Design and Flight Test of a Cable Angle/Rate Feedback Flight Control System for the RASCAL JUH-60 Helicopter

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ABSTRACT

The ability of a helicopter to carry externally slung loads makes it very versatile for many civil and military operations. However, the piloted handling qualities of the helicopter are degraded by the presence of the slung load. A control system is developed that uses measurements of the slung load motions as well as conventional fuselage feedback to improve the handling qualities for hover/low speed operations. Prior research has shown a fundamental trade-off between load damping and piloted handling qualities for a feedback control system with cable angle/rate feedback. A new task tailored approach proposed and implemented herein uses a method of switching between a load damping mode and a piloted handling qualities mode. These modes provide appropriate load feedback depending on the piloting task and flight regime. This provides improved handling qualities for maneuvering flight, and for improved precision load control at hover. A new mission task element (MTE) for precision load placement is developed to test the ability of the cable feedback system to improve load placement task performance. The improvements provided by this control system are demonstrated in a piloted flight test on the JUH-60A RASCAL fly-by-wire helicopter. The average load set-down time was reduced by a factor of two for the 1000lb load on a 56ft sling.

NOTATION

Acronyms

AC	Attitude Command
ALTHLD	Altitude Hold
CAF	Cable Angle/rate Feedback control law
DRB	Disturbance Rejection Bandwidth
DF	Development Facility
GM	Gain Margin
HQR	Handling Qualities Rating
LMR	Load Mass Ratio= (Load Mass)/(Load + Aircraft Mass)
MTE	Mission Task Element
OBL	Optimized BaseLine control law
PH	Position Hold
PIO	Pilot Induced Oscillation
PM	Phase Margin
RASCAL	Rotorcraft Aircraft Systems Concepts Airborne Laboratory
RC	Rate Command
RCHH	Rate Command Heading Hold
SAS	Stability Augmentation System
VH	Velocity Hold
XOVER	Cross-over frequency (rad/s)

Symbols

g	Gravity (ft/s^2)
$K_{hookfriction}$	Hook friction
L	Sling length
p_c, q_c	Roll and pitch cable angular rates, with respect to the inertial frame
s	La Place Variable
u, v, w	Aircraft longitudinal, lateral, and vertical body axes velocities
u	Input to model
V_{cmd}, P_{cmd}	Velocity command, position command

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x	Measured state
$\hat{x}$	Estimated state
$\ddot{x}_H$	Inertial hook acceleration component in the x-axis of the cable reference frame
y	Measured outputs
$\delta, \delta_{actuator}$	Pilot input, actuator input
$\delta_{lon}, \delta_{lat}$	Pilot control inputs for lateral and longitudinal cyclic
ΔMAG	Depth of magnitude notch in the aircraft attitude response near the load pendulum mode (dB)
ϕ, θ, ψ	Aircraft roll, pitch and yaw Euler angles with respect to inertial reference frame
ϕ_c, θ_c	Lateral and longitudinal inertial cable Euler angles, with respect to the level heading reference frame
ω_{-135}	Frequency where phase crosses through -135 degrees

INTRODUCTION

The operation of helicopters carrying externally slung loads has an important role in military and civilian applications for many diverse tasks such as delivering supplies, search and rescue, construction, fire-fighting, and logging. The additional utility of operating with a slung load comes at the cost of higher piloted workload due to the nature of controlling a two-body dynamic system: helicopter and slung load. The pilot must maneuver the helicopter effectively in order to fly to the drop-off point, monitor load motions, and eventually place the load down in a precise location – often without visibility of the load from the cockpit. The indirect control of the slung load motions through the helicopter rotor is essentially a noncollocated control problem for the pilot, which are notoriously difficult [1]. It is well known that the presence of heavy external loads causes degraded piloted handling qualities ratings, especially for configurations with long slings and heavy loads [2].

In the 1970s, two methods for providing active damping of the load emerged. The first method is a *direct* "on-load" control mechanism. The on-load actuator provides a direct control force (or moment) to the load, which can damp the load motions independently of the fuselage motions. Many examples of this type of system have been discussed in the literature; including an active arm [3] installed on the hook and an aerodynamically stabilizing fin on the load [4]. The second method is to *indirectly* control the load motion through load feedback to the rotor. To damp load motions, the helicopter must be used as an actuator to control the response of the load, and therefore the load cannot be damped independently of fuselage motions. The concept of using a feedback system to the rotor to *indirectly* damp the load motions by utilizing cable angle feedback was pioneered by Dukes[5], Gupta[6], Liu[7] and Hutto[8]. Lui and Gupta focused on optimal control methods for full-state feedback including load motions. Dukes and Hutto used classical control methods to improve load damping. Reference 7 provides a comprehensive trade-off study comparing these direct and indirect load controlling methods. It was concluded that the indirect feedback systems were more complex in implementation due to electronic technological limitations at the time (1970s), but were more robust in their effectiveness to differing load configurations as compared to control devices installed directly on the external load.

Modern electronic control technology enables much easier implementation of an indirect feedback control system of load motions to the helicopter rotor. This study focuses on the indirect feedback method because of its easy incorporation into an existing fly-by-wire system. It requires only a measurement of the load states, and flight control software changes, which requires relatively few hardware changes. In contrast, the direct method requires installation of additional actuators, which adds mechanical complexity and weight, and still requires the same sensors to measure the load motion.

There are very few past studies in which load feedback has been flight tested with a pilot in the loop. The only flight test example in the literature was conducted on the prototype Heavy Lift Helicopter in the 1970s [8]. Piloted evaluations were performed in flight and it was shown that load damping could be improved with cable angle feedback, although pilot comments indicated that the system made the load feel heavier, which was not desireable [8,9]. Recent flight test examples focus on unmanned aerial vehicles (UAVs), such as the the unmanned K-MAX helicopter [10], the GT-Max (9.8 ft rotor diameter) [11] and the indoor electric AAU Corona (2ft rotor diameter) [12]. These unmanned studies provide useful information about the effectiveness of load damping through load feedback to the rotor, but do not provide insight about pilot handling qualities.

The present authors have recently performed an analytical and piloted simulation study on the topic of pilot handling qualities for cable angle feedback [13], leveraging Lusardi's work on external load handling qualities criteria [2]. In Ref. 13 it was shown through analysis and in piloted simulation that a fundamental trade-off exists between load damping and handling qualities for attitude command systems with cable angle/rate feedback. A key recommendation of that study was to implement task tailored control laws that switch between load damping-focused and handling qualities-focused cable angle/rate feedback control modes depending upon the flight regime. This study builds upon the attitude command work of Ref. 13 by developing advanced task-tailored outer-loop modes and flight testing these control laws with pilots in the loop.

This paper demonstrates the trade-off between handling qualities and load damping, and documents the design and flight testing of a task-tailored control system with cable angle/rate feedback for external load operations. The development of the task tailored control laws using direct multi-objective optimization [14] and the development of an optimized baseline control architecture with the same fuselage feedback structure, but without cable feedback, are described. This paper also details the challenges of implementing the system on a real aircraft and solutions implemented successfully for these flight tests. In addition, a new mission task element (MTE) for precision load placement was developed to aid in evaluating the ability of the cable feedback system to improve performance on load placement tasks. Flight results are given for the JUH-60A RASCAL [15], including frequency domain plots, pilot comments and handling qualities ratings (for traditional MTEs [16] and a new Precision Load Placement MTE).

DESIGN TRADE-OFFS WITH CABLE ANGLE/RATE FEEDBACK FOR ATTITUDE COMMAND

As mentioned above, the use of cable angle/rate feedback to the rotor introduces a fundamental control trade-off because there is only one actuator available to control two bodies. A choice must be made between controlling the fuselage or load, as the two clearly cannot be independently maneuvered. Specifically, in order to achieve load damping, the helicopter must move over the external load to stop the load from swinging. This required aircraft motion is driven by the sensed load states, and may not be consistent with the commanded inputs from the pilot. In this case the helicopter acts as an actuator to control the load, and cannot be maneuvered independently of the load motion. Thus, maneuvering the helicopter interferes with load damping and vice-versa.

This fundamental trade-off was explored analytically in Ref. 13 for an attitude command explicit model following control system for the JUH-60A RASCAL fly-by-wire helicopter [15]. The configuration is a 56ft sling, with 5000lb load. The RASCAL aircraft is pictured with an external load in Fig. 1.

Three attitude command control systems were developed in Ref. 13 to demonstrate the trade-off between load damping and handling qualities for a cable angle/rate feedback control system.

1. Baseline Control System – This control system has conventional fuselage feedback only.

2. Load Damping Control System – This control system maximizes the external load damping. This control system uses fuselage, cable angle, and cable rate feedbacks.

3. Pilot Handling Control System– This control system provides the best piloted handling qualities possible with respect to the external load handling qualities specification described in Ref. 2 (and in the following section). This control system uses fuselage, cable angle, and cable rate feedbacks.

Figure 1. JUH-60A RASCAL helicopter with external load.

Piloted handling qualities criteria with an external load

The piloted handling qualities criteria for external load operations developed in Ref. 2 played an important role in the design of the control systems used in the trade-off study of Ref. 13. It is also important for the development of the task tailored control laws which will be described later in this paper. This new slung load handling qualities criteria provides insight into how slung loads degrade handling qualities, and which aspects of the response the pilots find undesirable. The slung load handling qualities specification is based on extensive flight test data on the UH-60, where a variety of sling lengths and load masses were tested with the Mission Task Elements in ADS-33E-PRF [16].

The slung load handling qualities specification relates the characteristics of the attitude frequency responses of the aircraft to the predicted piloted handling qualities ratings (HQR). An important characteristic of the response of an externally loaded helicopter is the notch in the attitude (at ~0.8 rad/s in Fig. 2) that is associated with the attenuation of the attitude response to pilot stick inputs because of load swing. This notch is not present for an internally loaded baseline helicopter, and becomes deeper with increasing external load mass ratio (LMR) as shown in Fig. 2. The depth of the notch, Δ_{MAG} illustrated in Fig. 2 for the LMR =0.33 case, relative to an internally loaded helicopter is the metric used to predict HQR in the y-axis of the handling qualities criterion shown in Figs. 3a-3b. A greater magnitude loss (caused by a heavier load) is associated with degrading handling qualities (HQR_≥4). The frequency of the -135 degree crossing of the phase response near the load mode, or the frequency of the minimum phase near the load mode if it does not cross -135 deg, is used in the x-axis criteria of the handling qualities specification (Fig 3). The frequency where the phase crosses -135 degrees decreases with longer sling lengths, due to the lower frequency load pendulum mode (at approximately $\sqrt{(g/L)}$). A lower ω_{-135} crossing correlates with degraded handling qualities in Fig. 3. The unaugmented configuration considered herein, with LMR = 0.25 (5000lb load) and a 56ft sling, has poor assessed lateral handling qualities (Fig. 3a) and border-line longitudinal handling qualities (Fig. 3b) for the legacy UH-60.

Based on these criterion, the shape of the attitude response due to piloted stick determines how the slung load affects the piloted handling qualities. These data indicate that by reshaping the magnitude response via feedback control, the handling qualities of the externally loaded helicopter could be improved by manipulating the depth of the magnitude notch and the frequency of the -135 crossing. This is the method that was used for the pilot handling control system in the trade-off study from Ref. 13.

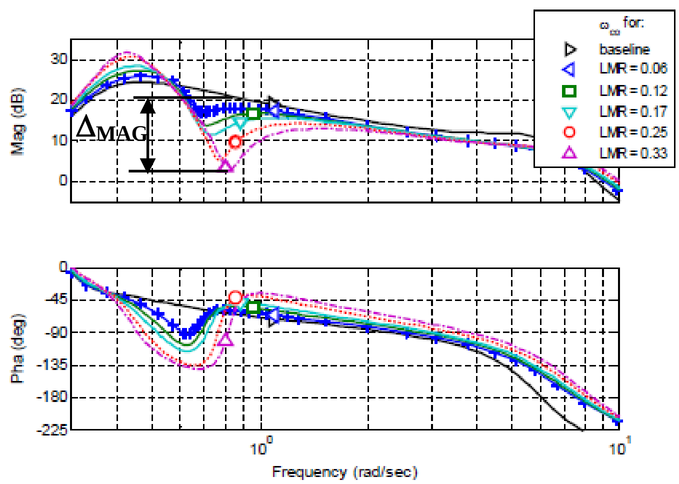


Figure 2. Roll attitude frequency response due to lateral cyclic for the 79ft sling with increasing LMR (Ref. 2).

