjunction with NASA, the University of Maryland, and California Polytechnic State University (San Luis Obispo) have jointly developed a state-of-the-art computational facility for aircraft flight control design and evaluation referred to as CONDUIT. As the acronym implies, CONDUIT (Control Designer's Unified Interface) provides an environment for design integration and data resource management (Fig. 1). CONDUIT is a sophisticated "associate" that provides comprehensive analysis support and design guidance to a knowledgeable control system designer; it is not a "turn-the-crank" optimization program. CONDUIT builds on an earlier design tool, GIFCORCODE, developed under the same cooperative effort.[7]

This paper describes the CONDUIT tool and case study applications to complex rotary-wing design and fixed-wing problems. The control system analysis and design optimization methods are presented first, including the definition of design specifications and system models within CONDUIT, and the multi-objective function optimization approach (CONSOL-OPTCAD) used to tune the selected design parameters. The rotorcraft flight control design example is based on the analysis and optimization of control laws for the RASCAL UH-60A helicopter. The NASA/Army RASCAL (Rotorcraft Aircrew Systems Concepts Airborne Laboratory) is equipped with a programmable fly-by-wire flight control system to support a range of research programs in flight control, simulation, and advanced displays.[8] CONDUIT is being used to evaluate the baseline control laws and control system hardware, as provided by the RASCAL flight control contractor (Boeing Helicopter), versus the ADS-33C specifications. Then the selectable system gains are optimized to improve system performance and handling

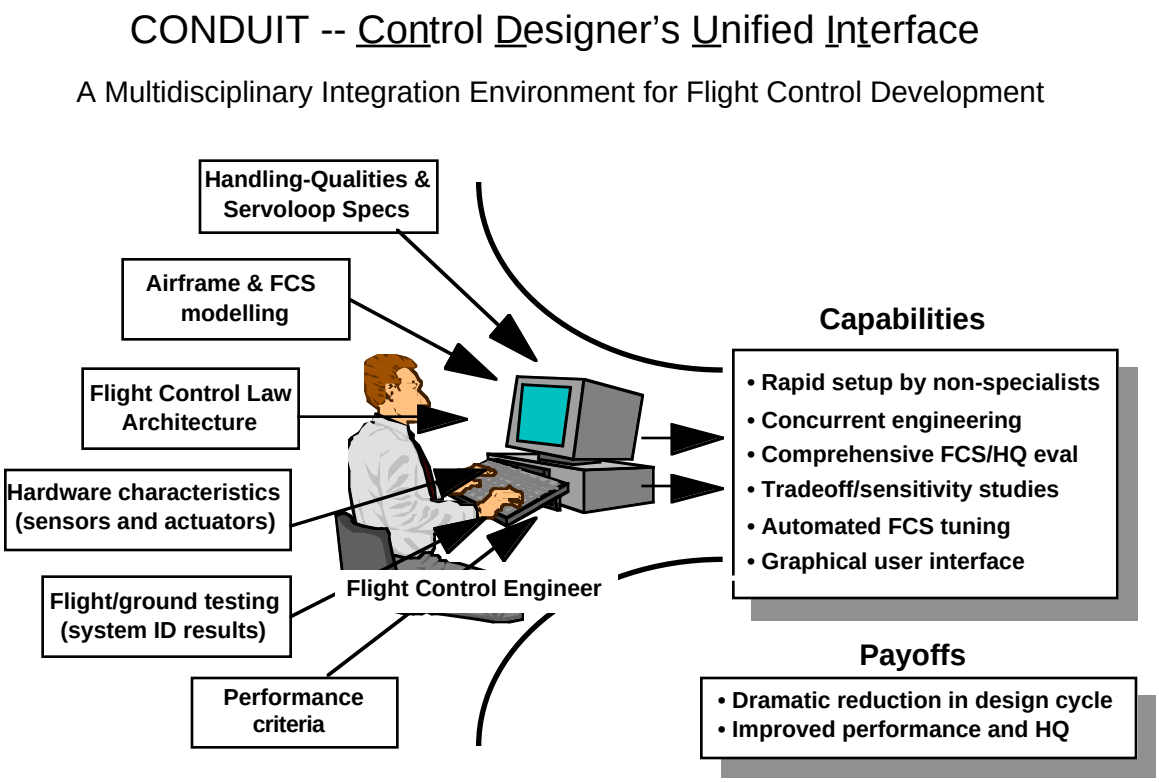


Fig. 1 CONDUIT control system integration and design evaluation process.

qualities. The CONDUIT results are based on dynamic response models of the UH-60A helicopter obtained from system identification, and thus are expected to be highly representative of actual RASCAL performance without further significant modification.

The second design example is based on the X-29A high performance fixed-wing aircraft. A unique feature of this fly-by-wire aircraft is its forward-swept wing configuration, which renders the bare airframe highly unstable and thus potentially more maneuverable than conventional configurations. The X-29A was developed by Grumman and flown at NASA Dryden Research Center.[9] Extensive flight data and handling-qualities results are available in the literature, including comparisons with handling qualities and servo-loop specifications, and design optimization studies. The results presented herein suggest that CONDUIT can provide options for considerable improvement in the X-29A handling qualities and servo-loop characteristics.

Key Features of CONDUIT

CONDUIT is built on top of the highly flexible MATLAB/SIMULINK system modeling and analysis environment,[10] which includes a graphical block diagram editor and block-diagram-to-code features. CONDUIT makes extensive use of the MATLAB graphical user interface (GUI) coding features to create a true interactive graphical user interface for problem setup and pushbutton program operation (Fig. 2).

The user graphically selects the desired handling qualities and flight control system specifications from a library of standard fixed- and rotary-wing specifications, or builds new specifications from generic time- and frequency-domain specifications. Specifications are wired to the simulation block diagram via a graphical editor, thereby avoiding any manipulation of the extensive MATLAB "m" files used for each specification. The user can click on and bend the specification boundary curves and the system automatically updates the relevant defining equations.

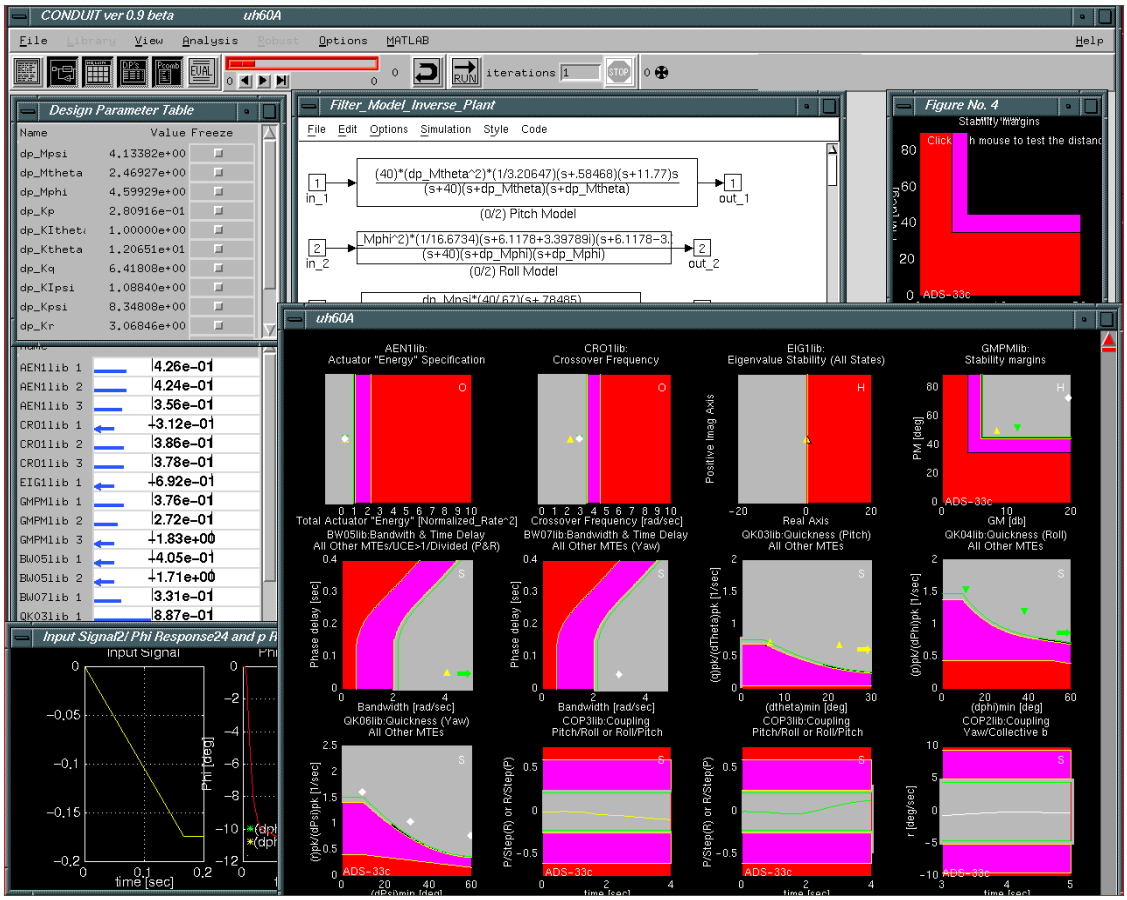


Fig. 2 Collage of CONDUIT displays.

Compliance with all active specifications is graphically displayed on the criteria with a single pushbutton command, thus significantly streamlining the system evaluation process. A key feature of CONDUIT is that a single mouse click on any of the specifications brings up an extensive set of supporting plots that present all of the relevant analyses associated with the specification. A state-of-the-art multi-objective function optimization environment (CONSOL-OPTCAD)[11] is integrated into CONDUIT to allow the user to tune selected design parameters (e.g., gains, time constants) for compliance with the active design specifications, or to update control laws for changes in modeling data and design specifications. An important application of the automated tuning capability is for examining the trade-offs between control system performance and actuator authority requirements, and between competing specifications. Finally, the CONDUIT problem definition and all results are stored and organized in a database for easy retrieval and comparative studies by the user.

CONDUIT Evaluation and Design Process

Overview

In developing CONDUIT, we have taken the view that the aircraft developer has already conducted a preliminary design study to determine an appropriate control law loop architecture. Alternatively, the selection of the control law architecture may have been based predominantly on historical precedent within a particular company. In either case, the control system analyst will use CONDUIT to evaluate the baseline design and to tune the design parameters for best system behavior.

CONDUIT has two basic modes of operation: setup and run. Within CONDUIT's setup mode, the user accesses SIMULINK to define (or import) the simulation mathematical model and control law architecture. The aircraft response models are obtained from analytical simulations or system identification results derived from flight/ground test data. The main aspect of problem setup in CONDUIT is the graphical selection and wiring of the handling qualities and servo-loop specifications. The user must also set up a small initialization file to define problem-dependent constants such as simulation time-step and test input signals.

In CONDUIT's run mode, the user establishes starting values for the design parameters and conducts an initial evaluation of all of the system specifications with the push of a single button. Supporting plots are examined for further insight into system behavior. Then the user can easily tune the design parameters manually with rapid access to all of the linear and nonlinear response implications, or use the automated tuning feature to achieve Level 1 ("desirable region") performance of all of the specifications. Finally, the optimization feature of CONDUIT can be exercised to tune the design parameters for best performance relative to a selected set of objective criteria.

