UH-60 Partial Authority Modernized Control Laws for Improved Handling Qualities in the Degraded Visual Environment

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ABSTRACT

The U.S. Army's helicopter fleet consists chiefly of aircraft developed in the 1960's and 1970's with flight control systems based on the requirements of that time. Since then, Army helicopter operations have changed from predominantly daytime, good visual environment (GVE) operations to night and degraded visual environment (DVE) operations. Rotorcraft handling qualities and flight control requirements did not address DVE operations until the introduction of ADS-33 in 1985. Numerous attempts to improve the handling qualities of rotorcraft in the DVE through flight control upgrades have been studied with the CH-47F DAFCS representing a successful partial-authority solution. In 2000, AFDD and Sikorsky developed the UH-60 Modernized Control Laws (MCLAWS) which were intended to satisfy the ADS-33 DVE requirements using the existing limited-authority actuators. While the original program ended in 2003, the effort was resumed at AFDD in 2012 with numerous improvements incorporated into the MCLAWS. Flight tests in brownout conditions at Yuma Proving Ground demonstrated that the MCLAWS resulted in reduced the pilot workload when compared to the legacy UH-60 SAS/FPS control system. A handling qualities evaluation conducted at Moffett Field in simulated DVE conditions on five ADS-33 mission task elements demonstrated Level 1 handling qualities.

NOTATION

ACAH	Attitude-Command/Attitude-Hold
DRB	Disturbance Rejection Bandwidth
DRP	Disturbance Rejection Peak
DVE	Degraded Visual Environment
GVE	Good Visual Environment
HQR	Handling Qualities Rating
MCLAWS	Modernized Control Laws
MTE	Mission Task Element
PAFCA	Partial Authority Flight Control Augmentation
SAS	Stability Augmentation System
UCE	Usable Cue Environment
VCR	Visual Cue Rating
ω_{co}	Cutoff Frequency
ω_n	Natural Frequency

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Presented at the AHS 70th Annual Forum, Montréal, Québec, Canada, May 20–22, 2014.

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INTRODUCTION

In the late-1960's, the U.S. Army began developing requirements for a medium lift, utility helicopter which was to replace the UH-1. In 1972, the Utility Tactical Transport Aircraft System (UTTAS) request for proposals was released and ultimately resulted in the development of the UH-60 Black Hawk helicopter which entered service 1979. The UH-60 partial-authority flight control system was designed to meet handling qualities requirements of the Prime Item Development Specification (PIDS) which was a tailored version of MIL-H-8501A (Ref. 1). As was common at that time, the UH-60 flight control system was designed for daytime flight; neither MIL-H-8501A nor the PIDS had DVE requirements.

ADS-33 (Ref. 2), introduced in 1985 and currently at revision E, specifically addressed flight control and handling qualities requirements for rotorcraft operations in the DVE in addition to the GVE. Table IV of ADS-33 specifies the minimum response-type required for Level 1 handling qualities in a given usable cue environment (UCE), e.g. for UCE = 2 (DVE), an attitude-command/attitude-hold (ACAH) response-type is required to achieve Level 1 handling qualities. Additionally, the bandwidth specification has different boundaries based on the UCE and the required agility, which drives other requirements, is reduced for DVE operations. Finally, many of the ADS-33 Mission Task Elements (MTEs) have relaxed performance tolerances for DVE conditions.

The UH-60A/L utilizes standard flight controls consisting of a mechanical center cyclic and collective lever for both pilots. The automatic flight control system (AFCS) consists of a Stability Augmentation System (SAS), Flight Path Stabilization (FPS), and stabilator. The SAS provides rate damping in roll, pitch, and yaw through the high-rate, limited-authority (±10%) SAS actuators. The FPS uses the limited-rate, full-authority trim actuators to provide additional augmentation and outer loop modes consisting of: (1) rate-command/attitude hold response-type in the pitch axis, (2) rate-command/heading hold response-type in the yaw axis, (3) airspeed hold at airspeeds greater than 60 knots, and (4) turn coordination at airspeeds greater than 60 knots. No augmentation is provided in the vertical axis which results in a vertical rate response-type. The introduction of the UH-60M in 2006 added a flight director and collective trim actuator to the flight control system which provided additional outer loop and autopilot modes including attitude hold in pitch and roll, altitude hold, and hover augmentation/gust alleviation, however it retained the rate-command response-type and is therefore predicted to receive Level 2 handling qualities ratings in the DVE.

The Study on Rotorcraft Survivability (Refs. 3, 4) identified loss of situational awareness (CFIT, DVE, object/wire strike) as a leading cause of combat non-hostile and non-combat helicopter mishaps and noted advanced flight control systems with modern control laws are a key enabling technology in reducing mishaps due to loss of situational awareness. Note, the term “modern control laws” does not necessarily refer to modern control techniques such as H_∞, LQR, etc., but rather refers to using modern requirements and hardware to develop control systems with improved handling qualities. The CH-47F DAFCS control laws were highlighted as a successful partial-authority (roughly ±10% in pitch and roll and ±20% in yaw) implementation of an advanced flight control system with modern control laws. ADS-33 requirements were considered during the design of the CH-47F DAFCS and the resulting control system used a digital flight control computer and included airspeed scheduled response-types and gains as well as position hold, translational rate command, and altitude hold modes (Ref. 5). During operational testing of the CH-47F DAFCS control laws, a comparison of DVE external load hook-up with a CH-47D (legacy, analog, rate response-type flight control system) and CH-47F DAFCS was conducted. The pilots reported that load hook-up took 8-10 times longer with the CH-47D than it did with the CH-47F.

In recent years, limited new acquisition programs have required the Program Managers to invest in improvements to the legacy systems and several research efforts have been conducted to apply ADS-33 and modern control design methods to legacy aircraft. From 2000 to 2003, Sikorsky Aircraft Company and the U.S. Army Aeroflightdynamics Directorate (AFDD) developed the UH-60 Modernized Control Laws (MCLAWS) (Refs. 6,7). Flight tests in the GVE demonstrated that the MCLAWS provided better handling qualities than the legacy UH-60A/L SAS/FPS. In 2007, AFDD and the U.S. Army Aviation Engineering Directorate (AED) improved upon the MCLAWS approach and applied it to the AH-64D (Ref. 8) demonstrating improved handling qualities in the DVE through piloted simulations. In 2011, AFDD and the Armed Scout Helicopter Program Office developed the short-term ACAH gain set for the OH-58D partial-authority (±10%) SCAS which resulted in improved handling qualities in the GVE and DVE (Ref. 9). Additionally during the development of the new ARH-70, AFDD and Bell collaborated on optimizing the proportional-integral-derivative (PID) stability and control augmentation system (SCAS) which provided a short-term ACAH response within the approximately 15-20% SCAS authority (Ref. 10).

In 2012, AFDD resumed work on the UH-60 MCLAWS incorporating updates based on flight control design optimization methods using CONDUIT® and handling qualities research conducted over the intervening years (Ref. 11). Control system improvements have been incorporated over two new iterations of the UH-60 MCLAWS. This paper provides a brief review of the legacy MCLAWS design as well as details of improvements to the control system and design methodology which have been incorporated. The results of flight tests conducted on the AFDD EH-60L at Yuma Proving Ground and Moffett Field are presented and discussed.

