Optimization and Piloted Simulation Results of the AH-64D Modern Control Laws

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ABSTRACT

The U.S. Army's Aviation Engineering Directorate led the first phase of a program to develop modern control laws (MCLAWS) for the AH-64D Apache Longbow to provide improved handling qualities for hover/low speed flight in a degraded visual environment. The design approach uses the existing partial authority stability augmentation system to provide both attitude command attitude hold and translational rate command response types over a useful range of aircraft velocities and attitudes to reduce pilot workload in degraded visual environments based on the requirements in ADS-33E. These new response types are integrated into a full envelope set of control laws providing a viable upgrade to the existing aircraft. Control law gains were optimized relative to handling qualities and control system performance requirements based on a high fidelity, analytical model drawing on deep system knowledge of relevant hardware and software related dynamics. A piloted simulation evaluation showed reduced pilot workload and improved handling qualities for the MCLAWS over the legacy flight control system.

NOTATION

ACAH	attitude command attitude hold
DVE	degraded visual environment
EDS	engineering development simulator
FLYRT	FLY Real Time simulation model
FTR	force trim release
HQ	handling qualities
HQR	handling qualities rating
MCLAWS	modern control laws
MTE	mission task element
PH	position hold
RACRS	risk and cost reduction system
SAS	stability augmentation system
TRC	translational rate command
UCE	usable cue environment

INTRODUCTION

The Aviation Engineering Directorate led the first phase of a program to develop modern control laws (MCLAWS) for the AH-64D. These control laws are aimed at providing both attitude command attitude hold (ACAH) and translational rate command (TRC) response types using the existing partial authority stability augmentation system (SAS). The goal is to improve hover/low speed handling qualities in a degraded visual environment (DVE) based on the requirements of ADS-33E (Ref. 1) to address safety issues associated with operating in harsh desert conditions where blowing sand and dust cause brownouts leading to increased accident rates.

Early MCLAWS development work was documented in a previous paper by Harding, et al (Ref. 2) where the overall design approach and the model following architecture were presented. A key element to the approach was the use of integrated design tools, including MATLAB/Simulink® for creating a graphical representation of the control laws, CIFER® (Comprehensive Identification from Frequency

Responses, Ref. 3) for model identification and CONDUIT® (Control Designers Unified Interface, Ref. 4) for control law analysis and optimization. CIFER® and CONDUIT® were both developed by the U.S. Army Aeroflightdynamics Directorate.

The program is currently in the final stages of control law development and has recently concluded preliminary piloted simulation evaluations in the Camber AH-64D risk and cost reduction simulator (RACRS) in Huntsville, Alabama. Funding has been secured for integration and flight testing phases to be led by The Boeing Company in Mesa, Arizona. Upcoming work includes a second piloted simulation evaluation to be conducted in the Boeing engineering development simulator (EDS) followed by flight testing scheduled for mid 2008.

This paper describes the AH-64D MCLAWS, including an overview of the three basic response modes and the blending strategy employed to produce a full envelope control law solution. Handling qualities analyses and control law optimization using CONDUIT® are discussed, including the impact of differences between the aircraft and simulation model dynamics on gain optimization. Finally, results of the preliminary piloted simulation evaluation to determine handling qualities ratings for several ADS-33E maneuvers are provided.

MODERN CONTROL LAWS

The AH-64D modern control laws were designed to provide improved handling qualities in hover/low speed flight by implementing appropriate response types to meet the requirements in ADS-33E for DVE conditions. In forward flight, the control laws are similar to the existing AH-64D rate feedback system. MCLAWS were developed primarily as a software upgrade to the existing partial authority SAS. The resulting design is a three-mode control system with automatic transitions between ACAH, TRC and rate response modes at the appropriate flight conditions to meet the requirements of ADS-33E.

The architecture for MCLAWS uses a model following approach to provide ACAH in the pitch and roll axes in hover/low speed. The pitch and roll attitude command models are described in Reference 2. Pilot inputs are passed through the command models to produce the desired rates and attitudes. These are passed through an inverse plant model to cancel the aircraft dynamics. Comparisons with the actual rates and attitudes produce feedback signals to reduce the difference between the two. The yaw and collective axes at hover use simple rate feedback and pilot command augmentation, or feed forward, similar to the legacy control laws.

TRC is achieved by closing the ground speed feedback loop outside the ACAH attitude loop. Pilot cyclic control inputs produce ground speed commands which are compared to the actual ground speed to produce error signals for the attitude command models. Position hold (PH) takes the same approach one step further. With PH engaged, the position feedback loop is closed outside the ground speed feedback loop resulting in the TRC mode being used to hold position. This series feedback structure assures that all feedback loops work together to achieve the same goal.

In forward flight, the control laws provide basic rate damping in all four control axes similar to the legacy control system. Roll attitude and velocity holds are available and are activated by cycling the force trim release (FTR). Additionally, heading hold and turn coordination are provided automatically depending on pedal activity and bank angle. For bank angles within ±4 degrees and no pedal control inputs, heading hold is active.

Altitude or flight path angle hold is pilot selectable at any airspeed depending on vertical rate. Altitude hold can be engaged for vertical rates less than 100 ft/min at hover/low speed and 200 ft/min in forward flight. Flight path angle hold works in either descent or climb for vertical rates above the altitude hold maximum limits. Control is achieved by varying the vertical rate with longitudinal ground speed to maintain a constant flight path angle. Flight path hold automatically transitions to altitude hold near hover or when the radar altitude goes below a safety limit to avoid flying into the ground.

Mode Blending

The MCLAWS response type architecture is shown in Figure 1. The basic response in hover/low speed is ACAH which is maintained in sideward and rearward flight out to the aircraft limit of 45 knots. With increasing forward ground speed, the system automatically transitions from ACAH to the forward flight rate mode between 20 and 25 knots. The transition has both ground speed and time based fade components to limit attitude disturbances for mild or aggressive transitions. During the transition, attitude feedback is faded out and rate commands are faded to zero leaving simple rate feedback. The yaw and collective axes are rate feedback across the entire flight envelope and do not have transition regions.

TRC and PH come together as a single pilot selectable mode. With TRC/PH selected, the system automatically transitions from ACAH to TRC as the aircraft's total ground speed goes below 10 knots. The reverse transition from TRC to ACAH occurs in one of two ways. Slowly increasing ground speed beyond 12 knots results in a time based fade into ACAH. Large control inputs which would command ground speeds greater than 14 knots cause the system to switch directly into ACAH mode to facilitate aggressive maneuvering from hover.