The following sections give more detailed information on CONDUIT operating features.

a. Problem Setup in CONDUIT

The first step of the problem setup in CONDUIT is the definition of the aircraft dynamics and control law architecture within SIMULINK and the selection of appropriate design specifications from the available libraries. The aircraft aerodynamic model is commonly a high-order linearized state-space representation that is numerically extracted from a complex nonlinear simulation model. System identification flight tests are often conducted early in the aircraft development program to validate and update the simulation characteristics.[12] The control law model must include port limits (e.g., for a limited authority fly-by-wire system) and actuator rate and displacement saturation limits. These nonlinear elements are vitally important in determining aggressive maneuvering behavior for moderate and large control inputs.

There are currently five graphical libraries comprising over 50 specifications in CONDUIT:

- rotorcraft in hover/low speed flight[2]
- rotorcraft in forward flight[2]
- fixed-wing lateral/directional characteristics[3, 13]
- fixed-wing longitudinal characteristics[3, 13]
- general system characteristics[4]

The user scrolls through the libraries (e.g., Fig. 3) and selects, using the mouse, the specifications appropriate to the problem.

Three levels of compliance are defined for each specification, following the handling-qualities levels convention.[2, 3] In the Level 1 region, the aircraft characteristics are "satisfactory without improvement." This is the desirable performance region and is indicated in blue on the color monitor (darkest shade in black and white). The bordering region is Level 2, "deficiencies warrant improvement." This is the adequate performance region, and may be acceptable under degraded system operations or for flight outside

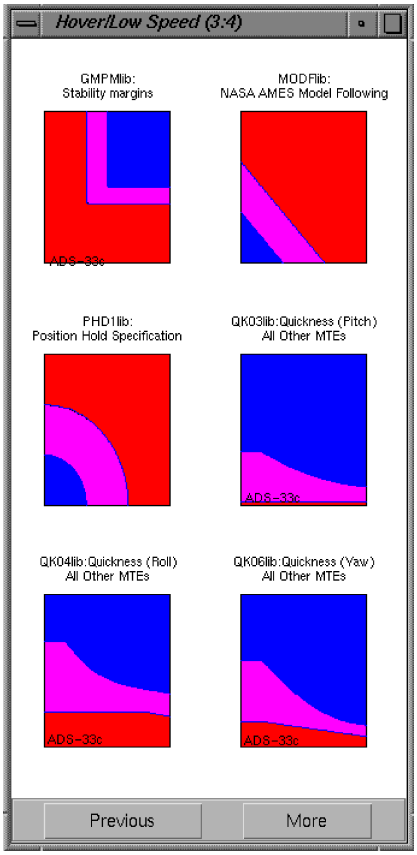


Fig. 3 Example window from the handling quality specification libraries.

the baseline envelope. This region is indicated in magenta on the color monitor (lightest shade in black and white). The final region is Level 3, "deficiencies require improvement." This is the inadequate performance region, where the mission task will be compromised. This region is indicated in red on the color monitor (intermediate shade in black and white).

The splines that define the boundaries between each level can be graphically altered to update the libraries with new specifications or to evaluate the sensitivity of a design to changes in the criteria. Additionally, CONDUIT accommodates the uncertainty in the simulation mathematical model and changes in actual flight condition relative to the reference condition by allowing the user to include a "design margin" as illustrated in Fig. 4. Thus, in flight, the control system performance can degrade into this design margin without entering the Level 2 region.

The specifications are then "wired" to the SIMULINK simulation model using a graphical "spec

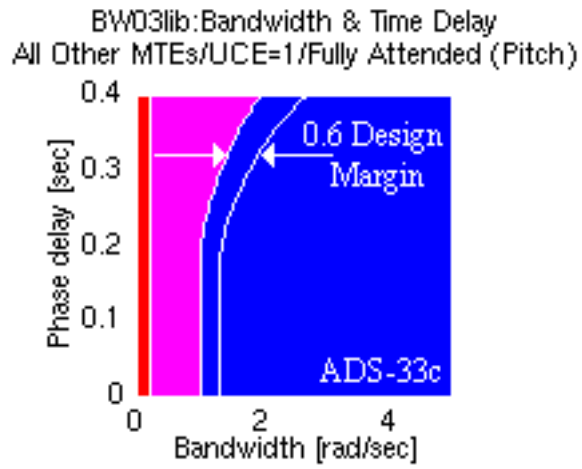


Fig. 4 Bandwidth specification including a 0.6 design margin.

editor." Here, the user declares each specification to belong to one of the following four classes: 1) hard constraint, 2) soft constraint, 3) performance criterion, or 4) check spec only. The selection of specification class defines the solution strategy for the CONSOL-OPTCAD optimization process. The input and output port connections for each specification are indicated in an information box in the spec editor, and are wired to the simulation block diagram with pull-down menus.

b. Baseline Evaluation

The user requests a complete evaluation of system behavior against the specifications by pressing a single "EVAL" button. CONDUIT executes the MATLAB scripts associated with each of the selected specifications and displays the results on the graphical specification plane. Multiple layers of supporting analysis plots are available to the user by simply clicking on the respective specification (Fig. 5). This feature gives the control system designer rapid insight into system behavior and the effects of control system changes on specification compliance.

c. Performance Comb

A distance algorithm in CONDUIT translates the location of the design point on each of the graphical specification criteria to a numerical rating. This normalized rating is based on the closest distance from the Level 1/2 and Level 2/3 border splines and the local width of the Level 2 region (d1, d2, and d3, respectively, in Figs. 6 and 7). A rating of "1" indicates that

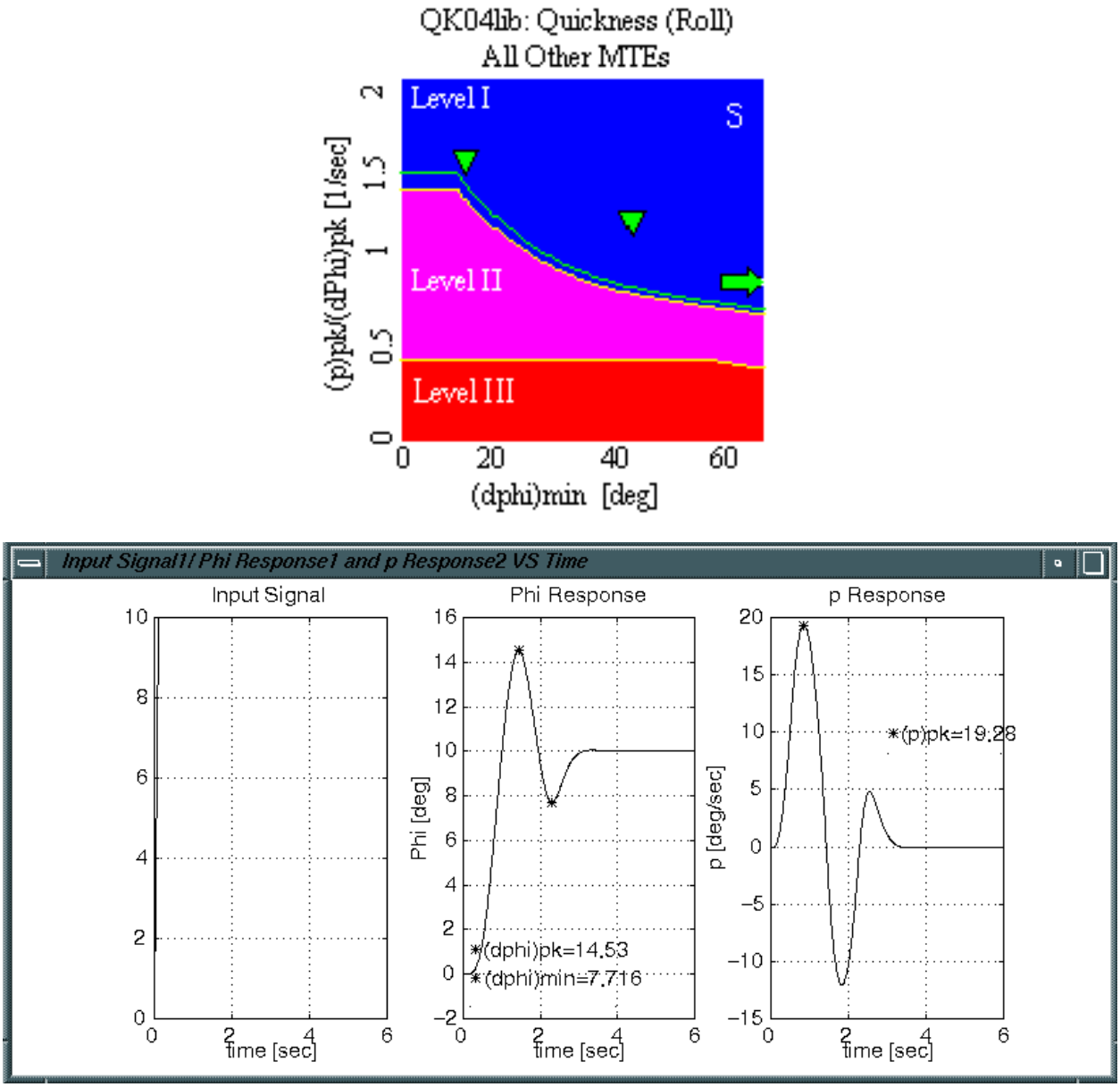


Fig. 5 Example of supporting plot that explains the results displayed on specification.

the design point lies on the Level 1/2 border spline. A rating of "2" indicates that the design point lies on the Level 2/3 border spline. The numerical ratings for each specification are displayed on a performance comb (Pcomb) bar chart as shown in Fig. 8. The color of the bars displayed on the monitor corresponds to the color-coding of the Level 1, 2, or 3 region that the data lie in. Figure 8 shows the mapping of the specification results into the Pcomb chart, and indicates the relative degree of compliance with each of the specifications. These numerical ratings are used by CONSOL-OPTCAD to tune the design, as is discussed in the next section.

d. Design Tuning

The user graphically selects design parameters that will be used by CONDUIT in the tuning process. Typically these are the feedback and feedforward parameters (e.g., gains, time constants) that are scheduled as a function of flight condition in modern fly-by-wire aircraft. CONDUIT feeds the design parameters and constraints in the form of a "pseudo C" program file to the optimization engine CONSOL-OPTCAD.

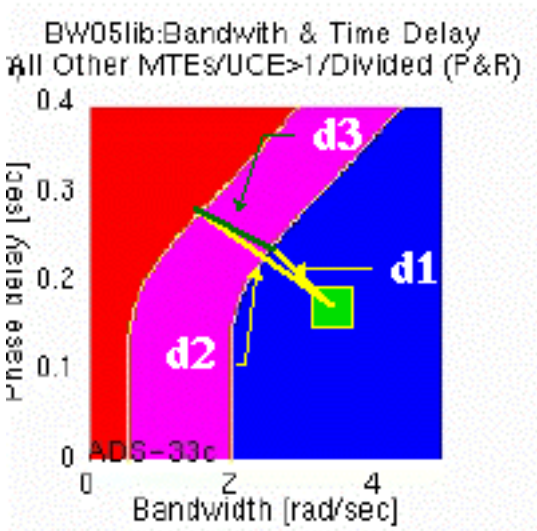


Fig. 6 The distance to the two splines is used to calculate the normalized value.