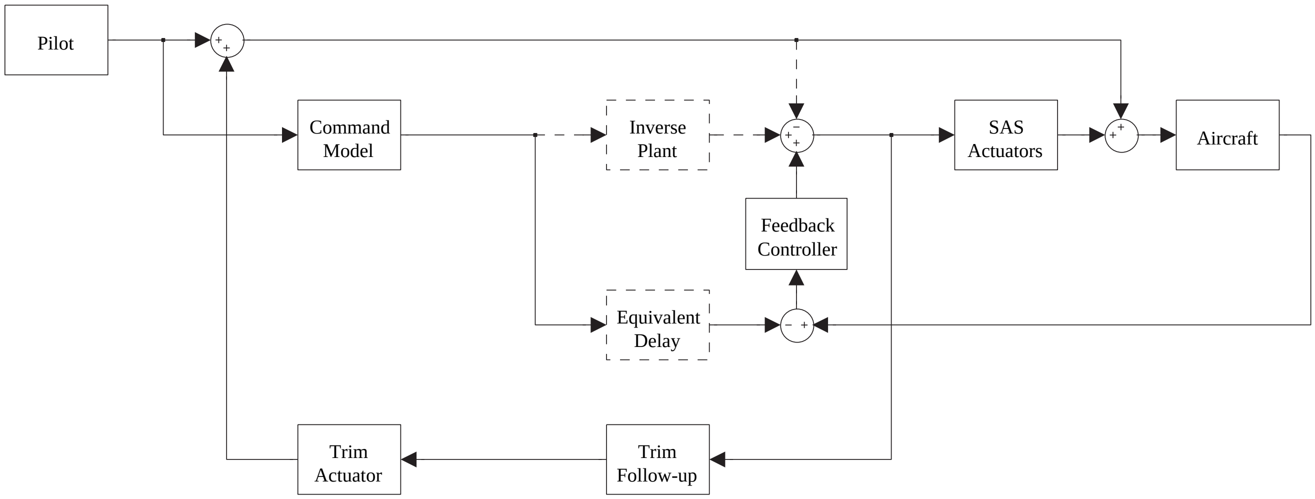
CONTROL SYSTEM ARCHITECTURE

This paper discusses three versions of MCLAWS, numbered V0, V1, and V2. The last version of the legacy control laws flown in 2003 has been designated MCLAWS V0. MCLAWS V1 leveraged recent experience in control law optimization techniques to achieve improved performance over the legacy MCLAWS V0 while maintaining the same control system architecture. Changes to the control law architecture and optimization of SAS vs. trim actuator authority were included in MCLAWS V2. Further details of these three versions are provided in the following sections.

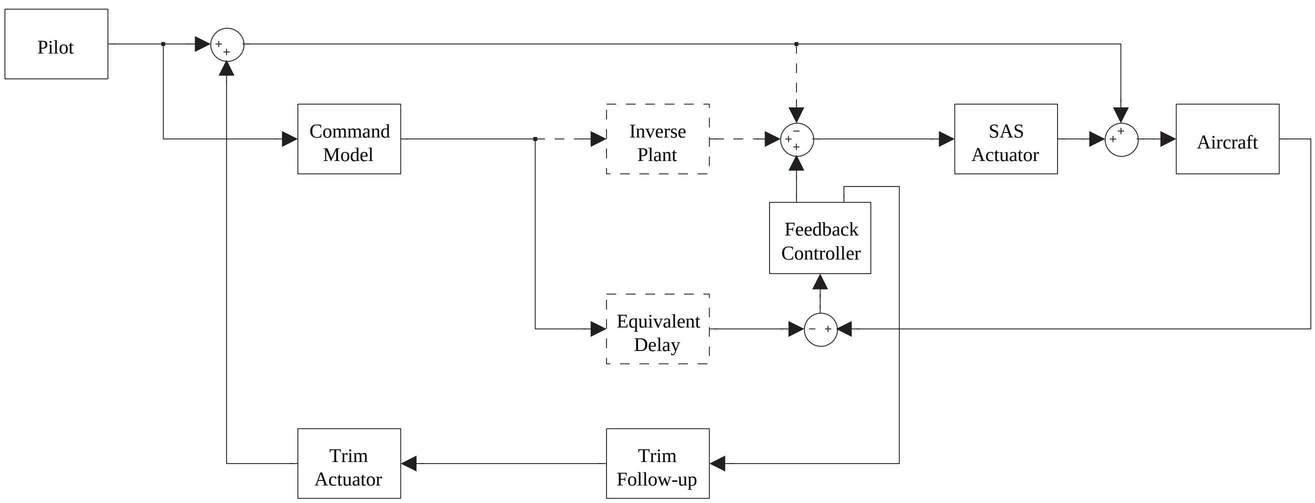
MCLAWS V0/V1

From 2000 to 2003, Sikorsky and AFDD collaborated under a National Rotorcraft Technology Center project to develop and flight test the UH-60 Modernized Control Laws. Several versions of MCLAWS were tested during this period, however, for this paper, only the final flight tested version will be considered. This final version of the legacy control laws has been labeled MCLAWS V0.

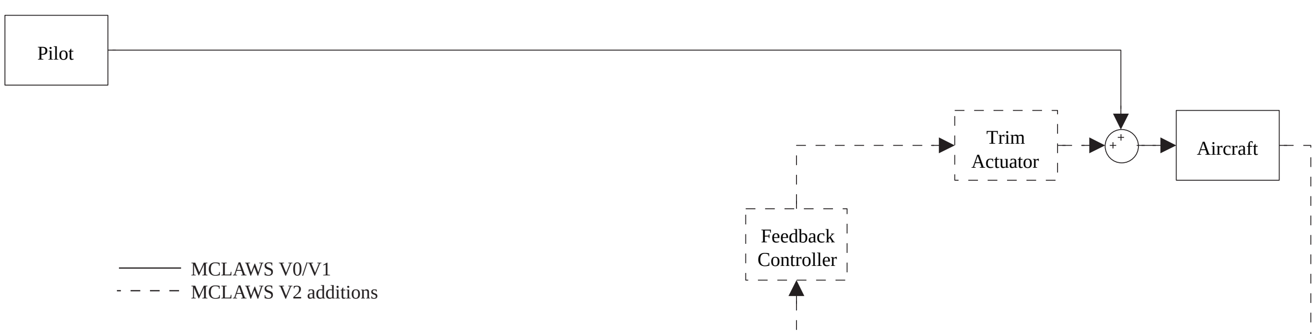
The solid lines of Figure 1 show the top level architecture of MCLAWS V0. The goal of MCLAWS V0 was to demonstrate improved handling qualities for hover/low-speed flight using the standard UH-60 limited-authority SAS actuators and limited rate trim actuators to provide an ACAH response-type in pitch and roll. The MCLAWS V0 pitch and roll architecture as shown in Figure 1(a) consisted of a command model and PID attitude feedback which provided commands to the SAS actuators. In order to increase the ACAH envelope out to 50 knots, the trim actuators were used to offload the SAS actuators through a trim follow-up system. At speeds greater than



(a) Pitch and roll axes



(b) Yaw axis



(c) Collective axis

Fig. 1: MCLAWS control system architecture

50 knots, the system transitioned to a rate-command response-type with rate-damping similar to the baseline SAS-only response.

The architecture of the directional axis, shown in Figure 1(b), also consists of a command model and feedback, however the feedback and actuator usage differs from the pitch and roll axes. For piloted inputs, the feedback is a rate damping system utilizing the yaw SAS actuator only. When the heading hold mode is engaged, PID feedback is used with individual commands going to both the yaw SAS and trim actuators in a frequency splitting arrangement.

As shown in Figure 1(c), MCLAWS V0 did not provide augmentation in the vertical axis as standard UH-60A/L model Black Hawks do not have collective SAS or trim actuators.

MCLAWS V1 used the same architecture as MCLAWS V0 however MCLAWS V1 incorporated logic changes and used a new set of optimized feedback gains. Changes to the logic included increasing the envelope of the ACAH response-type from 50 knots to 60 knots and setting a yaw rate threshold before heading hold engaged. During the MCLAWS V0 work in 2003, only the pitch axis gains were optimized using CONDUIT® (Ref. 7). In MCLAWS V1, the gains for all three axes were optimized. More details of the optimization strategy used is provided in a later section.

MCLAWS V2

The dashed lines in Figure 1 indicate components which were added for MCLAWS V2. For MCLAWS V2, the architecture of the pitch, roll, and yaw axes was changed to the explicit model following architecture chiefly through the addition of an inverse plant model and equivalent delay. Additionally, the mechanical path was subtracted from the commands to the SAS actuators so that the total command to the aircraft primary servos was consistent with the model following architecture. This approach for partial-authority model following was first proposed for the AH-64D MCLAWS (Ref. 8)

With the installation of a collective trim actuator on the AFDD EH-60L, it was possible to include vertical axis augmentation. When the pilot pulls the collective trim release trigger, the system acts just as it did for MCLAWS V0 and MCLAWS V1, i.e. it acts the same as the legacy SAS/FPS system. When the pilot releases the collective trim release trigger, the system automatically sets an open-loop constant deceleration velocity command initialized at the current vertical velocity. Once the commanded velocity drops below a threshold value of 30 ft/min, the system sets the reference altitude as the current altitude. This logic prevents large altitude overshoot for the case when the pilot releases the collective trim release trigger with a significant vertical rate of change.

Using commanded velocity rather than actual velocity in the logic allows for an additional feature in the vertical axis. The pilot can push or pull against the force without releasing trim to command a vertical rate of change and then release the collective lever back to the zero-force position and resume altitude hold at the original altitude. This functionality allows the pilot to briefly deviate from an altitude to avoid an obstacle and resume the original altitude without requiring the pilot to recapture the original reference altitude.

