

Development of Modern Control Laws for the AH-64D in Hover/Low Speed Flight

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ABSTRACT

Modern control laws are developed for the AH-64D Longbow Apache to provide improved handling qualities for hover and low speed flight in a degraded visual environment. The control laws use a model following approach to generate commands for the existing partial authority stability augmentation system (SAS) to provide both attitude command attitude hold and translational rate command response types based on the requirements in ADS-33E. Integrated analysis tools are used to support the design process including system identification of aircraft and actuator dynamics and optimization of design parameters based on military handling qualities and control system specifications. The purpose is to demonstrate the potential for improving the low speed handling qualities of existing Army helicopters with partial authority SAS actuators through flight control law modifications as an alternative to a full authority, fly-by-wire, control system upgrade.

NOTATION

ACAH	attitude command attitude hold
DH	direction hold
DVE	degraded visual environment
HH	height hold
HQ	handling qualities
MCLAWS	modern control laws
PH	position hold
RC	rate command
SAS	stability augmentation system
TRC	translational rate command
UCE	usable cue environment

INTRODUCTION

The AH-64 Apache was designed in the late 70's and went into service as the US Army's most advanced day, night and adverse weather attack helicopter in 1986. The flight control system was designed to meet the relevant handling qualities requirements based on MIL-F-8501 (Ref. 1). Only slight improvements were made to the flight control system during the D model upgrade years later. Although the AH-64 was designed to operate in all conditions, there were no dedicated handling qualities requirements to account for the increased pilot workload associated with operating in a degraded visual environment (DVE). As a result, the handling qualities are not optimum for all conditions. Operation in desert environments, where brown-outs are often encountered during takeoffs and landings, has resulted in increased accident rates. These accidents are associated with the pilot's loss of situational awareness due to a lack of visual cues and represent both a safety and cost concern. The US Army Safety Center recognizes this trend throughout the helicopter fleet. In a recent Safety Center accident investigation study, the number one material fix toward improving army aviation safety and reducing

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accidents by as much as 50% was identified as improving the hover and low speed handling qualities (Ref. 2). Similar findings were reported by Key based on Army helicopter pilot error mishap data (Ref. 3).

Since the design of the original AH-64 flight control laws, over 20 years of research in helicopter flight controls and handling qualities has shown that there is a degradation in handling qualities for near-earth tasks as the pilot's visual environment degrades. These degraded handling qualities result in higher pilot work load and increased accident rates. The research has also shown that the degraded handling qualities can be overcome by changing the control response type to provide increased stability. The results of this research led to the development of a new handling qualities specification for military rotorcraft ADS-33E (Ref. 4). ADS-33E incorporates a usable cue environment (UCE) rating scale to account for the lack of visual cues while operating at night and poor weather conditions. As the UCE degrades, the helicopter control response type must be improved from a rate command, to an attitude command, to a translational rate command system in order to maintain satisfactory handling qualities. All current army helicopters were designed before the specification was developed; however, flight control system upgrade programs are now required to meet some portions of the new specification. The Army's long term goal is to have all helicopter flight control systems for both new and legacy aircraft designed or upgraded to meet the more stringent handling qualities requirements of ADS-33E.

In 2005, the Aviation Engineering Directorate initiated a program to develop modern control laws (MCLAWS) for the AH-64D. The term modern, in this paper, refers to updated control laws (compared to the legacy system) that are designed specifically to meet ADS-33E handling qualities requirements by implementing new response types such as attitude command attitude hold (ACAH) and translational rate command (TRC). The goal was to apply the latest technology and analysis tools to develop new control laws for improved AH-64D handling qualities in hover and low speed flight using the existing mechanical control system. The program leveraged previous research on achieving an ACAH response type with limited authority systems (Refs. 5, 6) and a demonstration program on the UH-60 Black Hawk (Refs. 7, 8). The UH-60 program involved the design of modernized control laws to provide an ACAH response in low speed flight. The program included both a simulation evaluation and a flight test demonstration. The results confirmed the improved handling qualities for hover-related mission tasks over the legacy control laws using the existing $\pm 10\%$ authority SAS.

A key element in the success of the UH-60 MCLAWS program was the use of an integrated tool set for modeling, analysis and simulation. These same integrated tools provide the foundation for the work presented in this paper. Modeling was performed using Simulink[®] for graphic

programming. System identification of aircraft and actuator dynamics was accomplished in the frequency-domain using CIPHER[®] (Comprehensive Identification from Frequency Responses, Ref. 9). Control law analysis and optimization was performed using CONDUIT[®] (Control Designers Unified Interface, Ref. 10) with desktop simulation provided by RIPTIDE (Real-time Interactive Prototyping Technology Integration Development Environment, Ref. 11). CIPHER[®], CONDUIT[®] and RIPTIDE were all developed by the US Army Aeroflightdynamics Directorate.

This paper presents the development of modern control laws to improve the hover and low speed handling qualities of the AH-64D using the existing aircraft hardware including the force trim system and partial authority SAS actuators. Development was based on a linear flight dynamics model previously identified from frequency response flight test data using CIPHER[®] (Ref. 12). The identified model was linked to the control law model to form a closed loop simulation in Simulink[®]. An overview of the model following control law architecture used to achieve the required ADS-33E response types is presented. The impact of actuator saturation on the design is discussed. The primary focus of the paper is on the use of CONDUIT[®] to perform analysis and control law optimization against multiple handling qualities and control system specifications. Although piloted handling qualities ratings are not presented, the control law design was flown in RIPTIDE to evaluate the closed loop response characteristics in a piloted simulation environment.

OBJECTIVE

The objective of this study was to develop new flight control laws for the AH-64D to achieve Level 1 handling qualities in the day and in degraded visual environments (DVEs) in accordance with ADS-33E. The DVEs that were considered during the design and development of the system include a moonless, overcast night and brown-out conditions from dust kicked up during near earth operations. Both of these conditions result in a Usable Cue Environment of 3 (UCE=3). The mission task elements to be considered were those for attack rotorcraft.

The constraints on the study were that these objectives be achieved through software upgrades to the flight control laws with no significant changes to the mechanical flight controls. The existing flight control system includes mechanical linkages from the pilot and copilot/gunner stations to the primary actuators. Partial authority SAS servos are built into the primary actuators and are capable of augmenting the actuator output by $\pm 10\%$ of the total pilot control authority in the lateral, directional and collective axes. The pitch SAS has 20% forward and 10% aft authority. The trim feel system consists of a magnetic brake which allows the pilot to reset the stick forces using a force trim release button on the cyclic stick. There are no trim actuators on the AH-64D.

AIRCRAFT MODEL

Control law development requires an accurate model of the aircraft flight dynamics. The work presented here was based on a frequency domain identified model of the AH-64D at hover (Ref. 12). The model was identified using CIFER[®] with a state-space model structure that included the coupled dynamics of the rigid body, flapping, coning, dynamic inflow, lead-lag, and rotor rotational dynamics for a total of 12 degrees of freedom. Also included in the analysis were models of the actuator dynamics, including rate and position limits and the mechanical flight controls. Due to the short mechanical paths between the pilot controls and actuators for the longitudinal, lateral and collective axes, only the dynamics of the actuators were a concern for control law development. First order transfer function models of the actuator dynamics were validated using frequency response flight test data measured from the pilot input to the actuator output. The directional axis is different due to the much longer control path leading from the cockpit back to the directional actuator (located near the tail rotor). The impact of hysteresis and component flexibility results in additional phase roll-off in the pilot pedal to actuator frequency response. This additional phase roll-off was approximated with an effective time delay of 30 msec (Ref. 12) and included as a model of the mechanical system. The identified flight dynamics model, mechanical system, and actuator models were linked to an analytic model of the flight control laws to form a closed loop simulation in Simulink[®] (figure 1).