PH is available below five knots by cycling the FTR button which causes the system to drive the aircraft ground speed toward zero. Below one knot, position hold automatically captures position over the ground. Altitude hold and
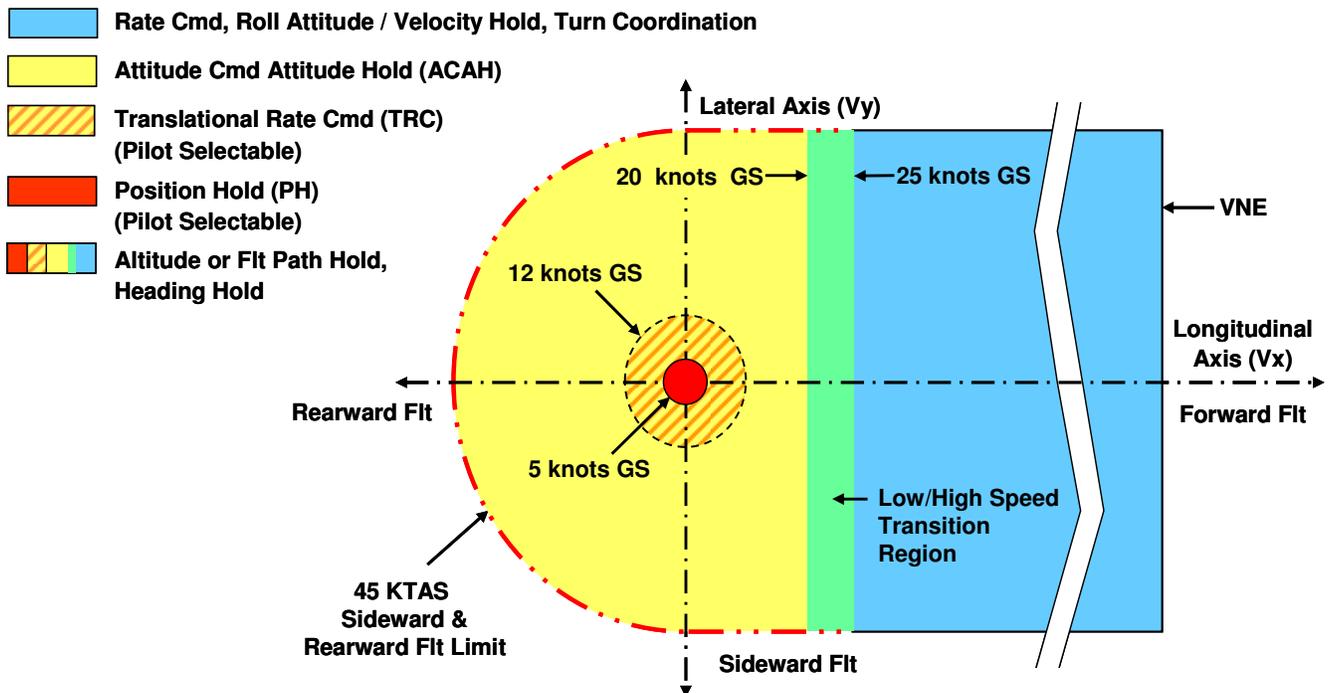
Figure 1. MCLAWS response type architecture

heading hold automatically come with position hold. When the cyclic controls are moved, position is released and the system reverts back to TRC mode.

Partial Authority Limitations

The amount of augmentation available to change the basic response of the helicopter is limited by the use of the partial authority SAS which does not have trim actuators. Despite this limitation, previous research has shown that most of the workload reduction in the DVE demonstrated with full authority ACAH systems can be achieved with a limited authority flight control system (Refs. 5, 6). The MCLAWS design included provisions for an expansion of the existing SAS authority from ±10% in roll, yaw and collective, and +20/-10% in pitch to a uniform ±20% in all axes. This expansion would involve a hardware modification to the SAS actuators and incorporation of improved system redundancy management algorithms. With the expanded SAS authority, the MCLAWS modes were designed to provide the basic ACAH and TRC characteristics over a useful range of aircraft velocities and attitudes to satisfy the intent of ADS-33E without persistently saturating the SAS.

ANALYSIS MODEL

A key element in the MCLAWS development was the use of integrated tools for modeling and analysis. Modeling was performed using Simulink® to create a graphical representation of the MLCAWS. Control law development was based on very accurate linear flight dynamics models previously identified from flight test data using CIFER®.

The identified models were linked to the control law model to form a closed loop simulation in Simulink®. Control law analysis and optimization was performed using CONDUIT®.

Successful optimization depends on accuracy in the analysis model which requires incorporating deep system knowledge regarding aircraft dynamics, mechanical controls, sensor filtering, and digital system delays. The aircraft dynamics were represented by separate 12 dof linear models at hover, 60 knots and 120 knots identified from frequency response flight test data (Ref. 7). The models were blended together to provide a continuous analysis across the speed range of interest. Analytical models of the actuator dynamics and sensor filtering were obtained from Boeing. Digital delays associated with the 64 Hz flight computer sampling rate and 50 Hz EGI (embedded global position system/inertial navigation unit) sensor update rate were also incorporated into the analysis.

Piloted Simulation Model

The design approach described above produces control system gains optimized for the actual aircraft (within the accuracy of the analysis model). In theory, these gains should be robust enough to perform well in the simulator. However, discrepancies between the simulation model and the aircraft can lead to less than optimum performance for piloted evaluations. The reverse approach of designing gains in the simulator produces results that often do not work well in flight test.

The MCLAWS piloted simulation was performed at the Camber RACRS facility. It uses the FLYRT blade element flight simulation model developed by Boeing (Ref. 8). The piloted evaluations documented in this paper were flown using RACRS' baseline FLYRT model (v6.1, 1998). Pilot comments using this model were that the simulation did not respond like the actual aircraft and the control loader characteristics gave the cyclic stick a heavy feel, unlike the aircraft. These issues led to an update of the FLYRT model, after the initial piloted evaluations being reported in this paper, to a more recent version available from Boeing (v2.1.8, 2006), and to modifications to the control loader force feel characteristics.

With the updated model, pilot comments greatly improved as the simulator was stated to be a good representation of the aircraft within the limitations of the fixed base simulation environment. Nevertheless, even with the new model simulation work using optimized gain sets for MCLAWS revealed increased overshoots or oscillations in the lateral axis response that were not evident in the analysis. To address this issue, frequency response data were collected to quantify the updated FLYRT model dynamics at hover.

Piloted frequency sweeps were flown in the simulator with the SAS-off. Data analysis showed the overall match between FLYRT and flight test data was very good. This reinforced pilot comments for the updated FLYRT model. The data were used to identify a 6 dof linear model of FLYRT using the same techniques used to identify the flight test models. This provided an equivalent linear FLYRT model for control law analysis. The goal was to expose potential dynamic differences between the aircraft and simulator in order to understand their impact on optimized control law gains.

A comparison of the damping and control power derivatives and effective rotor time delay (τ_f) for the identified models are provided in Table 1. The largest differences are in the pitch damping (M_q) and roll control power (L_{lat}). In general the FLYRT model has less damping, more control power and a smaller rotor time delay than the aircraft.

