Handling Qualities Improvements due to Height Hold System for ADS-33 Hover Maneuvers

D. Kris Ellis
Arthur W. Gubbels
National Research Council of Canada
Flight Research Laboratory
Ottawa, Ontario, Canada

Abstract

The NRC Flight Research Laboratory recently developed and flight tested a height hold controller suitable for aggressive low level maneuvering using the NRC Bell 205 Airborne Simulator. This paper describes the integration of a laser altimeter with an inertial/GPS navigation system for high resolution height above ground measurement, the development of advanced feedforward algorithms to counteract the effects of translational lift, and feedback control law optimization.

The RMS height errors in precision hovering maneuvers were 0.08 to 0.13 feet, whereas manually flown precision hovers had RMS height errors ranging from 0.26 to 0.32 feet. Similar performance improvements were evident for aggressive maneuvers, with acceleration/deceleration height hold peak-to-peak errors of ±3 feet versus ±14 feet for manual pilot control. The handling qualities ratings assigned to the height hold controller schemes demonstrated a 1 HQR improvement for pirouette, hover and side step, and a 0.5 HQR improvement for the pedal turn and acceleration/deceleration.

Nomenclature

a_1,b_1	Longitudinal and Lateral Flapping
AGL	Above ground level
FCC	Flight Control Computer
FRL	Flight Research Laboratory
GPS	Global Positioning System
h	height
IGE	In Ground Effect
INS	Inertial Navigation System
K_i	Integral Gain
K_p	Proportional Gain
K_d	Derivative Gain
NRC	National Research Council of Canada
OGE	Out of Ground Effect
PIO	Pilot Induced Oscillation
ϕ	Roll attitude
R	Rotor Radius
ρ	Density
RMS	Root Mean Square
T	Thrust
θ	Pitch attitude
θ_0	Collective Pitch
TPP	Tip Path Plane
UCE	Useable Cue Environment
u,v,w	body axis velocities
v_i	Induced Velocity
W	Weight

Introduction

Height hold systems are used to maintain a rotorcraft's height above the ground without the requirement for pilot control input. The use of a height hold system during helicopter operations, particularly in and around the hover and in poor visibility, is known to improve handling qualities and safety (Reference i). In poor cueing environments, the pilot can concentrate on horizontal positioning, relying on the height hold system to prevent descent and contact with the ground. ADS-33 (Reference i) specifies the use of a height hold system with an Attitude Command Attitude Hold response type for Level 1 handling qualities for most ADS-33 demonstration maneuvers in UCE 2. For Level 1 handling qualities in UCE 3 conditions, a height rate command controller with a translational rate command response type in the cyclic axis and heading hold is required. The performance of current production height hold systems is adequate for up and away flight and for benign hover maneuvers. However, typical partial authority systems provide inadequate performance for low level, aggressive maneuvering. With full authority systems becoming more common, there is the possibility of designing height hold systems suitable for aggressive, low level maneuvering. The design and demonstration of such a height hold system was performed using the NRC Bell 205 Airborne Simulator.

The Bell 205 Airborne Simulator, shown in Figure 1, is a single engine, two-bladed teetering rotor helicopter that was converted to operate as a full authority fly-by-wire experimental research helicopter. The Airborne Simulator consists of the host aircraft, a set of dual mode (mechanically or electrically controlled) full authority actuators, a general purpose computing system, a set of state and pilot input sensors and a variety of pilot displays. The Airborne Simulator is flown by two pilots; the evaluation pilot controls the aircraft in the fly-by-wire mode, and the safety pilot has the ability to fly the aircraft via the standard mechanical connections. The previous Bell 205 Airborne Simulator height hold system used a simple feedback structure consisting of height error derived from a radar altimeter and vertical rate calculated from a blending of integrated accelerometers and Doppler radar velocities. Although this system was capable of holding height within ±3 feet in a stabilized hover, the performance during dynamic maneuvers, such as the side step and acceleration/deceleration, was poor.

Figure 1: NRC Bell 205 Airborne Simulator

It was postulated that the integration of an improved height above ground measurement system would allow height feedback gains to be increased to levels capable of greater performance in the hover type maneuvers. Additionally, the use of feedforward control methods that employed translational rates and main rotor tip path plane orientation to generate lead on collective activity would improve height hold performance for dynamic maneuvers such as acceleration/decelerations. The addition of torque limiting would automatically prevent the height hold system from exceeding aircraft limits without the requirement for pilot intervention. A block diagram for this system is shown in figure 2.

The approach undertaken to develop the improved height hold algorithm was to first install a high accuracy laser distance meter to operate as a laser altimeter, and then to characterize the unaugmented height response of the test aircraft. Once the aircraft was characterized, feedforward and feedback routines were developed, analyzed, and optimized via desktop simulation. Next, flight tests were undertaken in order to evaluate system performance and handling qualities, and perform some fine tuning of the height hold algorithms. This paper briefly describes the development of the improved height hold controller for the Bell 205 Airborne Simulator, and then focuses on the resulting handling qualities improvements for use during hover ADS-33 maneuvers.

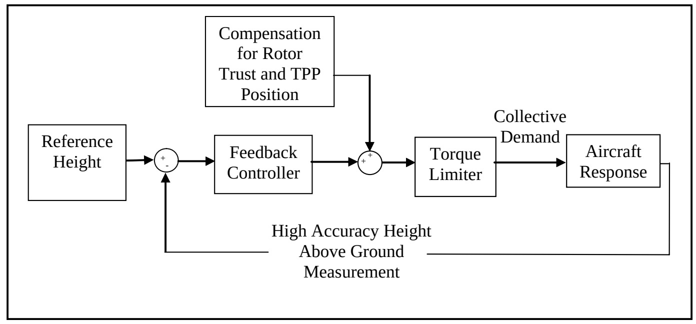

Figure 2: Height hold block diagram

Height Measurement System

An accurate and precise height measurement system was necessary to develop a high performance height hold system. For 'up and away' flight, a barometric altimeter and GPS/inertial height indication is sufficient, as it was not necessary for the height hold system to track the contour of the terrain. However, for flight closer to the ground, precise indication of height above ground and a height hold system capable of terrain following was required. The previous height hold system implemented on the Bell 205 Airborne Simulator used a radar altimeter to provide this information. The benefit of the radar altimeter is that the measurement is largely independent of aircraft attitude as the radar scaned a 60 degree arc of sky. However, the measurement is noisy, lacks adequate resolution, and is not sufficiently accurate to allow a height hold design that performs as well as a human pilot. Additionally, it has been observed over various projects involving world-referenced symbology, that the radar altimeter can drift over time resulting in large accrued height error.