MCLAWS DEVELOPMENT

The architecture for MCLAWS uses a model following approach to achieve the required response (figure 1). The aircraft is made to follow ACAH command models in pitch and roll and a rate command (RC) model in the yaw axis. Control is achieved through both feed forward control estimating from the inverse plant dynamics and response error feedback. Pilot control inputs produce the ideal response or commanded states through the command models. The commanded states are then used to construct an estimate of the total control input needed to duplicate the response through the inverse plant model. The commanded states are also compared to the measured states to generate feedback error. Together these signals are combined to represent the total control needed to fly the aircraft.

The AH-64 does not use mixing in the mechanical flight control system to remove the inherent pitch/roll or collective-to-yaw aircraft coupling. Control mixing is accomplished through the automatic flight control system. The MCLAWS architecture was structured to implement control mixing on the total control commands as shown in figure 1. With the mixing added, the resulting commands represent the total control input. In this partial authority SAS implementation, the limited authority SAS command is found by subtracting off the actual pilot inputs. This overview demonstrates the building blocks or inner loops of MCLAWS on which higher level modes such as TRC, position hold and heading hold are based.

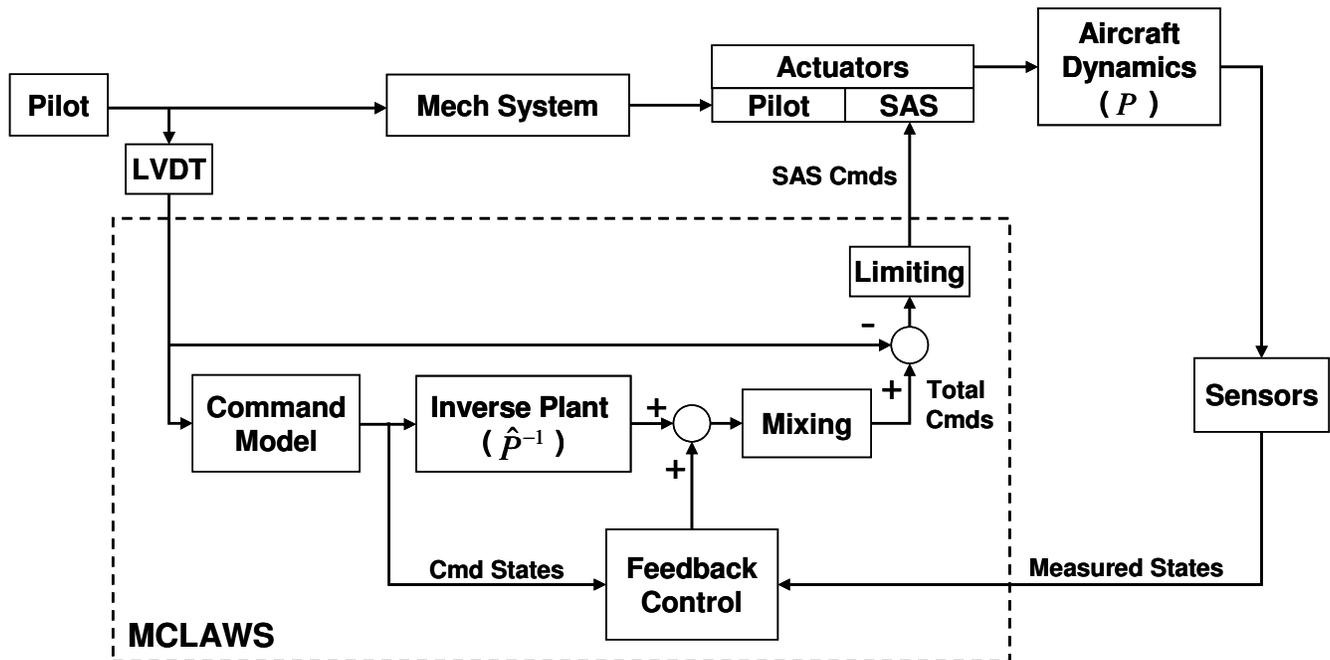


Figure 1. MCLAWS model following architecture

Response Types

Most helicopters, without augmentation, are rate response systems in all axes. This means control inputs produce corresponding angular or vertical rates. To maneuver or stabilize the helicopter in pitch and roll, the pilot must close the attitude loop by removing or reversing cyclic control inputs once the desired attitude is reached. The pilot needs sensory (usually visual) feedback to do this, so the task becomes more difficult in a degraded visual environment and more dangerous when operating near the ground. To overcome this problem, ADS-33E requires higher level response types as a function of the usable cue environment (UCE). As the UCE degrades, the required response type for the pitch and roll control progresses from rate response with good visual cues (UCE=1) to attitude command attitude hold (ACAH) with only fair visual cues (UCE=2) to translational rate command (TRC) plus position hold (PH) with poor visual cues (UCE=3). The progression provides more stability and reduces pilot workload by eliminating the task of closing control loops. The yaw and vertical axes requirements remain rate response with direction hold (DH) and height hold (HH) added as the UCE degrades. These requirements defined the approach for developing the AH-64D MCLAWS.

Command Models

The model following architecture provides the ability to change the aircraft response to fit a desired model. In the pitch and roll axes, ACAH is the desired model. ACAH means the aircraft attitude follows the pilot's cyclic stick. A step input to the cyclic stick produces a step response in attitude. A simple second order structure, similar to that used in references 5 and 6, is used to produce the ACAH response (figure 2). In the yaw axis, the helicopter is a rate response system in that the yaw rate follows the directional control inputs. This meets the requirement so the response does not necessarily have to be changed but using a first order rate command (RC) model allows the response to be manipulated to meet performance criteria such as response rise time and bandwidth.

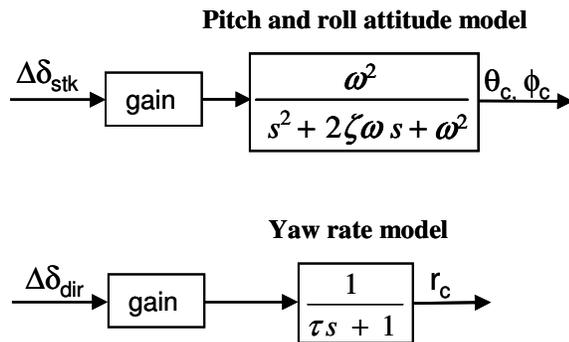


Figure 2. Command models

The break frequency for the second order command model is normally set to the Level 1 bandwidth required by ADS-33E or 2 rad/sec. Additional guidance is provided by Whalley and Howitt (Ref. 5), where the command model and open loop frequency responses are matched at higher frequencies to reduce SAS actuator activity, delay saturation, and improve predictability of control upon saturation. In this study, the break frequencies and gains were manually selected with both objectives in mind. Figure 3 shows a comparison of the open-loop roll attitude response for the linear model with the roll attitude command model. The gain (0.2 rad/in-stk) and frequency (2 rad/sec) were chosen to provide the required bandwidth and minimize the error between these responses at higher frequencies. A similar approach was used to define the pitch command model. The open loop yaw response of the AH-64D has a bandwidth of 0.5 rad/sec which is Level 3. The first order command model was set at 2.5 rad/sec to achieve the required bandwidth. The gain was adjusted based on comments from pilot-in-the-loop simulation. Command model parameters used in the MCLAWS are listed in Table 1.