Additionally, the vertical axis has a trim beeper. Short beeps (< 1 sec) will adjust the reference altitude by one foot per beep. Sustained beeps (≥ 1 sec) result in a ± 300 ft/min commanded vertical velocity.

CONTROL LAW OPTIMIZATION

During the 2000-2003 MCLAWS V0 work, the optimization was performed only on the pitch axis feedback gains, the optimization used a limited set of specifications, and the design margin was applied to all specifications (Ref. 7). Refinements in the CONDUIT® optimization process over the past decade (Ref. 12) have been incorporated into the optimization of the MCLAWS V1 and MCLAWS V2 feedback gains. The following discussion of control law optimization pertains to both MCLAWS V1 and MCLAWS V2 except in the case of the vertical axis control laws as they are only present in MCLAWS V2. The optimization approach used for this research closely follows the method developed by Mansur and Tischler (Ref. 13).

Analysis Model Validation

A key requirement for control law optimization and linear analysis is ensuring the analysis model is an accurate representation of the actual system. For this research, the analysis model included a 22-state identified model (Ref. 14) of the

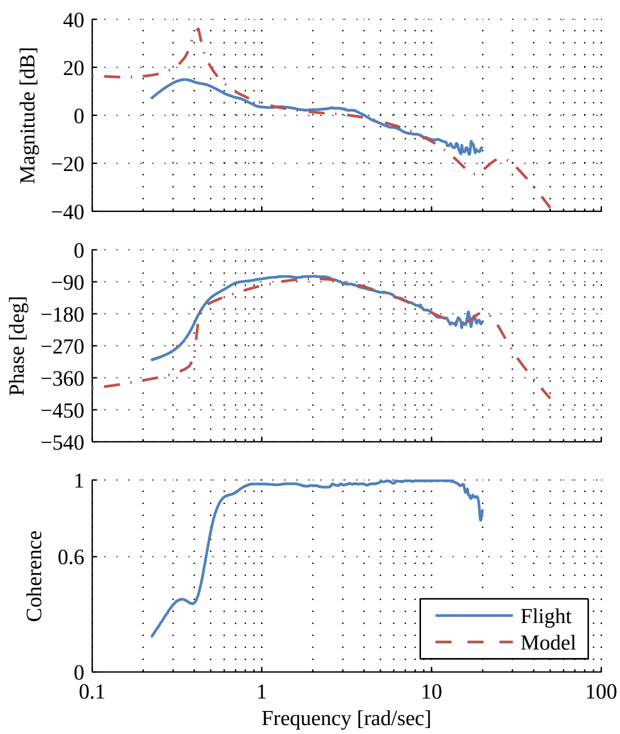


Fig. 2: Roll axis broken-loop validation

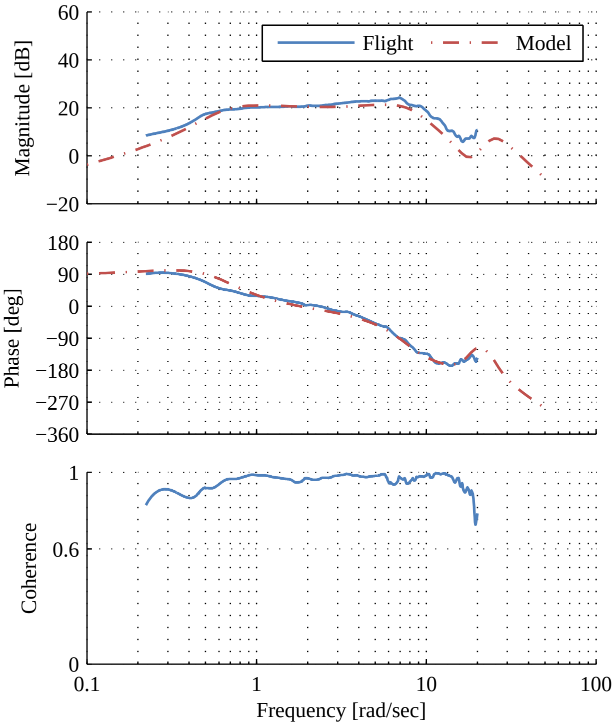


Fig. 3: Roll axis closed-loop validation $\left(\frac{p}{\delta_{lat}}\right)$

UH-60A/L dynamics which has been extensively validated and utilized over the past 17 years. A properly validated model improves the confidence that the predicted performance will match the performance seen in flight. Additionally, it provides accurate stability margin data which can be used to address safety concerns prior to flight. All validation was performed using system identification techniques (Ref. 15)

Among the first tests points of the renewed flight test effort in 2012 were frequency sweeps to be used for model validation. The test aircraft did not have the ability to inject automated chirps into the control system so only pilot frequency sweeps were collected, however it was possible to identify the broken-loop response in addition to the closed-loop response. The broken-loop response was identified from the piloted sweep data using the method from Tischler et al. (Ref. 7) in which the frequency responses of the individual broken-loop components were identified and combined via frequency domain arithmetic.

The roll axis broken-loop responses from the analysis model and from flight test data are compared in Figure 2. The excellent agreement between the flight data and analysis model over the frequency range of 1–12 rad/sec ensures that the crossover frequencies and stability margins will be well predicted by the analysis model. Equally good agreement was found in the pitch and yaw axes. Similarly, Figure 3 compares the roll axis closed-loop responses $\left(\frac{p}{\delta_{lat}}\right)$ of the analysis model and flight test data which also show very good agreement ensuring accurate prediction of system bandwidth.

SAS vs. Trim Actuator Control Allocation

The yaw feedback controller generated individual commands in a frequency splitting arrangement for each of the actuators as opposed to the pitch and roll axes where the trim actuator commands were the SAS actuator commands passed through a low-pass filter trim follow-up system. In MCLAWS V0, the commands to both the SAS and trim actuators had comparable frequency content. To support the current effort, a new specification was developed for the MCLAWS yaw axis optimization which sought to constrain the frequency separation of the commands going to the yaw axis SAS and trim actuators. This new specification considers the ratio of the SAS actuator command cutoff frequency to the trim actuator command cutoff frequency and constrains the ratio as follows:

$$1 \leq \frac{\omega_{co_{SAS}}}{\omega_{co_{trim}}} \leq 2\frac{\omega_{n_{SAS}}}{\omega_{n_{trim}}}$$

where ω_n is the natural frequency of the actuator. For the Black Hawk, the ratio of actuator natural frequencies is approximately $\frac{\omega_{n_{SAS}}}{\omega_{n_{trim}}} = 1.6$, thus the ratio of actuator command cutoff frequencies was constrained as $1 \leq \frac{\omega_{co_{SAS}}}{\omega_{co_{trim}}} \leq 3.2$. Using this specification in the optimization of MCLAWS V2 resulted in a predicted actuator command cutoff frequency ratio of approximately $\frac{\omega_{co_{SAS}}}{\omega_{co_{trim}}} = 2.30$.

Table 1: Yaw axis actuator command cutoff frequencies

	SAS Actuator	Trim Actuator	Ratio
MCLAWS V0	0.97	0.81	1.21
MCLAWS V2	2.08	0.76	2.76

Table 1 compares the actual cutoff frequencies of the actuator commands for MCLAWS V0 and MCLAWS V2 from flight test data collected during the Lateral Reposition MTE when the heading hold mode was engaged. The data show that

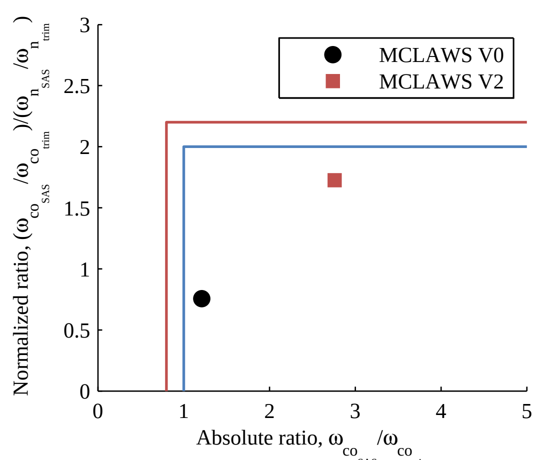


Fig. 4: Yaw axis actuator command cutoff frequency allocation specification

for MCLAWS V0, the frequency content to both actuators was similar while for MCLAWS V2 there was frequency separation between the two actuators as designed. The MCLAWS V2 identified value $\frac{\omega_{co_{SAS}}}{\omega_{co_{trim}}} = 2.76$ is close to the value predicted by CONDUIT®. Figure 4 shows the boundaries of the new specification and plots the MCLAWS V0 and MCLAWS V2 values. Along the x-axis is the absolute ratio of actuator command cutoff frequencies i.e. $\frac{\omega_{co_{SAS}}}{\omega_{co_{trim}}}$, while the normalized ratio on the y-axis is the absolute ratio normalized by $\frac{\omega_{n_{SAS}}}{\omega_{n_{trim}}}$.