In order to meet the requirements for this project, it was necessary to find a measurement system that would provide height measurement accuracy better than ± 1 foot. This was based on the premise that for a precision hover a height tolerance of ±2 feet is allowed for desired performance. Limiting height error to less than ±1 foot allows for a ±1 foot margin for error for the control system to work within. Previous experience at FRL with laser altimeters suggested that they would far exceed the height measurement requirements, and would provide an excellent reference for a height hold system.

The RIEGL LD90-3100HS laser distance meter was selected for its high accuracy, high bandwidth, and compact size. Data from this unit is received by an LN-200 inertial navigation computer via an RS232 serial connection at a data rate of 50 Hz. The measuring range is typically up to 150 meters with an accuracy of ± 15 mm and a resolution of 10 mm. The unit was installed in the belly of the aircraft and senses through a glass window. Output radiation from the laser is a Class 1 eye safe pulsed infrared beam.

Despite the fact that the laser altimeter provides a high accuracy and high resolution distance measurement, as a fixed beam it always points at the same angle relative to the aircraft attitude, as shown in Figure 3 (a). This results in a reported distance that is a function of aircraft pitch and roll attitude, unlike the RADALT, which scans an arc-of-sky, and reports the lowest altitude returned. To compensate for this effect, the raw measurement from the laser altimeter, is corrected for the pitch, θ, and roll angle, ϕ, to determine the height of the aircraft, *h*, as follows.

$$h = laser\ range \cdot \cos(\theta) \cdot \cos(\phi) \qquad (1)$$

With these corrections, and a lever arm correction to refer the laser altimeter to the same position as the inertial system, the laser effectively measures the height of the aircraft above the spot where the laser beam strikes the Earth. From the above relationship, it is clear that the use of a highly accurate attitude measurement system is required.

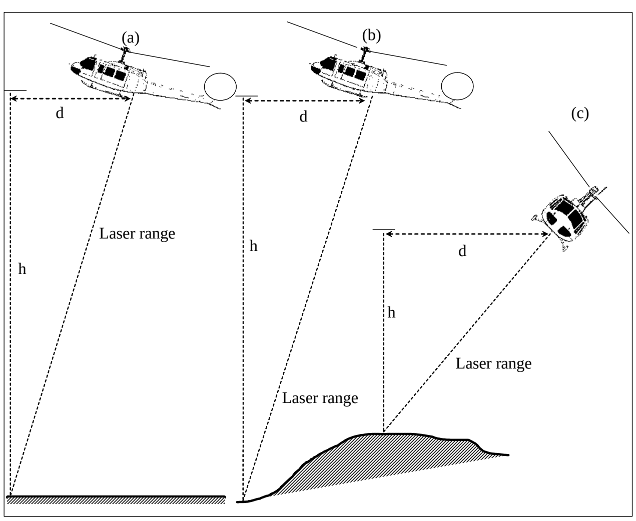

Figure 3: Comparison of laser range measurement and height above ground

During aggressive maneuvering over uneven terrain, sudden changes in height above ground measurement induced by attitude change with no corresponding vertical aircraft motion are possible as illustrated in Figure 3 (b). Additionally, with a high feedback gain height hold system it is undesireable to track the ground profile exactly, otherwise obstacles such as vehicles, boulders, foliage, etc, could result in unnecessary collective/torque activity, and a correspondingly rough ride. To account for this, and the terrain profile uncertainty while maneuvering, a mixed height complementary filter was designed. This filter employs the laser altimeter measurement to provide a low frequency reference, and blends in INS/GPS height data at high frequencies. The mixed height algorithm takes advantage of the fact that over a static terrain profile (i.e. relatively flat ground) changes in inertially sensed vertical position correlate well to height above ground, and that sudden changes in sensed terrain elevation (e.g. passing over a trench) will not result is a rapid reported height above ground change and subsequent increased vertical axis activity.

A block diagram of the mixed height algorithm employed in the Airborne Simulator is presented in Figure 4. Instead of using the laser altimeter to measure height above ground directly, the laser measurement is compared with the current inertial/GPS altitude to form an estimate of the elevation of the ground below the aircraft. By low pass filtering the ground estimate and subtracting the ground elevation from the inertial/GPS altitude, the mixed height algorithm effectively blends the laser altimeter in the low frequency band with the inertial/GPS altitude in the high frequency band.

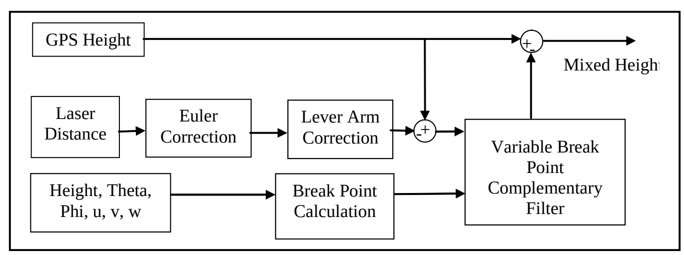

Figure 4: Mixed height block diagram

Due to the uncertainty in the terrain profile beneath the aircraft, it is desirable to de-weight the laser measurement when the laser beam points far away from the point over which the aircraft is currently located. Using the Euler angles from the inertial navigation system, the horizontal distance (designated *d* in Figure 3) is computed between where the laser beam reaches the Earth and a point on the Earth directly below the aircraft. The complementary filter breakpoint is scheduled between 0 and 1 rad/sec inversely proportional to the horizontal distance. This approach has the advantage that at lower altitudes, where tight height holding performance is required, the height measurement is almost exclusively based on the laser altimeter given the typical maneuvering attitude envelope of the helicopter. At higher altitudes, where height holding performance is less critical, the mixed height measurement is based more upon the inertial height, thereby smoothing out variations in terrain.

During trimmed forward and sideward, or accelerating flight, the laser altimeter points at terrain that has already been passed due to the geometry of the altimeter installation and rotorcraft flight dynamics. The complementary filter breakpoint scheduling de-weights the laser altimeter based ground height estimation effectively for this condition, however, to take advantage of the time during the flare of an acceleration/deceleration or side step when the laser beam points in the direction of motion, the point used in the horizontal distance calculation is the point on the ground directly below the aircraft plus an extrapolation of the aircraft position based on translational velocity. Using this predictive calculation, the laser measurement is given maximum weighting when the laser points to where the aircraft will be, rather than where the aircraft has been.