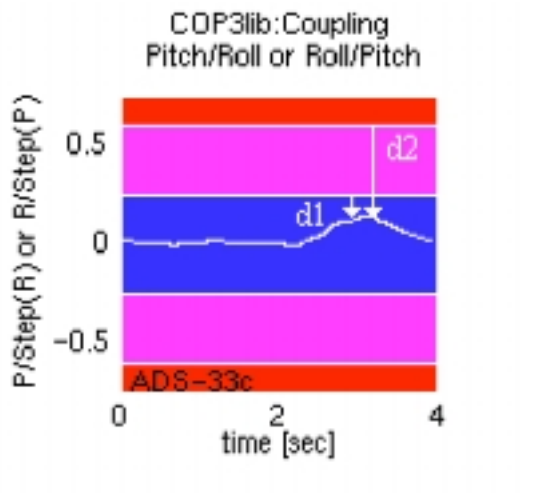


Fig. 7 Specifications that use vector data have the value determined by the "worst point" of the vector.

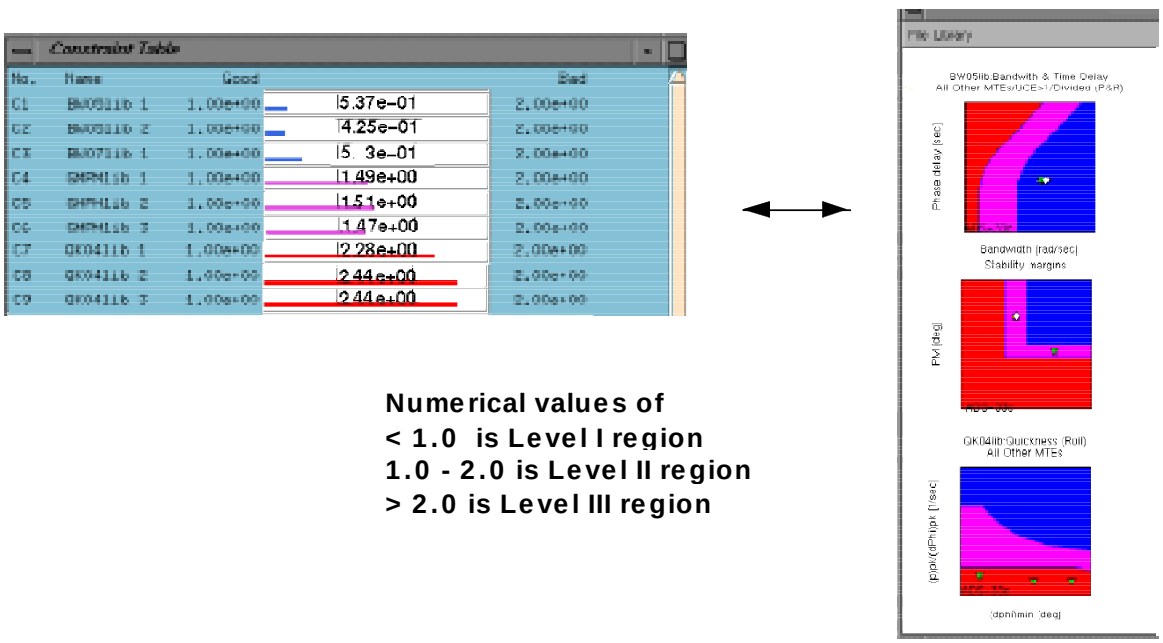


Fig. 8 The Pcomb displays the mapping the between graphical specifications and numerical ratings.

The theoretical basis for CONDUIT's automated tuning function rests on the assumption that any individual specification can be adequately approximated by a smooth (at least twice differentiable) function, mapping the design parameters into a real number. For example, if $\underline{x} \in \Omega \subset R^n$, where $\underline{x}$ is the n-vector of parameters and Ω is the set of admissible parameter values, then $f_i(\underline{x})$ is the specification. The specification can be a performance criterion, meaning that the goal is to minimize $f_i(\underline{x})$ over all $\underline{x} \in \Omega$, or it can be a constraint, meaning $f_i(\underline{x}) \leq \beta_i$ (β_i real) in order for $\underline{x}$ to be an admissible value for the design parameters.

The design problem, once it has been fully formulated, will be solved iteratively starting from some initial guess, $\underline{x}_o$, for the design parameters. For any constraint that is not satisfied at $\underline{x}_o$ (e.g., $f_j(\underline{x}_o) >$

β_j) an obvious way to proceed is to treat that constraint temporarily like a performance criterion and try to find an $\underline{x}$ that minimizes $f_j(\underline{x})$ subject to $\underline{x} \in \Omega$. In attempting to minimize $f_j(\underline{x})$, the computer will either move to an $\underline{x}$ that satisfies $f_j(\underline{x}) \le \beta_j$ or show that no such solution exists. Thus constraints and performance criteria are equivalent until a value of $\underline{x}$ that satisfies the constraints is found.

The previous paragraphs show that a typical design problem can be mathematically formulated as a constrained multi-criterion parametric optimization problem. In most such problems it is necessary to trade off among competing criteria. For example, in most control design problems, increasing the feedback gain improves tracking but degrades gain margin. In order to use the computer to assist in solving such a design problem it is necessary to reduce the multiple criteria to a single criterion that captures these trade-offs. It is well known that no weighted linear combination of criteria can do this. Mathematically,

$$\min_{\underline{x}\in\Omega} \sum_{i=1}^{m} \alpha_i f_i(\underline{x}), \quad 0 \le \alpha_i < \infty, \quad \alpha_i \text{ real} \tag{1}$$

always occurs at an $\underline{x}^*(\alpha)$ satisfying

$$\min_{\underline{x}\in\Omega} f_i(\underline{x}) \quad \text{for some } i, \quad 1 \le i \le m \tag{2}$$

In other words, the value of $\underline{x}$ that minimizes any linear combination of performance criteria always equals the value of $\underline{x}$ that minimizes *one* of the criteria. This is illustrated in Fig. 9a for a simple problem involving two design specifications and one design parameter. The weights can only change which specific criterion is optimized. All the others are ignored and no trade-off occurs.

A good way to combine the multiple performance criteria so as to balance competing objectives is as follows:

$$\min_{\underline{x}\in\Omega}\left(\max_{1\le i\le m} \alpha_i f_i(\underline{x})\right), \quad 0 \le \alpha_i, \quad \alpha_i \text{ real} \tag{3}$$

The great advantage of this formulation is that the optimal value of $\underline{x}$ can be placed anywhere in the region of the parameter space bounded by the minima of the individual criteria by appropriate choice of the α_i. This is shown for the simple example in Fig. 9b. Thus any

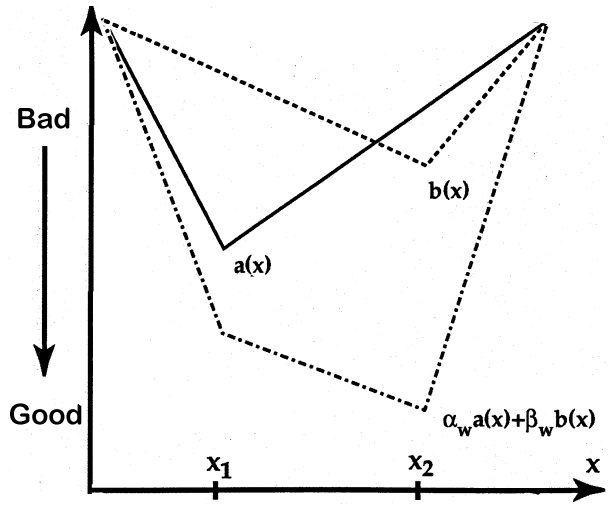


Fig. 9a Linear combination of performance criteria.

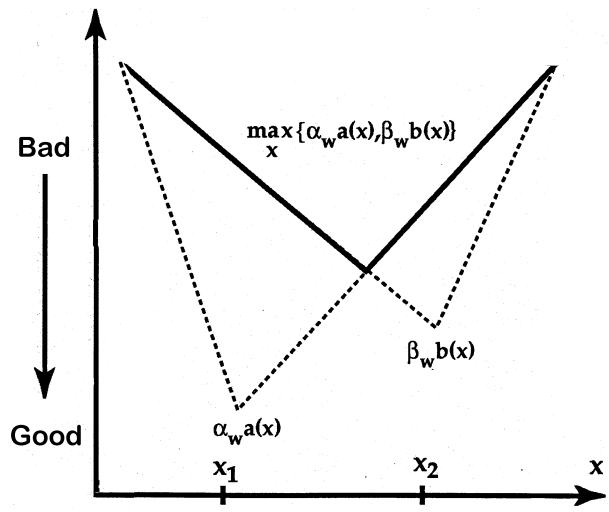


Fig. 9b Min/max solution approach used in CONSOL-OPTCAD.

reasonable choice of the α_i produces a trade-off among the specifications. The CONDUIT distance algorithm automatically normalizes the weightings for the specifications, using the natural choice of the width of the Level 2 regions. A designer could explore the trade-offs by adjusting the relative widths of the Level 2 regions.

The min/max formulation of Eq. (3) reduces the complex problem of multiple design criteria to a problem of minimizing a scalar performance measure subject to constraints. However, solving even the scalar optimization problem is difficult since the criteria values $\{f_i(\underline{x})\}$ are generally a highly nonlinear function of the design parameters ($\underline{x}$). CONDUIT employs the

CONSOL-OPTCAD[11] optimization engine to solve this difficult problem. As the iterative solution progresses and those $f_i(\underline{x})$ that correspond to constraints become satisfied they change from being performance criteria
to being constraints. Conceptually, such satisfied constraints redefine Ω. Thus, at each stage, CONSOL-OPTCAD is trying to solve a constrained parametric optimization problem. The best algorithm known at this time for solving such problems is Feasible Sequential Quadratic Programming (FSQP).[14, 15] This is the algorithm used by CONSOL-OPTCAD. The idea behind FSQP is to approximate the original optimization problem by a sequence of quadratic programming problems. This approximation should result in quadratic convergence near the optimum. The word "feasible" refers to the fact that the solution continues to satisfy any constraint at every iteration after the first one for which the constraint is satisfied.

System optimization using CONSOL-OPTCAD is conducted in three distinct phases. In Phase 1, the design parameters are tuned to ensure that the "hard constraints" are satisfied; these are typically absolute (or relative) stability in each loop and other Level 1 specifications that *must* be satisfied. Once all of the hard constraints meet the Level 1 criteria, the optimization process moves into Phase 2 and begins to work on the "soft constraints."

Most of the problem's specifications are declared as soft constraints. This choice allows CONDUIT to accept a solution that does not strictly meet all of the Level 1 requirements, but one that reaches the best possible compromise for the available actuator authority. If the design satisfies all of the Level 1 requirements for the soft constraints, CONSOL-OPTCAD has achieved a "feasible solution." Since any design that resides in the Level 1 region is feasible, Phase 2 optimization actually reaches a "family" of design solutions. Now the optimization process enters Phase 3.

In Phase 3, CONSOL-OPTCAD will tune the design parameters to optimize the system to the selected performance criteria, and thereby select a final "best design" from the family of feasible solutions. Two commonly used performance criteria for control system optimization are actuator energy and feedback-loop crossover frequency. Minimizing these parameters will ensure that the Level 1 design specifications are achieved with the minimum use of control authority and minimum sensitivity to sensor noise.

e. Trade-Off Studies

The user can systematically adjust control system hardware parameters and criteria splines and then quickly retune the design to generate trade-off curves. For example, an aircraft designer can evaluate the sensitivity of the required actuator performance to changes in the aircraft agility and maneuverability requirements. If modest relaxation in the criteria can allow the use of a significantly reduced actuator bandwidth (thus lower cost and weight), the manufacturer may seek a waiver of the specification from the procuring agency.

f. Databasing

A focus of the ongoing CONDUIT development effort is the integration of a database management system to catalogue all CONDUIT problem definition files and results. The completed databasing system will greatly improve the organization of the CONDUIT workspace as compared to the simple directory structure of MATLAB/SIMULINK. Previous design cases and associated results will be accessed by a single "case name," allowing new cases to be rapidly generated from stored configurations. An array of utilities will permit the detailed comparison of design configurations in plotted or tabular form. Design parameter and performance data will be plotted as a function of CONSOL-OPTCAD iteration to give the user maximum insight into the tuning process.