Table 1. Command model design parameters

	Pitch	Roll	Yaw
gain	0.08 (rad/in)	0.2 (rad/in)	0.35 (rps/in)
ω	1.7	2.0	
ζ	0.7	0.7	
τ			0.4

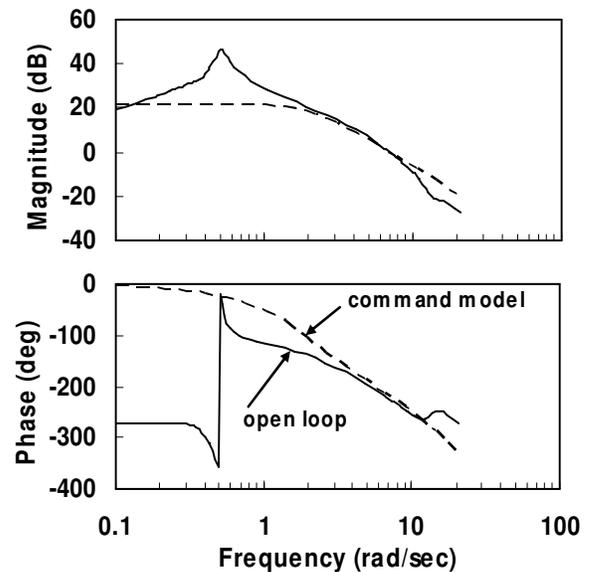


Figure 3. Roll attitude frequency response

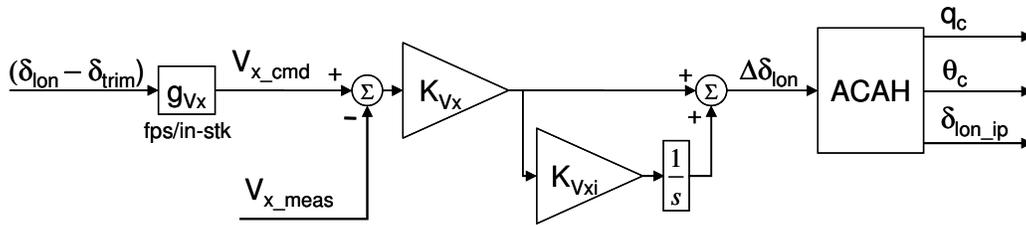


Figure 5. Longitudinal TRC mode

Translational Rate Command/ Position Hold

TRC means the translational ground speed follows the cyclic stick. A step input to the cyclic stick produces a step response in the aircraft's translational ground speed. With zero pilot inputs or a centered cyclic stick, TRC commands zero ground speed which is equivalent to position hold (an automatic hover). But a forward push on the stick commands the aircraft to move forward at a ground speed proportional to the stick displacement. This type of control is easy to fly because it requires no visual feedback to keep the aircraft upright. It does, however, reduce the pilot's perception of control power because the aircraft does not respond aggressively to control inputs. This can be objectionable depending on the task, especially for an attack helicopter. For this reason, TRC is implemented as a pilot selectable mode to be used when conditions or mission tasks dictate. Position hold is implemented as an integral part of TRC. With the stick centered at the hover trim control position, the commanded ground speed is zero and position hold automatically engages to hold position over the ground. Heading and altitude hold also come automatically with position hold to provide a three-axis stationary hold in inertial space.

When the TRC/PH mode is selected, the ground speed feedback loop is closed outside the attitude loop from the ACAH mode as shown in figure 5. Proportional and integral control produces an equivalent stick command to zero the difference between the commanded and measured ground speed. The equivalent or pseudo stick command is sent through the ACAH model to produce the appropriate attitude and rate commands to achieve the desired ground speed change. With this series arrangement, the TRC response is achieved through the ACAH command states.

The position hold mode takes the same approach one step further. When position hold automatically engages, 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 architecture has been used in other controllers (Ref. 13) as an efficient solution utilizing all the feedback loops working together to achieve the same goal.

Additional Hold Modes

The additional hold modes required by ADS-33E for near-earth operation in a DVE include heading hold and altitude hold. Heading hold is accomplished through the yaw rate command model in much the same way as described for position hold. The heading feedback loop is closed outside the yaw rate feedback loop creating a heading error signal that uses the yaw RC model to zero the heading error. This mode is provided automatically with position hold and whenever the yaw rate command is near zero. Altitude hold is accomplished through direct error feedback and is provided as a pilot selectable mode. It is also automatically engaged and disengaged with position hold.

Partial Authority Limitations

Changing the basic response of the helicopter to pilot inputs requires significant control authority, depending on flight condition. This is not a problem for a full authority fly-by-wire system or a system with full authority trim actuators. However, with a partial authority system without trim actuators, there are limits to what can be accomplished. At certain attitudes and ground speeds, the SAS actuators will saturate and the response dynamics revert back to the unaugmented helicopter. Despite this limitation, results have 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 same holds true for TRC systems, with the limits easily estimated by a low speed trim analysis.

TRC basically remaps the cyclic control to ground speed relationship. The static trim control inputs at the rotor do not change, but the position of the cyclic stick does due to steady SAS commands. Figure 6 shows a method of estimating the ground speed at which the SAS will saturate for the AH-64D. The flight test data are the trim cyclic control positions with ground speed. The TRC line represents the remapping recommended as the Level 1 boundary from ADS-33E. In order to achieve the desired TRC stick to ground speed relationship, the SAS must make up the difference. The plot demonstrates a TRC capability of up to 5 kts with a $\pm 10\%$ authority SAS and 12 kts with a $\pm 20\%$ authority SAS.