Table 1. Derivatives from identified hover models

Derivative	Flight-based	FLYRT-based	Percent Change
M_q	-0.625	-0.434	31
M_{lon}	0.027	0.029	7
L_p	-2.73	-2.55	7
L_{lat}	0.094	0.121	29
τ_f	0.121	0.098	-19

Comparisons of the roll and pitch rate responses of the identified linear models show a good match above 1 rad/sec (Figures 2 and 3). The area of concern is near the broken-loop crossover frequency (ω_c) for the attitude loop. The
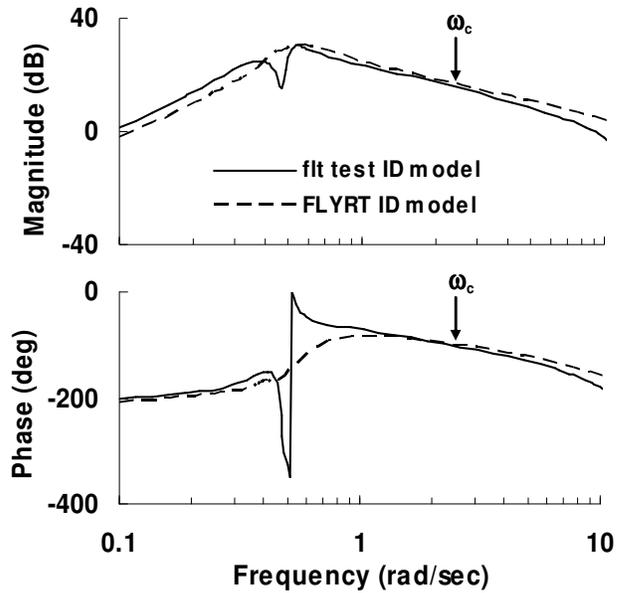
Figure 2. Unaugmented pitch rate response comparison for identified linear models
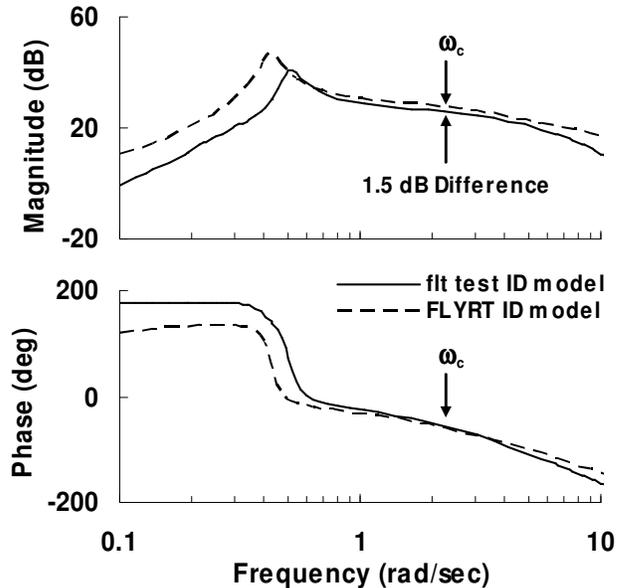
Figure 3. Unaugmented roll rate response comparison for identified linear models

frequencies shown on the plots were taken from the baseline MCLAWS analysis. In this area, small differences have an impact on stability which drives the optimization. The pitch rate responses of the two models are closely matched near the pitch crossover frequency at 2.5 rad/sec. In the roll axis, the higher control power of the FLYRT identified model is seen in the magnitude curve across the higher frequencies. This increased control power results in a higher broken-loop crossover frequency for the FLYRT model analysis and a reduction in lateral axis phase margin.

This could explain the lateral oscillations seen in the simulator. The overall impact on control system gains optimized for the simulator, as opposed to the aircraft, is addressed in a later section. Unfortunately, additional formal piloted evaluations using the upgraded FLYRT model could not be completed in time to be reported here.

CONDUIT® ANALYSIS

As mentioned earlier, CONDUIT® was used to perform the detailed analysis and optimization of the MCLAWS. This involved implementation of the Simulink block diagrams representing the control laws and the aircraft model in CONDUIT®, selection of criteria and specifications that embodied the design goals, selection of block diagram parameters that would be varied as part of the analysis/optimization, and finally using CONDUIT®'s optimization engine to vary those parameters until all specifications were satisfied. The CONDUIT® tunable block diagram parameters are referred to as "Design Parameters" and provide the means to adjust the control response to meet the requirements. The optimization engine in CONDUIT® uses a robust vector optimization algorithm (known as Feasible Sequential Quadratic Programming or FSQP) which ensures that every single specification is satisfied and not just a weighted sum of them.

Design Goals

As described earlier, the MCLAWS were designed to provide improved handling qualities in DVE within the constraints of the existing partial authority hardware. The goal for the ACAH design was to optimize the control laws such that the attitude responses of the aircraft closely resembled the command model responses in pitch and roll without significant overshoot or oscillations. This would in turn guarantee that the bandwidth and phase delay requirements stated in ADS-33E were satisfied since the command models were chosen for that purpose. The goal for the TRC design was for the aircraft ground speed response to be proportional to the pilot input, have a qualitative first order response characteristic with an equivalent rise time between 3.0 and 5.0 seconds, display minimal overshoot and oscillations, and have a smooth and non-oscillatory associated attitude response. For heading hold, the goal was to ensure a fast, smooth, and non-oscillatory disturbance rejection characteristic. Finally, for position hold, the goal was to achieve as quick a position disturbance rejection capability as possible without adversely affecting overall stability margins. To ensure good margins for both the inner and the outer loops, the margins were checked not only at the primary actuators but also directly at the position-error calculation points (Figure 4). Of course, all the stated goals had to be achieved while maintaining overall system stability, acceptable cross-axes coupling, and without encountering repeated or unacceptable actuator saturation characteristics.

Optimization Approach

Since the core response type of MCLAWS for hover and low speed is ACAH, the best approach for reaching an optimized design was to first concentrate on the inner ACAH loop to achieve the best ACAH design possible. The design parameters for the ACAH inner loop were then frozen and attention moved out to TRC and so on. This approach also limited the number of design parameters that the optimization engine had to deal with at each level, leading to a faster overall optimization process.

At each level the specifications and criteria applicable to that response type were evaluated and relevant design parameters tuned by CONDUIT®. Note that some of the specifications are applicable to all response types and were therefore repeated for each response type. For example, system stability and disturbance rejection had to be continually monitored as new loops were added and therefore each response type had its own gain/phase margin and disturbance rejection specifications.

Specifications: The specifications used for the MCLAWS were selected to ensure that the stated design goals were achieved.

1. The eigenvalue spec was used to verify that the closed loop system was stable. This was accomplished by checking that all the real parts of the eigenvalues of the system were negative or zero, ensuring that all the dynamics were stable or neutrally stable.

2. The stability margin specs were used to verify that satisfactory gain and phase margins were achieved for the broken-loop responses at both the actuators and at selected outer loop locations (Figure 4).

3. The bandwidth specs were included as key short-term response requirements in ADS-33E directly related to the step-response rise time for a piloted control input.

4. The generic rise time spec was used for TRC instead of the bandwidth spec. This spec fit the response with a low order equivalent system (LOES) consisting of a first order lag and a time delay. The rise time was estimated as the sum of the time constant of the first order system and the time delay. In addition to the rise time value, the cost of the fit was considered and controlled. If the cost of the fit was too large then the rise time value obtained could not be relied upon. Therefore, maximum allowable LOES cost specs were used to ensure that the fit cost was limited to an acceptable value.