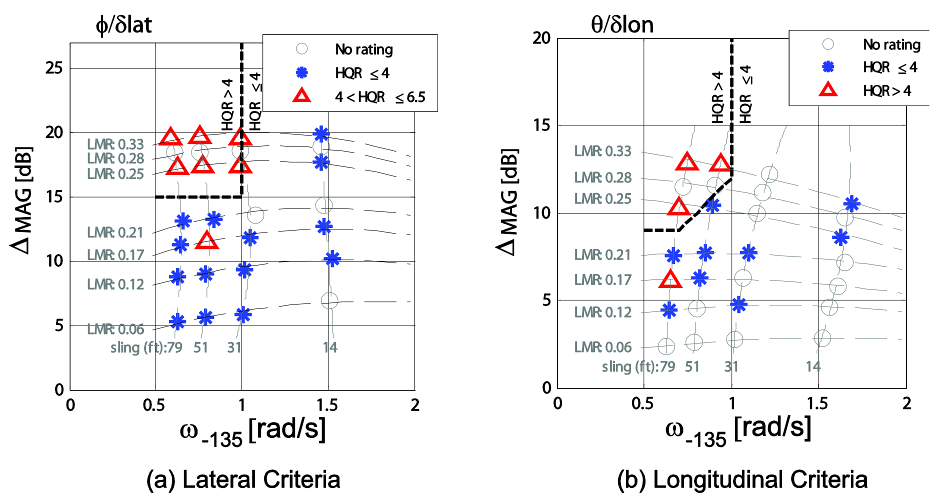


Figure 3. Slung load handling qualities criteria (Ref. 2), where HQR>4 represents poor handling.

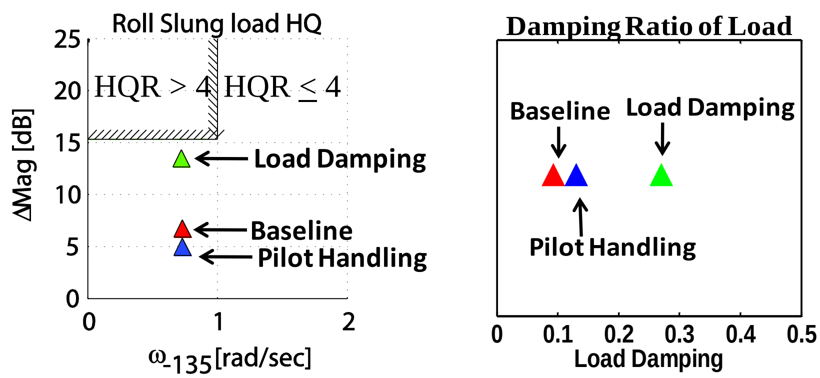
Design trade-offs

The three control systems described in the preceding sections; baseline, pilot handling, and load damping were designed using multi-objective optimization in Ref. 13 to provide the best designs that met all the specifications and minimized actuator activity. A flight validated, linear state-space aircraft model was used for this design and analysis, as described in Ref. 13. A comparison of the key trade-offs seen in the results are shown here for the lateral-axis only, as the same trends were observed in the longitudinal axis. Detailed results for all axes can be found in Ref. 13.

The pilot handling control system has the best predicted handling qualities of the three configurations. Figure 4a shows that the response is moving further from the "HQR $\geq$ 4" region of the external load handling qualities specification, as calculated from the closed loop roll attitude (ϕ) response in Fig. 5a. The closed loop attitude response shows a slight reduction in notch depth and reduced overshoot associated with the load mode in comparison to the baseline control laws. However, the pilot handling control system does not improve load damping by a large percentage as compared to the baseline case, as shown in Fig. 4b.

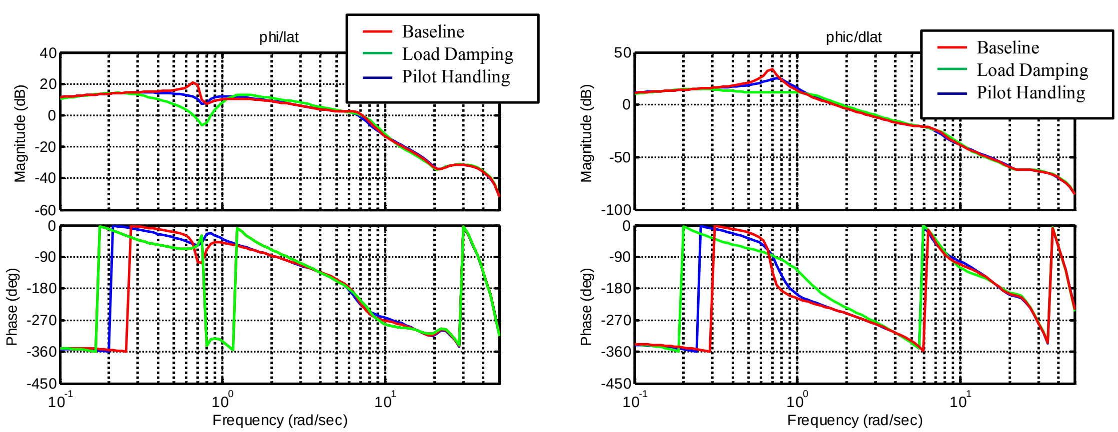
In contrast, the load damping control system provides a factor of 3 improvement in load damping over the baseline control system, as indicated by Fig. 4b. The lateral cable angle (ϕ_c) frequency response to lateral stick is shown in Fig. 5b, indicating a better damped response and reduced swing amplitude at the load pendulum mode. The trade-off is that the load damping cannot be achieved without drastically increasing the magnitude distortion of the roll attitude frequency response relative to the baseline design, as shown in Fig. 5a. Consequently, the handling qualities rating is predicted to be degraded for this configuration, as it lies on the boundary of the HQR>4 region, as shown by Fig. 4a. The load damping case exhibits more aircraft response distortion than either the baseline or the pilot handling control systems.

The doublet time responses for the three systems are shown in Fig. 6. Compared to the baseline control system, the pilot handling control system has a fuselage roll attitude response that best follows the commanded input, with better damped residual aircraft attitude oscillations and slightly better load damping. The load damping control system produces a poor aircraft attitude response, with large uncommanded roll reversals, but has excellent load damping. The time and frequency domain results illustrate the tradeoff between load damping and maneuvering handling qualities for the two systems incorporating cable feedback, as well as poor overall performance for the baseline system with only fuselage feedback.



(a)Handling Qualities (b) Load Damping

Figure 4. Roll slung load handling qualities specification for three optimized control systems.



(a) ϕ / δ_{lat} (b) ϕ_c / δ_{lat}

Figure 5. Closed loop bode plot overlays for three optimized control systems.

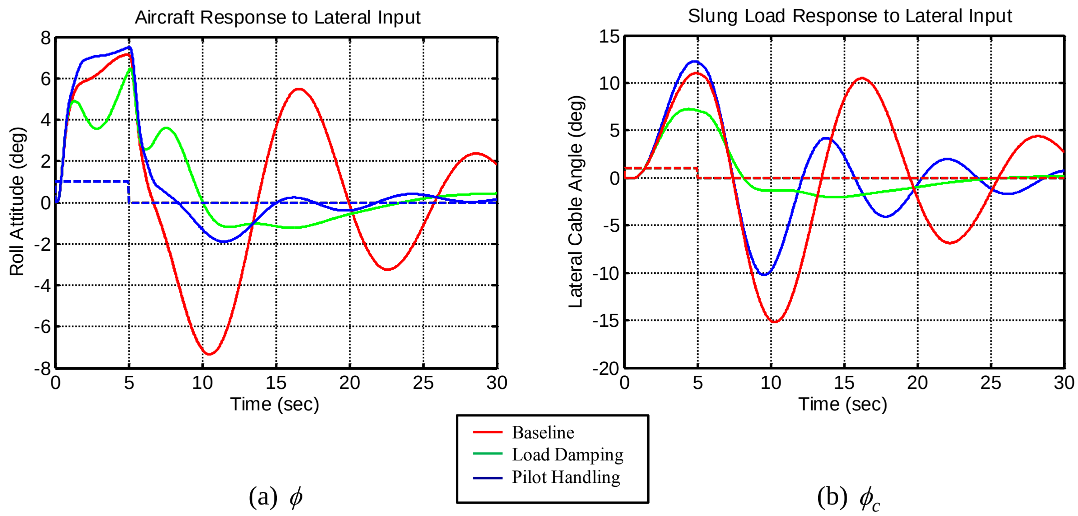


Figure 6. Closed loop time responses for three optimized control systems.

Additional insight into the tradeoff can be obtained by examining the optimized gains from the cable angle/rate feedback systems in Table 2. As shown in the table, the pilot handling control system relies heavily on cable angle feedback, while the load damping control system uses both cable angle and rate feedbacks. In order to damp the load, a large amount of cable rate feedback is required. This is consistent with experience and physical intuition that rate feedback typically provides damping properties. In contrast, to provide improved handling qualities characteristics, the rate feedback must be very small because it causes distortion in the aircraft attitude response [13]. Clearly, these two configurations cannot be achieved simultaneously.

Table 1. Load feedback parameters.

	Roll Axis Load Feedback Gains	
Control Law	Cable Rate (in-s/rad)	Cable Angle (in/rad)
Baseline	0	0
Load Damping	7.89	8.08
Pilot Handling	1.00e-4	3.98

Discussion of design trade-offs

As reported in Ref. 13, a fixed-based piloted simulation was performed to collect pilot opinions on the three attitude command control laws. All four experimental test pilots who evaluated the control laws favored the piloted handling control laws over the baseline and load damping control laws. These results were consistent with the analytical studies that predicted improved flying characteristics for the pilot handling control laws. The load damping control laws were not preferred, and were somewhat prone to pilot-induced-oscillations (PIO). With the load damping control laws, the pilots would often see the attitude 180deg out of phase with their inputs as the aircraft damped the load motions. This type of control response often leads to PIO.

The study of Ref. 13 led to the conclusion that the piloted handling cable angle feedback control laws are clearly better and safer for maneuvering the aircraft. However, for precision load placement, there were obvious operational advantages to quickly damping load motions automatically, despite the cost paid in maneuvering handling qualities.

Two solutions to this fundamental tradeoff are apparent. The first method is to choose a compromise design which is somewhere between the pilot handling and load damping cases, but is not optimal for either pilot handling or load damping. The second solution is to switch between the control laws in a task tailored strategy. This could be either a pilot selectable or an automatic load damping switch near hover but would default to the pilot handling control laws during maneuvering. This task tailored method would ensure that the control laws are optimal for the task, but comes at the cost of added complexity due to additional gain scheduling and mode transitions. The task-tailored method was recommended in the conclusions of Ref. 13, and it was decided to implement and evaluate this method in flight test as part of the present effort.

TASK TAILORED CONTROL LAW APPROACH

A task tailored design was employed to optimize the response characteristics as a function of the control task and aircraft state. From the previous results, it was clear that the pilot handling control laws should be used when the pilot is in the loop. Furthermore, it was preferred to use the piloted handling control laws for maneuvering and flight away from hover because the motions of the load are not critical in this regime, as long as they are stable. It was also apparent that the load damping control laws should be used in hold modes when the pilot is not in the loop. In addition, load damping should preferably be applied at very low speed and hover, where the load motion is most important since the load is mostly likely to be placed on the ground from this flight condition.

The moding architecture that was developed to implement the task-tailored control strategy is shown in Fig. 7. The system features attitude command, velocity hold, automatic deceleration, and position hold modes. The load damping (cable angle/rate feedback) control laws come on during the deceleration and position hold modes, which occur at low speed when the pilot has the cyclic in the center detent and therefore is not actively maneuvering the aircraft. The pilot handling (cable angle feedback) control laws are active during maneuvering when the stick is out of detent, and also in the velocity hold mode. The maximum speed for the control law is 40kts, since this study focused only on hover/low speed handling qualities and load placement tasks. A description of all the modes is provided in Table 2.