The pilots noted that for MCLAWS V1 and MCLAWS V2, the performance of the heading hold mode was significantly improved as compared to MCLAWS V0. Additionally, the MCLAWS V2 heading hold held the reference heading 70% tighter than the SAS/FPS heading hold mode as shown later in Table 4.

Optimized Gains

The control system feedback gains were optimized in CONDUIT® following the methods outlined in (Ref. 13) and using the new yaw axis specification. The optimization of MCLAWS V1, which did not have outer loop modes, was conducted as a single optimization of the three inner-loop axes. MCLAWS V2 was conducted as a nested optimization with the vertical axis as the outer-loop.

External load dynamics were considered in the optimization through the use of a FORECAST (Ref. 16) UH-60 dynamics model with a load mass ratio of $LMR = 0.25$ (5,500 pound external load weight). The stability margins were evaluated for both the loaded and unloaded model; pitch, roll, and yaw axes stability margins were the only specifications included for the external load case. Including the external load case stability margins in the optimization forced a compromise between the loaded case stability margins and some of the unloaded case handling qualities requirements. For the optimization of MCLAWS V1, the loaded case stability margins requirements were reduced to 30° of phase margin and 4 dB of gain margin which as was used for CH-53K analysis (Ref. 17) The disturbance rejection bandwidth boundaries for pitch and roll were also reduced. For the MCLAWS V2 optimization, the changes to the architecture allowed all specifications to be met at the standard values.

A design margin optimization was conducted to provide a spectrum of gain sets of increasing performance (i.e. crossover frequency and disturbance rejection bandwidth). Several gain sets were evaluated in flight and the final gains were selected based on pilot comments.

Table 2 compares the final CONDUIT® predictions of performance metrics for the three MCLAWS versions. Boldfaced items do not meet the ADS-33E-PRF (Ref. 2) or ADS-33E Test Guide (Ref. 18) requirements. For MCLAWS V0, disturbance rejection specifications and a loaded model were not used and the subsequent analysis showed that this earlier design did not meet several of the requirements. For MCLAWS V1, the boundaries of the disturbance rejection bandwidth and loaded stability margins specifications were reduced as discussed above. For both MCLAWS V0 and MCLAWS V1, the yaw bandwidth requirement was not satisfied, however this is normal for a UH-60. For MCLAWS V2, all specifications were satisfied at the default boundaries.

Table 2: Predicted performance for the three MCLAWS versions

	Specification	MCLAWS V0	MCLAWS V1	MCLAWS V2
Pitch	Crossover	3.90 rad/sec	3.04 rad/sec	3.25 rad/sec
	Phase Margin	**42.3**°	45.7°	56.9°
	Gain Margin	11.4 dB	14.0 dB	13.1 dB
	Bandwidth[a]	2.95 rad/sec	2.65 rad/sec	2.10 rad/sec 2.61 rad/sec
	DRB	**0.35** rad/sec	**0.42** rad/sec	0.56 rad/sec
	DRP	1.32 dB	1.84 dB	1.77 dB
	Phase margin w/ ext. load	69.5°	**38.8**°	45.0°
	Gain margin w/ ext. load	**5.52** dB	7.92 dB	6.90 dB
Roll	Crossover	3.01 rad/sec	3.25 rad/sec	4.03 rad/sec
	Phase Margin	65.6°	87.2°	59.2°
	Gain Margin	12.2 dB	11.5 dB	10.3 dB
	Bandwidth	4.75 rad/sec	5.02 rad/sec	3.26 rad/sec
	DRB	1.03 rad/sec	**0.62** rad/sec	0.96 rad/sec
	DRP	3.38 dB	1.54 dB	3.63 dB
	Phase margin w/ ext. load	**4.3**°	**30.0**°	45.0°
	Gain margin w/ ext. load	8.30 dB	7.00 dB	7.05 dB
Yaw	Crossover	2.90 rad/sec	3.54 rad/sec	3.56 rad/sec
	Phase Margin	72.2°	69.9°	61.8°
	Gain Margin	17.2 dB	14.9 dB	14.7 dB
	Bandwidth	**1.82** rad/sec	**1.85** rad/sec	2.42 rad/sec
	DRB	**0.40** rad/sec	0.97 rad/sec	0.94 rad/sec
	DRP	1.94 dB	3.20 dB	3.27 dB
	Phase margin w/ ext. load	80.2°	80.8°	69.2°
	Gain margin w/ ext. load	19.2 dB	16.9 dB	16.6 dB

[a] Two bandwidths were evaluated for MCLAWS V2 pitch axis and are discussed later in the paper

TEST AIRCRAFT

All flight tests for the MCLAWS V1 and MCLAWS V2 research were conducted on AFDD's EH-60L Advanced QuickFix Black Hawk helicopter, shown in Figure 5. The AFDD Flight Projects Branch (FPB) has removed all of the QuickFix equipment with the exception of the inertial navigation unit (INU) and associated navigation control panel and the control display unit (CDU) as well as all external antennas making the aircraft similar to a standard UH-60L. Numerous additional sensors have been installed on the aircraft to support various research projects including an EGI, a differential GPS

Fig. 5: AFDD's EH-60L research helicopter

receiver, and string potentiometers to measure the positions of the pilot flight controls, the SAS actuators, the inputs to the control mixer, and the primary actuators.

The Airframe Data System (ADS) is a Windows based PC which is the primary data recording system for the aircraft research systems. The ADS records approximately 120 signals, including analog signals such as string potentiometers for control positions and actuator displacements, engine data, and air data measurements; the I01 and I09 groups from the INU (primarily aircraft state data); and DGPS data. The data are recorded in individual files as commanded by the system operator, where each file represents a test point.

A programmable display generator (PDG), two 10-inch LCDs, and video recording equipment has been installed to conduct pilot cuing research. The BrownOut Symbology Set (BOSS) (Ref. 19) was used for all MCLAWS V1 and MCLAWS V2 testing. Three control law mode annunciators were added to the BOSS displays for the MCLAWS work: (1) MCLAWS engaged and response-type, (2) altitude hold engaged and reference altitude, and (3) heading hold engaged.

PAFCA System Hardware

The Partial Authority Flight Control Augmentation (PAFCA) system was developed in 2003 in order to implement the MCLAWS on the EH-60L. The PAFCA system consists of a SAS/trim interface box, research flight control computer (RFCC), and cockpit control panel. The RFCC is a VME form-factor computer running the VxWorks real-time operating system which is used to host the MCLAWS software. The RFCC receives aircraft state information from the INU, pilot control position data from string potentiometers, as well as discrete signals from the pilot controls and cockpit panels. The MCLAWS software generates actuator commands which are sent to the SAS/trim interface box. Digital outputs from the MCLAWS software are used to drive cockpit indicators in the form of lights and annunciators in the BOSS symbology. The RFCC also records MCLAWS specific data in a continuous file which is merged post-flight with the individual ADS data records.

The SAS/trim interface box contains relays which allow either the commands from the standard aircraft flight control computer or the RFCC through to the actuators. This allows the aircraft to be flown in either the standard UH-60 configuration or the MCLAWS configuration without changing out flight control computers. This feature made it trivial to perform a back-to-back comparison of the two flight control systems. It also allows non-MCLAWS research to be conducted without downtime needed to switch flight control computers. The SAS/trim interface box is controlled by a magnetically held switch and release button located on a panel in the cockpit center console within reach of either the evaluation pilot or the safety pilot.