Rotorcraft Control Law Design Study

a. Problem Setup

In this study, CONDUIT is used to analyze and tune the baseline control system for the RASCAL UH-60A fly-by-wire research helicopter[8] (Fig. 10). The RASCAL control law architecture is based on the Advanced Digital Optical Control System (ADOCS) explicit model-following system.[16] The schematic block diagram of Fig. 11 illustrates the important system elements. The block marked "Command Model" (M) contains the desired dynamic response characteristics, typically represented by low-order transfer functions. The block marked "Aircraft Dynamics" (P) is a 14 DOF linear state-space representation of the multi-input/multi-output UH-60 bare airframe dynamics and precompensation to improve dynamic decoupling.[17] The aircraft dynamics model was extracted from flight test data using advanced frequency-domain system identification

procedures specifically developed for the rotorcraft problem.[18] Inputs to the helicopter are via the

Fig. 10 The RASCAL UH-60 helicopter.

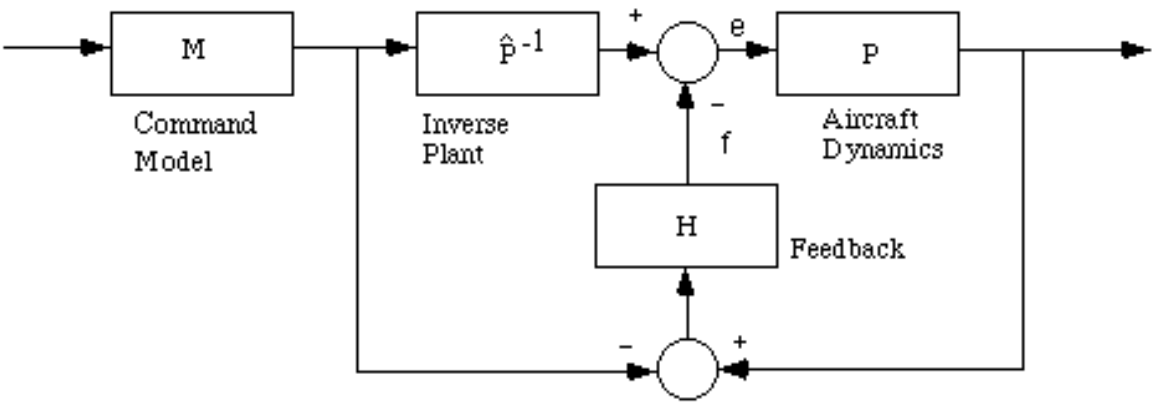


Fig. 11 Model-following block diagram.

main rotor swashplate for pitch, roll, and vertical control, and the tail rotor pitch for yaw control. The vertical loop is not closed in this study because the open-loop dynamics in this axis are well damped and already meet the relevant handling-qualities requirements. The block marked "inverse plant model" ($\hat{P}^{-1}$) contains the inverses of low-order transfer-function approximations of P. If the inverse plant model is accurate, the aircraft will track the desired "Command Model" (M) response with very low bandwidth feedback compensation (H). The feedback compensation (H) contains the feedback gains and compensators for ensuring stability, robustness, and disturbance rejection and suppressing any error arising from incomplete cancellation by the plant inverse.

The complete SIMULINK schematic of the RASCAL system is shown in Fig. 12. The design parameters consist of nine feedback gains and three model response parameters. The three model response parameters directly set the desired speed of commanded response for the pitch, roll, and yaw channels. The handling-quality specifications for this study are obtained from ADS-33C.[2] Feedback-loop specifications are also included to ensure adequate levels of stability and robustness, and to minimize control actuator saturation. The nine feedback gains are composed of three gains (proportional, integral, and rate) for each of the pitch, roll, and yaw channels. The "hard constraints" selected for this problem were gain and phase margin requirements for the feedback loops

and minimum stable real part for all closed-loop eigenvalues. Bandwidth, quickness, coupling, and wind gust rejection

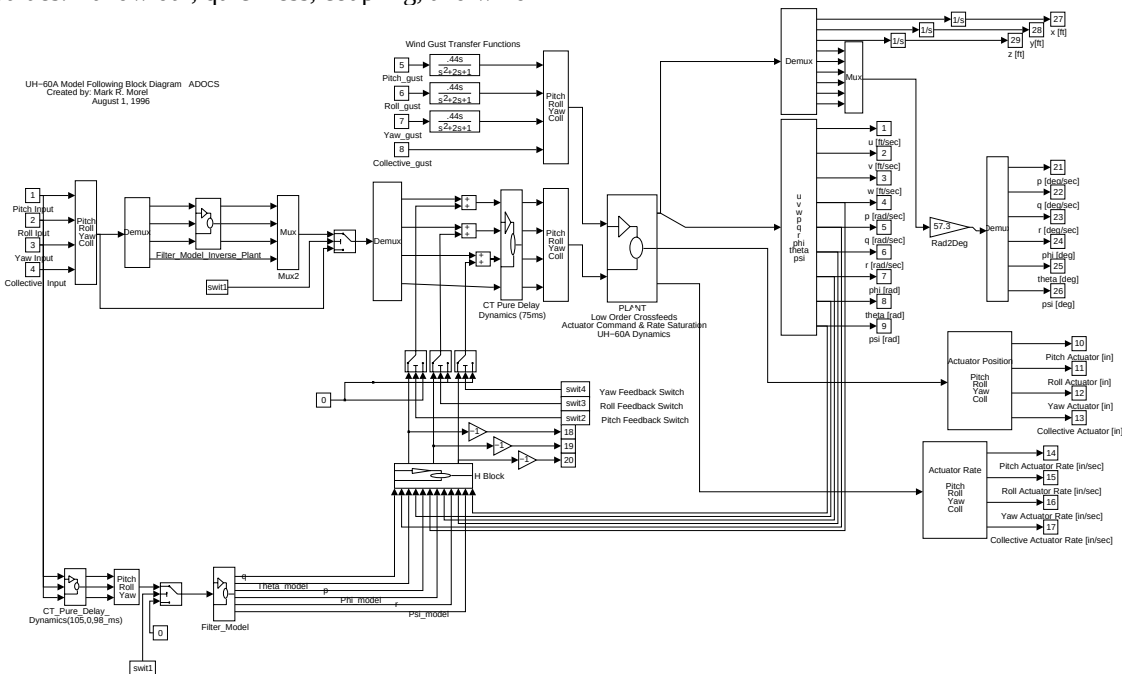


Fig. 12 SIMULINK diagram of the RASCAL model-following control laws.

specifications from ADS-33C[2] were all defined as "soft constraints." The performance criteria selected were the actuator energy and feedback-loop crossover frequency for each of the three loops (f/e in Fig. 11).

b. Baseline and Optimized Design Performance

The performance of the baseline RASCAL system design is shown on the CONDUIT specification window in Fig. 13. The baseline design meets the Level 1 criteria except for the yaw bandwidth and the pitch, roll, and yaw quickness. CONDUIT successfully tuned the design to reach a "feasible solution" that achieved all hard and soft constraints. The Phase 3 optimized design shown in Fig. 14 minimizes the selected performance criteria and meets Level 1 requirements for all specifications.

Table 1 compares the design parameter values for the optimized solution with the design parameter values for the baseline system. The baseline design does not use integral feedback loops; therefore, the gains for these loops are set to zero for the baseline design. Two noticeable changes for the optimized design are the increases in the roll and yaw command model frequency parameters (Mphi and Mpsi), so the associated quickness and bandwidth specifications could be met. Figures 15a and 15b show the supporting plot for the yaw quickness and yaw actuator energy specifications. The figures show that the yaw angle and yaw rate responses are smooth and do not possess any unwanted oscillations. The associated actuator position and rate responses (Fig. 15b) provide a complete picture of the system performance and indicate some degree of saturation. This information can be used to decide whether the actuators are sufficient for the system.

The Table 1 comparison also shows a large decrease in Kp along with an increase in the integral gain, KIphi. These changes allow a significant reduction (28%) in the roll crossover frequency, without sacrificing the low frequency model tracking. There is an attendant reduction in roll channel phase margin. Further reduction in the control energy usage is limited by the pitch, roll, and yaw quickness specifications, which have points resting on the design margin borders for small attitude changes. Further reductions in crossover frequency are restricted by the wind gust rejection response, which was relaxed to the design margin in all three channels.

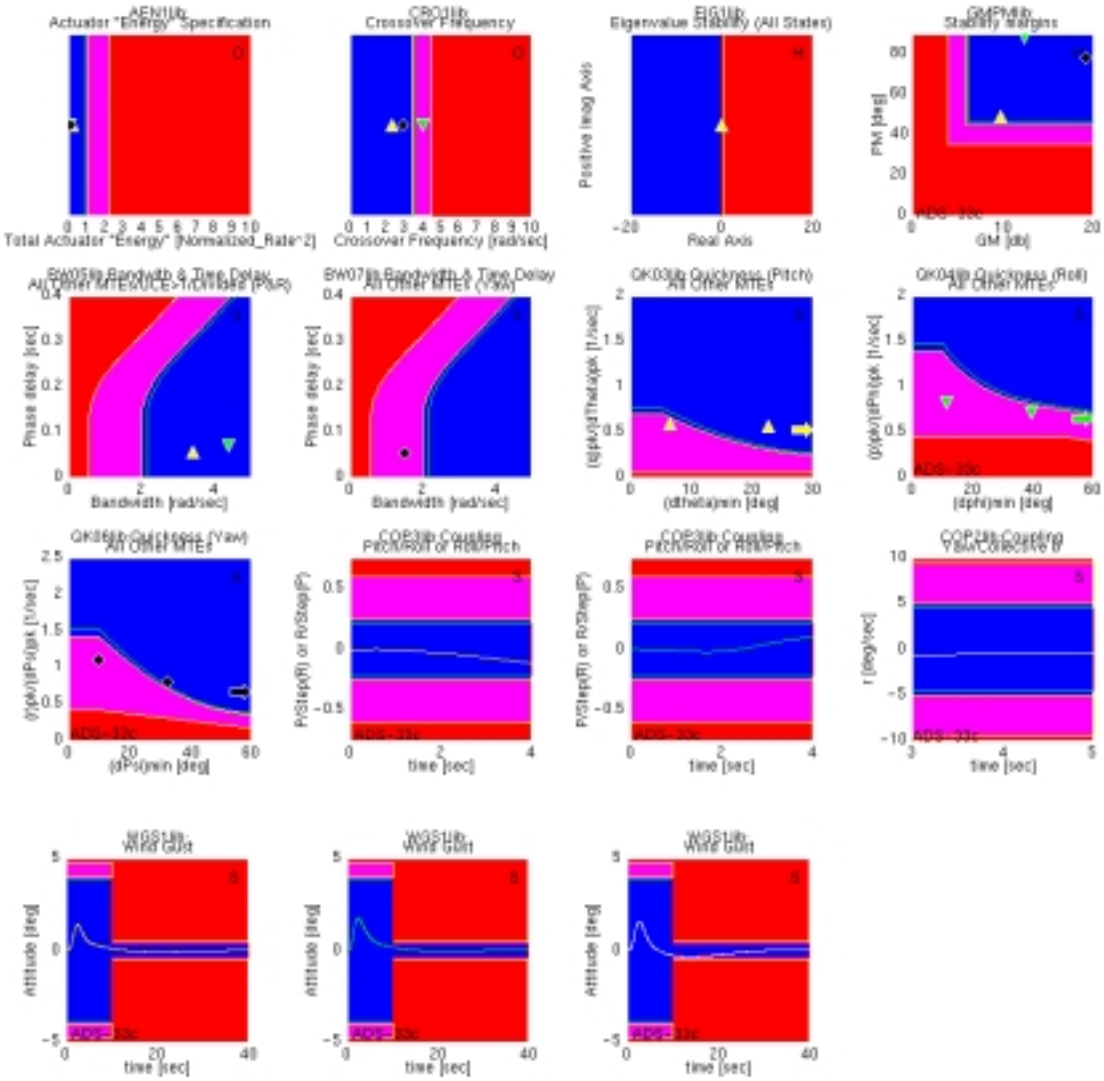


Fig. 13 RASCAL design using ADOCS gains.