This control law scheme for cable angle/rate feedback allows the pilot to maneuver with good handling qualities to the load set-down location. Once at the load setdown location, position hold is enabled and load damping occurs. By using the position beeper and collective, the pilot can put down the load in the desired location, while staying in the load damping mode. If at any time the pilot wants to maneuver the helicopter, the control system automatically switches to the handling qualities cable angle/rate gains when the stick leaves the detent position. The load damping returns when position hold or automatic deceleration is re-enabled. Thus, the task tailored control law combines both the load damping and pilot handling control laws into a multi-mode control law architecture and will be henceforth be referred to as the Cable Angle/rate Feedback (CAF) control law.

An optimized baseline system with fuselage feedback only was developed with the same command and hold modes but no load specific modes, as shown in Fig. 7 and described in Table 2. The baseline system does not switch gains in a task-tailored way since there are no cable feedbacks. This system provides a well designed and fair basis for comparison with the CAF system, since it has the same architecture (without cable feedback) and was designed against the same specifications. This control law extends the baseline attitude command/attitude hold system described in the previous trade-offs section of this paper to include velocity and position hold modes, and optimizes the fuselage gains for this configuration. This control law is referred to as the Optimized BaseLine control law (OBL).

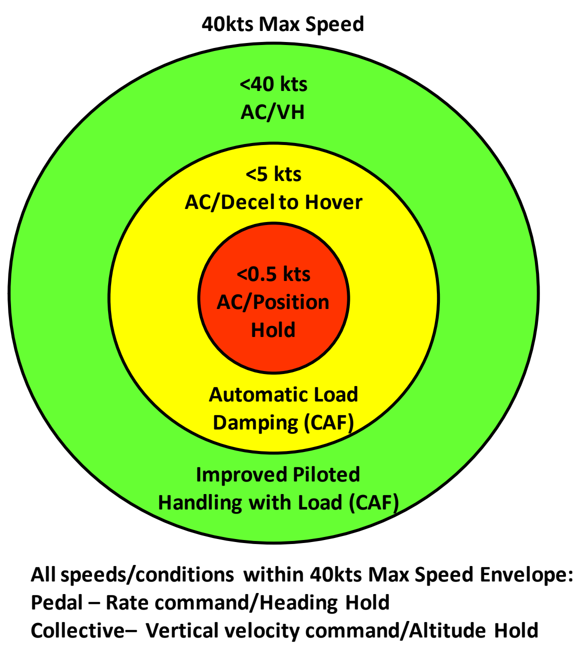


Figure 7. Control law modes for task-tailored cable angle/rate feedback control laws.

Table 2. Description of control law modes.

Mode	Control Laws	Description
Attitude Command (AC)	CAF, OBL	Most basic mode of operation. Attitude of aircraft is proportional to pilot stick (stick out of detent)
Velocity Hold (VH)	CAF, OBL	Control system will hold the current ground velocity when the stick is in detent.
Automatic Decel	CAF, OBL	When ground speed is <5kts the aircraft will automatically decelerate to a hover if the stick is in detent.
Position Hold (PH)	CAF, OBL	Aircraft will hold position if aircraft speed is < 0.5 knots and stick is in detent. Position beepers: Short beep = +/-1ft Long beep = translation at +/-2kts
Altitude Hold (ALTHLD)	CAF, OBL	Aircraft will automatically hold altitude when collective is in the detent position. Altitude beeper: Short beep = +/-1ft Long beep = +/-90 ft/min
Pilot Handling Load Feedback Mode	CAF only	Occurs when stick is out of detent position (pilot is maneuvering the aircraft)
Load Damping Load Feedback Mode	CAF only	Occurs during Automatic Decel and Position Hold when stick is in detent (pilot is not in the loop)

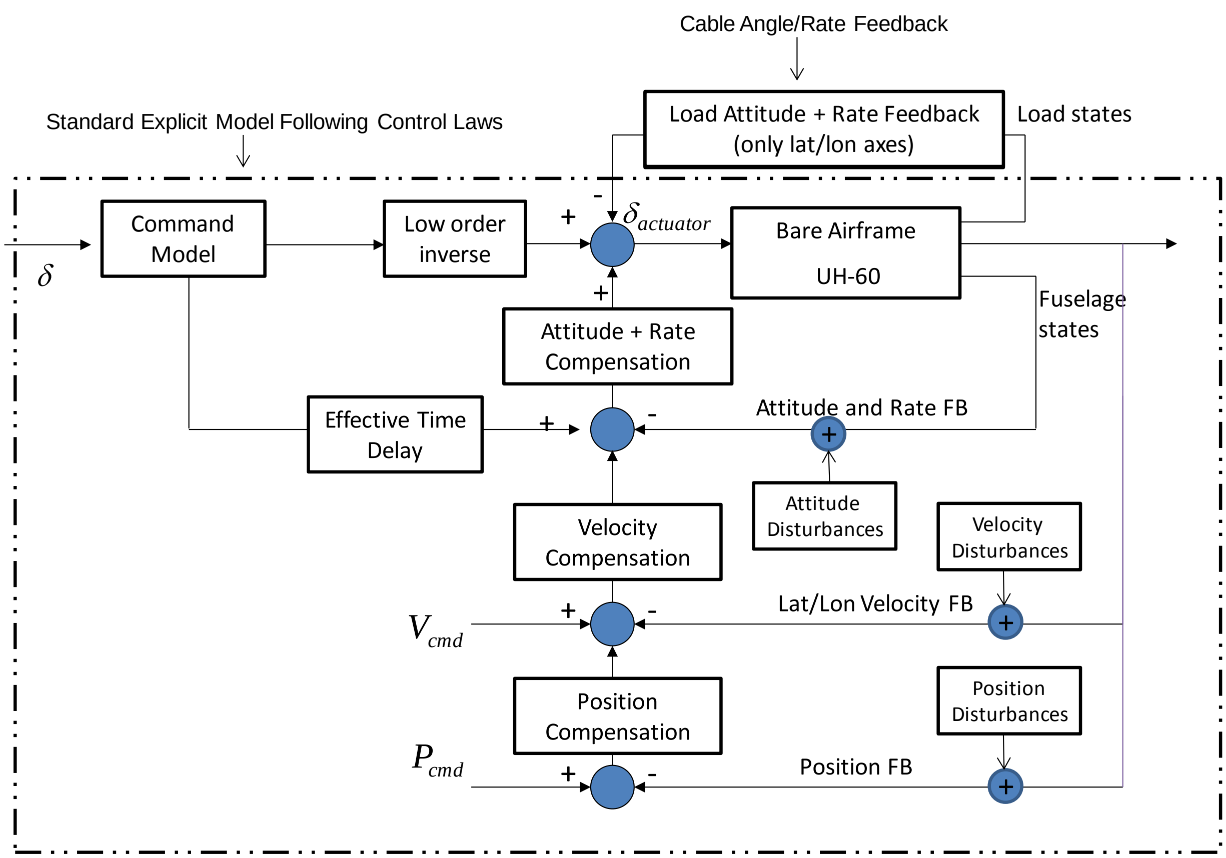


Figure 8. Control system architecture

Task Tailored Control Law Architecture

The task-tailored control laws with modes shown in Fig. 7 were implemented with architecture shown in Fig. 8 for the lateral and longitudinal axes. The basic attitude command control system is an explicit model following control law [17]. It is used when the stick is out of the detent position. The velocity and position hold modes were implemented with nested velocity and position feedbacks as shown in Fig. 8. The load cable angle and rate feedback loops were added in the longitudinal and lateral axes. The load cable angles are multiplied with a washout filter to avoid feedback due to changes in the trim longitudinal cable angle (θ_c) as the velocity increases. The load feedback is inertial (ϕ_c, θ_c) as opposed to relative to the aircraft to provide faster load damping (it is desired to damp the load in the inertial frame, not in the relative frame). Not shown in Fig. 8 is the vertical axis, which is vertical velocity command with altitude hold, and the yaw axis, which is rate command with heading hold. Load feedback is not active in the vertical or directional axes.

CONTROL LAW OPTIMIZATION

Two control laws were designed using the multi-objective optimization technique for determining feedback gains:

1. Cable Angle/Rate Feedback (CAF) – task-tailored control laws that switch between load damping and pilot handling load feedback methods and makes use of fuselage, cable angle and cable rate feedbacks. This control system is described in Table 2.

2. Optimized Baseline (OBL) – uses fuselage feedback only, with the load feedback gains set to zero. This control system is described in Table 2.

The multi-objective optimization technique is described in detail in Ref. 14. Due to the complicated nature of this problem with many modes, design specifications, in addition to gain scheduling and multiple configurations (e.g. different load masses) that must meet the requirements, this is a difficult control problem to tune by hand. Multi-objective optimization is useful to tune the gains to meet all the requirements using direct optimization techniques. The software used for the multi-objective optimization herein is CONDUIT® [18]. A flight validated linear state-space aircraft model of the UH-60 with external load dynamics was used for the optimization and analysis herein. Reference 13 provides detailed information about this model.

Design Specifications

The goal for the CAF optimization is for both modes (load damping and pilot handling) to meet the stability and gust rejection requirements. In addition, the pilot handling mode must meet the handling qualities requirements and the load damping mode must meet a load damping ratio greater than 0.25. Additionally, it is desirable to gain schedule as few gains as possible when transitioning in and out of the load damping mode. For the OBL configuration, the goal was to optimize one gain set to obtain the best possible performance relative to the CAF design, but without load feedback. This gives a level field for comparison against which to determine the benefits of the cable angle/rate feedback task-tailored control law.

The control law design was focused on one sling length (56ft) and load mass (5K), but was also required to meet stability margins for multiple load masses and sling lengths. The 56ft sling with a 5000lb load was chosen as the key design case because it represents the critical configuration (longest sling, heaviest load) that would be flown. The control laws were also required to meet stability margins for the unloaded configuration, which becomes relevant upon load set-down. The control laws also must revert to a system with acceptable margins if the cable angle sensors fail or are disconnected.

The control system was designed to meet the requirements for ADS-33E-PRF Level 1 handling qualities [16], stability margins [19], disturbance rejection [20], and external load handling qualities [2]. The design specifications of Table 3 were implemented in the multi-objective optimization to ensure that the control system would have the desired flying qualities.

A sequential optimization strategy, as described herein, was adopted in order to minimize the number of parameters that had to be gain scheduled to implement the task-tailored CAF control laws. The attitude command gains (including fuselage angular rate, attitude, and attitude integral gains, as well as cable angle and cable rate gains) for the pilot handling control mode were first optimized against the specifications. These pilot handling mode attitude and cable gains (vs. load damping gains) were used in velocity hold to improve ride quality by maintaining an optimized fuselage response. Thus, this attitude command gain set was fixed for the optimization of the velocity hold gains. For optimization of the position hold and automatic deceleration modes, the position feedback gains were optimized with most of the attitude command and velocity hold gains fixed, with the exception of the lateral and longitudinal cable angle and rate gains and the aircraft roll and pitch attitude gains. This limited set of attitude and cable gains were scheduled with the load damping mode in order to provide improved load damping. For the optimized baseline control system, the attitude command system was optimized and then the velocity hold and position hold gains were optimized around the fixed attitude command gains.

Table 3. Control system design specifications.