5. The disturbance rejection specs were included to check the disturbance rejection bandwidths. Disturbance response bandwidth is defined in CONDUIT® as the frequency at which the Bode
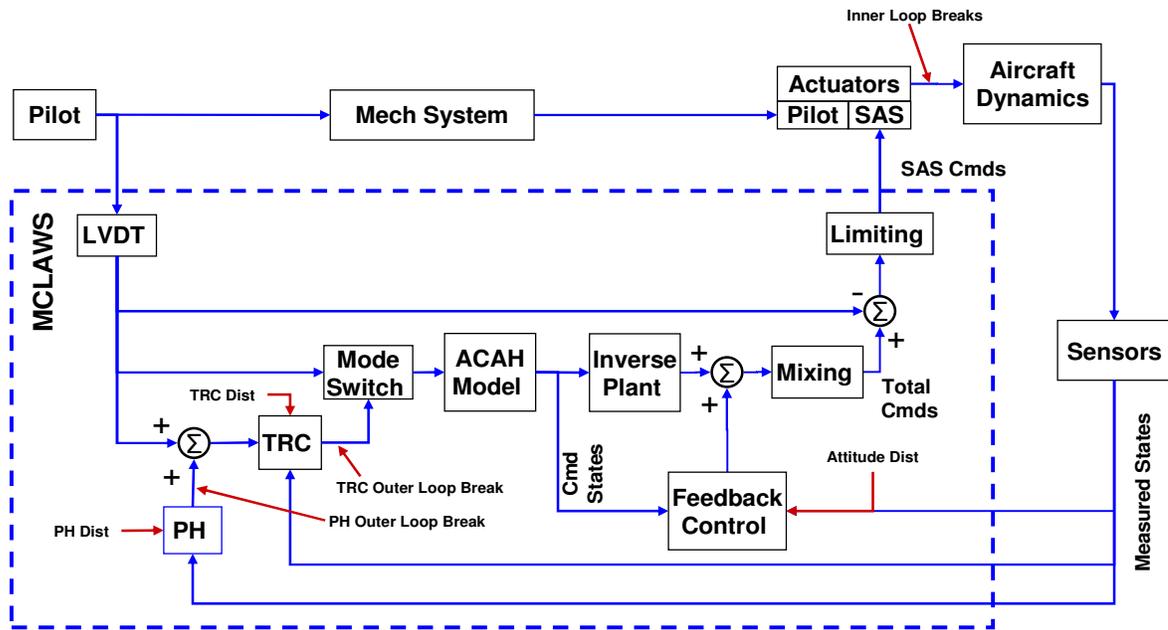
Figure 4. Overview of MCLAWS architecture

magnitude plot of the sensitivity function crosses the -3dB line. A higher disturbance-response bandwidth reflects tighter rejection of disturbances. Disturbance rejection capabilities of the system were evaluated for attitude, ground speed, and position, as shown in Figure 4.

6. System damping specs were needed in conjunction with the disturbance rejection specs to ensure that gains were not increased so high that system damping was compromised.

7. The model following specs were used to ensure that the aircraft responses followed the command models as desired.

8. Pitch/roll response coupling spec was used to ensure that lateral/longitudinal off axes responses remained within ADS-33E requirements.

9. Collective/yaw response coupling spec was used to ensure that the yaw response due to collective remained within ADS-33E requirements.

10. Actuator RMS and maximum crossover frequency specs were included as elements of a summed objective function to ensure that the best design was achieved with a minimum of over design.

In CONDUIT® each specification has three distinct regions corresponding to the 3 handling qualities levels:

- Level 1: satisfactory without improvement
- Level 2: deficiencies warrant improvement
- Level 3: deficiencies require improvement

The specifications are divided into 5 distinct categories: "Hard Constraints", "Soft Constraints", "Performance Objectives", "Summed Objectives", and "Check Only." Specifications dealing with system stability and margins are generally selected as "Hard Constraints" while specifications having to do with response characteristics and handling qualities are generally selected as "Soft Constraints." Performance measures such as broken loop crossover frequencies and actuator RMS are selected as "Performance Objectives" or "Summed Objectives."

CONDUIT® optimization proceeds by first attempting to move all "Hard Constraints" into Level 1 while ignoring all other specifications. This is referred to as Phase 1 of the optimization. After a set of design parameters are found that put all the "Hard Constraints" in Level 1, the design is usually stable and possesses satisfactory stability margins, though does not necessarily fly satisfactorily in terms of handling qualities. The optimization engine then attempts to find a set of design parameters which also put all the "Soft Constraints" in Level 1, while making sure that all "Hard Constraints" still meet the Level 1 requirements. This is referred to as Phase 2 of the optimization. When the design satisfies all the Level 1 requirements for both hard and soft constraints, a feasible, but not yet optimal, design solution is reached and the optimization process enters Phase 3. In Phase 3, CONDUIT® tunes the design parameters to optimize the system based on the selected objective criteria while ensuring the Level 1 requirements are still met, thereby ensuring minimum over design.

Selection of initial design parameters: CONDUIT® optimization proceeds much more smoothly and rapidly if the design parameters are assigned initial values based on the user's knowledge of the system. This is especially true of the design parameters which directly affect system stability margins. CONDUIT® can be used in manual mode to experiment with initial values for these design parameters. For example, the broken loop responses of the system can be plotted and the value of the angular rate feedback in each axes varied until desired crossover frequencies are achieved in all axes. The value of the attitude feedback gains can then be adjusted until satisfactory phase margins have been achieved. The resulting attitude and rate gains are not the optimized values; however, they provide a good starting point for the optimization engine. This and similar approaches were used to arrive at starting values of the design parameters.

Interaction of specs: One of the difficulties encountered during optimization is the sometimes conflicting requirements being imposed by the various specs. For example, the angular attitude disturbance rejection specs require an increase in the angular attitude feedback gains to increase the disturbance rejection bandwidths. An increase in the attitude feedback gains, however, generally result in a lowering of the broken loop phase curves at crossover, in turn resulting in a reduction in the phase margins. Therefore, an increase in the attitude feedback gains needed by the attitude disturbance rejection specs is opposed by the gain and phase margin requirements as dictated by the gain and phase margin specs.

As mentioned before, stability margin specifications are generally designated as hard constraints which the optimization engine satisfies before the soft constraints or objective criteria. Therefore, in most cases the stability margin specs are satisfied before the disturbance rejection specs, thus limiting the maximum disturbance rejection bandwidth that can be achieved. It is possible to achieve increased disturbance rejection bandwidths while maintaining satisfactory margins by also varying the angular rate feedback gain along with the angular attitude gains. The CONDUIT® optimization engine is well suited to exploring such interactions and finding compromise values that satisfy all requirements.

To explore the highest level of disturbance rejection that can be achieved while maintaining satisfactory stability margins, a new scheme employing ever increasing design margins on the disturbance rejection specs was employed. Taking advantage of the design margin optimization facility of CONDUIT® and the new capability to impose a design margin only on a selected set of specs, ever higher disturbance rejection bandwidths were imposed and the system re-optimized until no solution could be reached without breaking the stability margin requirements.