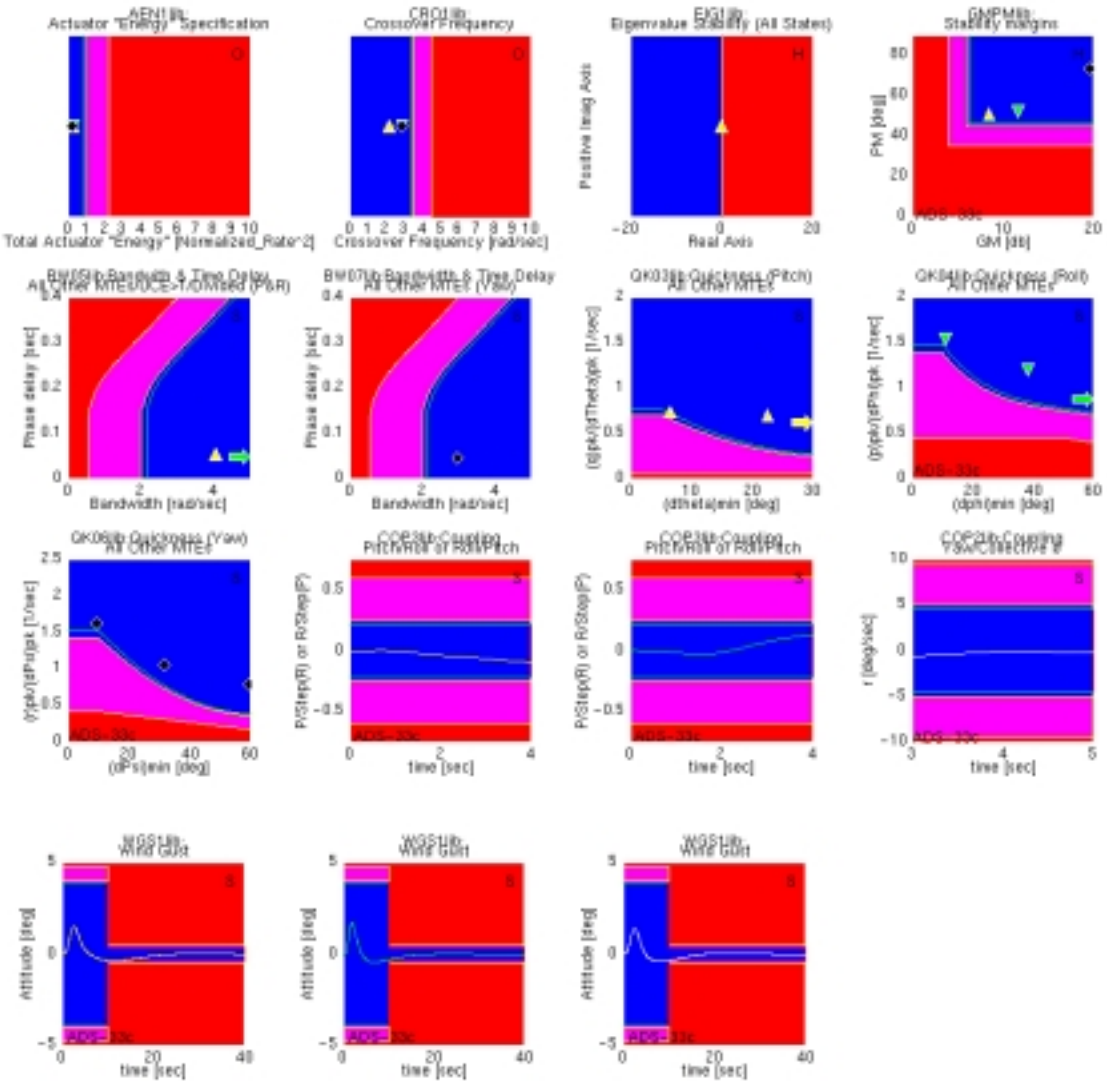
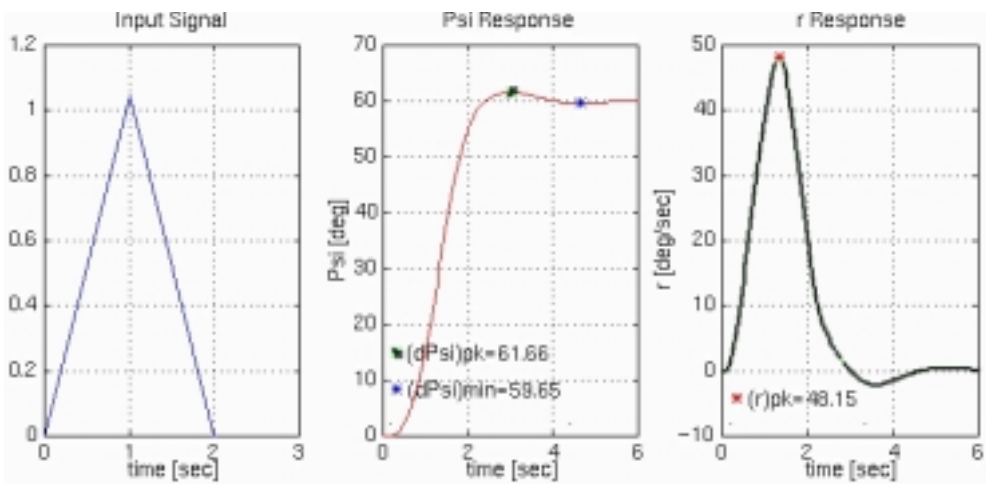


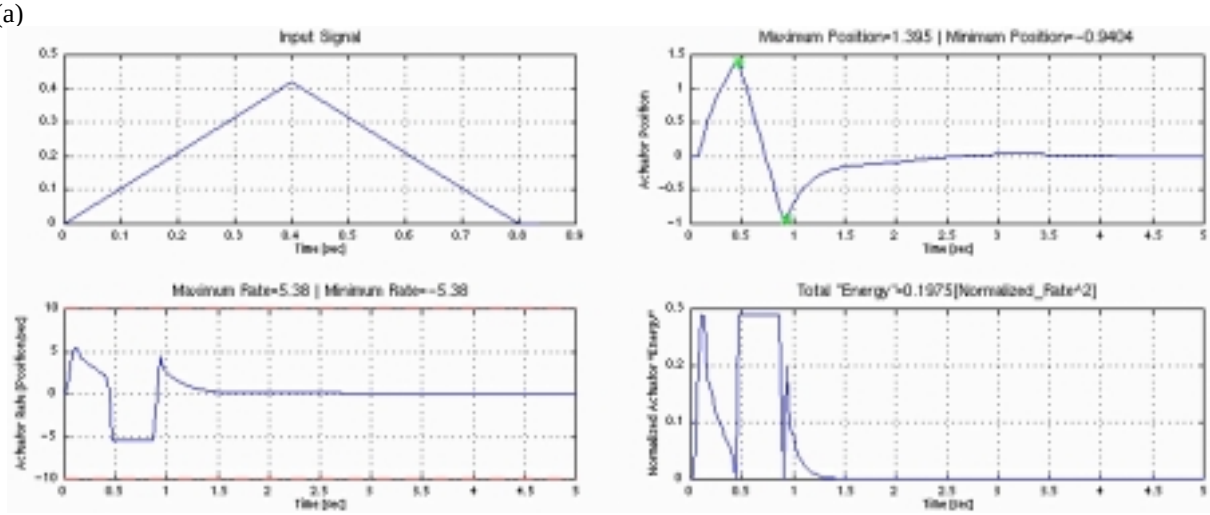
Fig. 14 Optimized RASCAL design.

Table 1 Comparison of design parameters for baseline[19] and CONDUIT solution

Design parameter	Function	Baseline value	Final value optimized in CONDUIT
Ktheta	Pitch proportional gain	13.6	12.1
Kphi	Roll proportional gain	8.0	8.5
Kpsi	Yaw proportional gain	7.6	8.3
Kq	Pitch rate gain	6.4	6.4
Kp	Roll rate gain	2.4	0.28
Kr	Yaw rate gain	3.2	3.1
KItheta	Pitch integral gain	0	1.0
KIphi	Roll integral gain	0	2.3
KIpsi	Yaw integral gain	0	1.1
Mtheta	Pitch command model frequency	2.0	2.5
Mphi	Roll command model frequency	2.5	4.6
Mpsi	Yaw command model frequency	2.0	4.1



(a)



(b)

Fig. 15 Supporting plots for the yaw quickness and actuator energy specifications.