Specification (CONDUIT Mnemonic)	Description	Constraint Type	Axes	Modes
EigLcG1	Eigenvalues in left-half plane [1]	Hard	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH
StbMgG1	Gain and Phase margin (45 deg, 6 dB) [19]	Hard	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH
BnwPiH1	Pitch bandwidth for acquisition and tracking, Attitude Command Requirements [16]	Soft	Pitch	AC
BnwRoH2	Roll bandwidth for other M.T.E.'s, Attitude Command Requirements [16]	Soft	Roll	AC
BnwYaH1	Yaw bandwidth for acquisition and tracking [16]	Soft	Yaw	RCHH
BnwPiS1	Pitch External Load Handling Qualities Criteria [2] Level 1 required for HQs CAF mode and OBL	Soft	Pitch	AC
BwnRoS1	Roll External Load Handling Qualities Criteria [2] Level 1 required for HQs CAF mode and OBL	Soft	Roll	AC
CouPRH2	Coupling between pitch and roll [16]	Soft	Pitch/Roll	AC
CouYaH2	Coupling between collective and yaw [16]	Soft	Yaw	RCHH
DstBwG1	Disturbance rejection bandwidth [20]	Soft	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH
DstPkG1	Disturbance rejection peak magnitude [14]	Soft	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH
FrqHeH1	Heave response bandwidth [16]	Soft	Heave	AC, ALTHLD
HldNmH1	Normalized attitude hold response to disturbances [16]	Soft	Pitch, Roll, Yaw	AC, RCHH
ModFoG2	Performance of Aircraft as compared to command model [17]	Soft	Pitch, Roll, Yaw, Heave	AC, RCHH
DmpTmG1	Damping ratio of Load from log decrement method $\zeta > 0.08$ - AC, VH, PH for OBL $\zeta > 0.1$- AH, VH for CAF (pilot handling mode) $\zeta > 0.25$ - PH for CAF (load damping mode)	Soft	Pitch, Roll	AC, VH, PH
TrkErG1	RMS of load response in turbulence	Soft	Pitch, Roll	AC, VH, PH, ALTHLD
CrsLnG1	Minimizes Cross-over frequency [14]	Summed Objective	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH
RmsAcG1	Minimizes Actuator RMS [14]	Summed Objective	Pitch, Roll, Yaw, Heave	AC, VH, PH, ALTHLD, RCHH

Control Law Optimization Results

Key attitude command characteristics for the optimized designs are shown for the 5000lb load, with a 56ft sling in Table 4. The attitude command characteristics are slightly different than those presented in Ref. 13 due to considerations for the outer loops (such as designing in extra phase margin) and small changes based on pilot comments from the initial shake-down flights. Table 4 shows that the CAF control laws have much improved stability margins and attitude disturbance rejection, in addition to slightly improved load damping.

Figure 9 shows that the CAF control laws in attitude command (pilot handling mode of task-tailored control law) have less magnitude distortion near the load mode, moving the predicted handling qualities deeper into the HQR≤4 region for the stick-out of detent piloted response. The improvements in the stability margins for CAF are mainly due to changes in the broken-loop shape around the load mode as seen in Fig. 10, which compares the broken loop responses of the two configurations. It is worth mentioning that cable feedback provides loop shaping at the frequency of the load mode and as such, we have found that it is robust to a variety of sling lengths and load masses (which change the frequency of the load mode). This is a large benefit over an inverse notch type compensator which could provide the same improvements in loop shape for one configuration, but would have to be scheduled with sling length and load mass to operate robustly.

Figure 10 shows that the OBL design has a crossing at ~0.8 rad/s, which is associated with low phase margin. The phase margin is 34.9 deg in this configuration, and cannot be increased within the constraints of the optimization. The OBL roll attitude integral gain was reduced to 0.1 in order to achieve this phase margin, which results in degraded gust rejection and closed loop performance as compared to the CAF system that has an integral gain of 0.5. In addition, the CAF configuration changes the loop shape in order to have a low frequency crossing at 1 rad/s, and the highest cross-over at 4.69 rad/s is somewhat reduced from the OBL design, which is beneficial because it excites less high frequency actuator activity.

Another key improvement with the cable angle feedback in attitude command is the roll angle disturbance rejection bandwidth. The disturbance rejection bandwidth (DRB) improves from .71 in OBL configuration to 2.24 in the CAF configuration, which indicates that attitude disturbances will be rejected much more quickly for the CAF configuration. This is due to attenuation of disturbances near the load mode with CAF, which is shown in Figure 11 in the circled area of the plot. This causes the disturbance response to cross the -3dB line at a higher frequency, increasing the disturbance rejection bandwidth.

Table 4. Attitude command control law characteristics: longitudinal and lateral axes (5K, 56ft sling).

	Lateral					Longitudinal				
	GM [dB]	PM [deg]	XOVER [rad/s]	Phi - DRB [rad/s]	Load Damping Ratio	GM [dB]	PM [deg]	XOVER [rad/s]	Theta - DRB [rad/s]	Load Damping Ratio
OBL	5.89	34.90	5.41	0.71	0.08	11.95	40.03	2.84	0.63	0.08
CAF	6.78	47.55	4.69	2.24	0.14	10.48	45.84	3.19	0.72	0.11

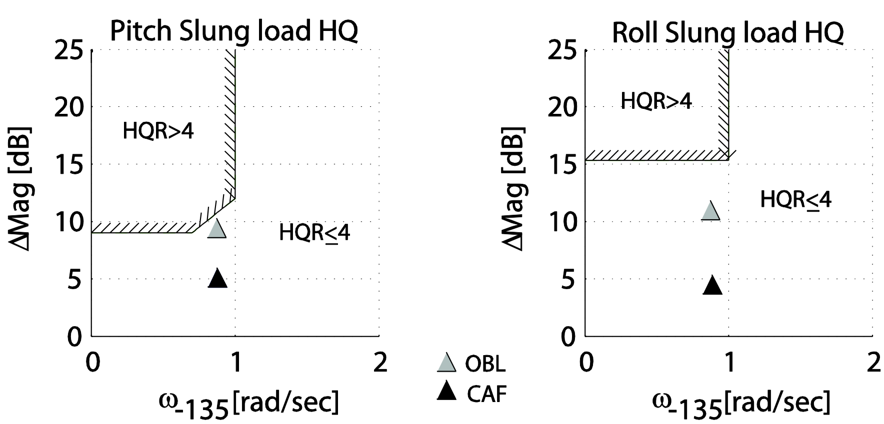


Figure 9. Handling qualities specification, attitude command mode (5K, 56ft sling).

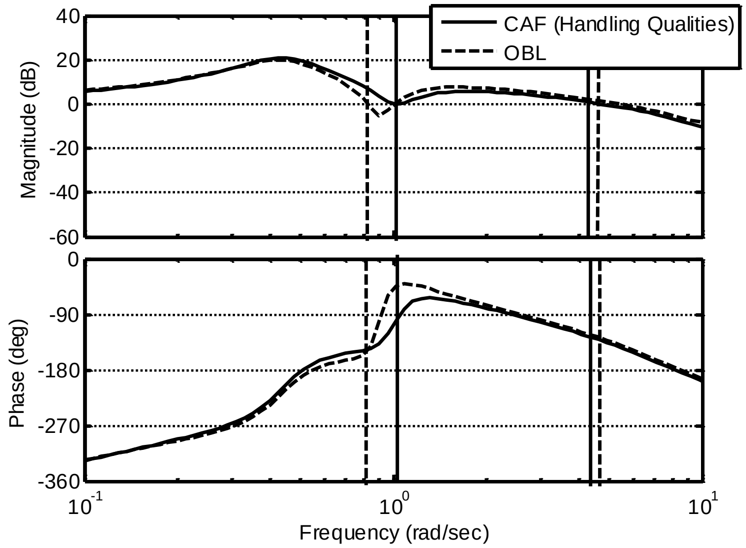


Figure 10. Lateral broken loop response, attitude command mode (5K, 56ft sling).

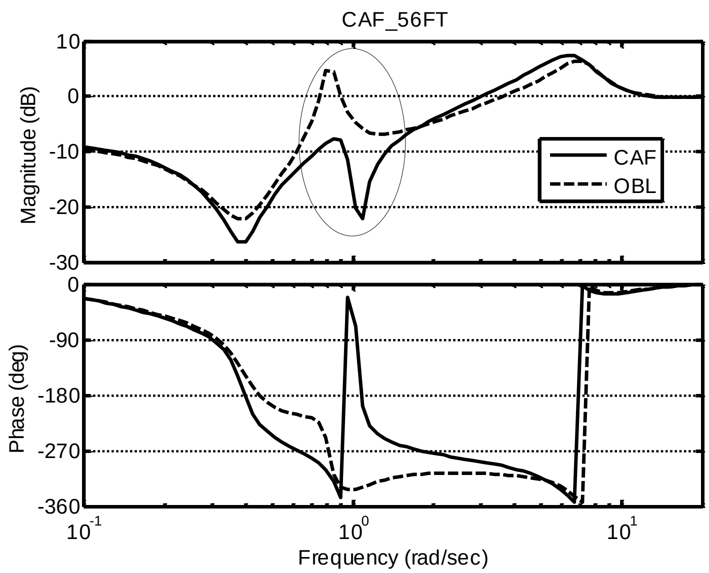


Figure 11. Roll attitude disturbance response (ϕ/ϕ_{gust}), attitude command mode (5K, 56ft sling).

The velocity and position hold characteristics of the optimized control systems are shown in Table 5. The stability margins shown in Table 5 are calculated with the loop broken at the actuator. The CAF system has better stability margins and greatly improved load damping, as well as similar disturbance rejection bandwidth (DRB) characteristics to the OBL design. Recall that the longitudinal and lateral cable angles and rates, as well as pitch and roll attitude gains are scheduled with the load damping mode, which is active in position hold to provide a much improved load damping response.

The disturbance rejection bandwidth result in, for example, lateral position is defined as response to a disturbance in the lateral position feedback as shown in Fig. 8. This response is at low frequency (i.e. DRB~0.2), much lower than the load mode at ~0.8 rad/s, and thus the effect of load interaction is not present in these metrics. However, in the time responses, there is a trade-off with position hold performance and load damping for higher frequency disturbances that cause the load to swing, as shown for a pulse disturbance to roll attitude in Figs. 12-14. In this case, the OBL design does better at controlling the aircraft position, as shown in Fig. 12, even though the CAF control laws have essentially the same position disturbance rejection bandwidth as the OBL design. However, the CAF design does much better at controlling the load motion, as shown in Fig. 13. This relates to the key trade-off of cable angle/rate feedback to the rotor; that the system cannot control the aircraft and load motions independently. This principle is further illustrated by Fig. 14, which shows that the aircraft must move over the load to damp the load motions. In Fig. 14a, the OBL aircraft position is out of phase with the load response, whereas for the CAF control system in Fig. 14b the aircraft follows the load position, effectively damping the load at the cost of greater position variance.

The directional and vertical controller characteristics are given in Table 6. These axes do not have cable angle feedback so the designs are very similar for CAF and OBL.

Table 5. Position and velocity control law characteristics: longitudinal and lateral axes (5K, 56ft sling).

	Lateral - in position hold						Longitudinal - in position hold					
	GM [dB]	PM [deg]	XOVER [rad/s]	v - DRB [rad/s]	Y - DRB [rad/s]	Load Damping Ratio	GM [dB]	PM [deg]	XOVER [rad/s]	u - DRB [rad/s]	X - DRB [rad/s]	Load Damping Ratio
OBL	5.95	33.42	5.15	1.01	0.29	0.17	8.08	47.86	9.50	1.04	0.22	0.15
CAF	7.47	42.50	4.19	1.22	0.27	0.28	9.12	46.50	10.29	1.12	0.21	0.25

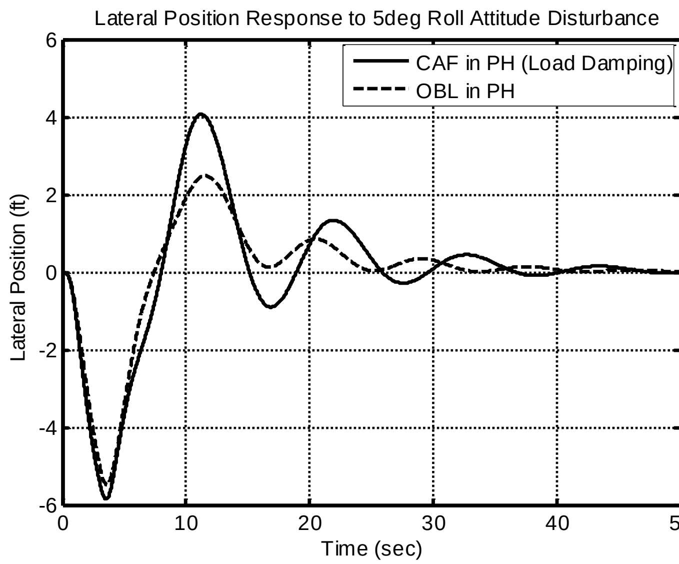


Figure 12. Lateral position response in PH to 5 deg roll attitude pulse disturbance (5K, 56ft sling).