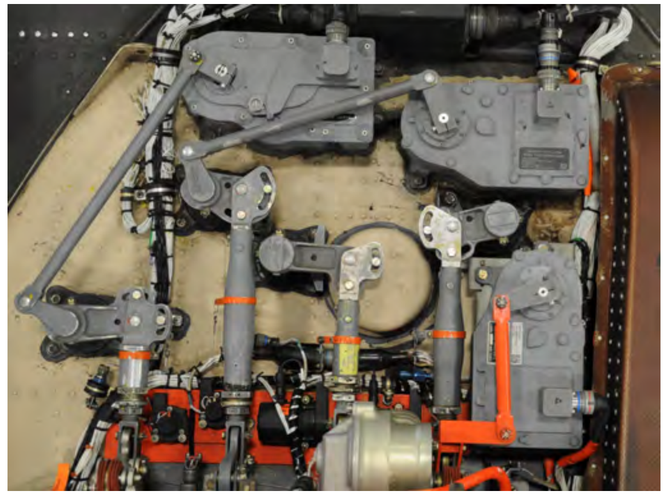


Fig. 6: AFDD's EH-60L trim actuators (clockwise from top left: yaw, roll, collective)

Collective Trim Actuator

In order to provide vertical axis augmentation in MCLAWS V2, the FPB procured a collective trim actuator and installed it on the EH-60L; the collective trim actuator is the same model which has been installed on U.S. Air Force HH-60G helicopters as a part of the Advanced Hover Hold Stabilization system. Figure 6 shows the yaw, roll, and collective trim actuators installed on the top deck of AFDD's EH-60L. Aside from different mechanical stop positions, the collective trim actuator is nearly identical to the roll and yaw trim actuators. The collective actuator is in the lower right with the orange linkage connecting the actuator to the collective control rod. Additionally, the UH-60L collective grip was replaced with an Air Force HH-60G grip which maintained all the features of the UH-60L grip and added the necessary trim release trigger switch and a COM/ICS switch which was re-purposed to serve as a trim beeper.

MCLAWS V1 BROWNOUT FLIGHT TESTS

During the summer of 2013, MCLAWS V1 was evaluated in brownout conditions at the Yuma Proving Ground in Arizona over the course of six weeks as a part preliminary flight testing for the U.S. Air Force led 3D-LZ Joint Capabilities Technology Demonstration (JCTD); the JCTD demonstration flights will occur in 2014. The primary focus of the 2013 preliminary flight test program was to evaluate a LADAR sensor system and the BOSS guidance equations and symbology in brownout conditions. More details of the entire 2013 3D-LZ test effort are presented by Szoboszlay (Ref. 20) with a focus on the LADAR system and BOSS symbology.

Fig. 7: Burro and Sidewinder landing zones

Test Location

Flight tests were conducted at the Yuma Proving Ground in southwestern Arizona, either at Laguna Army Airfield (KLGF) or at prepared dust lanes approximately 4 nautical miles north of the airfield. There were a total of three prepared dust lanes which were named Burro, Sidewinder, and X-ray. X-ray was used to evaluate the LADAR system and had numerous small obstacles distributed in set patterns in the landing area. Sidewinder was used for brownout landings and had numerous large and small obstacles surrounding the landing area. The Burro landing zone was set up next to Sidewinder for use during the hover task. Using separate landing zones for the hover task and landing task provided time for the dust to clear from one landing zone while a maneuver was performed at the other. Figure 7 shows the Burro and Sidewinder landing zones and some of the obstacles surrounding them. The landing zones are distinguished by the lighter areas which have been tilled to increase the amount of dust present during the tasks. In the figure, the aircraft is making an approach to the Sidewinder landing zone; Burro is in the foreground and X-ray is about 1 km to the south. For the MCLAWS V1 evaluation, only the hover maneuver was evaluated which occurred at the Burro landing zone.

Test Methodology

A total of seven test pilots participated in the 3D-LZ flight tests and of these, five conducted evaluations of the MCLAWS V1. Three of the pilots were from the U.S. Army and two were from the U.S. Air Force, all were experimental test pilots.

Each of the participating evaluation pilots were at Yuma for five days. On the first day, the pilots were provided a range briefing, as well as briefings covering the LADAR system, the BOSS symbology and guidance equations, and MCLAWS V1. On the second day, familiarization flights were conducted at the airfield, first without cockpit masking and then with partial masking in which the views out of the greenhouse, chin bubble, and lower half of the evaluation pilot door window were covered using sun shades. On the third day, flights were conducted at the airfield with full cockpit masking (greenhouse, chin bubble, all of evaluation pilot door window, and the evaluation pilot windshield covered with sun shades) as well as a brief trip to the test range (without masking). The fourth day served as a dry run with the majority of the flight taking place at the dust lanes. The full evaluation occurred on the last day during which all runs were "record" runs.

During the dry run flights, after the last run for a given configuration, the pilots were asked to provide visual cue ratings (VCRs) based on the symbology in order to determine the usable cue environment (UCE). As stipulated by ADS-33, the VCRs were only collected when the pilots were flying with the legacy SAS/FPS system which provides the required rate response-type (Ref. 2). After the final run of each configuration on the evaluation flight, each pilot was asked to provide handling qualities ratings (HQRs), NASA TLX workload ratings (Ref. 21), and comments. During the post flight debrief, each of the test points was discussed and video of pilot displays and external cameras was reviewed allowing the pilots to provide additional comments.

Test Matrix

The MCLAWS portion of the testing at Yuma consisted of a comparison of the MCLAWS V1 against the baseline SAS/FPS during an approach to brownout hover task. The MCLAWS flight envelope was only expanded to 20 ft AGL, thus the aircraft was not permitted to land while the MCLAWS were engaged (see the 3D-LZ paper (Ref. 20) for details on landings with the SAS/FPS control system).

The approach to brownout hover task was initiated at 0.8 nautical mile away from the intended hover point, at a ground speed of approximately 80 knots, and an altitude of approximately 250 ft AGL. The pilot then followed the BOSS guidance to descend and decelerate to a 30-ft hover at a designated point over the Burro landing zone. Once established in a stable hover, the pilot was then required to maintain position within the ADS-33 Hover MTE position tolerances (Table 3) for 30 seconds. The pilots were assisted during the hover maintenance portion of the task by additional cues in the BOSS symbology which provided clear indicators of task performance in relation to the desired and adequate tolerances presented in Table 3.

Table 3: Maneuver tolerances for hover maintenance portion of 3D-LZ approach to brownout hover task

	Desired	Adequate
Maintain the longitudinal and lateral position within $\pm X$ ft of a point on the ground:	3 ft	6 ft
Maintain altitude within $\pm X$ ft:	2 ft	4 ft
Maintain heading within $\pm X$ deg:	5 deg	10 deg

Results

Figure 8 plots the worst average attitude and translational rate visual cue ratings against the ADS-33 usable cue environment boundaries and shows that the hover maneuver was conducted in UCE = 2 conditions (UCE ¿ 2 is considered DVE). The

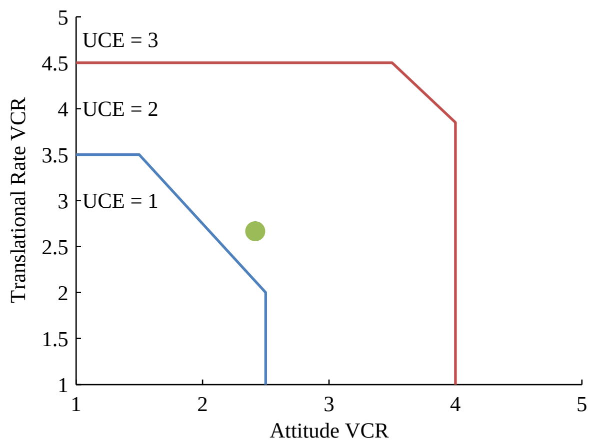


Fig. 8: Visual cue ratings for the 3D-LZ approach to brownout hover task

visual cue ratings were collected using the BOSS displays for cues, as in the brownout there were no usable cues outside the aircraft.

Table 4 compares the root mean square errors for position, altitude, and heading during the 30 second hover portion of the task for the legacy SAS/FPS system and MCLAWS V1. In horizontal and vertical position, MCLAWS V1 has smaller errors however the differences are generally minor ($< 15\%$). This is to be expected as the aircraft dynamics and wind conditions were the same and neither system had a position hold mode. In the directional axis, the MCLAWS V1 heading hold reduced the heading error by 70% and was much preferred by the pilots. While the heading error was less with MCLAWS V1, the heading requirement was not an important factor during the task as both systems maintained heading within tolerance.