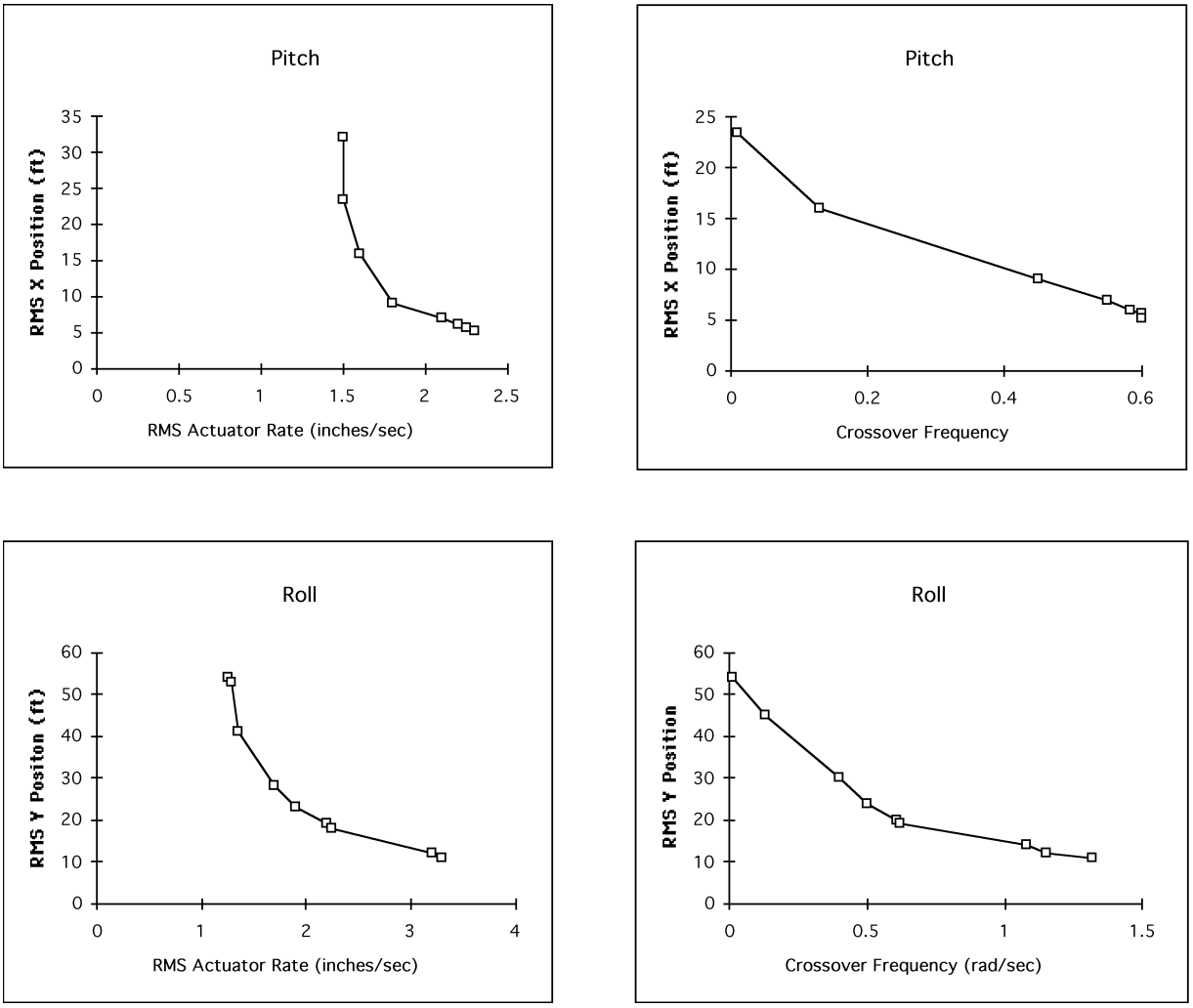


Fig. 16 CONDUIT studies showing trade-off of position station accuracy against required actuator rate and crossover frequency.

c. Position Hold Trade-Off

An example of how CONDUIT can be used to examine the trade-off between hover hold performance and actuator requirements is shown in Fig. 16. In this example, position and velocity feedback gains were tuned to reach various levels of hovering station-keeping accuracy, while the helicopter was subjected to a simulated wind gust time history. A position hold specification was employed as a soft constraint to enforce desired levels of station-keeping accuracy for a specified wind gust strength. The results show significant gains in hover hold performance for actuator rates of up to 2 in./sec, but little improvement for higher rates.

X-29 High Performance Fixed-Wing Aircraft Control Law Design Study

The X-29A (Fig. 17) was an experimental aircraft flown at the NASA Dryden Flight Research Center to demonstrate the integration of several aerodynamics and controls technologies into a highly maneuverable aircraft. It is a relatively small, single-seat aircraft powered by a single F404-GE-400 engine. The vehicle incorporates a forward-swept wing and static instability to reduce trim drag and enhance maneuverability.[20] The aircraft has three surfaces used for longitudinal control: all moving canards, symmetric wing flaperons, and aft fuselage strake flaps. The wing-canard planform results in a high level of instability that has a time-to-double amplitude near 150 msec.[21] There exist both low- and

Fig. 17 X-29A forward-swept wing fly-by-wire demonstrator.

high-frequency instabilities resulting in a very limited frequency range of stability. Also, the baseline control system has a crossover frequency more than half the canard actuator mode, which if pushed a little higher excites the actuator frequency.

a. X-29A Design Method and Flight Test Experience

The X-29A control law design approach concentrated on maximizing robustness rather than maneuverability for envelope expansion flight tests. Thus, as discussed in detail in Ref. 21, initial flight tests of the X-29 handling qualities indicated that the aircraft characteristics were Level 2 (adequate). The main deficiency reported by the pilots was sluggishness in the pitch axis. A design optimization effort was undertaken to determine if the pitch responsiveness could be improved without adversely affecting the controllability, thus improving the handling qualities of the aircraft. An optimization technique was developed at Dryden that was based on a single cost function with several frequency domain derived components. This cost function was selected to ensure minimum acceptable stability levels and reasonable surface activity, and to minimize the closed-loop resonance and required pilot compensation, based on the Neal-Smith criterion.[22]

Flight test engineers were not able to reach the design goal of 10 deg lead compensation and 0.0 dB resonant peak while maintaining adequate stability margins and reasonable surface activity. However, the pilot lead was reduced by almost 50% from the original gains and the achieved resonant peak was below 1.0 dB for the given design point. The pilot comments suggested a significant improvement in the vehicle's pitch response with the new gains. The design process showed a definite trade-off between the stability constraints, the surface activity, and the achievable Neal-Smith criterion. The resulting design had borderline stability margins and surface rates approaching the maximum capability of the system. CONDUIT was exercised to determine if further improvements in the dynamic response characteristics were achievable by tuning the control system design parameters.

b. Problem Setup in CONDUIT

Figure 18 shows the block diagram of the X-29 longitudinal control law created in the CONDUIT setup phase. The linearized models were developed and verified with flight test data from Dryden.[9] The longitudinal control law uses proportional and integral compensation in the forward path to improve aircraft pitch responsiveness. The lead-lag filter in the feedback path compensates for lags introduced by high-order dynamics. Stabilization is provided by feedback of vertical acceleration (n_z), pitch rate (q), and (estimated) pitch acceleration ($\dot{q}$). The pitch acceleration is estimated using a complementary filter that combines the canard signal and a two-point derivative of pitch rate. The "g" command authority is scheduled as a function of Mach number, altitude, and roll rate and is commanded linearly with stick position. The design parameters chosen in this study are the four feedback gains (G1, G2, G3, and G8), two PI controller gains (XKI1 and XKP1), two lead filter parameters (a1 and b1), and

one pilot command gain (G7). Table 2 summarizes the purpose of these gains and their baseline values.

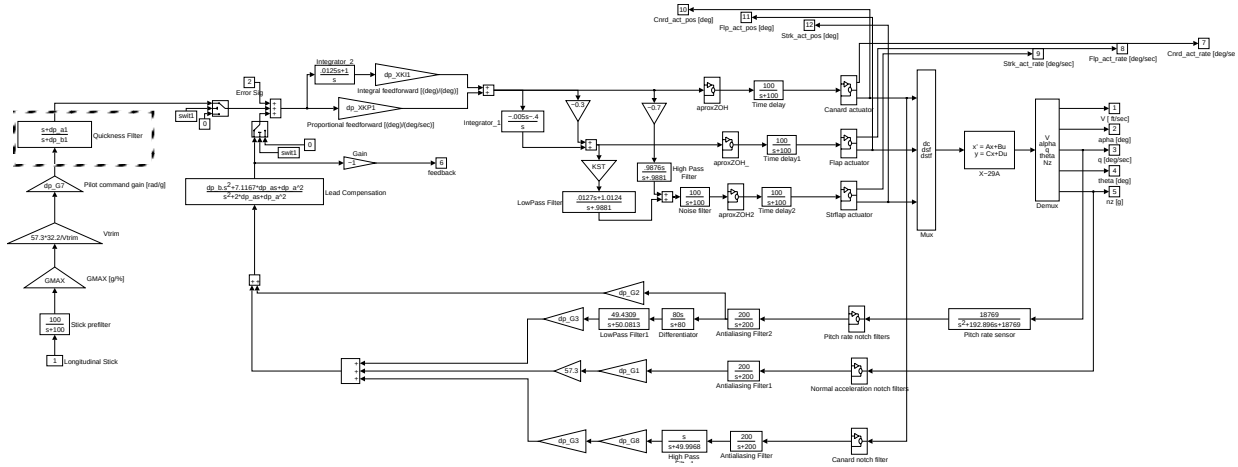


Fig. 18 Longitudinal ND control laws for up-and-away flight.

Table 2 X-29A design parameters

Design parameter	Function	Baseline value	Optimized baseline value	Quickness filter included value	Change relative to baseline (%)
XKI1	Integral gain	1.0	1.4	1.9	91.8
XKP1	Proportional gain	0.23	0.20	0.18	–20.9
G1	n_z feedback gain	0.0054	0.0054	0.0054	0
G2	$\dot{q}$ feedback gain	–3.6	–3.2	–2.1	–40.8
G3	q feedback gain	–0.18	–0.25	–0.25	–37.8
G7	Pilot gain	3.54	3.8	7.2	103.2
G8	High frequency q gain	16.7	15.6	12.8	–23.1
a1	Quickness filter zero	NA	NA	2.7	–31.8
b1	Quickness filter pole	NA	NA	8.3	–31.0
a	Lead compensator parameter	120.0	112.6	92.5	–22.9
b	Lead compensator parameter	11.0	10.3	8.4	–23.6

The “hard constraint” specifications chosen for the longitudinal analysis were 1) feedback-loop stability margins, 2) minimum stability for all closed-loop eigenvalues, and 3) a restriction on allowable change in the steady state “g/stick” response. The “soft constraint” specifications were 1) the Neal-Smith criterion,[22] 2) an updated mission oriented Bandwidth requirement for Flight Categories A and D,[13] and 3) a time-domain attitude quickness specification proposed in Ref. 13. The Phase 3 performance criteria were selected as 1) the Neal-Smith optimization specification, which minimizes the closed-loop resonance and required pilot compensation; 2) the actuator energy specification;
and 3) the crossover frequency specification. Several specifications were chosen as “check only.” These included the Smith-Geddes criterion, the Control Anticipation Parameter criterion (CAP), and the ω_{sp}, $T_{\theta 2}$, ζ_{sp} criterion. The CAP and ω_{sp},$T_{\theta 2}$, ζ_{sp} parameters are determined in CONDUIT from a lower-order equivalent system (LOES) fit[3] of the complete end-to-end system frequency response.

There are several advantages to the CONDUIT problem definition in comparison with the optimization design technique used by X-29 engineers. The first is that CONDUIT uses multi-objective optimization, which allows the relative importance of each specification to be determined by using “hard constraints,” “soft constraints,” or “performance criteria” rather than a single cost function incorporating the requirements of several specifications. Second, the optimization design method used by the X-29 engineers was limited to the Neal-Smith frequency domain criterion, which depends on the linear system performance. This ignores the nonlinear influence of actuator saturation, which is captured by the time-domain quickness specification[13] implemented in the CONDUIT solution. Another important aspect of the CONDUIT solution was the balance of improvements in agility against the associated increase in actuator energy requirements.

c. Baseline System Analysis in CONDUIT

The performance of the baseline X-29 design[9] as determined by CONDUIT is shown in Fig. 19. This baseline design corresponds to the “Normal-Digital” mode for up-and-away flight control law architecture. The flight condition for this analysis is Mach 0.7 at an altitude of 20,000 ft.

The baseline X-29 aircraft meets all the hard constraints except the stability margin criterion (GM = 7.9 dB, PM = 41.3 deg). Level 1 requirements for bandwidth requirement are met (soft constraint). Predicted handling qualities based on the Neal-Smith criterion (soft constraint) are borderline Level 1. However, the pitch quickness (soft constraint) performance is deep in the Level 2 region. In addition, the Neal-Smith optimization criterion is far from the desired 0 dB resonance and 10 deg pilot lead compensation. Also, the LOES based criteria and the Smith-Geddes criterion are also in the Level 2 regions. These results suggest that the pitch characteristics of the aircraft are inadequate. This corresponds well to the pilot comments concerning sluggish response in the pitch axis for the initial design.[21]

CONDUIT was next used to determine how much of an improvement could be made within the confines of the baseline system architecture, the selected nine design parameters, and the available actuator authority.