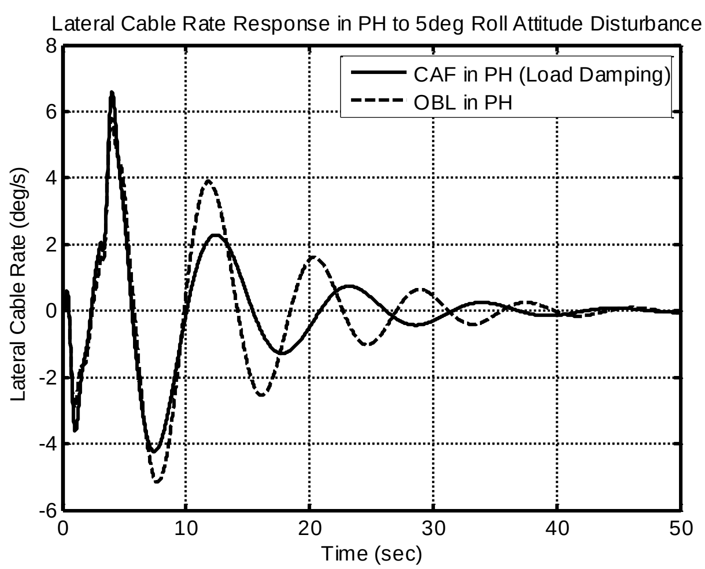
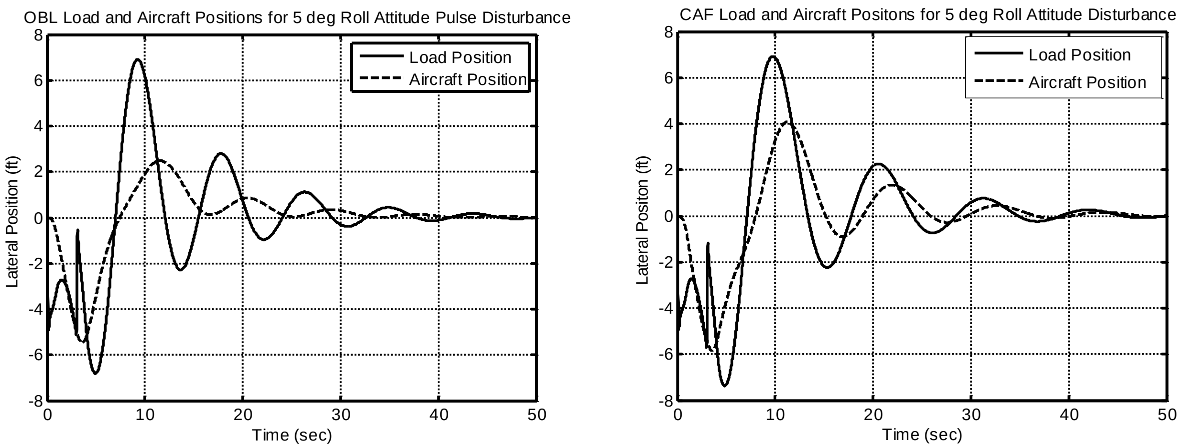


Figure 13. Load response in PH to 5 deg roll attitude pulse disturbance (5K, 56ft sling).



(a) OBL (b) CAF

Figure 14. Aircraft and load position responses in PH to 5deg roll attitude pulse disturbance (5K, 56ft sling).

Table 6. Directional and pedal control law characteristics (5K, 56ft sling).

	Pedal - yaw rate command/heading hold				Collective - in Altitude Hold				
	GM [dB]	PM [deg]	XOVER [rad/s]	Psi - DRB [rad/s]	GM [dB]	PM [deg]	XOVER [rad/s]	w - DRB [rad/s]	H - DRB [rad/s]
OBL	11.09	60.79	3.67	0.73	16.84	46.22	1.27	0.98	0.52
CAF	11.09	60.69	3.68	0.76	13.77	47.71	1.66	1.26	0.68

IMPLEMENTATION FOR FLIGHT TEST

The preceding sections of this paper described linear, analytical results of cable angle feedback. In order to successfully integrate and flight test the cable angle/rate feedback control laws on the RASCAL helicopter several engineering challenges had to be overcome. These challenges included:

1. Design, installation and integration of a cable angle/rate sensor

2. Removal of load-sling interaction modes from the measured load motion

3. Elimination of vertical load bounce mode effects from the vertical motion measurements

4. Designing an effective filter for the aircraft radar altimeter

Cable Angle/Rate Sensor

The US Army Aeroflightdynamics Directorate researchers had previously employed an Embedded GPS/INS (EGI) in slung loads to measure inertial load motions and to calculate cable angles in post flight analysis. The high quality and reliability of the EGI data motivated the use of these sensors to calculate real-time cable angles for use by the CAF control laws. This lead to the requirement to integrate the EGI in the load with the MIL-STD-1553b data bus on RASCAL so that it could communicate with the flight control computer. A wired MIL-STD-1553b bus connection between the load EGI and the RFCS has been implemented in order to minimize measurement latency and to maximize signal integrity (and safety). This configuration extends the 1553 muxbus up to 81 ft outside of the aircraft fuselage along the path of the sling as shown in Fig. 15. A dual-redundant electrical ground connection between the aircraft and the load has also been implemented to prevent excessive current travel along the 1553 bus and to protect the sensitive and expensive systems used for flight control. The sensors are not flight critical because RASCAL has a fail-safe flight control system. However, the RASCAL 1553 bus has also been modified to automatically reconfigure to an internally terminated configuration if electrical connection to the external load is severed.

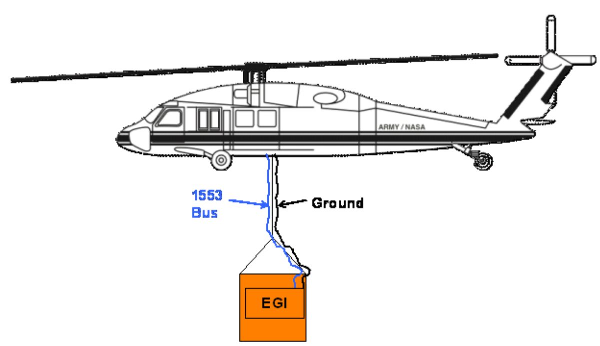


Figure 15. RASCAL 1553 muxbus extension.

Elimination of Load-Sling Interaction Modes

The measurement of the load motion from the EGI on the load is particularly sensitive to any rocking motion of the load. These motions are measured as a load angular rate or attitude, but are not the pendular motions in which we are interested in damping. Once the EGI measurements of load angle are transformed to cable angles (which are in an axis system that is aligned with the aircraft heading) using the equations described in Ref. 13, these rocking motions show up as unwanted "noise" in the cable angles and rates. This "noise" would occur for any sensor located on the load (another example would be a vision based sensor that tracks markings on the load), but can be minimized by taking measurements at the hook as in the case of the unmanned KMAX [10] or by developing an approach to remove this effect from the measured data, which is the approach taken herein.

The natural frequency of this rocking motion can be estimated by using a simple model of the sling that is modeled not as a single massless rigid cable, but instead as a cable with mass that is divided into three segments as shown in Fig. 16. The resulting modes that arise from this model are a pendular mode and two sling modes. The linear equations are given by Eq. (1).

This model can be extended to divide the sling into as many segments as desired. As shown in Fig. 17, four masses (five segments) are sufficient to accurately predict the first pendulum mode as well as the two slung load modes. The model natural frequencies correlate well to the peaks in the power spectral density of the angular rate responses of the load from the flight data in Fig. 17. The model predicts that the sling mode frequencies change slightly with the load weight (1000lb vs. 5000lb), which is consistent with the flight data.

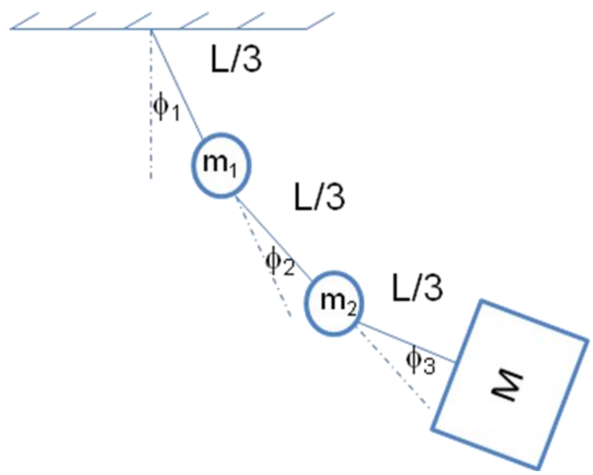
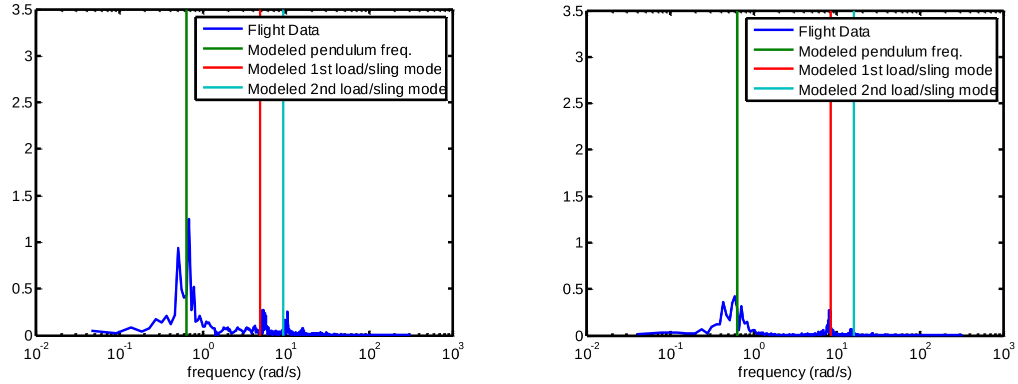


Figure 16. Sling model with 3 segments.

$$\begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & L/3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 2L/3 & 0 & L/3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & L & 0 & 2L/3 & 0 & L/3 \end{bmatrix} \begin{bmatrix} \dot{\phi}_1 \\ \ddot{\phi}_1 \\ \dot{\phi}_2 \\ \ddot{\phi}_2 \\ \dot{\phi}_3 \\ \ddot{\phi}_3 \end{bmatrix} = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 \\ -g & 0 & g(m_2+M)/m_1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ -g & 0 & -g & 0 & gM/m_2 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \\ -g & 0 & -g & 0 & -g & 0 \end{bmatrix} \begin{bmatrix} \phi_1 \\ \dot{\phi}_1 \\ \phi_2 \\ \dot{\phi}_2 \\ \phi_3 \\ \dot{\phi}_3 \end{bmatrix} \tag{1}$$



(a) 1000lb load, 4 mass model (b) 5000lb load, 4 mass model

Figure 17. Comparison of sling power spectral density from flight data, as compared to model.