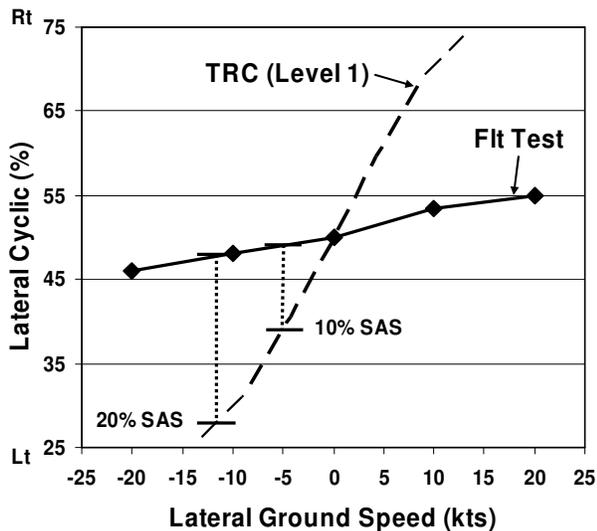
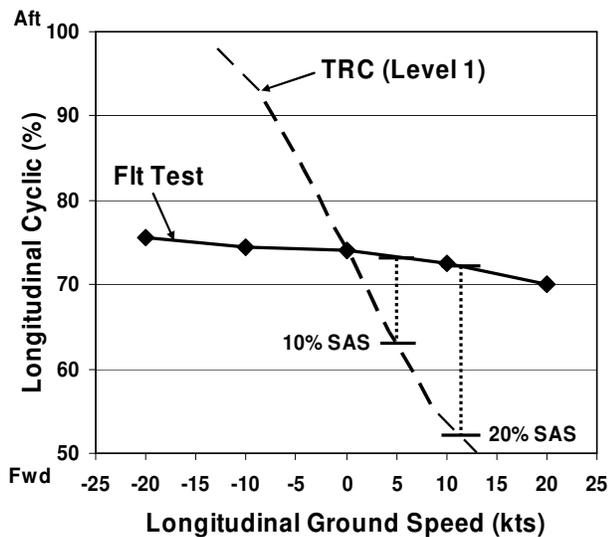


Figure 6. SAS authority limits on TRC

The MCLAWS response type architecture that was designed to meet the hover / low speed flight requirements of ADS-33E, assuming a $\pm 20\%$ authority SAS, is shown in figure 7. Without the TRC/PH mode selected, MCLAWS provides ACAH below 40 knots ground speed. (Although not shown, the forward flight control laws would be rate command attitude hold above 40 knots.) With TRC/PH selected, mode blending from ACAH to TRC at 12 knots ground speed is automatic. Below 1 knot, position hold automatically captures position over the ground. When the controls are moved, position is released and the system reverts back to TRC mode.

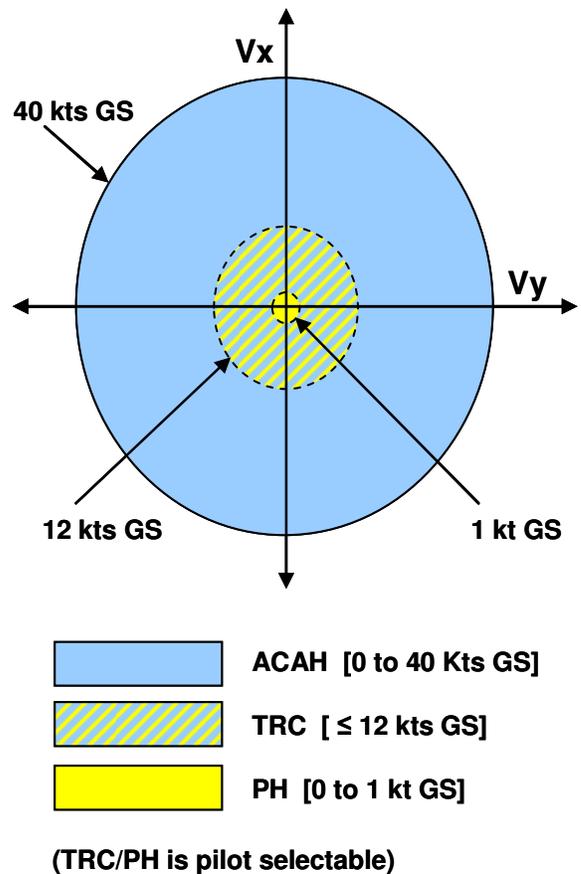


Figure 7. MCLAWS response type architecture

CONDUIT ANALYSIS

As mentioned earlier, the control system design, evaluation, and optimization software tool CONDUIT[®] was used throughout the development of the MCLAWS. CONDUIT[®] is built upon the capabilities of MATLAB[®]/SIMULINK[®] and is used extensively by US industry, academia, and the government. The control system architecture is defined as a SIMULINK[®] block diagram schematic with many gains, time constants, and dynamic block parameters that need to be tuned to meet a large number of competing design requirements (such as command tracking, stability margins, gust response, and robustness to uncertainty). CONDUIT[®] allows the designer to tune the system, either manually or via a powerful optimization engine, to best meet the selected set of requirements and ultimate performance objectives. There is no limitation on the control system architecture that can be used. The MCLAWS design is based on a model-following architecture, but other studies have considered designs based on PID, LQR, H-infinity, and dynamic inverse architectures. CONDUIT[®] has proven very useful in comparing the benefits and drawbacks of these design choices (Ref. 14).

Design Parameters

In CONDUIT[®], the various block diagram parameters to be tuned are referred to as “Design Parameters.” These design parameters provide the means to adjust the control response to meet the design requirements. In manual mode, CONDUIT[®] can be used as a powerful calculator. The designer can quickly analyze the effects of variations of the design parameters on how the system satisfies the various specifications. One or more design parameters can be manually changed and the effect on specifications quickly depicted. This same task would take many hours to accomplish without CONDUIT[®], as the designer would have to manually work through the generation of all the required information, time response data, Bode plots of broken and closed loops, actuator saturation information, etc, before comparing the results to the selected set of specifications. In optimization mode, CONDUIT[®] uses a robust vector optimization algorithm (known as Feasible Sequential Quadratic Programming or FSQP) to automatically tune the selected design parameters to achieve a design that satisfies the requirements with the minimum use of the available control authority. The vector optimization ensures that each of the selected specifications are satisfied, rather than a simple average value of the specifications that could leave some very good and others very poor. Finally, CONDUIT[®] can then be used to evaluate the design for trade-offs associated with achieving increased performance beyond the minimum requirements and building in robustness margins to changes in vehicle characteristics and degradations in sensor data quality, etc.

Specifications and Optimization Strategy

The most important aspect of setting up a design problem in CONDUIT[®] is the selection of the various specifications which embody the requirements of the system. These specifications can be selected from a large library of specifications built into CONDUIT[®], encompassing both generic system stability and performance requirements and aircraft response and handling qualities requirements. This step requires that the designer thoroughly understand the design requirements and constraints prior to using CONDUIT[®] to optimize the design parameters. In selecting the specifications, the designer has to ensure that: (1) each specification is influenced by at least one of the design parameters; (2) each design parameter influences at least one of the selected specifications; (3) the design space is properly constrained; and (4) there are no two design parameters with equivalent effects. The first condition ensures that there is a means to drive each specification metric (e.g., bandwidth or stability margin) into the satisfactory region. The second condition ensures that there is some effect on the response of varying each design parameter, so that the optimizer can see some influence in

tuning each of the parameters. The third condition recognizes that optimization will always drive system performance towards the boundaries. The collection of specs must provide a balance that constrains the solution. For example, the requirement to maintain a reference condition in the presence of disturbances (i.e., “gust response spec”) drives up system gains, while requiring a satisfactory stability margin with reasonable actuator activity ensures that the gains will not be too high. The fourth condition ensures that the optimization solution is not numerically singular. Satisfying these four conditions ensures that the optimization problem statement is properly posed. A comprehensive “Sensitivity Analysis” toolset in CONDUIT[®] assists the designer in evaluating the suitability of the problem statement, troubleshooting problems in reaching an optimized solution, and assessing the uniqueness and certainty of the optimized solution.