As the aircraft climbs above 500 feet AGL (the maximum reliable range of the laser altimeter), the mixed height measurement has to smoothly transition to a height above ground based solely on the inertial/GPS altitude measurement. Also, during maneuvering flight, such as the banked turn depicted in Figure 3c, it is possible to exceed the range of the altimeter while remaining within 500 feet of the ground. Sudden jumps in the calculation of height above ground were deemed unacceptable owing to the high feedback gains utilized by the height hold system. Therefore, when the range of the laser altimeter is exceeded, the complementary filter breakpoint is set to zero to completely de-weight the laser data. Effectively, this freezes the low pass filter tracking the ground elevation, and the output of the mixed height algorithm becomes the inertial/GPS altitude minus the last known good estimate of the ground elevation. Once the laser becomes in-range again, the mixed height algorithm resumes tracking the ground elevation with a bandwidth of no greater than 1 rad/sec. Therefore, if the aircraft climbs out of the laser measurement range, then re-enters range over different terrain, the mixed height algorithm smoothly adjusts to the new terrain profile.

Height Hold System Simulation & Development

The approach taken for the height hold system involved a decoupling/feedforward outer loop that determined the amount of main rotor thrust required to balance against gravity for any given initial condition, and a feedback control path that removed any accumulated error and compensated for uneven ground and unmodelled effects. This section describes the development and simulation of the feedforward/decoupling component and the feedback control law.

The previous height hold system employed on the Bell 205 Airborne Simulator consisted of a proportional plus derivative style classical control system, which relied entirely upon feedback of height and height rate. Since a height error must be present in order for this system to work, this required a high level of feedback gain in order to achieve minimal changes in height while maneuvering, but resulted is a stiff/rough ride quality and no performance improvement over a manually flown aircraft.

The height hold system described in this paper uses a feedforward approach to generate lead on the collective position and improve performance over the use of feedback alone. This approach is similar to that which a pilot employs while performing maneuvers.

In essence, a height hold system attempts to select a collective lever setting that develops main rotor thrust component normal to the earth equal to the weight of the aircraft. In a zero wind 'wings level' hover this a fairly trivial matter, since the thrust required is equal to the weight of the aircraft, and the thrust generated by the rotor is easily calculated via momentum theory. The thrust generated is directly proportional to collective lever setting since it controls the angle of attack of the main rotor blades. The situation becomes more complicated as the helicopter pitches and rolls in the hover. The thrust required is now a trigonometric function of Euler angle, and control positions, since the thrust is generated normal to the main rotor axis of rotation (nominally parallel to the swashplate angle). As the helicopter develops velocity, and begins to climb/descend or transition to forward flight the formulation of thrust becomes more complex. A vital parameter for the calculation of main rotor thrust is rotor inflow.

Rotor inflow is the name given to the flowfield induced by the rotor at the rotor disc, thus contributing to local blade incidence and dynamic pressure. A real induced flow of a rotor includes components due to shed vorticity from all blades, extending far into the wake of the aircraft. However, for the purpose of rudimentary analysis, it is generally sufficient to only consider the downwash component of inflow (reference ii). Thrust formulations used in this paper employ the simplest representation of the rotor wake, the actuator disc model, which assumes infinite blades able to support a pressure differential across them. This model combined with momentum theory (laws of conservation of mass, and momentum), form the basis of the thrust model employed here, with some extensions to cover forward flight and ground effect. Based on these assumptions, the following relationship for induced velocity can be determined. For a complete derivation of this relationship, see reference iii.

$$v_i = \frac{W \sec\theta_{TPP} \sec\phi_{TPP}\left(1-\left(\frac{24}{4(laseralt+8)}\right)^2\right)}{2\pi R^2 \rho \sqrt{u^2+v^2+(w+a_1u+b_1v-v_i)^2}}$$

The above equation was solved iteratively in the FCC at 64Hz using the last converged value of induced velocity as an initial guess. A combined bisection and Newton gradient method is used to arrive at the solution (Reference iv). Optimization parameters were set such that the solution was considered to have converged when within 0.05 feet/s, or 30 iterations had passed. In simulation evaluations using flight test data, at most 5 iterations were required.

The relationship for thrust can be expanded with values appropriate for a Bell 205, and using the assumptions that rotor speed is constant at 5.4Hz, and air density is at standard temperature and pressure:

$$T = 277.58\left(w + a_1u + b_1v + 9.47\theta_0 - 77.45 - v_i\right)$$

Using the induced velocity relationship, the above equation can be re-written to provide collective position:

$$\theta_0 = \frac{W \sec\theta_{TPP} \sec\phi_{TPP}\left(1-\left(\frac{24}{4(laseralt+8)}\right)^2\right) - 277.58(w+a_1u+b_1v-77.45-v_i)}{2628}$$

By solving the above equation iteratively, and using previously calculated rotor states, the collective position required in order to maintain height can be calculated. This formed the basis of the feedforward component of the control law, the details of which are available in reference iii.

For the feedback component of the control system, the most logical method of maintaining height was to feed back a signal proportional to the height error. While this undoubtedly would work, it was not ideal owing to the slow response of the vertical axis, and only low gains would result in a stable system. The solution was to employ height rate as a damping term to increase the bandwidth of the inner loop vertical axis.

Since the helicopter responds to collective inputs with a height rate, it would seem intuitive that no integral action in the closed loop controller would be required to obtain a zero steady state error condition, however this is unfortunately not the case. Ground effect will arrest the height rate, by increasing effective thrust for a descent, and reducing effective thrust for a vertical climb. As a result some integral action is required in order to ensure that there is zero steady state error during an IGE engagement of the height hold system. The use of integrators in flight control systems can often result in lowered stability, and oscillations, or even actuator runaways; thus it is desirable to minimize any requirement for integral action. Since only slight integral action is required to compensate for ground effect, it was decided to limit the authority of the integral action through the use of an anti-windup integrator. An integral gain of 0.1 inches/(ft s) was chosen as a reasonable level of integral gain since it would result in an inch of collective applied over 10 seconds for a steady error of 1 foot.