The pilots were asked to provide NASA TLX ratings (Ref. 21) which provides a qualitative metric to assess pilot workload during a task. The TLX ratings consist of six subratings each on a ten-point scale which assess different aspects of workload, e.g. physical, temporal, mental, etc. The subratings are summed together to provide the cumulative workload for the task where lower cumulative ratings indicate lower pilot workload. Figure 9 compares the cumulative workload ratings for the legacy SAS/FPS with the ratings for MCLAWS V1 provided by four of the evaluation pilots. For all four pilots, the MCLAWS V1 reduced the workload for the approach to brownout hover task.

Table 4: Root mean square errors during hover maintenance portion of 3D-LZ approach to hover task

Axis	SAS/FPS	MCLAWS V1	Percent Change
Lateral	1.19 ft	1.16 ft	-2.7%
Longitudinal	1.82 ft	1.69 ft	-7.0%
Altitude	1.95 ft	1.71 ft	-12.4%
Heading	0.99°	0.30°	-69.7%

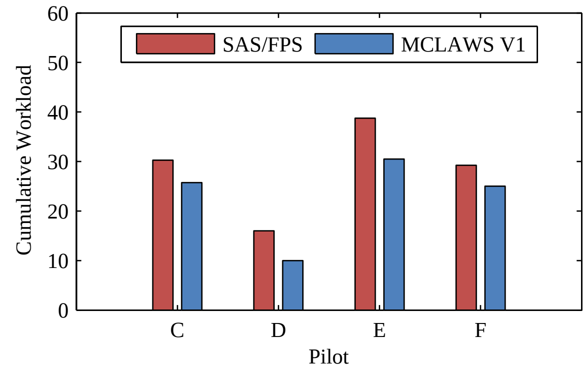


Fig. 9: NASA TLX workload ratings for the 3D-LZ approach to brownout hover task

The handling qualities ratings collected from the pilots is presented in Figure 10. The filled symbols represent the average of all the ratings and the open symbols represent the maximum and minimum ratings. When evaluating the SAS/FPS, the pilot had more difficulty meeting the desired tolerances than they did with the MCLAWS V1 resulting in the higher workload demonstrated by the TLX ratings. Overall, the MCLAWS received better handling qualities ratings than the SAS/FPS which is in line with the reduced workload when evaluating MCLAWS V1.

Pilot comments collected during the flight and post-flight debriefing were consistent across the pilots. They noted that the workload was less with the MCLAWS V1 which matches with the TLX workload data presented in Figure 9. Additionally the pilots noted that the 30 second hover maintenance portion of the task was significantly easier with the MCLAWS V1.

Other pilot comments noted that MCLAWS V1 increased precision when following symbology during the decelerating approach phase and during the hover maintenance phase and improved performance through effective translational lift. The SAS/FPS system was preferred during departures, as it allowed the pilot to be more aggressive, and during large turns

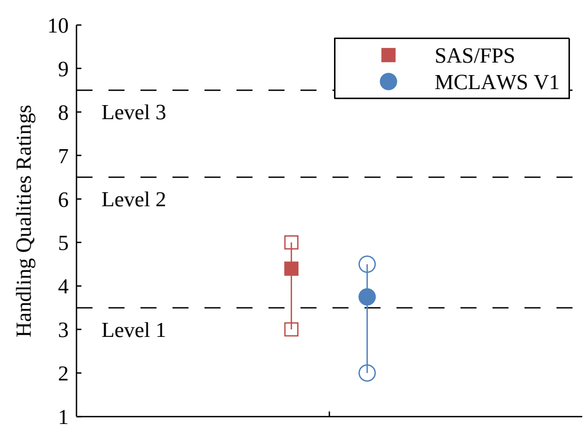


Fig. 10: Handling qualities ratings for the 3D-LZ approach to brownout hover task

(≥ 90°) since the ACAH response-type of MCLAWS V1 required that the cyclic be held against the force gradient for prolonged periods during these maneuvers. Holding against the force was required due to deficiencies in the way the cyclic force trim release currently operates in MCLAWS V1. It is intended in a future version of MCLAWS that the force trim release will function similarly to the legacy system which would allow the pilot to zero out the cyclic forces about a new trim position during the turn.

Overall, MCLAWS V1 provided similar or better performance, reduced the pilot workload, and improved the handling qualities ratings compared to the baseline SAS/FPS in the brownout conditions.

MCLAWS V2 HANDLING QUALITIES EVALUATION

In January 2014, the MCLAWS V2 simulated DVE handling qualities evaluation was conducted on AFDD's hover/low-speed MTE course (Ref. 22) located at Moffett Federal Airfield (KNUQ) in California. Four experimental test pilots evaluated the system, two each from AFDD and Aviation Applied Technology Directorate (AATD). Five of the ADS-33 Mission Task Elements (MTEs) were selected for the MCLAWS V2 evaluation: Hover, Hovering Turn, Vertical Maneuver, Lateral Reposition, and Depart/Abort.

Pitch Axis Command Model Natural Frequency

When MCLAWS V2 was developed, the structure of the pitch and roll command models was changed from critically damped second-order systems to underdamped second-order systems with a damping ratio of $\zeta = 0.707$. The natural frequencies of the new command models were selected such that the rise times with the new natural frequencies closely

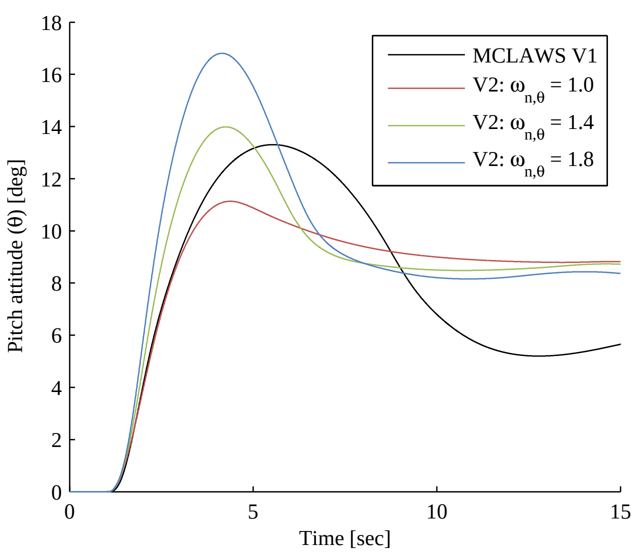


Fig. 11: Pitch axis step responses of the four pitch axis command model natural frequency configurations

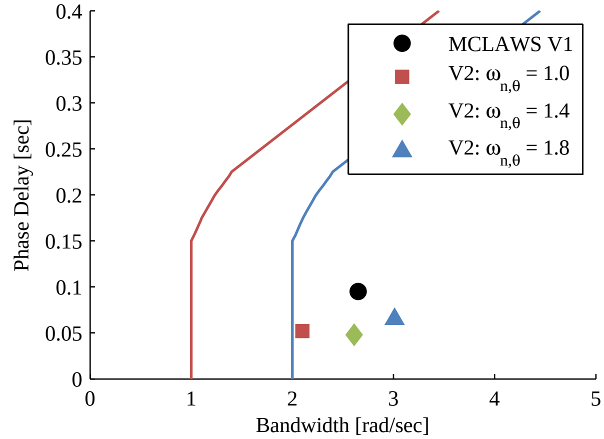


Fig. 12: Bandwidths of the four pitch axis command model natural frequency configurations

matched the rise times with the old. Additionally, the stick gains were increased in MCLAWS V2 based on pilot feedback which resulted in a larger steady-state value in MCLAWS V2.

For the pitch axis, a natural frequency of $\omega_{n,\theta} = 1.8\,{}^{\text{rad}}/_{\text{sec}}$ was selected. Figure 11 compares the step responses from a 0.75 inch step cyclic displacement of MCLAWS V1 and MCLAWS V2. The figure shows that MCLAWS V2 has an improved settling time and a comparable large ($\sim$ 100%) overshoot.

This large overshoot seen in MCLAWS V1 and MCLAWS V2 with a natural frequency of $\omega_{n,\theta} = 1.8\,{}^{\text{rad}}/_{\text{sec}}$ resulted from SAS actuator position limiting. For MCLAWS V2, the command model natural frequency was reduced in order to reduce this overshoot. Lowering the natural frequency directly reduced the aircraft bandwidth as illustrated in Figure 12 and resulted in a slower response to piloted inputs. Based on pilot feedback, a natural frequency of $\omega_{n,\theta} = 1.0\,{}^{\text{rad}}/_{\text{sec}}$ was selected for the handling qualities evaluation due to its reduced overshoot for large inputs. However, the first pilot to perform the Hover MTE with the natural frequency of $\omega_{n,\theta} = 1.0\,{}^{\text{rad}}/_{\text{sec}}$ found the low bandwidth to be objectionable so the natural frequency was increased to $\omega_{n,\theta} = 1.4\,{}^{\text{rad}}/_{\text{sec}}$ and both natural frequency configurations were evaluated back-to-back as much as possible.