Optimization Results

The CONDUIT® optimization engine was used to optimize the design parameters of the system until Level 1 requirements were achieved for all the included performance and handling qualities specs. Then, design margin optimization, described earlier, was used to systematically increase the disturbance rejection capabilities of the design while maintaining satisfactory margins. Finally, the design was optimized using summed objectives including actuator RMS and maximum crossover frequency specs to ensure that the best design was achieved with a minimum of over design. Table 2 lists the values of the longitudinal, lateral, and directional design parameters along with the corresponding values from the AH-64D legacy flight control system and the percent change between the two. As may be seen, all values have changed significantly compared to the legacy design, some by several orders of magnitude.

Table 2. Optimized design parameters

Design Parameter	AH64D Baseline	MCLAWS	Percent Change
Ktheta	0.8594	0.33594	-61
Ktheta_int	na	0.01634	-
Kq	0.4655	0.39807	-15
Ku	0.0046	0.13833	2907
Kui	0.00023	0.01127	4800
Kx	0.061	0.17852	193
Kphi	0.4641	0.2907	-37
Kphi_int	na	0.06596	-
Kp	0.2149	0.05741	-73
Kv	0.0076	0.08054	960
Kvi	0.00038	0.00745	1861
Ky	0.061	0.18507	203
Kpsi	0.4297	0.2322	-46
Kpsi_int	0.1592	0.04141	-74
Kr	0.376	0.30115	-20

The main display of results in CONDUIT® is the Handling Qualities (HQ) window (Ref. 4) which graphically displays the current value of each spec plotted against spec boundaries as defined by ADS-33E or other sources. Figure 5 shows the CONDUIT® HQ window for the design parameters shown in Table 2 and is an overview of the final optimized results. Note that Figure 5 shows only part of the complete handling qualities window. Also, note the emphasis on stability margins and disturbance rejection characteristics which provide the primary specs for trading off system performance and stability. Consistent with the optimization approach already described, both stability margins and disturbance rejection bandwidths are generally at or near the Level 1 / Level 2 boundary.
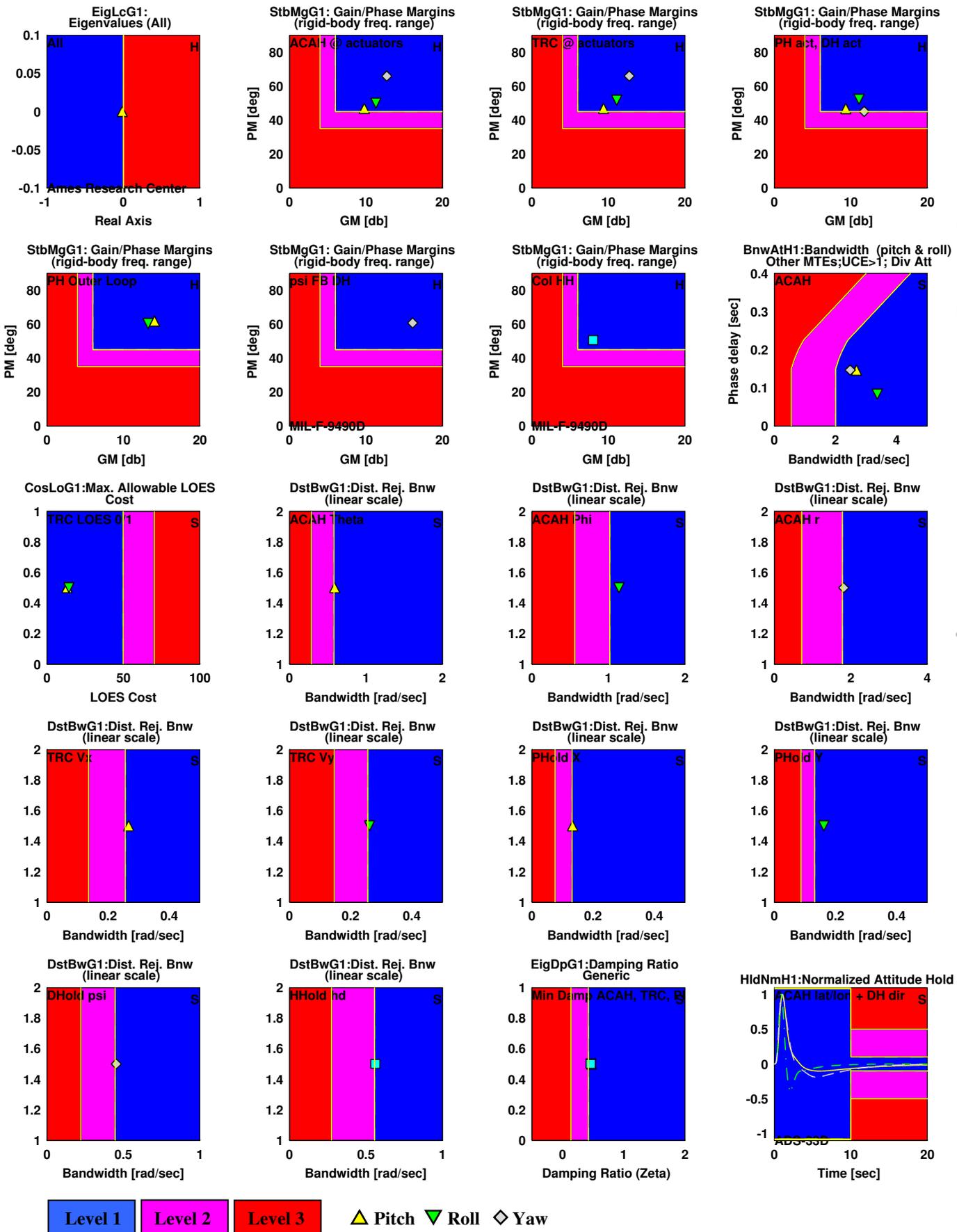
Figure 5. CONDUIT® Handling Qualities window (MCLAWS, partial)

**StbMgG1: Gain/Phase Margins
(rigid-body freq. range)**
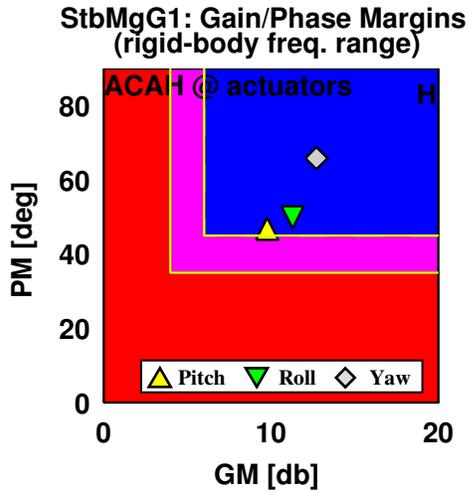
Figure 6. Stability margin spec for pitch, ACAH, at primary actuators

As mentioned earlier, each specification shown in the CONDUIT® HQ window encompasses three distinct regions. The red (dark gray in BW) region in each spec represents Level 3 handling qualities, the magenta (light gray in BW) region represents Level 2, and the blue (white in BW) region represents Level 1. The current value for each spec is calculated in the background by generating the required plots and using them to determine the value of such parameters as gain and phase margins, closed loop bandwidth, disturbance rejection frequency, model following accuracy, etc., and marked against the spec boundaries. These background plots and calculations are readily available to the user. Since the CONDUIT® HQ window contains every spec being evaluated for the design, it tends to be busy and hard to follow in printed form. Therefore, several of the specs from the HQ window are presented here to highlight the most important results.