The integral term limit value chosen for flight test was ± 1 inch of collective displacement based on some early flight test data performed with no integral terms. During these tests, moderate aggression acceleration/

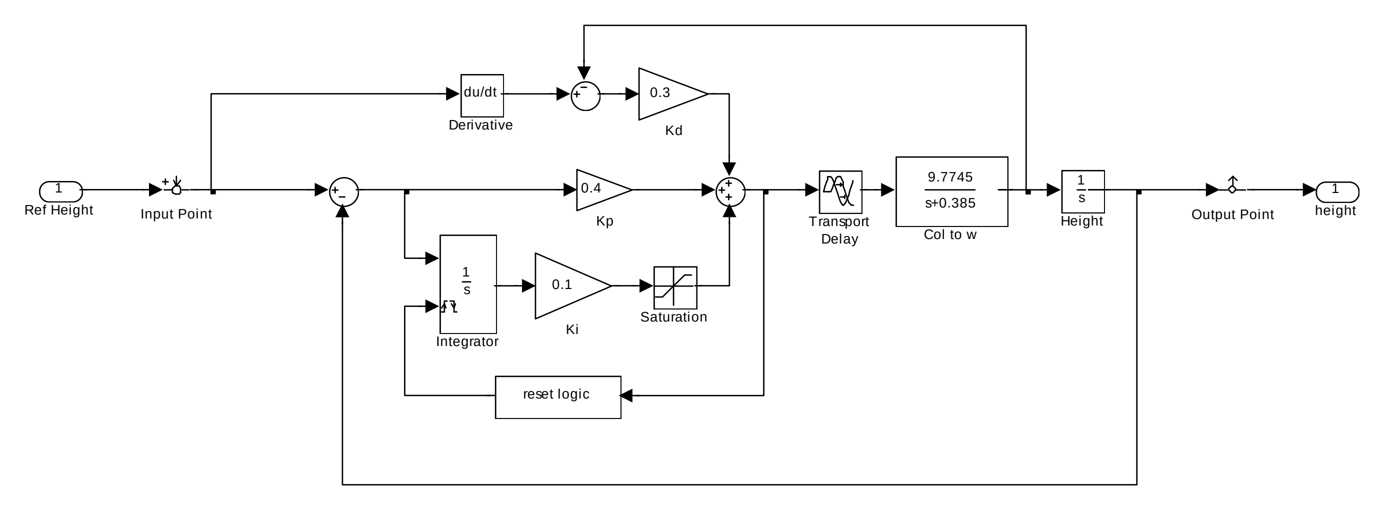

Figure 5: Feedback Structure Block Diagram

decelerations were performed with a feedback controller and no feedforward controller. Integration of height error, subject to the integral gain of 0.1 inches/ft/s^2 revealed that only 0.5 inches of collective would be commanded by the integral term. The limit was set at ±1 inch in order to allow for more aggressive maneuvering. Figure 5 presents the block diagram of the finalized height hold feedback controller. The reset condition for the integrator is set to prevent integrator windup when saturated.

Flight Test Experiment

To determine the influence of the height hold algorithm on the handling qualities of the helicopter, it was decided to perform evaluations using a baseline control system with borderline Level 1/Level 2 handling qualities. Maneuvers were flown by two pilots using a baseline attitude command/attitude hold control system for the longitudinal and lateral axes, and a rate command system for the directional axis. Three options were evaluated for the vertical axis:

1. Unaugmented, direct collective control
2. Height hold feedback control
3. Height hold feedback control plus feedforward

The following maneuvers were selected for evaluation:

1. Precision Hover
2. Hover Turn (Pedal Turn)
3. Pirouette
4. Acceleration/deceleration
5. Side Step

The ADS-33 maneuvers were selected spanning a range of high precision maneuvers (hover, pedal turn, pirouette), and high aggression maneuvers (acceleration/deceleration and side step).

The precision hover was selected since it requires a strict height tolerance of ±2 feet, and demonstrates the performance of the height hold algorithm in a precision maneuver. Of particular interest was the difference in flying technique using the height hold algorithms versus manual height control.

The pedal turn was selected since it is fundamentally a single axis task, yet involves compensating for the inherent cross coupling of the helicopter in the lateral axis due to the high tail rotor thrust line and the vertical axis due to the drivetrain dynamics.

The pirouette was selected as it is a multi-axis precision task, requiring significant pilot attention to the lateral and directional axes in order to maintain speed and proper heading, while longitudinal inputs must be made in order to remain within the fore/aft position limits. Height is to be held within ±2 feet for the duration of the maneuver. This task was chosen to illustrate the ability of a height hold algorithm to increase the pilot's 'spare capacity' and allow him to focus more on the other axes involved in the task.

The acceleration/deceleration was selected as it is an aggressive longitudinal axis task that involves accelerating through translational lift, and a rapid deceleration. Although the height tolerance defined by the *desired* conditions of ADS-33 are generous (maintain height below 50 feet), the collective inputs are aggressive and of high magnitude.

The side step was chosen as another aggressive maneuver to complement the acceleration/deceleration task, but in the lateral axis. The height tolerances are more strict on the side step (±10 feet for desired performance), and the maneuver is not symmetrical in terms of collective displacement required, likely owing to the requirement to pass through tail rotor vortex ring condition.

Handling qualities are discussed in the following section on a maneuver-by-maneuver basis with a focus on the performance measurements and pilot comments. Handling qualities ratings are collectively discussed following the individual maneuver discussions.

Handling Qualities Results

Precision Hover

Baseline: Pilots reported that in the baseline configuration desired performance was achievable, though much of the fore/aft position tolerances were used. The heave axis was identified as the most active axis, with small continuous low frequency collective inputs required to maintain height within desired conditions.

Feedback Height Hold: With the feedback height hold algorithm enabled, both pilots noticed improved height retention. Pilots reported that workload was significantly reduced with the height hold on, which allowed sufficient spare capacity to spend less time looking at the hover board and more time checking the longitudinal cues. The axis with the highest workload became the yaw axis, which had a slight tendency to oscillate.

Feedback plus Feedforward Height Hold: Pilots did not perceive a difference between this mode and pure feedback for the precision hover task.

Figure 6 presents the precision hover performance for Pilot 1 for all three test configurations. From the figure it can be seen that with the height hold on the x and y RMS position error was decreased versus the baseline case. With the height hold feedforward and feedback selected the total position error was reduced by 40%. It is postulated that further improvements may be seen in degraded visual environment conditions, where the increased spare capacity generated by the height hold algorithm can be translated into attempts at better recognizing the existing cues.