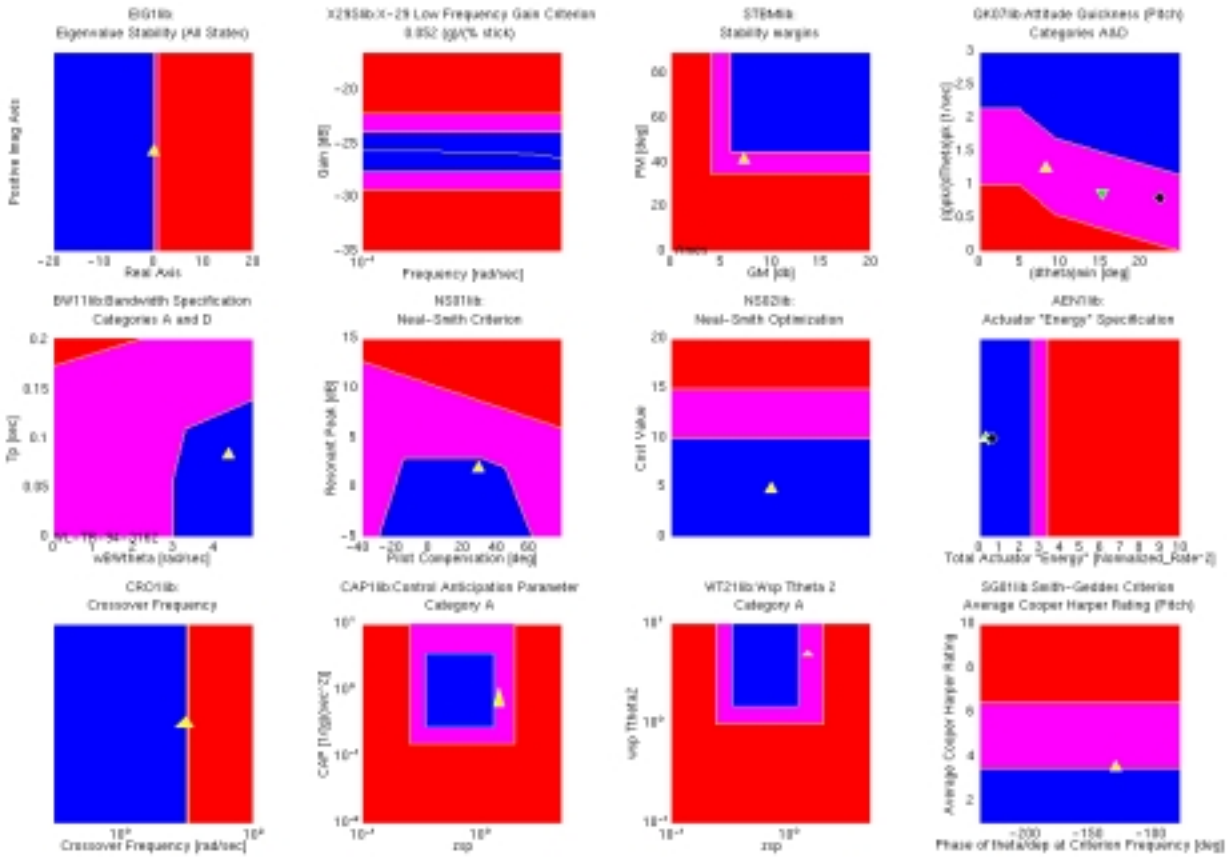


Fig. 19 Baseline X-29A performance and handling qualities results.

The key concerns were to meet the stability requirements, improve the moderate amplitude quickness, and reduce the required pilot compensation. The selected performance criteria were: minimum actuator energy and minimum crossover frequency.

d. Optimized X-29 Control System Performance

The optimization of the X-29 control laws using CONDUIT revealed some interesting aspects of the problem as formulated. First, it was revealed that the feedback gain on n_z (G1) had very little effect on the system response, and thus degraded the progress of the optimization algorithm. Therefore, this value was frozen at its baseline value. Second, it was revealed that there was no solution that meets all of the problem constraints using the existing X-29 architecture and selected nine design parameters. The best solution within the existing architecture is shown in Fig. 20. Although improvements from the baseline design are observed, the moderate amplitude quickness requirements could not be met using the existing architecture. The most noticeable improvement is the increased phase margin required to meet Level 1 stability margin requirements. The optimized baseline design parameters are listed in Table 2**.**

In order to address the deficiency in the response quickness, we included a first order lead-lag filter in the pilot command path. This “quickness filter” is seen in Fig. 18 with a dashed box surrounding it. Baseline values of 4.0 and 12.0 were chosen for the filter zero (dp_a) and pole (dp_b). Starting with the baseline values and the two added design parameters, CONDUIT was used to tune the eleven design parameters in the new architecture. With addition of the quickness filter CONDUIT quickly converged to an acceptable solution by meeting all the hard and soft constraints. With the hard and soft constraints met, CONDUIT reached Phase 3, and was further able to reduce the crossover frequency and actuator energy. The optimized solution including the quickness filter is seen in Fig. 21. The resulting design parameters and the

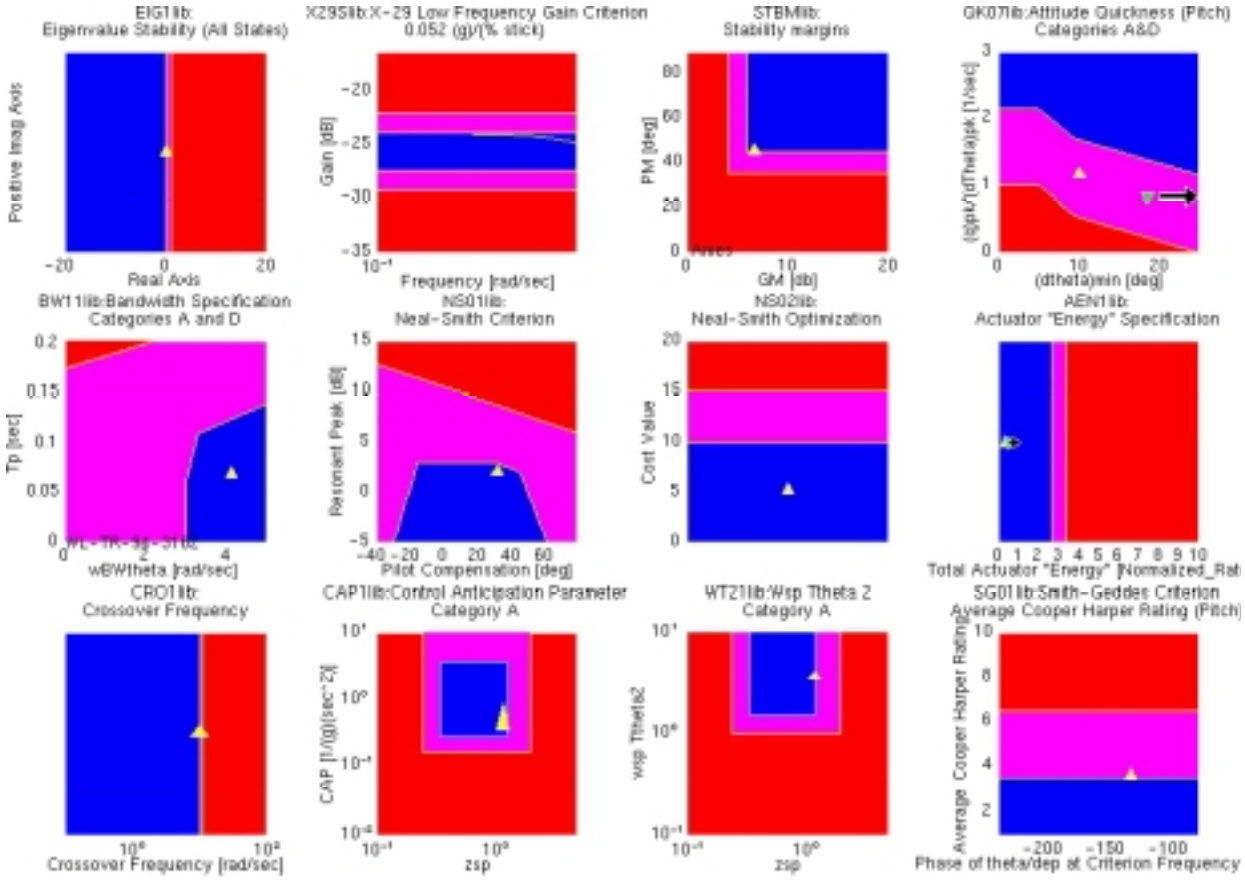


Fig. 20 Optimized X-29A performance and handling qualities results (optimized baseline).

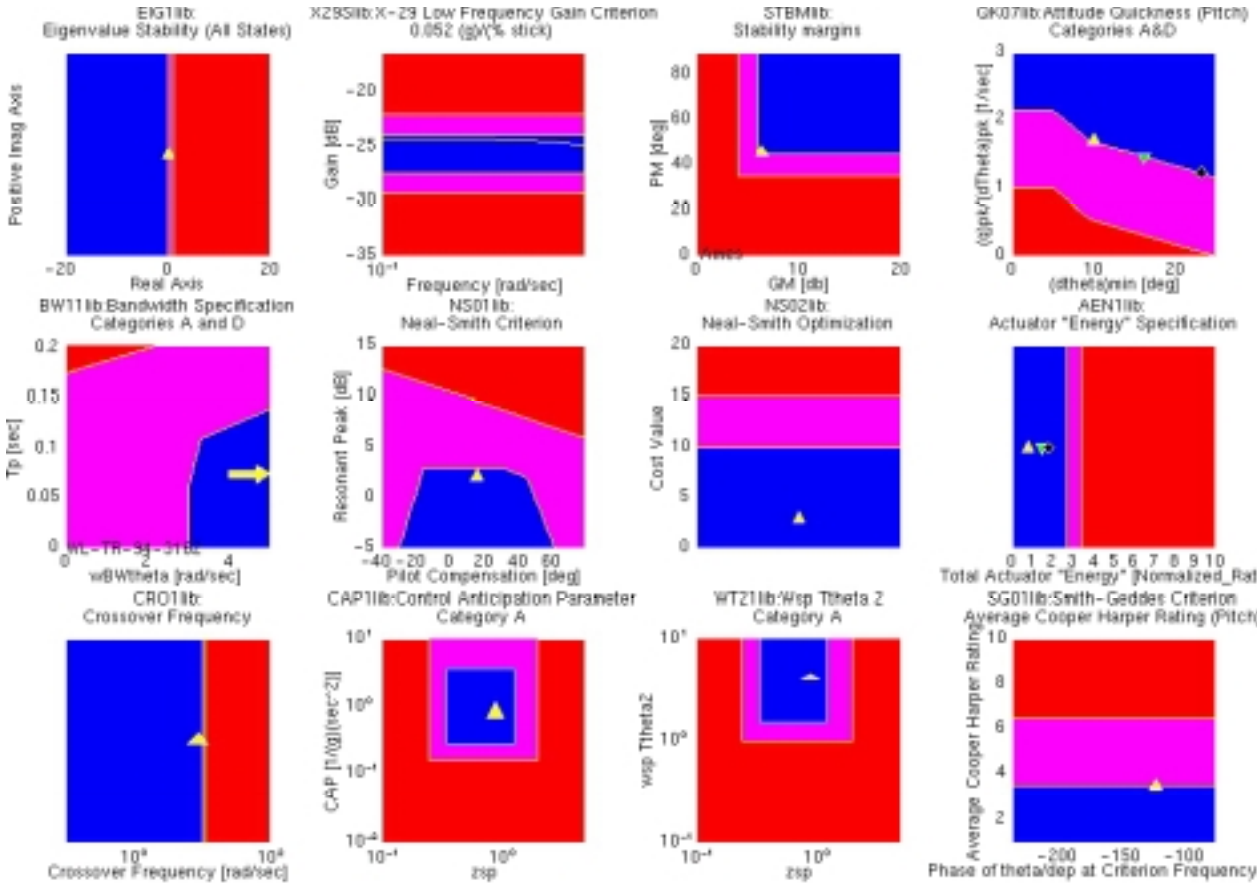


Fig. 21 Optimized X-29A performance and handling qualities results (with quickness filter).

percent change from the baseline design parameters are found in Table 2.