Figure 6 shows the gain/phase margins spec for the ACAH response type with the loops broken at the primary actuators (Inner Loop Breaks in Figure 4). As may be seen, the gain and phase margins in roll, pitch, and yaw all satisfy the Level 1 requirements of 6 db gain margin and 45 degrees phase margin.

Figure 7 shows the corresponding supporting plot for the pitch case. The plot shows a crossover frequency of 2.5 rad/sec with a phase margin of 46.8 degrees and gain margin of 9.8 db. Note the closeness of the pitch phase margin value to the boundary in Figure 6, which indicates that the optimization has pushed the phase margin towards the boundary to ensure optimum performance with a minimum of over design. Of course, not all the spec values can be pushed close to the boundaries since optimization stops when further changes in the design parameters would cause one of the specs to cross the Level / Level 2 boundary into Level 2.

Gm=9.7867 dB, (w=6.0646) Pm=46.7664 deg. (w=2.5018)
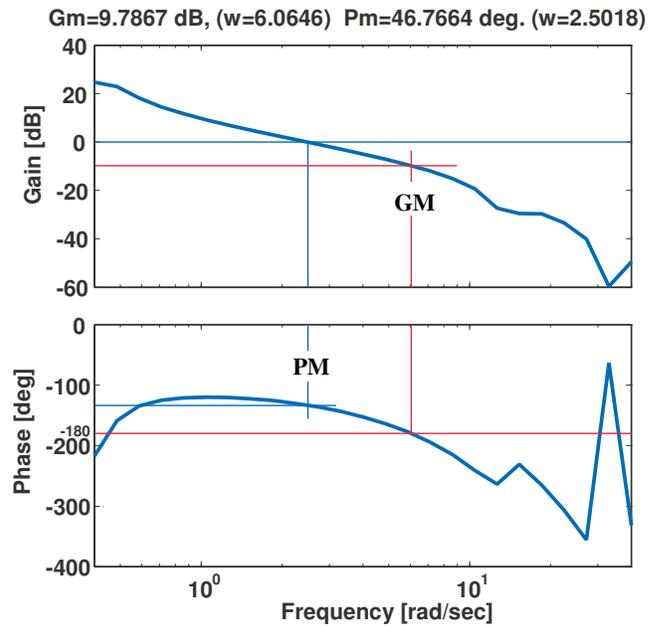
Figure 7. Stability margin supporting plot for pitch, ACAH, at primary actuators

**StbMgG1: Gain/Phase Margins
(rigid-body freq. range)**
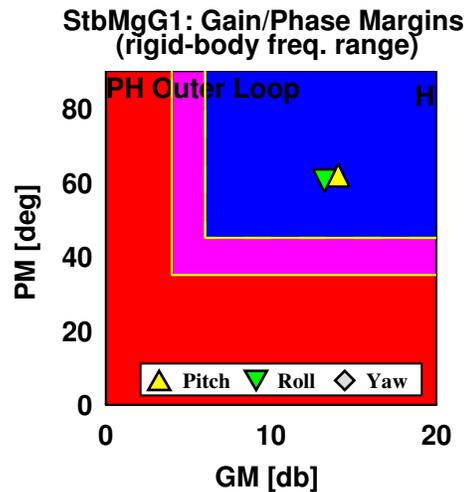
Figure 8. Stability margin spec, PH, at outer loop position error calculation point

As mentioned earlier, system stability for the outer loops, such as position hold, was not only checked with the loops broken at the primary actuators but also with the loops broken at the point of feedback error calculation (PH Outer Loop Break in Figure 4). Figure 8 shows the results for the position hold stability margin spec with the loop broken at the position error calculation point. As may be seen, both lateral and longitudinal position hold loops show Level 1 margins above the 6 db gain and 45 degrees phase requirement.

BnwAtH1:Bandwidth (pitch & roll)
Other MTEs;UCE>1; Div Att
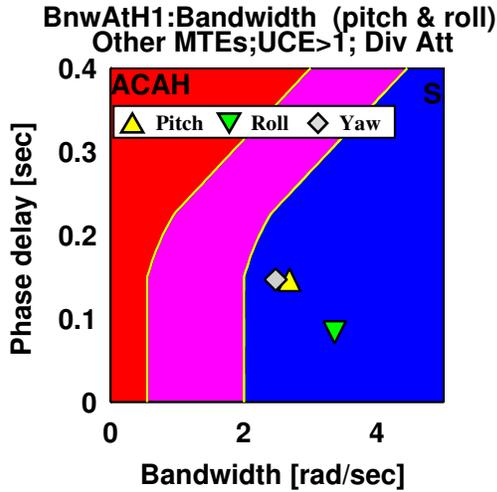
Figure 9. Bandwidth spec, ACAH

DstBwG1:Dist. Rej. Bnw
(linear scale)
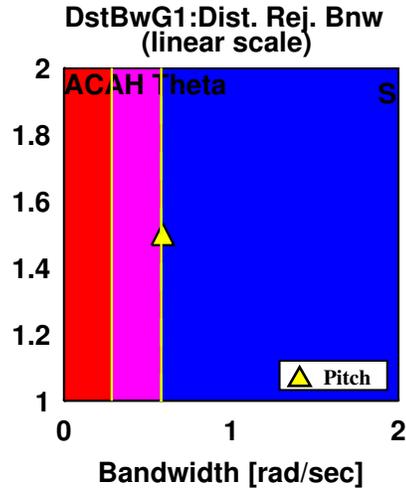
Figure 11. Pitch attitude disturbance rejection spec,
ACAH
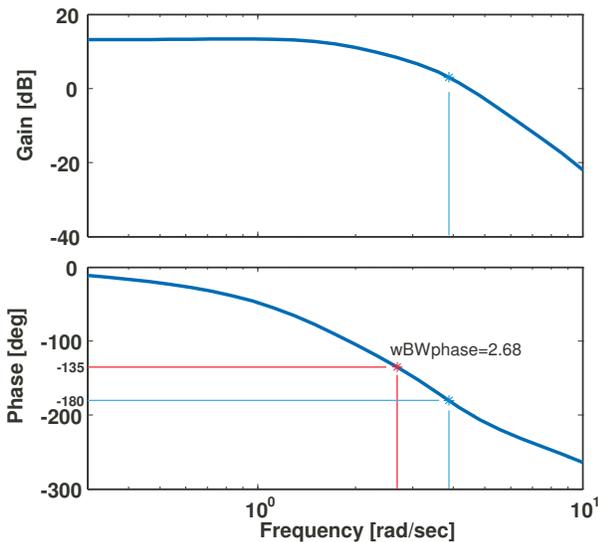
Figure 10. Bandwidth spec supporting plot for pitch,
ACAH
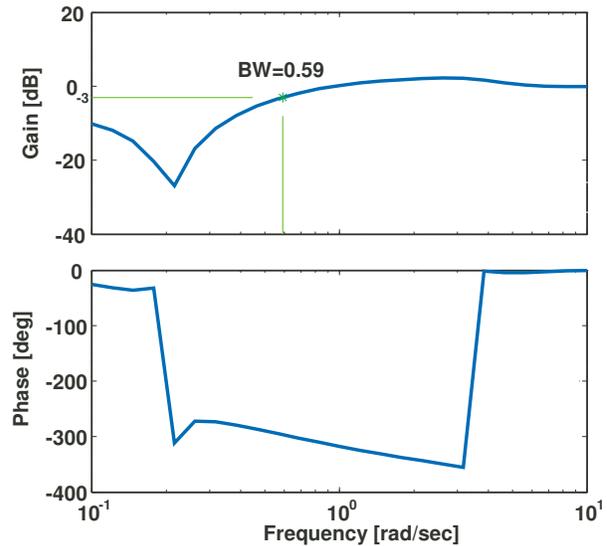
Figure 12. Pitch attitude disturbance rejection spec
supporting plot, ACAH