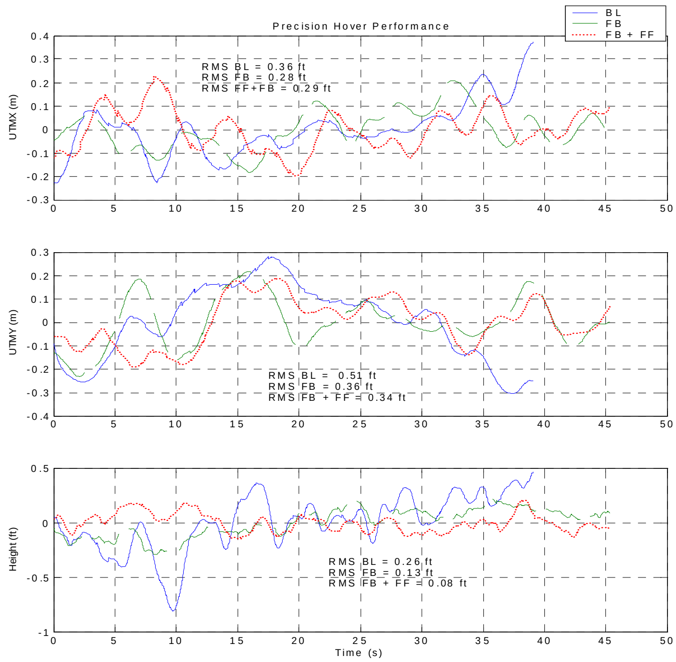

Figure 6: Pilot 1 Precision Hover Performance

Hover Turn

Baseline: Both pilots rated the yaw axis as the primary workload driver, citing nonlinearities in aircraft response (i.e. constant pedal position did not result in constant yaw rate), coupled with high spring gradient mechanical characteristics for the pedals. This resulted in reduced aggression. Small continuous collective inputs were required throughout the maneuver, though the heave axis was not regarded as a high workload axis for this task. Significant pilot compensation was required in the lateral axis as a result of the high tail rotor thrust line which caused the helicopter to bank and translate during the rapid pedal input.

Feedback Height Hold: Both pilots commented that the reduced workload resulting from the height hold algorithm allowed them to focus on minimizing position drift. The increase in spare capacity was quite evident, however deficiencies in yaw axis remained the primary workload driver.

Feedback plus Feedforward Height Hold: Pilots did not perceive significant differences between this mode and the pure feedback height hold for the hover turn maneuver.

Pirouette

Baseline: Pilots indicated that during the maneuver the lateral axis presented the highest workload, followed by the heave axis. Small, gradual collective inputs were required throughout the maneuver, especially as the helicopter passed through translational lift. Both pilots indicated that the most pronounced deficiency with the controller was the yaw axis, which had a tendency to result in a slight PIO while arresting the maneuver.

Feedback Height Hold: Height errors were barely resolvable with the height hold controller activated. Pilots commented on increased spare capacity which allowed them to further focus on maintaining groundspeed and longitudinal positioning. The yaw axis remained the most significant deficiency of the controller. Both pilots felt somewhat uneasy to rest their left hands on their laps while performing the maneuver, and commented that there was a sensation of a slight loss in situational awareness that would normally be present through the collective axis.

Feedback plus Feedforward Height Hold: Pilots did not perceive significant differences between this mode and the pure feedback height hold for the pirouette maneuver.

Figure 7 presents a time history of the height error for Pilot 1's pirouettes. From the figure it can be seen that the height hold controllers had similar performance to the manually flown pirouette, with the exception of there having been slightly more low frequency error build up in the manually piloted pirouette. RMS height errors were 1.15 feet for the baseline case, and 0.53 feet and 0.29 feet for the height hold feedback and feedback plus feedforward controllers respectively.

Figure 8 presents a time history of the height error for Pilot 2's pirouettes. From the figure it can be seen that the height hold controllers offered improved height precision versus the manually controlled collective pirouette. In the baseline controller case a low frequency trend to lose height over the maneuver was readily apparent while both the height hold controllers maintain aircraft height over ground to within ±1 foot of the reference height. RMS height errors were 1.19 feet for the baseline case, and 0.91 and 0.78 for the height hold feedback and feedback plus feedforward controllers respectively.

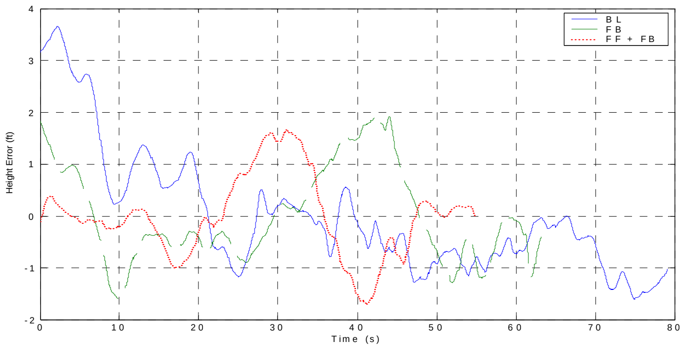

Figure 7: Pilot 1 Height Error for Pirouette

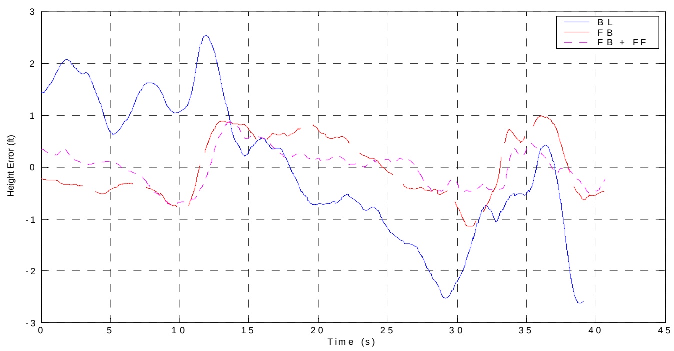

Figure 8: Pilot 2 Height Error for Pirouette

Acceleration/deceleration

Baseline: Both pilots employed a similar technique for the baseline acceleration/deceleration maneuver, opting to descend slightly on the acceleration and balloon slightly on the deceleration. Pilots commented that the sluggish pitch axis made it difficult to anticipate the stopping point of the acceleration/deceleration. Longitudinal cyclic and collective control were cited as the primary workload drivers for this task.

Feedback Height Hold: Pilots indicated that upon first experience with the height hold system for the acceleration/deceleration maneuver that they were hesitant and tentative owing to a feeling of ‘disconnectedness’ with the vertical axis. The lack of manual collective control effectively reduced situational awareness regarding torque margin and proximity to rotor speed limits. This resulted in poor performance acceleration/decelerations initially, until confidence was gained with the system, and a slightly altered piloting technique was adopted. Pilots reported that they were able achieve desired aggressiveness by modulating pitch rates and attitudes during the acceleration portion of the maneuver while monitoring the torque gauge. During the deceleration, instead of looking forward to gauge height errors, pilots spent more time looking through the chin bubble and right window to gauge stop distance and lateral track. During the deceleration, pilots approached or met the rotor speed limit, due to the limited situation awareness regarding the collective control. Pilots expressed initial surprise when they found that height performance was only slightly worse than the hand flown acceleration/decelerations, despite the lack of use of their left hand. The only perceivable height errors were a slight tendency to drop during the acceleration pitch rate, and a tendency to balloon during the deceleration.