The set of specifications selected for the MCLAWS design is shown in figure 8, which depicts the CONDUIT[®] Handling Qualities (HQ) window. The specifications are also listed in tabular form in Table 2. As may be seen from figure 8, each specification shown in the CONDUIT[®] HQ window encompasses three distinct regions. The dark gray region in each spec represents Level 3 handling qualities (“deficiencies require improvement”), the light gray region represents Level 2 (“deficiencies warrant improvement”), and the white region represents Level 1 (“satisfactory without improvement”). CONDUIT[®] divides the various criteria into 5 distinct categories: “Hard Constraints”, “Soft Constraints”, “Performance Objectives”, “Summed Objectives”, and “Check Only”.

Optimization proceeds by first attempting to move all “Hard Constraints” into Level 1 while ignoring the 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 proceeds to find a set of design parameters which also puts 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[®] will tune the design parameters to optimize the system based on the selected objective criteria, while ensuring that the Level 1 requirements are still met, thereby ensuring minimum over design. Typical objective criteria are actuator activity (RMS) and broken loop crossover frequency (see for example reference 8).

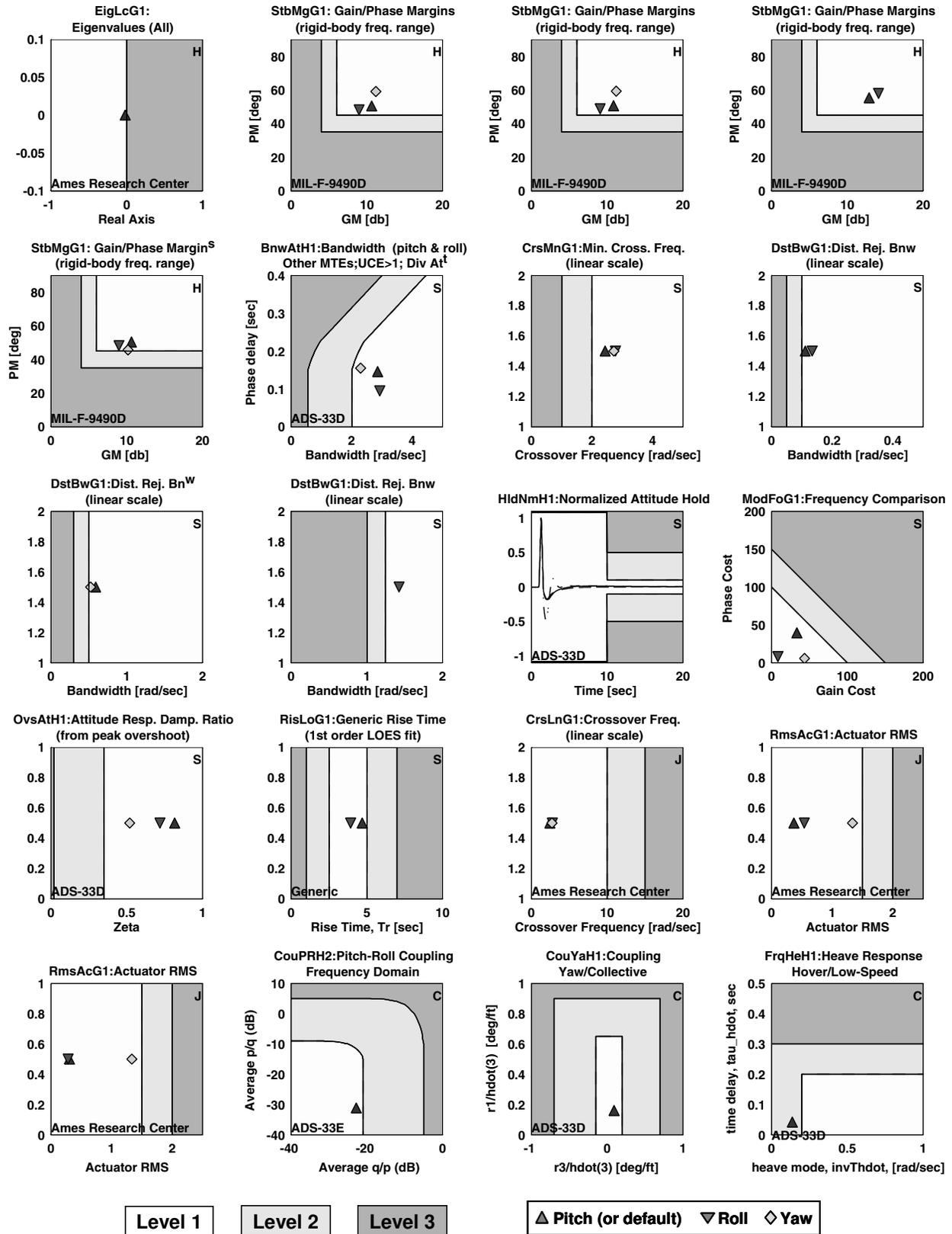


Figure 8. Specifications used for the MCLAWS project in CONDUIT[®]

Table 2. Specifications used for CONDUIT[®] analysis and optimization

Requirements	Source	Spec Name	Axis	Constraint Type
Eigenvalues	Ames	EigLcG1	N/A	Hard
Stability margins	MIL-F-9490D	StbMgG1	ACAH: Pitch, roll, and yaw * TRC: Pitch, roll, and yaw * DH: Yaw * PH: Xpos and Ypos * PH: Xpos and Ypos **	Hard
Bandwidth	ADS-33	BnwAtH1	ACAH: Pitch, roll, and yaw	Soft
Minimum crossover frequency	Ames	CrsMnG1	ACAH: Pitch, roll, and yaw *	Soft
Disturbance rejection bandwidth	Ames	DstBwG1	ACAH: Pitch and roll PH: Xpos and Ypos DH: Yaw	Soft
Attitude hold	ADS-33	HldAtH1	ACAH: Pitch and roll	Soft
Model following	Ames	ModFoG1	ACAH: Pitch, roll, and yaw	Soft
Damping ratio	ADS-33	OvsAtH1	ACAH: Pitch, roll, and yaw	Soft
Generic rise time	Ames	EigDpG1	TRC: Vx and Vy	Soft
Crossover frequency	Ames	CrsLnG1	ACAH: Pitch, roll, and yaw *	Objective
Actuator RMS	Ames	RMSAcG1	TRC: Pitch, roll, and yaw ACAH: Pitch, roll, and yaw	Objective
Pitch/roll coupling	ADS-33	CouPRH2	Pitch/roll	Check only
Yaw/collective coupling	ADS-33	CouYaH1	Yaw/collective	Check only
Heave response	ADS-33	FrqHeH1	Collective	Check only

* loop broken at actuators

** loop broken at position error

AH-64D MCLAWS Design Goals

As described earlier, the MCLAWS design has a model following architecture within the constraints of a partial authority implementation. For hover and low speed flight, the design provides an ACAH response type in pitch and roll and an RC response type (with direction hold) in yaw. Below the TRC threshold ground speed, the combined TRC/PH mode is available if selected.