Simulated DVE

For improved safety, evaluations were conducted in the GVE and the cues for the evaluation pilot were degraded in order to simulate DVE conditions. The cues were degraded to UCE = 2 as described in the ADS-33E-PRF Test Guide (Ref. 18) using standard night vision goggles equipped with apertures and neutral density filters and a neoprene shroud to eliminate peripheral cues (Figure 13). The filter stack was adjusted before each flight to ensure UCE = 2 conditions. During familiarization with the goggles, the pilots commented that it was quite similar to flying with the night vision goggles at night due to the reduced visual acuity and the loss of peripheral cues which resulted in more longitudinal drift.

Fig. 13: Modified night vision goggles and shroud to simulate DVE conditions

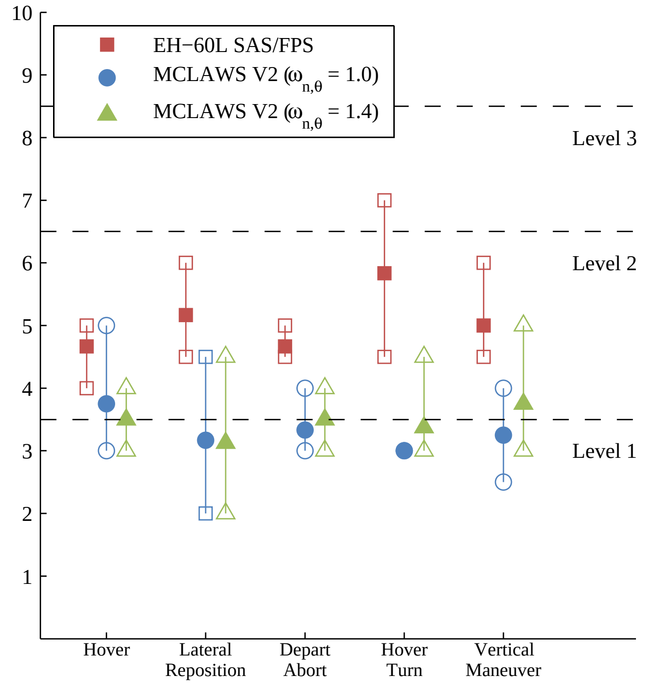


Fig. 14: Comparison of handling qualities ratings for SAS/FPS and MCLAWS V2 in simulated UCE =2 conditions

Test Methodology

Flight testing consisted of two flights per pilot. The first flight was a familiarization flight in which the pilots were familiarized with the MCLAWS V2 response and the ADS-33 MTE course in GVE conditions. Once the pilots were comfortable in the GVE, they put on the night vision goggles and neoprene shroud in order to become accustomed to the degraded visual cues for each of the MTEs.

Pilot ratings and comments were collected for each MTE during the second flight. Upon completion of each MTE in each configuration, a pilot questionnaire (Ref. 13) was used to assess the performance of the configuration during the task in six areas:

1. Pilots' ability to be aggressive
2. Pilots' ability to be precise
3. Ride quality
4. Predictability of the aircraft response
5. Overall aircraft handling qualities ratings using the Cooper-Harper rating scale (Ref. 23)
6. PIO tendencies if applicable using the PIO rating scale (Ref. 24).

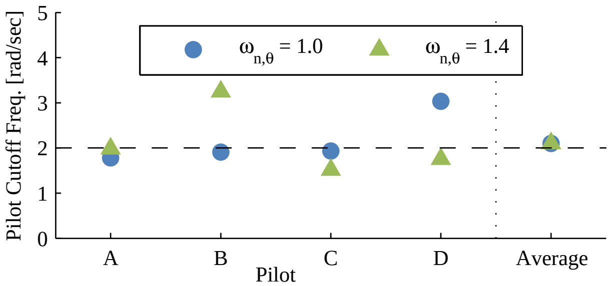
Additionally, for any task in which the pilot flew both MCLAWS V2 pitch axis command model natural frequency configurations, the pilots were asked to provide a preferred configuration.

Results

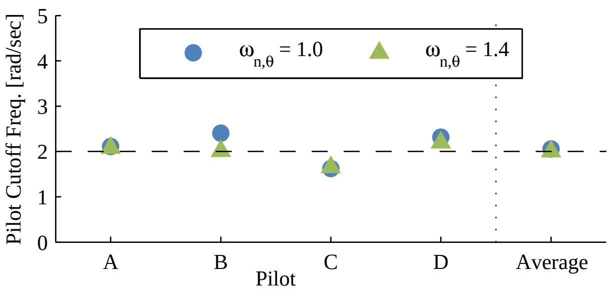
Figure 14 compares the handling qualities ratings of both configurations of MCLAWS V2 with the baseline SAS/FPS in the DVE. The ratings for the SAS/FPS were collected in 2008 as a part of the UH-60M Upgrade risk-reduction work (Ref. 25). The ratings were collected during testing on the EH-60L in order to provide a baseline with which to compare the UH-60M Upgrade control laws. The DVE evaluation was conducted for the same set of MTEs using the same night vision goggle setup for simulating the DVE as used for the MCLAWS V2 testing. For this testing, only handling qualities ratings exist, as the additional rating scales (precision, aggressiveness, etc.) used in the MCLAWS testing are a recent addition to to the pilot questionnaire.

In the DVE, the baseline SAS/FPS control system was rated Level 2 while the MCLAWS V2 configurations were predominantly rated Level 1. While ratings for the SAS/FPS control system were not collected during the January 2014 testing, some of the pilots did fly the SAS/FPS and MCLAWS configurations back-to-back. The pilots noted that when flying the MCLAWS V2 configurations there was a significant reduction in workload and desired performance was achieved more often. Only small differences existed in the handling qualities ratings for the two MCLAWS V2 configurations.

The altitude hold mode was noted to be a contributing factor in reducing the pilot workload. During the Hover and Hover Turn MTEs, all four pilots allowed the altitude hold mode to regulate the vertical axis. For the Lateral Reposition MTE, the pilots generally stayed out of the loop in the vertical axis, though some pilots did enter the loop occasionally during aggressive decelerations to the finish gate. During the Depart/Abort MTE, one pilot was always in the loop in the vertical axis, two pilots would occasionally enter the loop during the deceleration, and one pilot rarely entered the loop.



(a) Lateral axis



(b) Longitudinal axis

Fig. 15: Average pilot cutoff frequencies for both MCLAWS V2 configurations

Much like the handling qualities ratings for the two MCLAWS V2 configurations, there was little difference between the aggressiveness, precision, ride quality, and predictability ratings when averaged across all the pilots. When considered on a pilot-by-pilot basis, these additional ratings were highly correlated with the pilots' preferred configuration for the task. In the cases when a pilot would give the same handling qualities rating for both configurations, the preferred configuration had better ratings for aggressiveness, precision, ride quality, and/or predictability.

Though neither MCLAWS V2 configuration was universally preferred, a trend was apparent. For the Hover MTE, Hovering Turn MTE, and Vertical Maneuver MTE, all of which have tight horizontal position tolerances, the lower bandwidth case was preferred 75% of the time. This contrasts with the Lateral Reposition MTE and Depart/Abort MTE both which have looser position tolerances and are conducted at higher velocities and for which the higher bandwidth case was preferred 66% of the time.

The average pilot cutoff frequencies during the 30 second hover portion of the Hover MTE are presented in Figure 15. The dashed line at 2 rad/sec represents the ADS-33E-PRF, low phase delay bandwidth requirement for UCE $>$ 1 Level 1–Level 2 boundary. Previous research (Ref. 26) suggested that when the pilot cutoff frequency is below the aircraft bandwidth, the cutoff frequency can be taken as the task bandwidth. Additionally, in order to achieve the best handling qualities, the aircraft bandwidth should be greater than the highest task bandwidth from among the MTEs; the Hover MTE task bandwidth was found to be the highest task bandwidth of the MTEs evaluated.

From the data in Figure 15, though there are two outliers, it can be seen that the average task bandwidth for the Hover MTE based on all the runs were nearly identical for both bandwidth configurations in pitch and roll at about 2 rad/sec. This data confirms the current ADS-33E-PRF UCE $>$ 1 bandwidth requirement Level 1–Level 2 boundary.