Feedback plus Feedforward Height Hold: With the feedforward and feedback height hold system activated, pilots noticed improved height hold performance immediately. There were no perceivable height errors throughout the maneuver, and safety pilots reported that the collective motion resultant from the feedforward plus feedback controller was “pilot-like”. Pilots did mention that there were increased heading errors resulting from collective activity coupling into yaw axis. As was the case with the pure feedback height hold, pilots commented that there was a reduced situational awareness and a feeling of disconnectedness with the aircraft. Pilots found that the best technique for flying the maneuver was to control torque during the acceleration by managing the pitch rate and attitude. They also indicated that increased exposure, experience, and training with the height hold system would make them more comfortable. The increased spare capacity was put to use during the deceleration, allowing the pilots to spend more time looking at the lateral drift and stop distance cues. Pilots mentioned that with the height hold feedback plus feedforward system activated that there was an increased potential to exceed rotorcraft limits given the reduced cueing through the vertical channel.

Figure 9 presents the acceleration/deceleration performance for Pilot 1 in the baseline, and height hold configurations. From the figure it can be seen that the height performance was dramatically improved using the feedback plus feedforward height hold system. With this system activated, the height error was reduced from ±8 feet to approximately ±3 feet. The increased heading errors associated with the loss in torque situational awareness were evident from the heading time history.

Figure 10 presents the acceleration/deceleration performance for Pilot 2 in the baseline, and height hold configurations. As was the case with Pilot 1, there was a readily observable increase in height hold performance with the feedforward plus feedback height hold system verus the baseline and pure feedback cases. Similarly, there were more pronounced variations in heading during the deceleration with the feedforward active versus the baseline case.

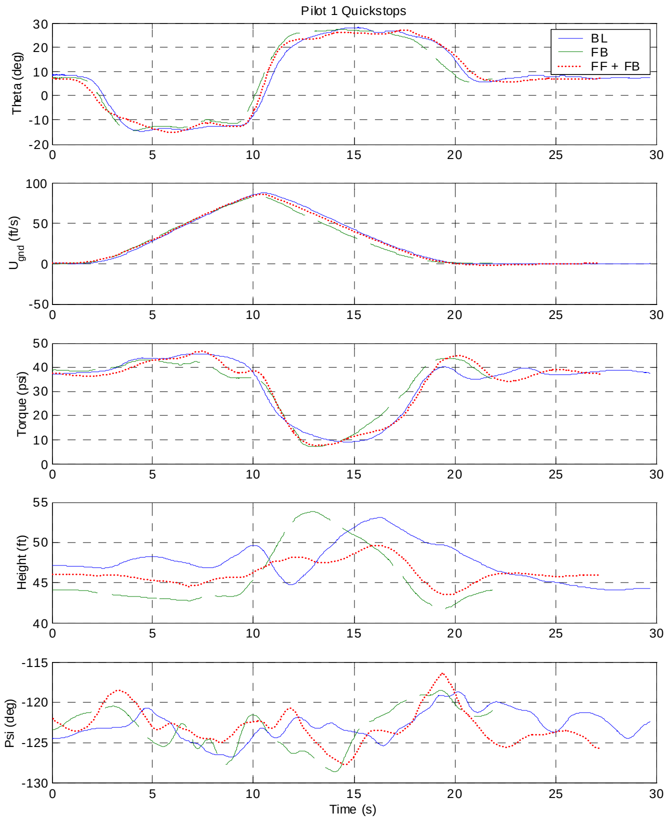

Figure 9: Pilot 1 Acceleration/deceleration

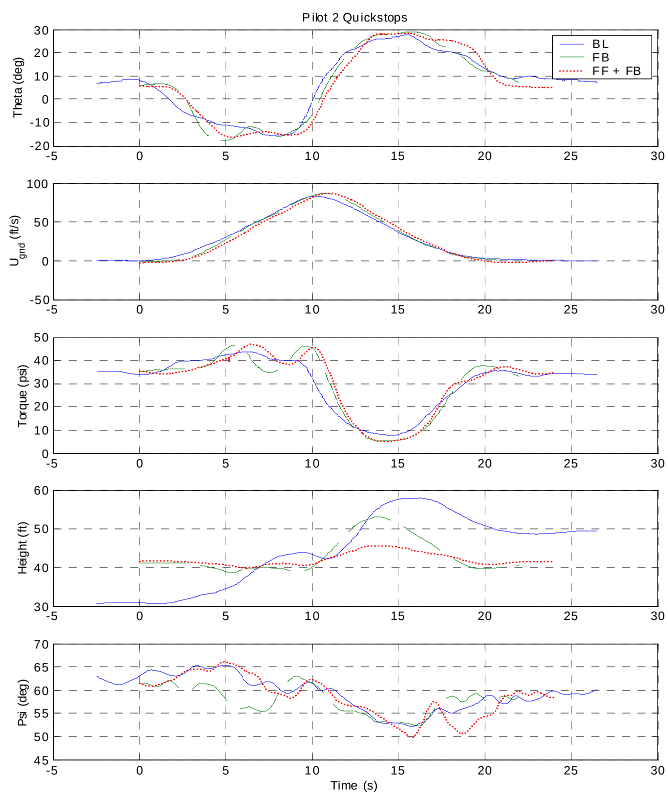

Figure 10: Pilot 2 Acceleration/deceleration

Side steps

Baseline: Pilots reported that the side step was the most difficult maneuver that they were tasked to fly in terms of workload. The primary workload driver was the lateral/directional coupling from the high tail rotor thrust line, and the requirement to manage the collective. There was a tendency to balloon on the stop, coupled with a yaw to the right on the left going side step. Pilots reported that they employed low gain collective control throughout the task, owing to the generous margins implicit in the ADS-33 definition for desired performance in the side step (maintain height within ±10 feet).

Feedback Height Hold: With the feedback height hold selected, the helicopter tended to drift downward slightly on the roll in, which prompted the pilots to be initially less aggressive on the roll out. Pilots commented that as the height was dropping they felt compelled to make collective inputs, reinforcing the feeling of 'disconnectedness' with the aircraft. Height holding performance was reported as slightly worse than for the manually flown baseline case. Slightly less pilot compensation was required throughout the maneuver with the height hold active, allowing the pilots to focus more on tracking performance, and meeting the stop line. This tended to result in more aggressive side steps versus the baseline case. Pilots required more training runs in order to meet the ADS-33 desired criteria with the height hold active, as it required a modified piloting technique due to the lack of torque cueing through the collective controller. The yaw axis was cited as the primary workload driver for this task, particularly at the stops.