The goal for the ACAH portion of the design was to optimize the control laws such that the attitude responses of the aircraft closely resemble the responses of the selected command models in pitch and roll (rate response in yaw) without significant overshoot or oscillations. This would in turn guarantee that the bandwidth and phase delay requirements stated in ADS-33E are satisfied. The goal for the TRC portion 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 no less than 2.5 seconds and no greater than 5 seconds (Ref. 4), display minimal overshoot and oscillations, and have a smooth and non-oscillatory associated attitude response. For the heading hold portion, the goal was to ensure a fast, smooth, and non-oscillatory disturbance rejection characteristic. Finally, for the position hold portion, the goal was to achieve as quick a position disturbance rejection capability as possible without adversely affecting overall stability margins. To this end, the margins were checked not only at the primary actuators, but also directly at the position error calculation points. Of course, all the stated goals had to be achieved while maintaining overall system stability, acceptable cross-axes coupling, and without encountering unacceptable actuator saturation characteristics.

Selection of MCLAWS Specifications

The specifications used for this project and depicted earlier in figure 8 where selected to ensure that the above stated goals were achieved.

Stability & stability margin specifications. The eigenvalues spec verifies that the closed loop system has only stable or very slow unstable poles. The stability margin specs verify that satisfactory gain and phase margins are achieved for the broken-loop responses. Four separate stability margin specs were used: one for ACAH, one for TRC, one for PH mode, breaking the loop at the position error, and finally one for PH mode and heading hold mode (DH), breaking the loop at the actuators. The additional PH stability margin spec, with the loop broken at the position error, was used because it allows a better understanding of the characteristic of the PH response, even though both PH specs would ultimately go unstable at the same time. The minimum damping ratio spec was included to ensure that the closed-loop response was sufficiently damped. The minimum crossover frequency was included to ensure that the optimization did not push the feedback crossover frequencies too low while attempting to satisfy gain and phase margin requirements.

Piloted control response bandwidth requirements. The bandwidth specs are key short-term response requirements in ADS-33E, and are directly related to the step-response rise time for a piloted control input. The bandwidth spec was only applied to ACAH. In a model following architecture, as is used for the MCLAWS, the bandwidth characteristics of the closed loop system are primarily affected by the response characteristics of the command model. As explained earlier, the ACAH command models for the MCLAWS were selected based on both performance requirements and frequency matching with the bare airframe response and subsequently frozen during analysis and optimizations. The bandwidth specs basically indicate

that the closed loop response of the vehicle with the selected command models satisfy the requirements of ADS-33E for bandwidth and phase delay. For PH, the generic rise time spec was used instead, which fits the response with a first order equivalent system and uses the values obtained to estimate the rise time.

Disturbance response requirements. In a model following architecture, the control response is set via the command model, while stability and disturbance rejection is set via the feedback (i.e., regulator) loop. A well-defined disturbance rejection requirement is needed to ensure that a compromise between good stability margins and good disturbance rejection is reached. A time domain requirement for the closed-loop disturbance rejection performance is defined in ADS-33E. This requirement is to evaluate the attitude hold capability using a pulse-type control input injected at the actuator as the disturbance and to determine whether the response returns to within 10% of the peak, or one degree (whichever is greater), within 10 seconds (20 seconds for pitch). This settling-time spec from ADS-33E has been found to be poorly suited for control system design optimization. Also, the 10-20 sec settling time criteria has been found to be too loose in recent flight test experience (Ref. 15). An alternative frequency-domain specification has been developed that provides better guidance for the feedback optimization.

For a generic feedback control system, as shown in figure 9, the disturbance rejection bandwidth is evaluated based on the classical sensitivity function, $S(s)$,

$$S(s) \equiv \frac{y(s)}{\delta_g(s)} = \frac{1}{1 + G(s)C(s)H(s)} \quad (9)$$

The disturbance rejection bandwidth can be derived from the Bode magnitude curve of a sensitivity function (figure 10). A gust response bandwidth is defined in CONDUIT[®] as the frequency at which the Bode magnitude plot of the

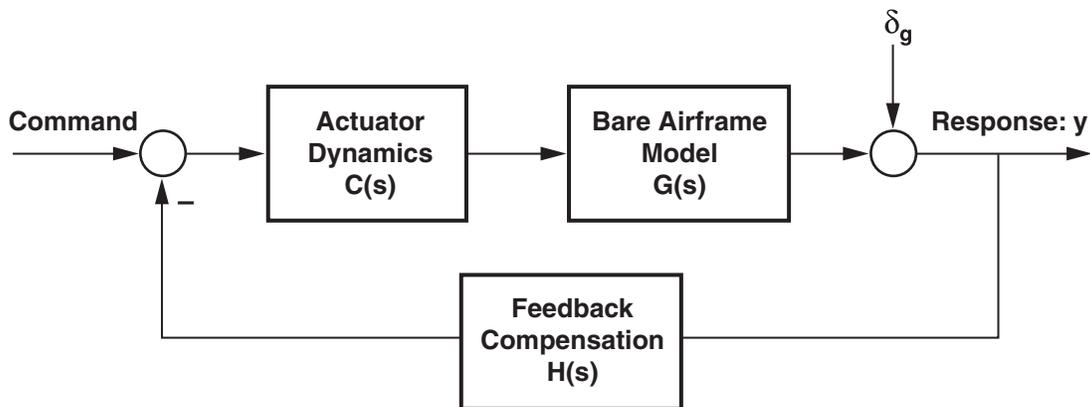


Figure 9. Schematic diagram to derive sensitivity function

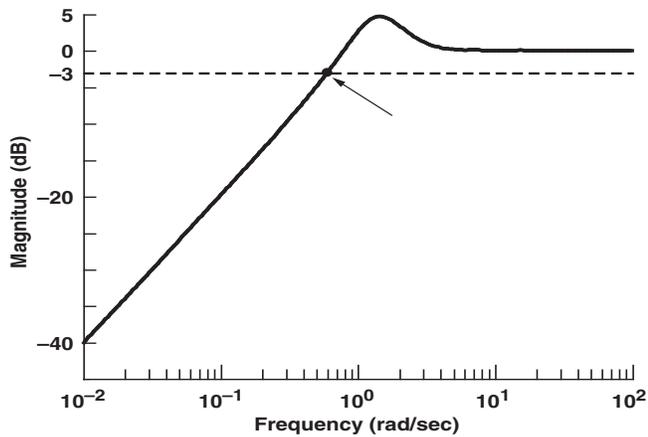


Figure 10. Typical Bode magnitude plot of a sensitivity function

sensitivity function crosses -3dB line. A higher gust-response bandwidth reflects tighter rejection of disturbances and shorter settling times. The proposed requirement for the attitude hold is 0.5 rad/sec and for position hold is 0.1 rad/sec. There is a close mapping of this requirement to the ADS-33E settling-time metric, but the associated requirement is for a much shorter settling time than provided for in ADS-33E.

Objective Functions. As discussed above, a summed objective function is minimized to ensure that the design requirements are achieved with minimum over design. This provides a unique solution that just achieves the design requirements. Generally, summed objectives are comprised of the crossover frequency and the actuator root mean square (RMS) specs for each channel.