CONCLUSIONS

Improvements based on research conducted over the past 10 years has been incorporated into the UH-60 MCLAWS partial-authority control system. The results of two flight tests conducted in brownout and simulated DVE conditions indicate:

1. With consideration of actuator position and rate limits during control system design, it is possible to implement the explicit model following control system architecture on a partial-authority aircraft and achieve the attitude-command/attitude-hold inner loop response and vertical velocity-command/altitude-hold vertical axis response which meet the ADS-33E-PRF UCE = 2 requirements.
2. The UH-60 MCLAWS partial-authority flight control system has demonstrated through piloted flight test evaluation reduced pilot workload and has achieved Level 1 handling qualities in the DVE.
3. Pilot cutoff frequency data collected during the Hover MTE provides confirmation of the current ADS-33E-PRF DVE bandwidth requirement Level 1–Level 2 boundary.

ACKNOWLEDGMENTS

The authors would like to thank everyone who contributed to the success of this research effort. Firstly, the experimental test pilots in addition to LTC Carl Ott who participated in the handling qualities evaluation: MAJ Joseph Minor (AFDD), MAJ Paul DeCecchis (AATD), and MAJ Marc Dalziel (AATD), as well as those who participated in the Yuma brownout flight tests: MAJ Karl Seekamp (USAF) MAJ Joel Soukop (USAF), CW4 Terry Duquette (AATD), and CW5 John Woodyard (160th SOAR(A) SIMO). Additional thanks to Todd Dellert (AATD) for his support during the development of the MCLAWS.

Thanks also to the engineering personnel at AFDD: Ernesto Moralez, David Bui, Gary Leong, and Doug Greaves of NASA Ames for their support with the MCLAWS hardware and software. Thanks to Zoltan Szoboszlay and Nathan Mielcarek for their assistance with the BOSS symbology. Finally, thanks to the L-3 Vertex technicians, especially Casey Blaskowski, Juan Saucedo, and Tom Lynn.

REFERENCES

[1] Anon., "General Requirements for Helicopter Flying and Ground Handling Requirements," MIL-H-8501A, September 7, 1961.

[2]Anon., "Handling Qualities Requirements for Military Rotorcraft," ADS-33E-PRF, March 21, 2000.

[3]Lindell, D., "Study on Rotorcraft Survivability - Summary Report," Department of Defense, September 2009.

[4]Couch, M. and Lindell, D., "Study on Rotorcraft Safety and Survivability," American Helicopter Society 66th Annual Forum, Phoenix, AZ, May 2010.

[5]Irwin, J. G., Einthoven, P. G., Miller, D. G., and Blanken, C. L., "ADS-33E Predicted and Assigned Low-Speed Handling Qualities of the CH-47F with Digital AFCS," American Helicopter Society 63rd Annual Forum, Virginia Beach, VA, May 2007.

[6]Sahasrabudhe, V., Faynberg, A., Blanken, C. L., and Hindson, W. S., "Modernized Control Laws: From Design to Flight," American Helicopter Society 4th Decennial Specialists' Conference on Aeromechanics, San Francisco, CA, January 2004.

[7]Tischler, M. B., Blanken, C. L., Cheung, K. K., Swei, S. M., Sahasrabudhe, V., and Faynberg, A., "Modernized Control Laws for UH-60 Black Hawk Optimization and Flight-Test Results," *AIAA Journal of Guidance, Control and Dynamics*, Vol. 28, (5), 2005, pp. 964–978.

[8]Harding, J. W., Moody, S. J., Jeram, G. J., Mansur, M. H., and Tischler, M. B., "Development of Modern Control Laws for the AH-64D in Hover/Low Speed Flight," American Helicopter Society 62nd Annual Forum, Phoenix, AZ, May 2006.

[9]Berger, T., Tischler, M. B., Blanken, C. L., Fujizawa, B. T., Harding, J. W., Borden, C. C., Cothren, L. E., Wright, J. J., Arterburn, D. R., and Pfrommer, M. R., "Improved Handling Qualitied for the OH-58D Kiowa Warrior in the Degraded Visual Environment," American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 2011.

[10]Christensen, K. T., Campbell, K. G., Griffith, C. D., Ivler, C. M., Tischler, M. B., and Harding, J. W., "Flight Control Development for the ARH-70 Armed Reconnaissance Helicopter Program," American Helicopter Society 63rd Annual Forum, Virginia Beach, VA, May 2007.

[11]Blanken, C. L., Tischler, M. B., Lusardi, J. A., and Ivler, C. M., "Aeronautical Design Standard - 33 (ADS-33) . . . Past, Present and Future," AHS Rotorcraft Handling Qualities Specialists' Meeting, Huntsville, AL, February 2014.

[12]Tischler, M. B., Ivler, C. M., Mansur, M. H., Cheung, K. K., Berger, T., and Berrios, M. G., "Handling Qualities Optimizations and Trade-offs in Rotorcraft Flight Control Design," RAeS Rotorcraft Handling Qualities Conference, Liverpool, England, November 2008.

[13]Mansur, M. H. and Tischler, M. B., "Flight Test Comparison of Alternate Strategies for Multi-Loop Control Law Optimization," American Helicopter Society 69th Annual Forum, Phoenix, AZ, May 2013.

[14]Fletcher, J. W. and Tischler, M. B., "Improving Helicopter Flight Mechanics Models with Laser Measurements of Flapping," American Helicopter Society 53rd Annual Forum, Virginia Beach, VA, April-May 1997.

[15]Tischler, M. B. and Remple, R. K., *Aircraft and Rotorcraft System Identification – Engineering Methods with Flight Test Examples*, AIAA, Reston, VA, second edition, 2012.

[16]Kim, F. D., *Formulation and Validation of High-Order Mathematical Models of Helicopter Flight Dynamics*, Ph.D. thesis, University of Maryland, 1991.

[17]Sahasrabudhe, V., Faynberg, A., Pozdin, M., Cheng, R., Tischler, M., Stumm, A., and Lavin, M., "Balancing CH-53K Handling Qualities and Stability Margins in the Presence of Heavy External Loads," American Helicopter Society 63rd Annual Forum, Virginia Beach, VA, May 2007.

[18]Blanken, C. L., Hoh, R. H., Mitchell, D. G., and Key, D. L., "Test Guide for ADS-33E-PRF," AMRDEC SR AMR-AF-08-07, July 2008.

[19]Szoboszlay, Z. P., McKinley, R. A., Braddom, S. R., Harrington, W. W., and Savage, J. C., "Landing an H-60 Helicopter in Brownout Conditions Using 3D-LZ Displays," American Helicopter Society 66th Annual Forum, Phoenix, AZ, May 2010.

[20]Szoboszlay, Z. P., Fujizawa, B. T., Ott, C. R., Savage, J. C., Goodrich, S., and McKinley, R. A., "3D-LZ 2013 Flight Test: Landing an EH-60L Helicopter in a Brownout Degraded Visual Environment," American Helicopter Society 70th Annual Forum, Montréal, Québec, Canada, May 2014.

[21]Hart, S. G. and Staveland, L. E., "Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research," *Human Mental Workload*, edited by P. A. Hancock and N. Meshkati, North Holland Press, 1988.

[22]Kasper, E. F., "Establishment of a Permanent Aeronautical Design Standard-33 Low-Altitude Flight Test Facility," RDECOM Technical Report RDMR-AF-10-02, April 2013.

[23]Cooper, G. E. and Harper, R. P., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," NASA TN D-5153, April 1969.

[24]Anon., "Flying Qualities of Piloted Aircraft," MIL-STD-1797B.

[25]Fletcher, J. W., Mansur, M. H., Moralez, E., Robinson, D. E., Arterburn, D. R., Cherepinsky, I., Driscol, J., Morse, C. S., and Kalinowski, K. F., "UH-60M Upgrade Fly-By-Wire Flight Control Risk Reduction using the RASCAL JUH-60A In-Flight Simulator," American Helicopter Society 64th Annual Forum, Montréal, Québec, Canada, April-May 2008.

[26]Fujizawa, B. T., Lusardi, J. A., Tischler, M. B., Braddom, S. R., and Jeram, G. J., "Response Type Tradeoffs in Helicopter Handling Qualities for the GVE," American Helicopter Society 67th Annual Forum, Virginia Beach, VA, May 2011.