Feedback plus Feedforward Height Hold: Both pilots indicated that with the feedforward plus feedback height hold system active they were able to pay more attention to tracking, particularly in the heading axis versus the baseline condition. Height holding performance was improved over both the pure feedback case and the baseline. The improved height holding performance allowed the pilots concentrate on maintaining the desired aggressiveness of the task whereas with the pure feedback case the drop in height during the roll in prompted pilots to be less aggressive. Pilots reported that the yaw axis was the fundamental deficiency with the controller, owing to the high degree of cross coupling. Since the pilots could not anticipate the torque response of the aircraft there were occasional yaw errors due to the drivetrain response to collective inputs made by the height hold system.

Figure 11 presents time histories of the side steps performed by Pilot 1 in the baseline and height hold configurations. From the figure it can be seen that there were pronounced heading errors during the roll out with the pure feedback based height hold active. Additionally, the improved aggressiveness of the side steps can be seen in the velocity trace, with the height hold on cases having a slightly steeper 'V' shape.

Figure 12 presents time histories of the side steps performed by Pilot 2 in the baseline and height hold configurations. As was the case with pilot 1, heading errors during the roll out were seen with the feedback only height hold active. It is believed that this was due to the change in torque required as the collective was used to compensate for the drop in height during the roll into side step maneuver. The feedforward plus feedback height hold case did not exhibit this heading error owing to the smoother collective inputs generated via the feedforward routine. The smoother collective inputs generated less sudden torque response, and thus proved easier for the pilots to predict and control. From the figure it can also be seen that the feedforward plus feedback height hold algorithm offered improved height holding performance versus the baseline and pure feedback cases.

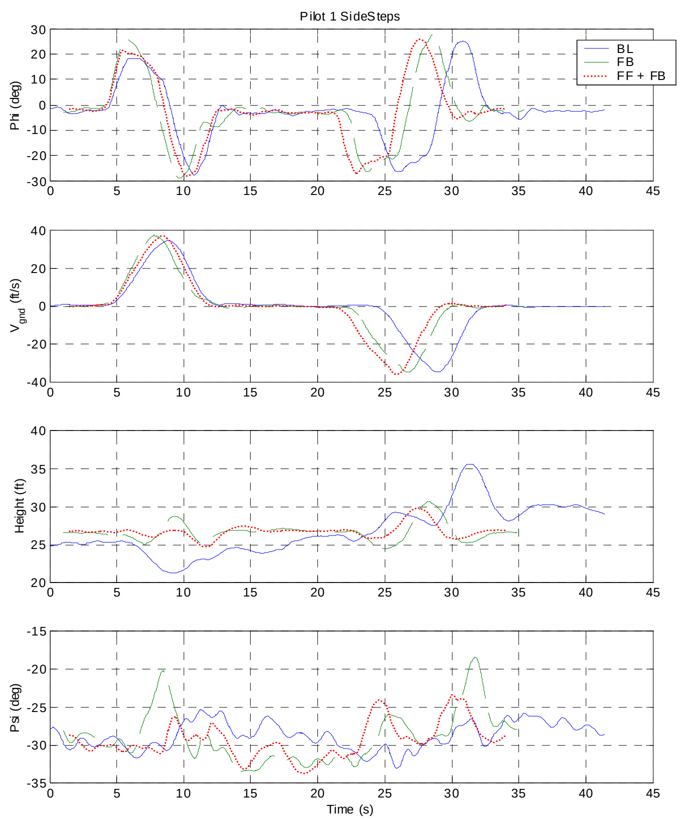

Figure 11: Pilot 1 Side step Performance

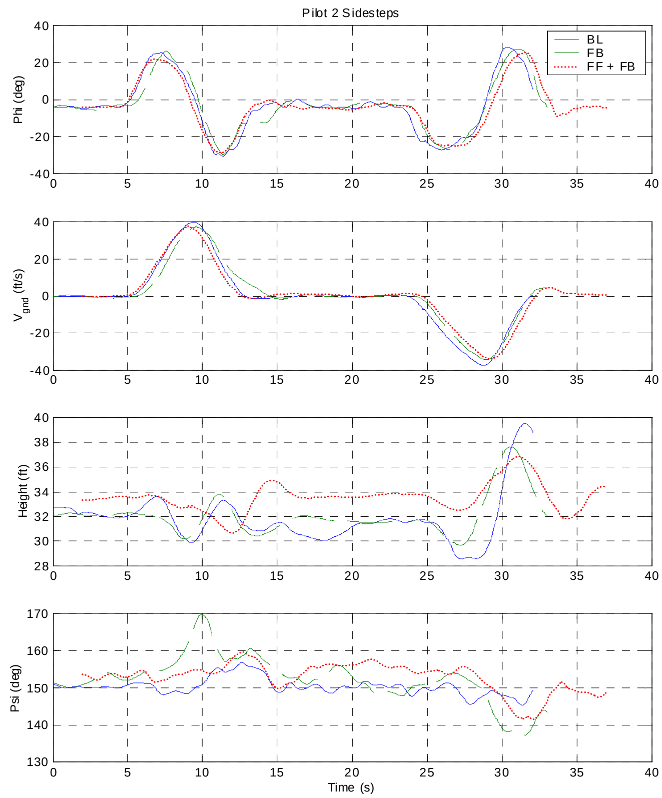

Figure 12: Pilot 2 Side step Performance

<u>Handling Qualities Ratings</u>

Figure 13 presents the handling qualities ratings assigned by Pilot 1 to the various ADS-33 maneuvers flown in the baseline, feedback height hold, and feedback plus feedforward height hold configurations. From the figure it can be seen that for the range of maneuvers, the height hold system provided a noticeable improvement in the handling qualities. The feedback plus feedforward was rated equal with the pure feedback height hold system for the precision maneuvers such as the pirouette, pedal turn, and precision hover. This was not an unexpected result, as the feedforward does not have a significant effect until there are significant velocity and or attitude changes in the aircraft state. Pilot 1 only rated the feedback plus feedforward differently than the pure feedback height hold for the side step maneuver, where the yaw response of the feedforward plus feedback height hold was noticeably better. Improved height hold performance was observed for the acceleration/ deceleration maneuver, however this did not translate into a handling qualities rating improvement due to deficiencies in other axes.