Figure 9 shows the bandwidth spec for ACAH with the optimized design parameters shown in Table 2. It can be seen that the ADS-33E bandwidth and phase delay requirements are satisfied for all axes. It should be noted that the primary contributor to system bandwidth for a model following design is the command model and therefore the results here indicate that the selected command models are satisfactory.

Figure 10 shows the supporting bandwidth plot for the pitch case. For an attitude response type, ADS-33E defines the bandwidth as the 45 degree phase bandwidth which is around 2.7 rad/sec in this case. The phase delay value is calculated using the point of 180 degrees of phase and a point at twice that frequency.

Figure 11 shows the pitch attitude disturbance rejection spec and shows that the pitch attitude disturbance response has a bandwidth of almost 0.6 rad/sec. As mentioned earlier, the Level 1 / Level 2 boundaries of the disturbance rejection specs were continually moved to the right (higher bandwidth) using design margin optimization until system damping was compromised. In effect, the Level 1 / Level 2 boundaries of the disturbance rejection specs were used as tuning knobs to maximize the disturbance rejection capabilities of the system.

Finally, Figure 12 shows the supporting plot for the pitch attitude disturbance rejection spec and depicts the calculation of the 0.6 rad/sec bandwidth at -3 db of gain.

In addition to ensuring that all the included specs were satisfied to Level 1, the Analysis Tool in CONDUIT® was used to manually check the responses of the system with the optimized gains. For example, time domain plots of system responses to position disturbances in both lateral and longitudinal axes were analyzed to ensure that the system quickly rejected the disturbance and that the response was smooth and non-oscillatory with the least possible amount of overshoot. The finalized gains were then ported to the RACRS simulation facility and used in piloted evaluations.

PILOTED EVALUATION

Piloted evaluations were conducted in the RACRS simulator (Figure 13) owned by the U.S. Army Program Manager-Apache Attack Helicopter (PM-AAH). RACRS was the prototype Longbow Crew Trainer and is currently maintained by Camber for PM-AAH. It is a tandem seat, fixed-base simulator that uses actual aircraft displays and controls wherever possible. It has five 50-inch LCD monitors for out-the-window display, providing the pilot with a 180° lateral field-of-view. RACRS incorporates head-tracking technology to allow the use of the Integrated Helmet and Display Sight System (IHADSS). The aircraft model used during the evaluation was the original FLYRT model (v6.1, 1998) developed by Boeing.

Figure 13. Pilot evaluations in RACRS simulator

Test Objective

The objective of this evaluation was to compare the hover and low speed handling qualities of the AH-64D with the legacy control laws versus the optimized MCLAWS. Six pilots participated in the evaluations including representatives from the U.S. Army and Boeing. Each pilot flew a series of mission task elements (MTE's) from ADS-33E and provided a handling qualities rating (HQR) for each MTE using the Cooper-Harper HQR scale. In addition, engineers evaluated each test point quantitatively

to compare actual performance to the adequate and/or desired performance criteria specified in ADS-33E.

Mission Task Elements

The MTE's for this test included the hover, pirouette, vertical maneuver, slalom, and sidestep maneuvers. These MTE's were chosen as mission-representative maneuvers for which handling qualities improvements in the hover and low-speed regimes would enhance mission effectiveness and overall safety. In addition, normal traffic pattern and brownout takeoff and landing MTE's were developed to evaluate specific elements associated with MCLAWS.

The brownout takeoff and landing MTE was designed to demonstrate enhanced lift-to-hover capabilities of MCLAWS to improve safety in brownout conditions. It consisted of a ground takeoff to hover in simulated brownout conditions, a vertical climb to exit brownout conditions, and a vertical descent to landing at the task initiation point. The normal traffic pattern task was designed to demonstrate smooth transitioning from one control mode to another as the aircraft was accelerated from hover to forward flight and then decelerated back to hover.

Discussion of Results

During the initial evaluation using the original FLYRT model (v6.1, 1998), pilots noted differences in the simulator flight dynamics and control force characteristics compared to the actual aircraft. These differences degraded the results and made the simulator prone to pilot induced oscillations for high precision tasks using the legacy control laws. These same issues did not have as large an impact on the results for MCLAWS due to the higher level of augmentation and larger reduction in pilot workload. Although the same flight model was used for both sets of control laws, evaluations with the legacy control laws were suspended after the first pilot's evaluation. The results presented in this paper include those from a single pilot for the legacy control laws and from all six pilots flying MCLAWS with the old model and control force-feel characteristics.