CONDUIT[®] Results for MCLAWS

After all the specs were wired up to the MCLAWS block diagram, CONDUIT[®] was allowed to run and optimize the selected design parameters in order to satisfy the selected specifications. As figure 8 shows, all selected specs were satisfied in Level 1 except the heave response spec, which remains in Level 2. This does not indicate a problem as the MCLAWS does not contain a heave loop, and therefore the heave response evaluated is simply the bare airframe heave response characteristic, which, as previously known, does not satisfy Level 1 requirements.

Figure 8 shows that all closed loop poles are stable, that satisfactory margins are achieved in ACAH, TRC, PH, and DH, that the system bandwidth and phase delay in ACAH satisfy the Level 1 requirements and that system rise time in PH is also Level 1. Additionally, the figure indicates that the system displays good off-axes coupling characteristics, good overall damping and attitude hold characteristics, and satisfactory actuator saturation behavior. The details of the calculations of the many points plotted on the specifications in figure 8 can be seen in associated supporting plots generated by CONDUIT[®]. For example, figure 11 depicts

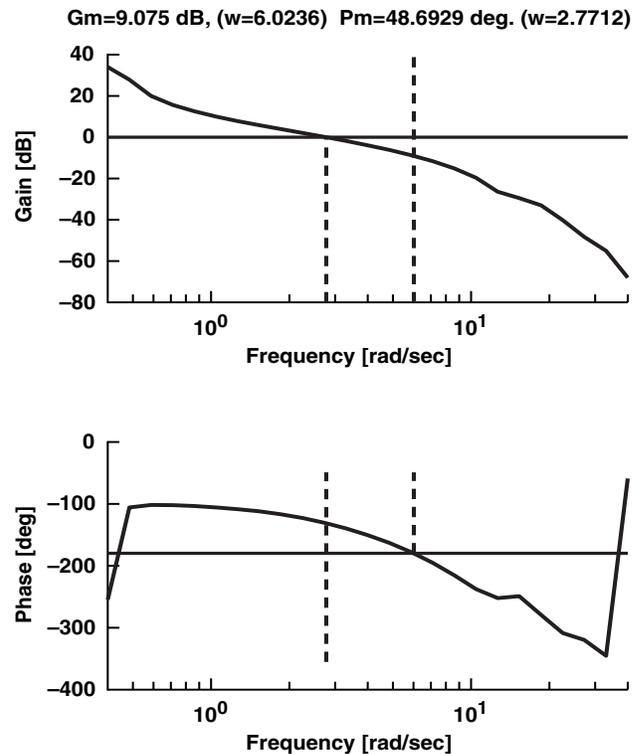


Figure 11. Lateral stability margin in ACAH

the ACAH broken loop response in roll, at the actuator, and shows how the gain and phase margin values of 9.1 dB and 48.7 degrees, respectively, were calculated.

Figure 12 depicts the roll attitude response to a 0.5 inch lateral step input at the pilot stick in ACAH and clearly shows the attitude command characteristic of the response along with good attitude hold characteristic even over a 10 second maneuver. The figure also shows that the aircraft response follows the command model closely, which confirms that closed loop bandwidth and phase delay requirements are satisfied. Figure 13 depicts the longitudinal ground speed response to a 0.5 inch longitudinal (positive aft) stick input in TRC and shows the translational rate command characteristic of the response. The response is seen to have a definite first order characteristic with a rise time (time to reach 63.2% of the steady state value) of about 4.5 seconds which satisfies the 2.5-5.0 second requirement specified in ADS-33E. The figure also shows the desirable smooth characteristic of the associated pitch attitude response.

Figure 14 depicts the pitch attitude disturbance response of the system in ACAH and shows that the system quickly and smoothly recovers from a 3 degree disturbance input within 5 seconds. Finally, figure 15 depicts the response of the system to a 3 ft position disturbance and shows that the system returns to its original position quickly and without large oscillations. The figure also shows that the associated translational rate and pitch attitude responses are also smooth and non-oscillatory.