The data in Fig. 17 indicate that it is essential to eliminate the load rocking components from the cable angle measurements due to the frequency content. Noise at approximately 1Hz is not a desirable frequency to feedback, considering that it is near the coupled roll-flap mode for the UH-60A at ~7 rad/s [13]. This is also in the frequency range in which the pilot would be very aware of additional uncommanded motions [21]. However, this motion is at too low of a frequency to filter out using a low pass filter, which would add considerable time lag to the load feedbacks. It would be possible to put a narrow notch filter, which would reduce lag, but would have to be scheduled with load mass and sling length, since these two parameters affect the frequency of this mode quite strongly. Since neither a low pass nor notch filter are practical for this case, a simple estimator was designed to smooth the load measurements. The estimator uses measured load motions as well as aircraft accelerations. It is based on simple linear pendulum equations of motion, which use the acceleration of the hook as an input and the pendular motions of the load as an output:

$$\begin{bmatrix}\dot{q}_c \\ \dot{\theta}_c\end{bmatrix} = \begin{bmatrix}-K_{hookfriction} & -g/L \\ 1 & 0\end{bmatrix}\begin{bmatrix}q_c \\ \theta_c\end{bmatrix} + \begin{bmatrix}-1/L \\ 0\end{bmatrix}\left[-\ddot{x}_H\right] \tag{2}$$

The hook acceleration ($\ddot{x}_H$) is calculated from the (filtered) derivative of the hook velocities. The hook velocities are calculated by transferring the measured aircraft inertial velocities from the CG to the hook with the measured aircraft angular rates (and the known CG to hook geometry). This inertial acceleration is then transformed into the cable coordinate system and $\ddot{x}_H$ is the resulting x-component. The hook friction coefficient $K_{hookfriction}$ can be tuned to match the observed load damping from flight data, but the estimator works well with $K_{hookfriction} = 0$ as shown for the results herein. The sling degrees of freedom in Eq. (1) are not included intentionally because we want to eliminate these motions from the estimated load response. Then a state-estimator was designed:

$$\dot{\hat{x}} = (\mathbf{F} - \mathbf{LH})\hat{x} + \mathbf{G}u + \mathbf{L}y \tag{3}$$

$$\mathbf{F} = \begin{bmatrix}-K_{hookfriction} & -g/L \\ 1 & 0\end{bmatrix}, \quad \mathbf{G} = \begin{bmatrix}-1/L \\ 0\end{bmatrix} \tag{4}$$

$$\mathbf{H} = \begin{bmatrix}1 & 0 \\ 0 & 1\end{bmatrix}, \quad \mathbf{L} = \begin{bmatrix}0.5 & 0 \\ 0 & 0.5\end{bmatrix} \tag{5}$$

$$\hat{x} = \begin{bmatrix}\hat{q}_c \\ \hat{\theta}_c\end{bmatrix}, \quad y = \begin{bmatrix}q_c \\ \theta_c\end{bmatrix} \tag{6}$$

$$u = [-\ddot{x}_H] \tag{7}$$

The values of the L matrix are set very low in order to force the natural frequency of the estimator to be just slightly above the pendulum mode of the load. This ensures that the measured data is used at frequencies at and below the load mode. Then the model, which does not include the sling dynamics, dominates the estimated response at higher frequencies. This method succeeds in filtering the sling mode "noise" in the EGI data as shown in Fig. 18. The state-estimator does not introduce lags such as in the heavily filtered raw data shown in Fig. 18. The heavily filtered data uses a 2nd order Butterworth filter with cutoff frequency of 2 rad/s, which adds approximately 1 second of lag and would considerably degrade the stability margins of the CAF system. A similar estimator to that given in Eqs. (3-7) was used in the lateral axis.

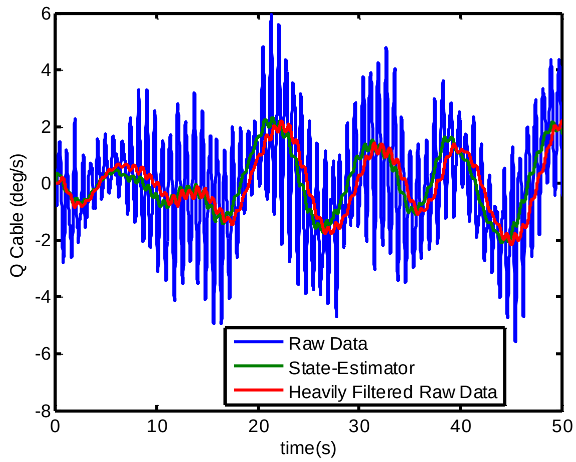


Figure 18. Longitudinal cable rate data from flight (5K, 56ft sling).

Load bounce mode notch filters

Another source of sensor "noise" which must be considered and addressed is the effect of the load "bounce" mode on the sensed aircraft vertical motion quantities. The load-sling dynamics also have a vertical mode where the sling stretches and contracts, similarly to a spring. This mode is at approximately 15 rad/s for the load configuration that was flown as seen in the autospectrum of the vertical velocity for the 5000lb load on the 56ft sling, shown in Fig. 19. The intial flight tests of the control laws did not include a notch filter to eliminate this mode from the vertical velocity feedback. Consequently, this caused the load bounce mode to be fed back through the collective in the vertical velocity command mode and altitude hold mode, resulting in small but very lightly damped oscillations at this frequency. The pilots could detect this vibration and found it unsettling. The oscillations were eliminated by including a notch filter (F_{notch}) on the vertical velocity feedback path:

$$F_{notch} = \frac{s^2 + 2(0.01)(14.5)s + (14.5)^2}{s^2 + 2(0.6)(14.5)s + (14.5)^2} \qquad (8)$$

The notch filter was designed to be fairly wide (at the cost of additional phase lag at cross-over) since the frequency range of the load bounce mode was observed to vary from 14.5 to 17 rad/s depending on the load mass and sling length.

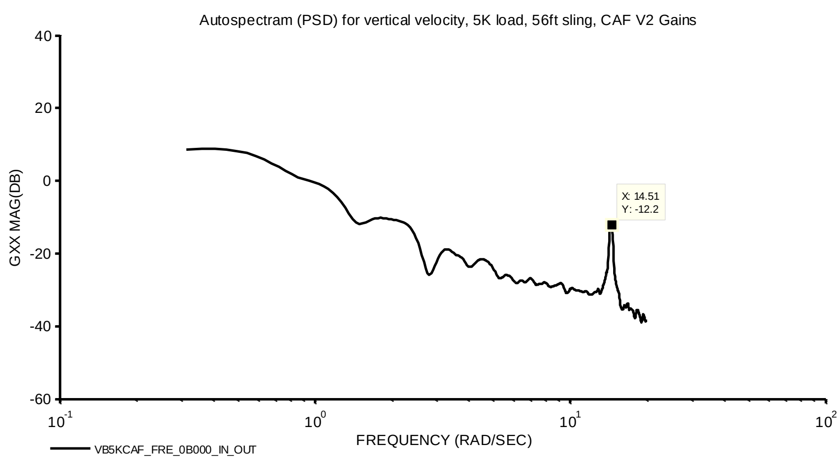


Figure 19. Autospectrum for vertical velocity from flight.

Radar altitude complimentary filters

Radar altimeters are very noisy sensors. This is exacerbated when an external load is moving in its sensing area. A complimentary filter with integrated vertical velocity (w_{EGI}) from the EGI on RASCAL was developed and worked well to improve the altitude signal (H_{RadAlt}) for the unloaded configuration. A complimentary filter time constant of $T_C=6$ was found to work well in flight testing:

$$H_{Filtered} = H_{RadAlt}\frac{1}{T_C s+1} + \left(\frac{-w_{EGI}}{s}\right)\frac{T_c s}{T_c s+1} \qquad (8)$$

However, with an external load, this filtering is not sufficient when the load swings forward and blocks the radar altimeter. Depending upon on the sling length and altitude, the radar altimeter can jump hundreds of feet when the load swings beneath the radar altimeter. The external load angle measurement is used to change the time constant when the load is sensed to be swinging forward. The time constant is changed from $T_C=6$ to $T_C=50$ when the load sensor indicates that the load is swinging forward more than 4 degrees. This approach was used for both the CAF and OBL configurations. Since this does not affect the CAF/OBL comparison, the authors thought it was fair to use the load sensors for complimentary filtering on both configurations to increase safety in the vertical axis. The complimentary filter is beneficial because it does not add lag like a regular low pass filter, but it can become biased (i.e. steady-state error), particularly for high time constants. This is the motivation for switching the time constant with load swing instead of fixing the time constant at a value of $T_C=50$.

Examples of the raw and filtered signals are shown in Fig. 20, for the depart-abort maneuver with a 5000lb load. During the deceleration, the load swings forward, causing a sharp downward spike the in the radar altimeter signal at 25 seconds. The complimentary filter is effective at smoothing this spike, as well as some smaller anomalies in the measurement signal observed in the 15-23s period of the maneuver.

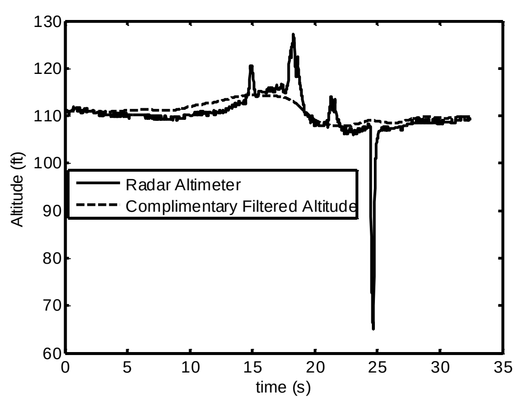


Figure 20. Complimentary filtered altitude during depart-abort maneuver from flight (5K, 56ft sling).

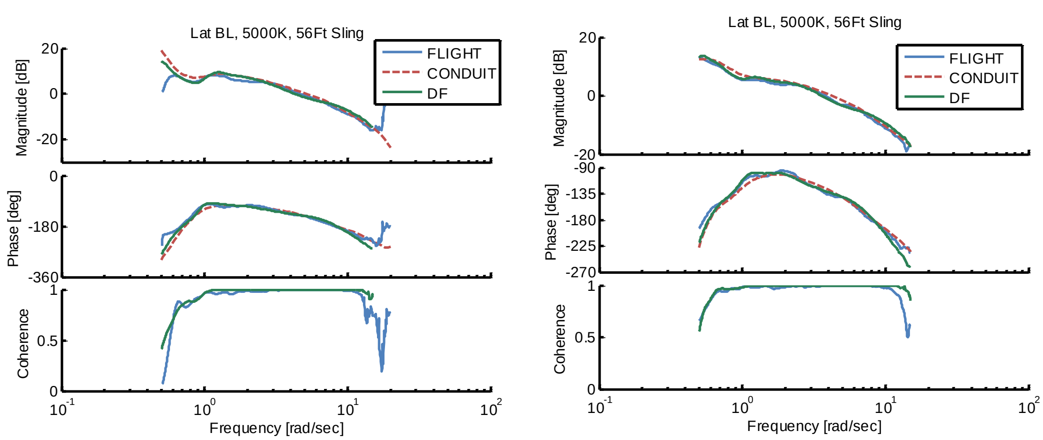
FLIGHT TESTING

The aircraft used for flight testing of the control system is the RASCAL JUH-60 helicopter, which was developed by and is operated by the Aeroflightdynamics Directorate of the US Army at Ames Research Center in Moffett Field, CA. The RASCAL, shown with an external load in Fig. 1, provides a full authority, fly-by-wire system for the evaluation pilot, and a backup hydro-mechanical system with limited authority SAS for the safety pilot [15]. Flight testing was performed with 1000lb and 5000lb external loads, on a 56ft sling.

The flight testing began with validation of the flight-measured responses against the model for CAF and OBL using frequency sweeps and CIFER® [22] techniques to ensure that the responses of the closed and broken loop systems were as expected. The next step was to perform back-to-back comparisons of the OBL design with the CAF design to determine how handling qualities were affected by load feedback. The MTEs that were performed were lateral reposition, depart-abort, precision hover, and precision load placement. The precision load placement task is a newly proposed MTE that focuses on placing the load on the ground in a precise delivery location.

Flight Validation

The broken loop responses for the 1000lb and 5000lb loads were validated in order to ensure the stability margins were consistent with the model predictions. Figure 21 shows the 5K broken loop response compared with the linear model for OBL (a) and CAF (b). As shown in the figures, the flight test broken loop responses closely track both the CONDUIT linear model response and the non-linear simulation development facility (DF) response. The DF is a hardware in the loop simulator which uses the GenHel non-linear flight validated model [23] of the UH-60 dynamics.



(a) OBL (b) CAF

Figure 21. Broken loop responses from flight, non-linear simulation (DF) and linear model (CONDUIT) (5K, 56ft sling).

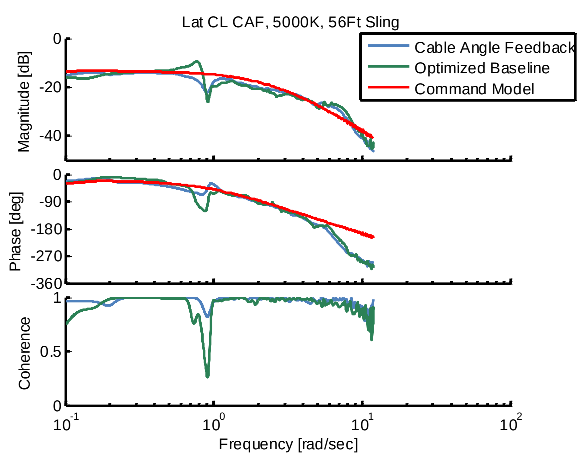
The stability margins calculated from the broken loop responses at the actuator were also close to those expected from the model. The stability margins and cross-over frequencies determined from flight are compared to the linear model (CONDUIT) and the development facility non-linear model (DF) in Table 7. The phase margin improvement in flight between the OBL and CAF from 37.77 to 45.39 is very close to the results predicted by the model.