The pilot HQR results are provided in Figure 14. The solid symbols for MCLAWS indicate the average rating of the six pilots and the range bars indicate the minimum and maximum ratings obtained. In all maneuvers except the sidestep, the average results were just into the Level 2 handling qualities region with at least one pilot rating in the Level 1 region. Comparisons show the legacy control laws to have degraded ratings for the hover, pirouette and vertical maneuvers. The slalom maneuver has comparable results between the legacy and MCLAWS since the forward flight characteristics were not significantly altered.
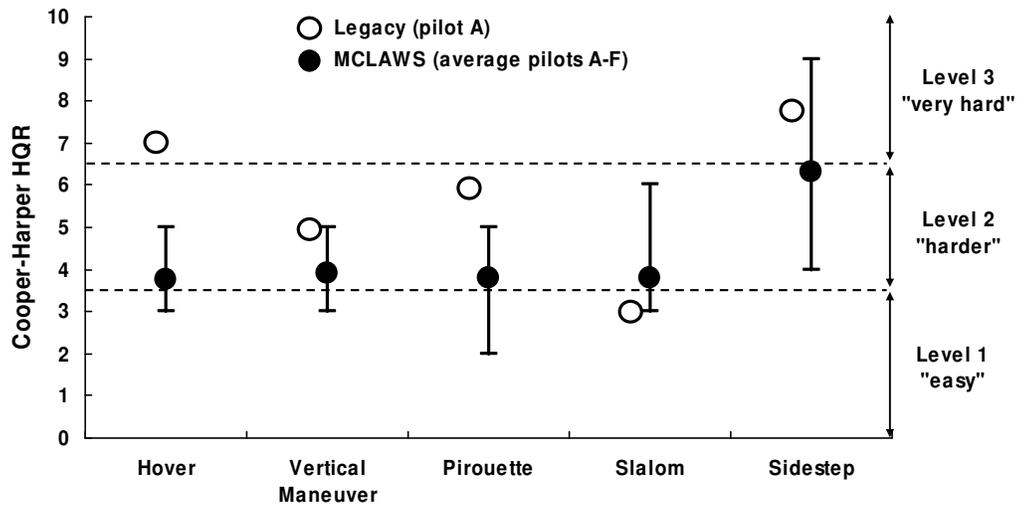
Figure 14. Handling qualities ratings from piloted simulation
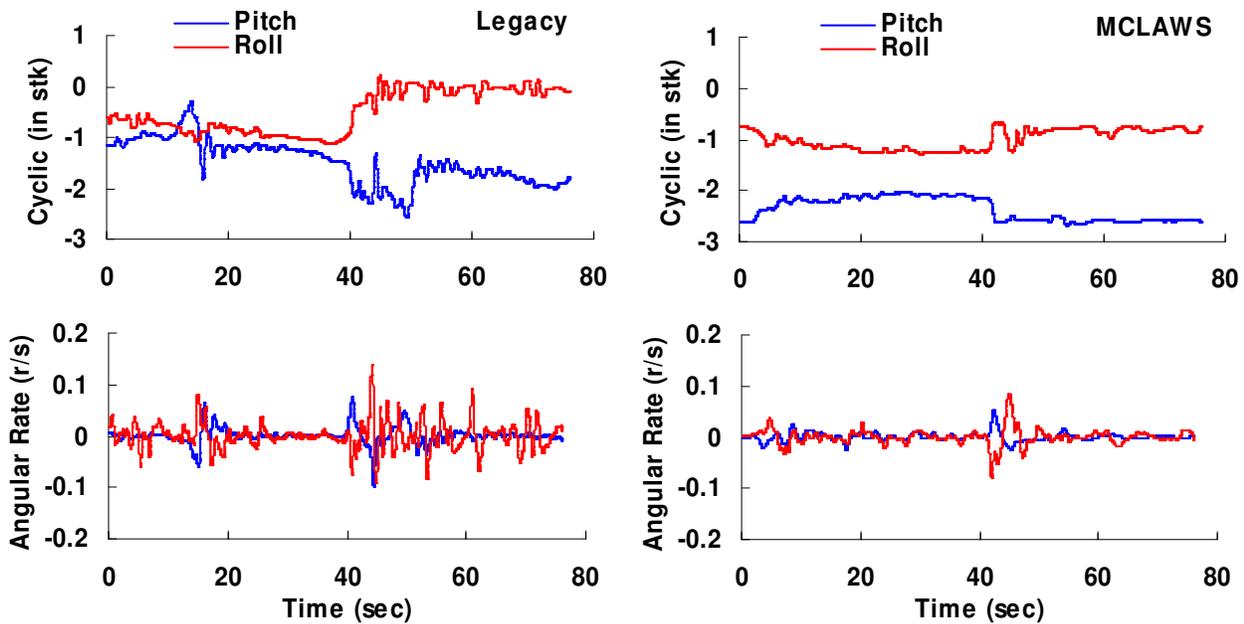
Figure 15. Time histories from legacy control laws vs MCLAWS for the ADS-33E hover maneuver

Figure 15 shows time history data of the pilot cyclic control inputs and angular rate responses during typical hover maneuvers. The maneuvers start with a diagonal translation to the hover board followed by a deceleration to a stabilized hover. The deceleration starts at about 40 secs in both cases. Note the increased control activity and angular rate response for the legacy control laws vs MCLAWS. This higher level of activity correlates with the degraded HQR results when flying the legacy control laws. It also correlates with pilot comments regarding increased

workload while flying this maneuver with the rate response system versus using the TRC mode with MCLAWS.

The sidestep MTE was rated as the most difficult maneuver by each pilot. During the sidestep task, the aircraft model tended to drift aft during deceleration. The evaluation pilots had difficulty detecting this aft drift due to the lack of visual cues available at high bank angles. Specifically, the vertical field-of-view was approximately 45 degrees in the simulator. Had additional visual cues been available, as in the actual aircraft or in a "dome" simulator, the pilots

would likely have met the adequate performance requirements, resulting in improved HQR's.

All evaluation pilots agreed that the brownout takeoff and landing MTE was very easy with the MCLAWS engaged. In fact, the maneuver was flown as a single-axis (collective-only) task. The normal traffic pattern MTE added value to the evaluation in that it verified smooth transitions between the hover, low-speed, and forward-flight control modes and demonstrated the level flight and turn coordination capabilities of MCLAWS.

Although this data was influenced by the simulator fidelity issues described, the evaluation demonstrated the potential for reduced pilot workload and improved handling qualities with response types such as ACAH and TRC regardless of aircraft dynamics or visual environment.

Adjusting Control Law Gains for Simulation

Very limited, piloted simulations were subsequently conducted using the updated FLYRT model (v2.1.8, 2006). During these simulations, certain degraded response characteristics were noted that were not evident in the analysis. It was thought that the differences between the linear flight-data-based model used in the analysis and the FLYRT model used in RACRS were contributing to these discrepancies. Therefore, the flight-data-based model was replaced with one generated from FLYRT frequency sweep data and the CONDUIT® analysis was revisited with the new model.

Using the FLYRT-based model with the gains optimized for the flight-data-based model, it was noted that the lateral phase margin for ACAH response type was less than 45 degrees and that the rise time for lateral TRC was faster than 3.0 seconds. The optimized gains used with the flight-data-based model were manually adjusted to bring all specs into Level 1 with the FLYRT-based model. Table 3 shows the design parameters that were changed and compares the new values to those used with the flight-data-based model. The low phase margin required reductions to the lateral feedback gains thus impacting the performance of the closed loop system. A future piloted simulation in RACRS is planned and will use the upgraded FLYRT model and these modified gain values which take into account the response dynamics of the actual model being flown.

Table 3. Design parameter changes to achieve Level 1 with FLYRT-based model

DP	Flight-based Model	FLYRT-based Model	Percent Change
Kx	0.17852	0.18745	5
Kphi	0.2907	0.23256	-20
Kv	0.08054	0.06846	-15
Kpsi	0.2322	0.24381	5

CONCLUSIONS

Modern control laws (MCLAWS) have been developed for the AH-64D and evaluated in a piloted simulation to demonstrate improved handling qualities in hover/low speed flight. Key elements of this work include:

1. The MCLAWS were developed as a full envelope set of control laws with three separate response types including ACAH and TRC in hover/low speed and a rate response in forward flight to provide a flight control system upgrade to the existing aircraft.

2. CONDUIT® was used for detailed analysis and optimization of MCLAWS design parameters using a three stage process including: 1) optimization to Level 1 requirements for performance and handling qualities specs, 2) design margin optimization to increase disturbance rejection characteristics while maintaining Level 1 stability margins, and 3) use of summed objectives like actuator RMS to prevent over-design.

3. The dynamics of the simulation model impact the performance of control laws for piloted evaluations. Degraded stability margins could result in oscillatory response and require feedback gain reductions.

4. Piloted simulation results demonstrated reduced pilot workload and improved handling qualities with MCLAWS versus the legacy control laws for the hover/low speed MTEs evaluated.

ACKNOWLEDGMENTS

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