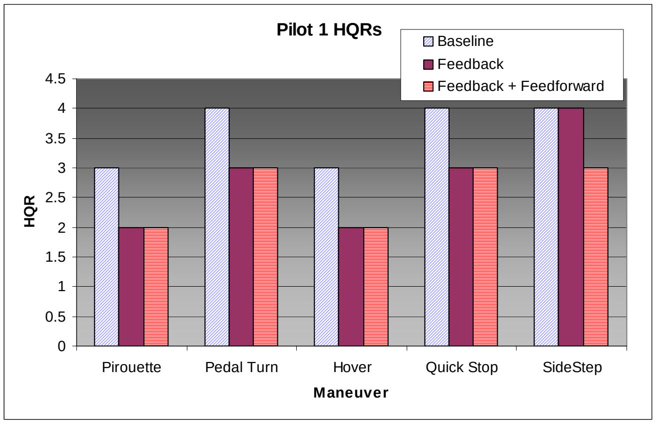

Figure 13: Pilot 1 Handling Qualities Ratings

Figure 14 presents the handling qualities ratings assigned by Pilot 2 for the various ADS-33 maneuvers flown in the baseline, and height hold configurations. The ratings revealed that the feedback plus feedforward height hold system was better than the pure feedback system for the side step maneuver. This was primarily due to the better yaw axis characteristics resulting from the smoother collective motions commanded via the feedforward algorithm. Pilot 2 ranked no difference between height hold systems and baseline configuration for both the pedal turn and acceleration/deceleration, despite commenting on a slightly reduced workload with the height hold active. The reason for the lack of change in rating was that the pilot felt that deficiencies in other axes (particularly yaw and pitch) warranted further improvement.

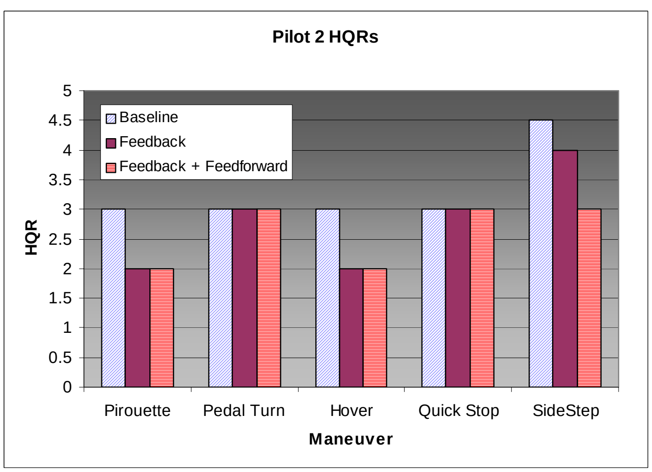

Figure 14: Pilot 2 Handling Qualities Ratings

With the height hold system with feedback and feedforward active, the control system was ranked as Level 1 for all maneuvers performed, versus the borderline Level 1/Level 2 performance achieved using the baseline control system. It is believed that further differences between the baseline and height hold systems would have become evident had testing been performed in degraded visual conditions, as pilots consistently reported that they were attempting to use the added spare capacity afforded to them via the height hold system to better resolve cueing, but handling qualities ratings were limited by performance ceilings in other axes.

Conclusions & Recommendations

Although this study of height hold control laws was limited in scope (no comprehensive test of torque limiting, high altitude, or nap-of-earth flight), and number of test subjects (2), it nevertheless demonstrated the ability of these control laws to reduce pilot workload, improve handling qualities, and improve precision versus manual collective control, even in good visual environments. The performance of the height hold system described in this paper in precision hovering maneuvers was such that RMS height errors were 0.08 to 0.13 feet, whereas manually flown precision hovers had RMS height errors ranging from 0.26 to 0.32 feet. Similar height hold performance improvements were experienced for the aggressive maneuvers, with acceleration/deceleration height hold peak-to-peak errors of ±3 feet with the feedback plus feedforward height hold activated versus ±14 feet for manual control. The addition of feedforward to the height hold system improved performance for the aggressive maneuvers, reducing acceleration/deceleration height errors from ±6 to ±3 feet. Height hold performance during the side-step maneuver was comparable with that of manually flown side steps, but with improved low frequency precision. The handling qualities ratings assigned to the height hold controller schemes demonstrated a 1 HQR improvement for pirouette, hover and side step, and a 0.5 HQR improvement for the pedal turn and acceleration/deceleration. Further improvements in handling qualities ratings were not realized due to deficiencies in other axes, not due to limitations in height hold controller performance.

The use of high accuracy height above ground measurements via complementary filtered laser altimeter and INS/GPS was instrumental in enabling the height hold control laws to employ sufficiently high gains to exceed manually piloted height holding performance. Additionally, the feedforward routines described earlier proved to improve height hold performance during the aggressive ADS-33 maneuvers, and resulted in improved handling qualities ratings for the side step.

A greater number of test subjects would have provided more subjective handling qualities data and comments, however good agreement between the two pilots tested in the investigation demonstrated performance improvements and reduction of workload levels effected by the use of a height hold controller. It is believed that tests in a degraded visual environment would have showed further handling qualities improvements versus the baseline case, as the pilots would be able to make better use of the spare capacity afforded to them by the height hold system to better resolve the available cues.

The test pilots made consistent comments regarding a slight loss of situational awareness with the height hold systems activated. Collective displacement provides tactile cues to the pilot regarding torque, rotor speed, ground effect, and translational lift. Since the height hold algorithms used in this investigation did not require, or allow collective displacements, pilots lost this source of cueing. Pilots suggested that some form of active tactile cueing would be desirable, particularly to prevent overtorque or overspeed conditions. This tactile cueing could be implemented in the collective axis, provided that the collective is configured as a vertical rate command/height hold controller. Such a controller would allow the pilot to adjust height rate via collective displacement, and would maintain height while the controller is in a nominal zero position. This arrangement, coupled with active torque and rotor speed limit cueing, and closed loop maximum torque command capability should provide all the salient benefits of the height hold controllers tested, while allowing the pilots to perform tasks involving vertical rates. This system would require a thorough investigation of engage transients, and suitable flight controls mechanical characteristics. Further developments on this proposed control methodology are expected in the near future.

References

[i] Aeronautical Design Standard, “Handling Qualities Requirements for Military Rotorcraft”, ADS-33E-PRF, U.S. Army Aviation and Missile Command, Aviation Engineering Directorate, Redstone Arsenal, Alabama, March 2000.

[ii] Padfield, G.D., Helicopter Flight Dynamics: The Theory and Application of Flying Qualities and Simulation Modeling, AIAA Education Series, Oxford, U.K., 1996

[iii] Ellis, K., Gubbels, A.W., Dillon, J., “Bell 205 Height hold System Development and Flight Test”, National Research Council Canada, LTR-FR-217, December 2004.

[iv] Press, W.H., Flannery, B.P., Teukolsky, S.A., Vetterling, W.T., Numerical Recipes, Cambridge University Press, 1986.