The closed loop responses determined from flight change as expected with cable angle feedback. As an example, the roll attitude response is shown for the 5K load with OBL and CAF as compared to the command model in Fig. 22a. As expected, the CAF design for the 5K load has less magnitude and phase distortion as compared to OBL. The closed loop CAF response with the 1K load in Fig. 22b has slightly more distortion than OBL because CAF was optimized for the 5K load configuration. CAF overcorrects for the 1K load, causing some additional distortion in the handling qualities mode but more load damping.

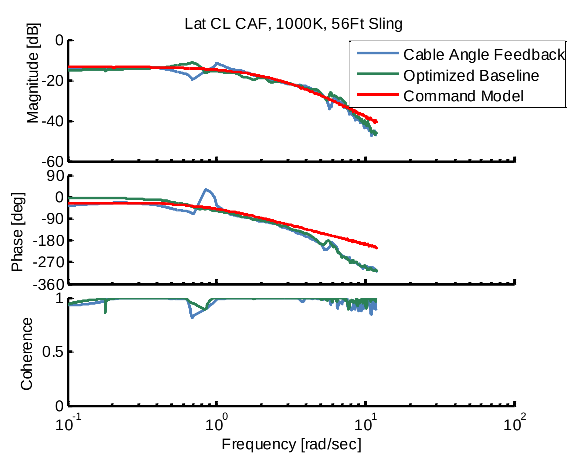
Figures 23- 24 illustrate improvements in the load damping with CAF relative to OBL for both the 5000lb and 1000lb loads, respectively. The 5000lb load frequency response (ϕ_c) to an actuator chirp in PH mode is shown in Fig. 23a. The time response for an acceleration to ~20kts and deceleration back to hover is shown in Fig. 23b. The load damping is improved as the aircraft comes to a hover, as expected with the task tailored control laws. Figure 24a shows the 1000lb load damping has improved in the frequency domain. As seen in Figure 24b, the load response has greatly improved for the entire maneuver, as it was nearly undamped for the OBL control laws with this light load.

Table 7. Lateral stability margins from flight and models in PH mode (5K, 56ft Sling)

Lateral Axis	**Optimized Baseline (OBL)**			**Cable Angle/Rate Feedback (CAF)**		
Data Source	**Gain Margin (dB)**	**Phase Margin (deg)**	**Cross-over (rad/s)**	**Gain Margin (dB)**	**Phase Margin (deg)**	**Cross-over (rad/s)**
FLIGHT	6.01	37.77	4.62	8.2	45.39	3.83
DF	5.93	38.46	4.56	7.02	46.53	3.68
CONDUIT	5.95	33.42	5.15	7.47	42.50	4.19

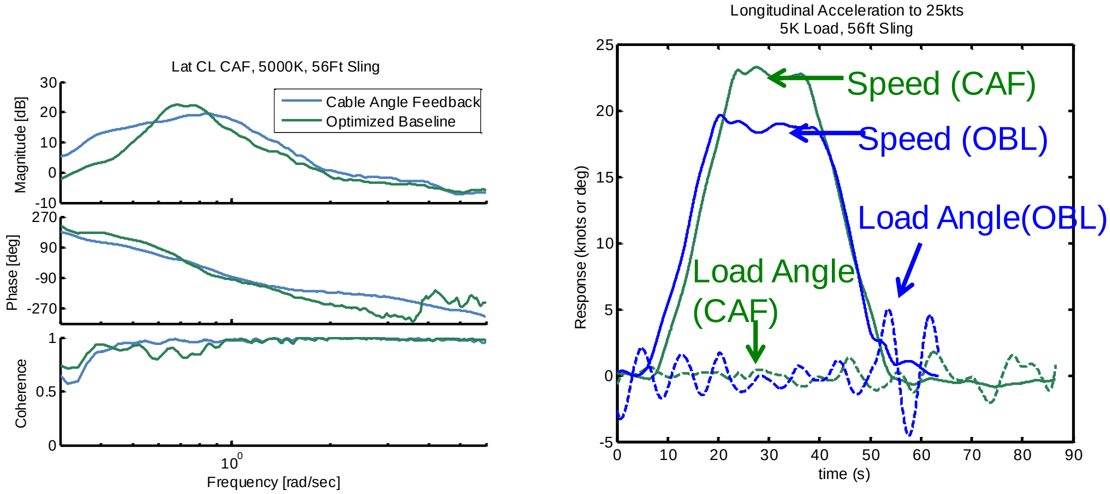


(a) 5K



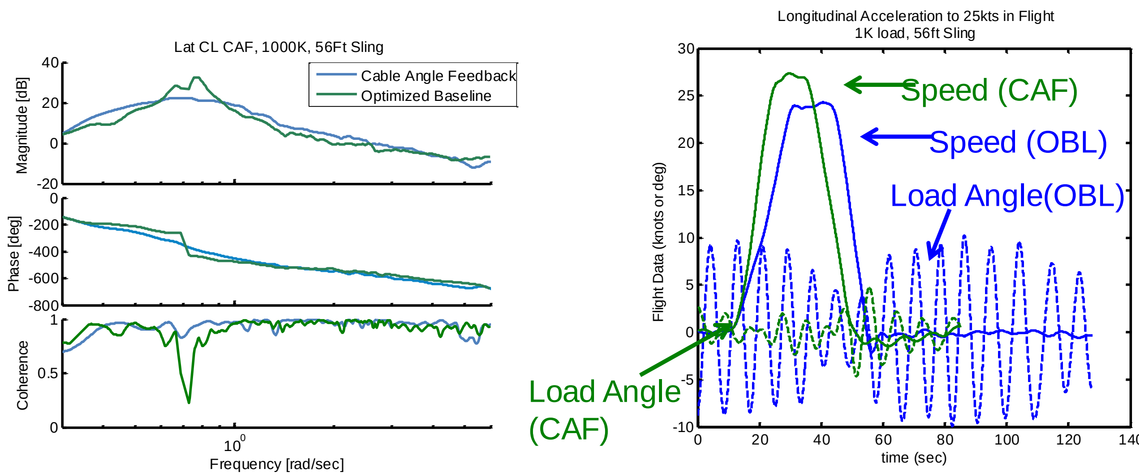
(b) 1K

Figure 22. Flight closed loop responses in attitude command mode (5K and 1K loads, 56ft sling).



(a) Cable Angle (ϕ_c) Frequency Response (b) Time Response

Figure 23. Flight load response, PH mode (5K, 56ft sling).



(a) Cable Angle (ϕ_c) Frequency Response (b) Time Response

Figure 24. Flight load response, PH Mode (1K, 56ft sling).

Load placement MTE

The load placement MTE was developed to address the need for a task that focused on load motions and load operations. For example, during the 1K lateral-reposition maneuver for the UH-60 (LMR ~0.06), the load often swings at an amplitude greater than 30 degrees and is nearly undamped. This swinging does not significantly affect the HQR because the load is relatively light compared to the aircraft and thus does not greatly distort the response to pilot inputs for this task. The load placement MTE addresses the motion of the load and how that affects the handling qualities while delivering a lightly damped load to a precise location on the ground within a finite time. The load placement task is described in the bullets below:

- **Objectives.** The objectives of the load placement MTE are to check the ability to translate with, stabilize, and set down an external load at a specific location, within a reasonable time limit. In addition, this task checks the ability to set load down without any residual motion of the load on the ground, such as dragging or swinging.

- **Description of Maneuver.** Initiate the maneuver at a ground speed between 6 and 10 knots, with a load clearance of 20 feet above ground level. The load placement target shall be oriented approximately 45 degrees relative to the heading of the rotorcraft. The load placement target is a ground referenced point, from which the deviation in the set-down point is measured. The ground track should be such that the rotorcraft will arrive over the target hover point (See Fig. 25). Once the aircraft is stabilized in a hover over the load placement target, the crew chief will provide verbal instructions to assist the pilot in placing the load. These instructions should follow the form of *direction-count-hold* as in “Right, 3-2-1, hold” or “Down, 3-2-1, hold” to position the load and set it down.

- **Description of the Test Course.** The suggested test course for this maneuver is shown in Fig. 25. Note that the desired and adequate boxes refer to the load set-down point, not the helicopter position during maneuver.

- **Performance Standards.** Accomplish the transition to hover in one smooth maneuver. It is not acceptable to accomplish most of the deceleration well before the load target point and then creep up to the final position. The load swing should be contained within the desired boundaries (or adequate if trying for adequate performance) before placing the load on the ground. The load should not perceptibly drift, swing, or drag after initial ground contact. All other performance standards are given in Table 8.

Table 8. Precision load placement MTE standards.

	Externally Slung Load	
	GVE	DVE
Desired Performance		N/A
• Attain a controlled hover within X seconds of initiation of deceleration:	10 sec	
• Maintain altitude during translation and hover within +/- X ft:	4 ft	
• Controlled set-down of external load within X seconds of hover:	50 sec	
• Load set-down position should be within a box +/- X ft larger than the footprint of the external load on all sides:	3 ft	
• The load should have no perceptible drift at touchdown	√	
Adequate Performance		N/A
• Attain a controlled hover within X seconds of initiation of deceleration:	15 sec	
• Maintain altitude during translation and hover within +/- X ft:	6ft	
• Controlled set-down of external load within X seconds of hover:	120 sec	
• Load set-down position should be within a box +/- X ft larger than the footprint of the external load on all sides:	6 ft	

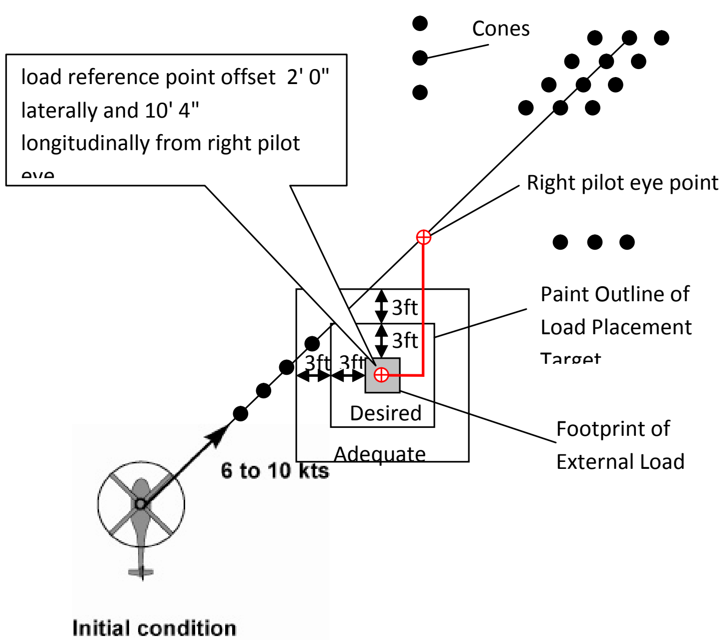


Figure 25. Load placement MTE course.

Handling qualities evaluations

Handling qualities evaluations were performed with three army experimental test pilots on the RASCAL JUH-60A. The tests were performed in a single-blind study (e.g. the pilots were not told which control laws they were flying), with back-to-back comparisons between the two control laws. Four tasks were flown: Hover, Lateral Reposition, Depart-Abort and the Load Placement MTE. These tasks are appropriate for the hover and low speed operations with an external load.

The results of the handling qualities evaluations are shown in Table 9. From the table, it is clear that the control laws were very similar and mostly provided Level 1 Handling Qualities Ratings (HQRs). The areas where there were key differences in the ratings were for the precision hover task with the heavy load, and for the load placement with the light load. These are highlighted in Table 9. These results show that the key trade-off between load control and aircraft control is important in the handling qualities ratings.

Figure 26 provides an explanation for the slight degradation in HQs with CAF for the Hover MTE with the 5K load. For the CAF control laws, we see that there is one position excursion that occurs as the aircraft is settling down from the deceleration part of the task. This causes the pilot to stay in the loop longer, and thus not does turn over the aircraft to PH until later in the record. This is the reason for the slightly worse handling qualities for CAF as compared to OBL. The fact that the load is much better controlled for CAF during this hover maneuver does not improve the handling qualities ratings because it is a fuselage-based task.