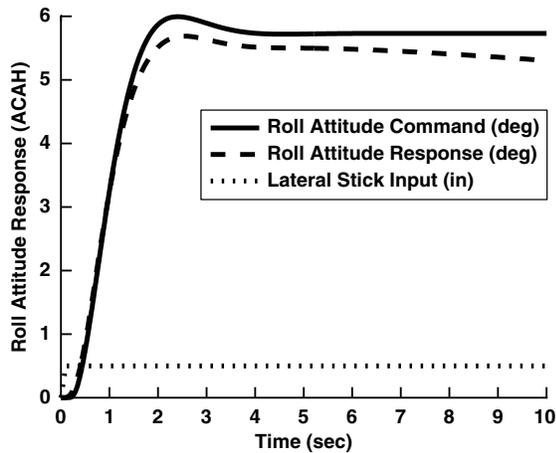


Figure 12. Step response to a 0.5 in lateral stick input in ACAH

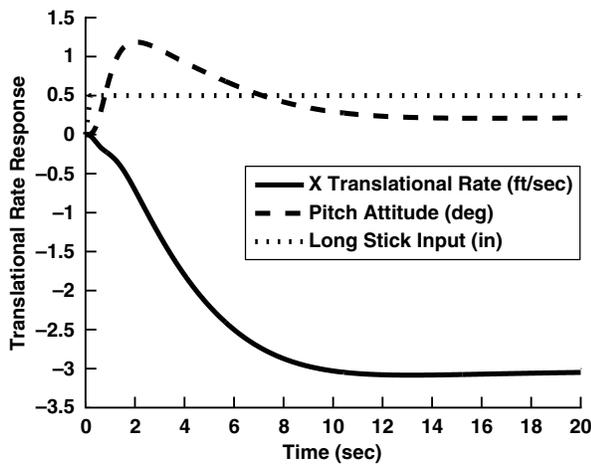


Figure 13. Step response to a 0.5 in longitudinal stick input in TRC

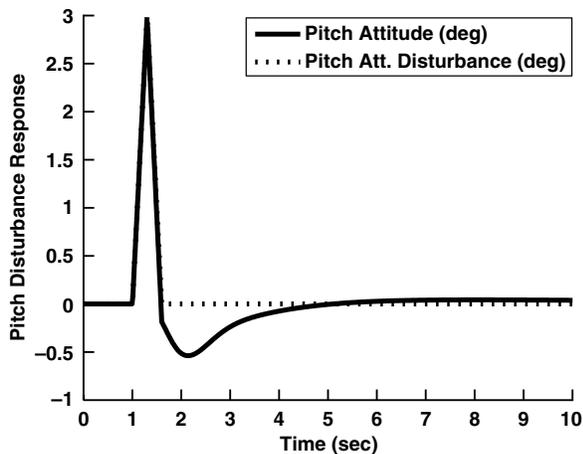


Figure 14. Pitch attitude disturbance rejection in ACAH

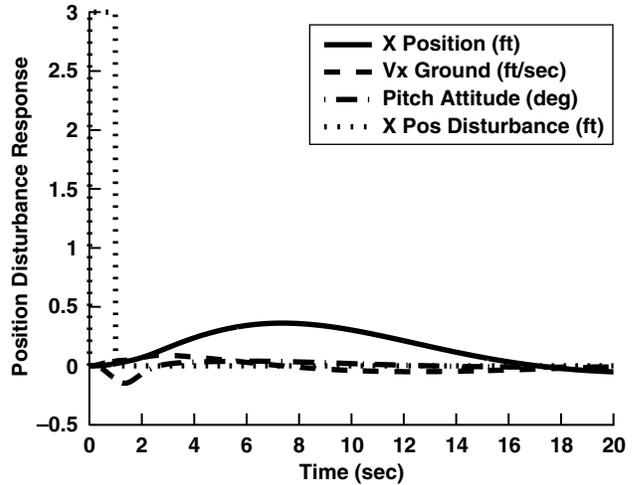


Figure 15. Position disturbance rejection in PH

COMPARISON WITH LEGACY AH-64D

A model of the legacy AH-64D control laws was created in Simulink[®] and validated as described in reference 12. The model included the stability and command augmentation (SCAS) modes, selectable hold modes, gain scheduling and switching logic suitable for evaluating the servoloop stability and handling qualities requirements of the closed loop system. The model was used in this effort as a baseline to compare response characteristics of the AH-64D with the legacy control laws versus the MCLAWS. The aircraft dynamics were represented by the same identified linear model in both analyses. Table 3 compares the bandwidth and phase delay in the pitch, roll and yaw axes at hover. As previously discussed, the command models in the MCLAWS design determine these characteristics and are used to assure all bandwidths are Level 1 (>2 rad/sec) for divided attention operations in DVEs. The MCLAWS show an increase in bandwidth for all three axes with the pitch axis improving from Level 2 (<2 rad/sec) to Level 1.

Table 3. Bandwidth and phase delay at hover

Axis	AH-64D		MCLAWS	
	ω_{BW}	τ_P	ω_{BW}	τ_P
pitch	1.96	0.19	2.86	0.15
roll	2.82	0.14	2.93	0.09
yaw	2.14	0.15	2.29	0.15

The fundamental difference between the response of the AH-64D with the legacy system (SAS-on) and the MCLAWS is demonstrated with a lateral doublet (figure 16). Under normal operation with no selectable modes, the MCLAWS is an ACAH response system while the legacy

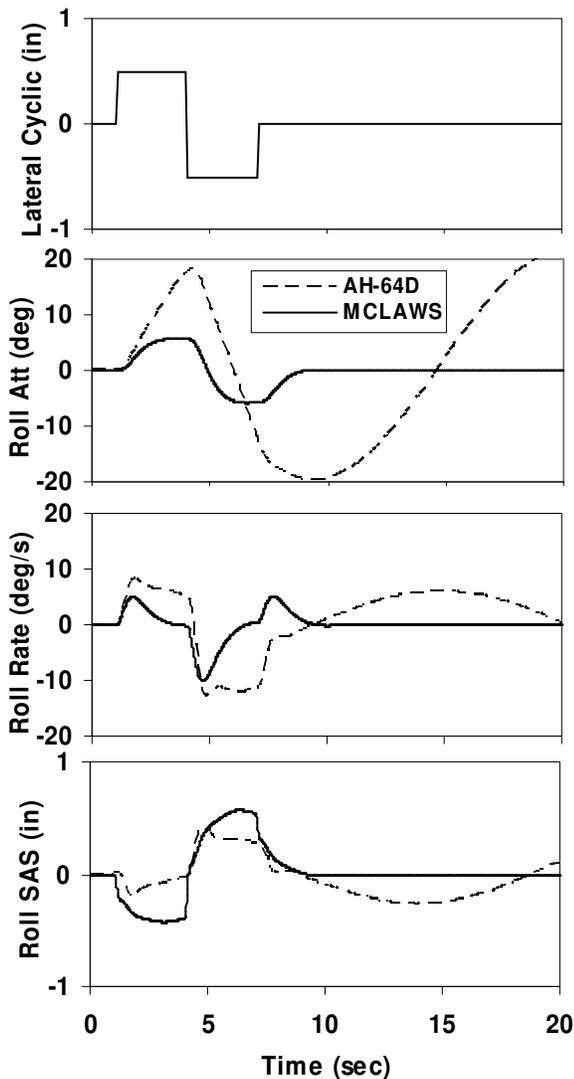


Figure 16. Response to 0.5 in lateral doublet at hover

aircraft is a rate response system. Note that the roll attitude follows the lateral cyclic input for MCLAWS while the roll rate follows the lateral cyclic input for the AH-64D with the SAS-on. This plot demonstrates the fundamental advantage of ACAH which is a predictable and stable attitude response resulting in reduced pilot workload for low speed maneuvering.

SIMULATION

Real-time simulation played an important role in the development of the AH-64D MCLAWS (Ref. 16). The CONDUIT[®] analysis focused on stability and performance metrics of individual modes, but the handling qualities characteristics of ACAH and TRC, the response blending between modes, and pilot interface issues had to be evaluated with a pilot-in-the-loop simulation environment. The Real-time Interactive Prototype Technology Integration

Environment (RIPTIDE, Ref. 11) provided this capability. It combined processes for inceptors and graphics along with a real-time executable of the developing MCLAWS and the linear aircraft models. RIPTIDE is a Linux based software tool that provides a fixed base simulator environment. Because it was hosted on the same computer as CIFER[®], Simulink[®], and CONDUIT[®], it greatly facilitated rapid iterations between Simulink based control system design and simulated flight tests. Targeted control law design parameters were refined during simulated flight and guided by real-time pilot feedback regarding specific flight modes and handling qualities tasks. For quick evaluations, RIPTIDE was used as a desktop simulation (figure 17). For more immersive simulations, a second, networked RIPTIDE workstation simulation helped drive three side-by-side projections to create a 135 degree pilot's field of view (FOV) with a basic crew station and equipped with three PC compatible inceptors (joysticks) (figure 18). Together, these simulations provided an effective demonstration of the significant handling qualities improvements obtained with the MCLAWS.



Figure 17. RIPTIDE desktop simulation



Figure 18. RIPTIDE 135 deg FOV simulation

CONCLUSIONS

Modern control laws have been developed for the AH-64D to provide improved handling qualities for hover/low speed flight in a degraded visual environment. Key elements of this work include:

1. The MCLAWS provide both ACAH and TRC response types using the existing partial authority SAS and mechanical flight control system. The results demonstrate that control laws designed to meet the Level 1 requirements of ADS-33E can provide handling qualities improvements over legacy control laws using the same mechanical system.
2. A model following approach was used to produce an ACAH response type providing the inner control loop around which TRC and PH loops were closed in series. This architecture was simple to implement and provided an efficient means to achieve the response types required by ADS-33E.
3. The command models determine the bandwidth and phase delay characteristics of the system and were selected to match the open-loop frequency response and thereby minimize saturation transients.
4. CONDUIT[®] was used for detailed analysis and optimization of MCLAWS handling qualities and feedback performance to the many relevant and competing specifications. A good balance between the gust rejection performance and stability margin requirements was achieved in the optimized design by including new frequency-domain gust response criteria based on the classical sensitivity function.
5. The RIPTIDE simulation played an important role in control law development, and provided an effective demonstration of the significant handling qualities improvements associated with MCLAWS.

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