The stability margins for this design (Fig. 22) are about the same as those achieved for the optimized baseline (Fig. 20). However, there is now a substantial improvement in the moderate amplitude quickness (Fig. 23) and bandwidth (Fig. 24) relative to the optimized baseline. Figure 25 shows that the required pilot compensation (Lead = 16.2 deg) is about half that of the baseline system (Lead = 29.8 deg). As expected, the canard actuator is being taxed more severely; however, the system is less susceptible to actuator noise because the baseline crossover frequency (ω_c = 9.63 rad/sec) was reduced (ω_c = 8.99 rad/sec). The equivalent end-to-end response damping (Fig. 26) of the optimized system has been reduced from ζ_{sp} = 1.46 to ζ_{sp} = 0.895, due to the lead contribution of the quickness filter.

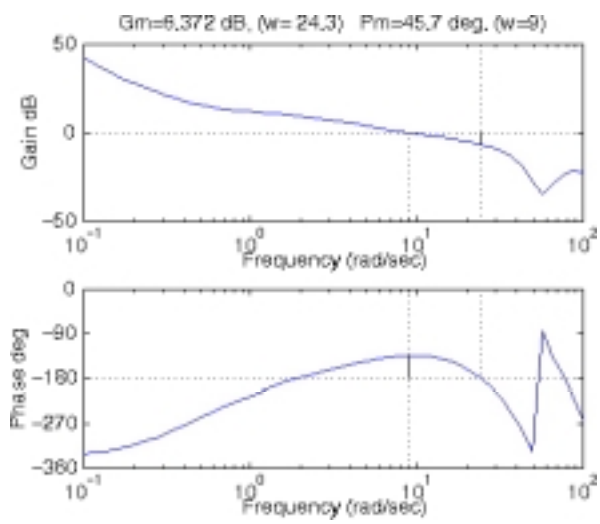


Fig. 22 Optimized X-29A stability margin results.

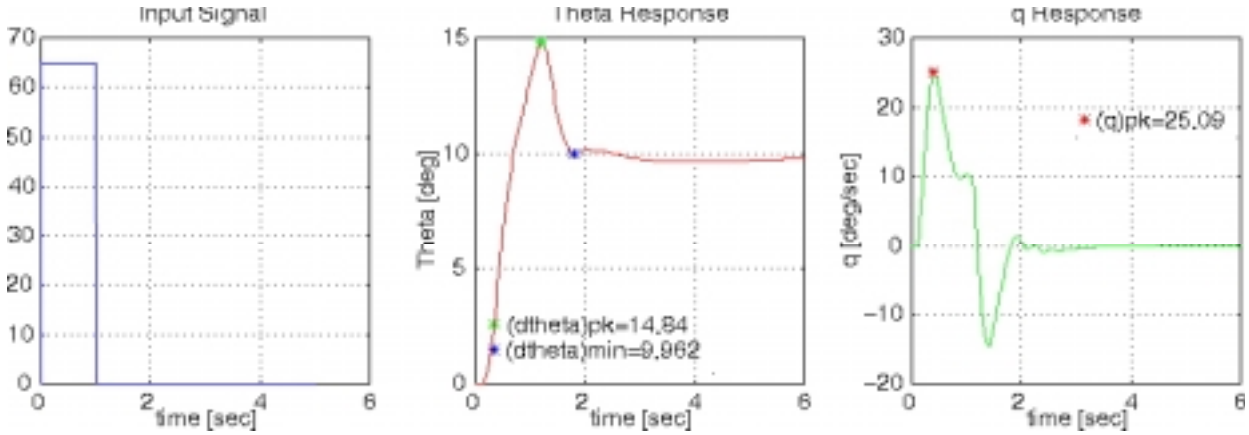


Fig. 23 Optimized X-29A moderate amplitude quickness requirement results.

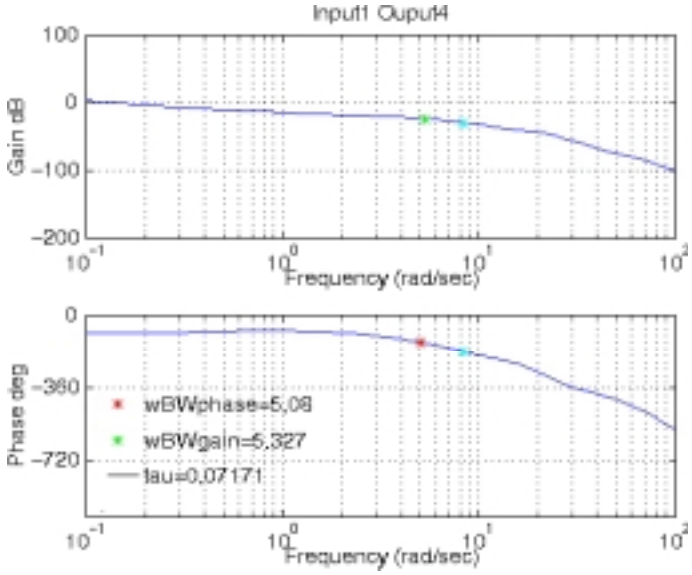


Fig. 24 Optimized X-29A bandwidth requirement results.

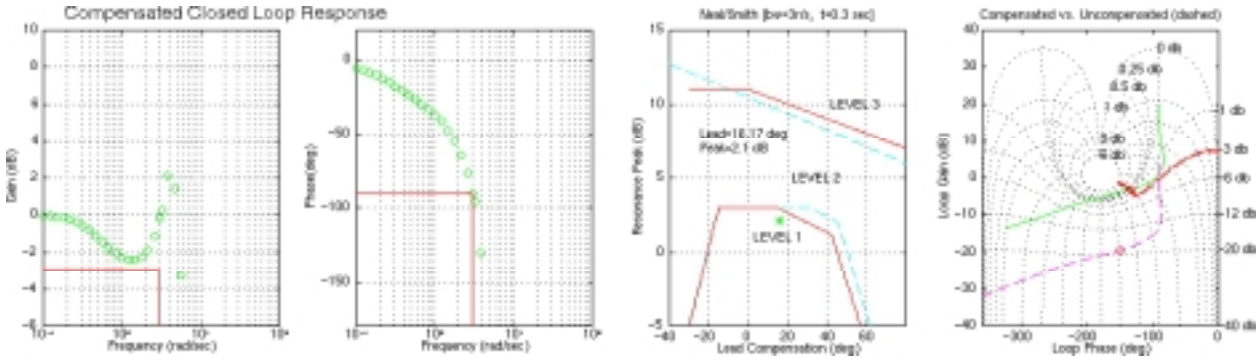


Fig. 25 Optimized X-29A Neal-Smith results.

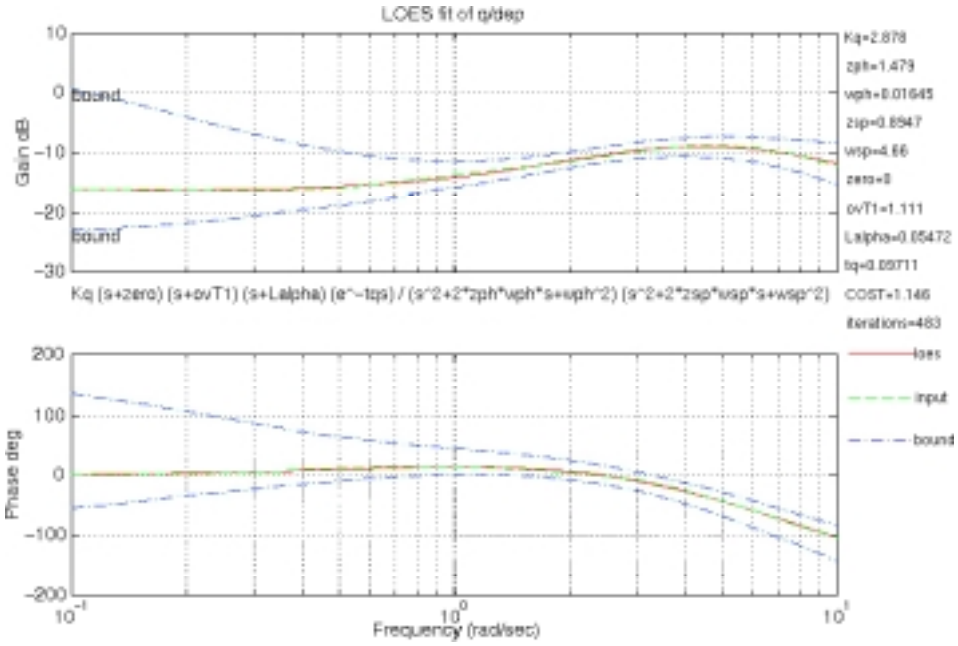


Fig. 26 Optimized X-29A LOES parameters.

These results show that CONDUIT was able to achieve increased agility and improved stability margins within the constraint of the existing actuator authority. All of the desired handling quality requirements were met, including the "check only" criteria: Smith-Geddes, CAP, and ω_{sp},$T_{\theta 2}$, ζ_{sp}.

Summary

1. A new computational facility for aircraft flight control design and evaluation, CONDUIT, has been developed and demonstrated. CONDUIT offers a state-of-the-art graphical environment for integrating simulation models and control law architectures with design specifications and constraints. This tool provides comprehensive analysis support and design guidance to a knowledgeable control system designer. CONDUIT offers the potential for significant reduction in time and cost of design, analysis, and flight test optimization of modern flight control systems.

2. Libraries of preprogrammed specifications for rotorcraft, fixed-wing aircraft, and servo-loop design are rapidly configured to the user's design problem. Compliance with all of the active specifications is graphically displayed on the criteria with a single pushbutton command, thus significantly streamlining the system evaluation process. A comprehensive set of supporting plots is available for each specification, thereby giving the analyst rapid insight into the control system behavior. A state-of-the-art multi-objective function optimization environment (CONSOL-OPTCAD) is integrated in CONDUIT to allow the user to tune selected design parameters (e.g., gains, time constants) for compliance with the active design specifications and selected performance specifications.

3. Case study applications to complex rotary- and fixed-wing flight control problems were presented. In the helicopter example, the baseline RASCAL UH-60 control system, as provided by the flight control contractor, is evaluated versus the ADS-33C handling-quality specifications. Then the selectable system gains are optimized to meet all system performance and handling-qualities specifications. In the X-29 fixed-wing example, CONDUIT analyses show that the handling qualities for the baseline control system exhibit poor quickness and inadequate stability margins. No significant improvement in quickness is achievable by adjusting the controller parameters for the baseline control law architecture. The inclusion of a quickness filter in the pilot command path provides an additional degree of freedom for control system tuning. CONDUIT successfully exploits the trade-off between forward loop and feedback dynamics to significantly improve the expected handling qualities and stability robustness.

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