For the load placement task, the load can be set-down much more quickly and accurately on the ground. This is made possible by the improved load damping which becomes active in PH mode for the task-tailored control laws. However, this load damping comes at the cost of reducing the precision on the hover MTE. This is consistent with analytical studies of this control system, as shown in Figs. 12-14, which show a clear trade-off between load damping and position maintenance of the fuselage.

As shown in Table 10, the 1000lb load (which is poorly damped for the OBL design) set-down time is approximately twice as fast with the CAF control laws. The 5000lb load set-down times are also improved, but not as drastically. The relationship between load set-down time and increased load damping is further illustrated by Fig. 27. We see that the load motions are much more controlled for the CAF control laws and so the load set-down can be achieved more rapidly. Pilot comments indicate this is the reason for the improved HQR with the CAF control laws for the load placement task.

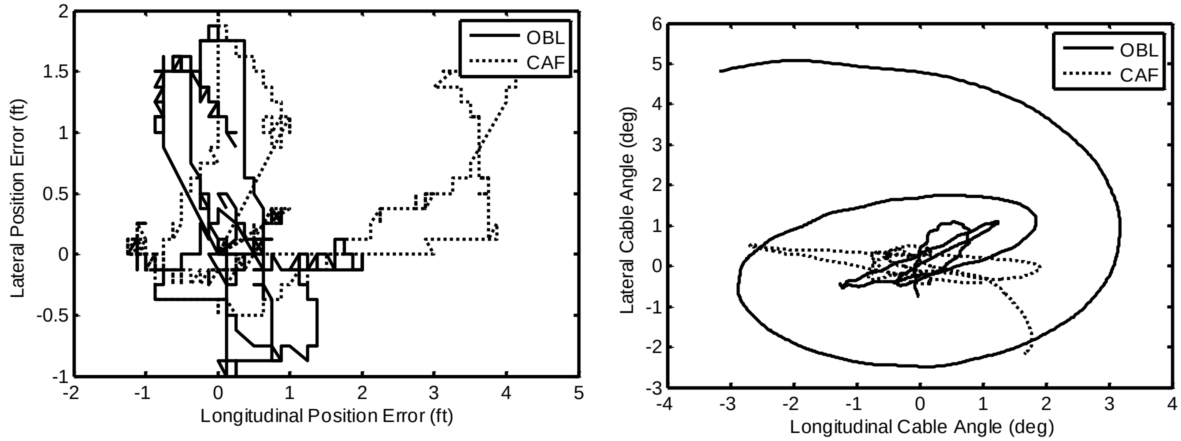
Handling qualities ratings for the lateral-reposition and depart-abort MTEs were not significantly affected by the presence of CAF, even though the load responses were vastly improved. During these maneuvers, the lateral cable angles were very poorly damped for OBL and well damped for CAF as shown in Fig. 28. These results indicate that the control laws were successful in providing an improved load response while maintaining good handling qualities for these larger-amplitude tasks.

Table 9. Average handling qualities ratings (56ft sling).

	LAT REPO, 1K	LAT REP, 5K	DEPART-ABORT, 1K	DEPART-ABORT, 5K	HOVER, 1K	HOVER, 5K	LOAD PLACEMENT, 1K	LOAD PLACEMENT, 5K
OBL	2.67	2.50	3.33	3.00	3.17	3.67	4.50	3.00
CAF	2.67	3.00	2.83	3.17	3.67	4.67	3.33	2.50
DELTA	0.00	-0.50	0.50	-0.17	-0.50	-1.00	1.17	0.50

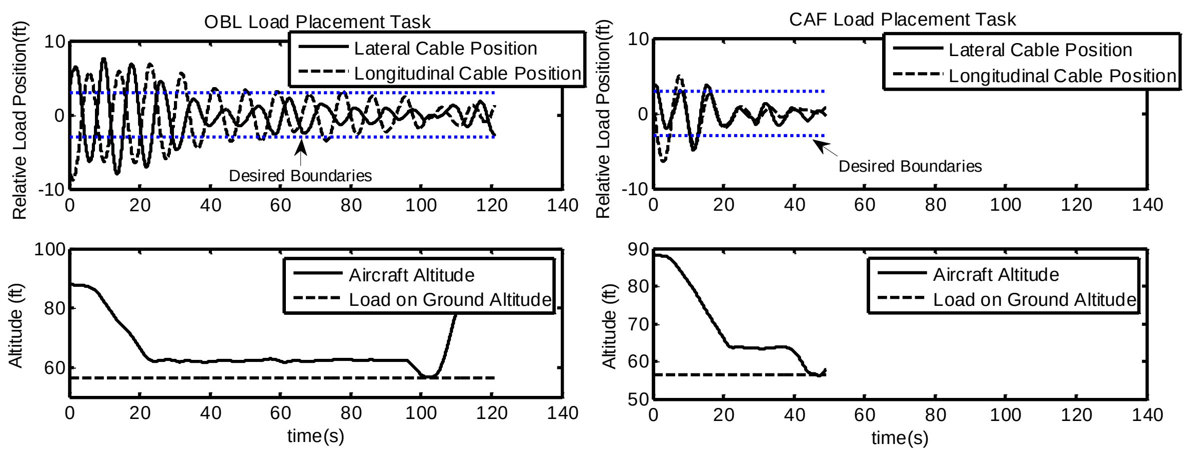
Table 10. Average time to controlled set-down of external load (56ft sling).

	LOAD PLACEMENT, 1K	LOAD PLACEMENT, 5K
OBL	80.05s	45.5s
CAF	39.5s	31.33s



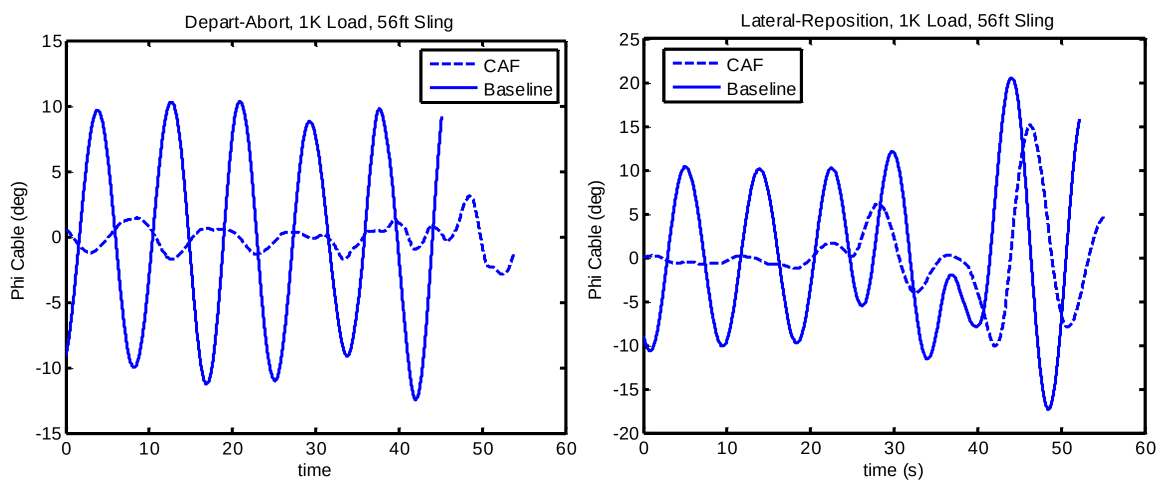
(a) Position Error (b) Cable Angle

Figure 26. Hover MTE responses from flight (5K, 56 ft sling).



(a) Position Error (b) Cable Angle

Figure 27. Precision load Placement MTE responses from flight (1K, 56ft sling).



(a) Depart-Abort Cable Angle (b) Lateral Reposition Cable Angle

Figure 28. Lateral cable angles (ϕ_c) during MTEs from flight (1K, 56ft).

DISCUSSION

The task-tailored control laws provided improved load damping at hover and improved handling characteristics for maneuvering as compared to the legacy UH-60 control laws. The HQRs for the legacy UH-60 control laws (from Ref. 2) are shown in Table 11 as compared to the CAF and OBL control laws. Note that only calm day ratings for precision hover were included in Table 11 in order to have a fair comparison with the legacy control law evaluations. One of the pilots performed the precision hover task for OBL and CAF in 12-15kts of wind.

While the handling qualities rating were similar for the depart-abort and lateral reposition tasks with CAF vs. OBL, both were well within Level 1 (HQR<3.5), and CAF provided a more controlled load response as well as some qualitative improvements. One of the pilots commented that the key advantage is that "If the pilot stays in the loop a little longer (while the load damping settles down), during initial position capture, the result is a very stable aircraft, without residual oscillations due to the load." This is beneficial in providing the pilot with a more stable attitude response and better damped load behavior, and "could be helpful in degraded visual environments (DVE) to eliminate residual aircraft motion due to load oscillations".

The key drawback of the setup with the cable angle/rate task tailored control laws which use load damping active in the PH mode was for the precision Hover MTE. As discussed in the previous sections of this paper, the load damping mode slightly degrades precision position maintenance of the fuselage in PH. One pilot explained this very clearly remarking that "For aircraft maneuvers requiring tight control to capture a position, the workload with CAF was higher, however, CAF was superior for precision load placement." In the future, it may be better to have the load damping mode be a pilot selectable mode so that load damping does not interfere with precision hover when the load is not being placed on the ground. The task-tailored CAF control laws provided a very clear improvement in the load placement task, especially for a lightly damped load. The load can be placed on the ground more quickly and with better accuracy using CAF. The operation is also much safer for ground crew because the load is more predictable and has less overall swing.

Advanced modes such as altitude hold, velocity hold and position hold in the baseline control laws provided a large improvement in the handling qualities as compared to the legacy UH-60 SAS, as shown by Table 11. The legacy UH-60 with partial authority SAS, which only features a rate command mode, has much worse handling qualities ratings as compared to the OBL or CAF control laws. However, CAF was required in order to get a major improvement in the load placement task as compared to the legacy UH-60 aircraft (Level 2 to Level 1).

In the words of one of the evaluation pilots "overall, the CAF system is beneficial, but would require additional crew training in order to understand the best way to take advantage of the load damping mode." The pilots felt that CAF worked well behind the scenes to provide a more stable external load during low speed maneuvering. The most difficult aspect of external load operations, requiring the highest pilot workload, is the hookup and set-down of the load. The pilots felt that "CAF, when combined with well performing hold modes, effectively drives that workload down to minimal levels."

Table 11. Average HQRs for legacy UH-60 SAS vs. CAF and OBL (56ft sling).

	LAT REP, 5K	DEPART-ABORT, 5K	HOVER, 5K	LOAD PLACEMENT, 1K
LEGACY	4.5	4	4.5	5
OBL	2.50	3.00	3.25	4.50
CAF	3.00	3.17	4	3.33

CONCLUSIONS

A task-tailored cable angle/rate feedback (CAF) control system was developed in order to evaluate the benefits of load motion sensing in a fly-by-wire control system. A well designed optimized baseline (OBL) fly-by-wire control law (that does not use cable angle feedback) was developed for comparison with the cable angle system. A blind handling qualities flight-test evaluation was performed with army experimental test pilots. The following conclusions can be drawn from the results:

1. There is a key trade-off between load damping and aircraft handling qualities, which can be exploited with a task tailored control law. This approach effectively mitigated the non-collocated aircraft/load control problem in flight.

2. Both OBL and CAF control laws significantly improved the handling qualities relative to the legacy UH-60 with a partial authority SAS by providing advanced augmentation with hold modes including attitude command/ velocity hold, position hold, and altitude hold. The CAF control laws were required to improve the load placement task to Level 1 performance and the load set-down time was reduced by a factor of 2 for the 1000lb load.

3. The load placement MTE task was useful for evaluating the handling qualities associated with the load set-down task. This is an important, high workload task for external load operations that is not captured by the current set of aircraft-focused ADS-33E-PRF tasks.

4. Cable angle/rate feedback control laws provided improvements in stability margins, load set-down times and load placement accuracy, as well as improvements in safety to ground personnel as

compared to an optimized baseline fuselage feedback only control system.

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