Evaluation of Limited Authority Attitude Command Architectures for Rotorcraft

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Abstract

Previous work has shown that an attitude-command-attitude-hold with height-hold (ACAH+HH) Response-Type provides significant workload reduction in the degraded visual environment (DVE). That work resulted in a requirement for an ACAH+HH Response-Type in the military rotorcraft flying qualities specification, ADS-33E, for low speed, low altitude flight in degraded visual environments. The supporting data for that requirement is based on tests with full authority flight control systems. The results reported herein indicate that it is possible to achieve most of the workload reduction in the DVE that accrues from a full authority ACAH system, with a limited authority flight control system. Limited authority ACAH was also found to be a significant safety enhancement for brownout encounters.

Background

Research and testing sponsored by the U.S. Army Aeroflightdynamics Directorate has shown that the use of an attitude-command-attitude hold with height-hold (ACAH+HH) stability augmentation system (SAS) is an effective way to compensate for the loss of visual cueing in degraded visual environments (DVE) (see References, 1, 2, and 3).

The results of that work led to the Useable Cue Environment (UCE) scale that sets the requirement for Response-Types in the U.S. Army Rotorcraft Flying Qualities Specification ADS-33E (Reference 4) [1]. Certain tests are specified in ADS-33E to determine the UCE with the vision aids available in the helicopter. If the tests indicate that the UCE = 1, a Rate Response-Type is adequate to achieve Level 1 handling qualities. However, if the tests show that UCE = 2, an ACAH+HH system is necessary to achieve Level 1. As an example, testing has shown that ANVIS-6 Generation II night vision goggles produce a UCE = 1 on a full-moon night, but this degrades to UCE = 2 on a overcast night with no nearby ambient lighting.

The RAH-66 Comanche helicopter is an example of the implementation of the UCE methodology in ADS-33E. The RAH-66 employs selectable SAS modes. When operating in a "good visual environment" (GVE), the baseline Rate mode ("Core AFCS") is employed. If operating in the DVE (e.g., night vision goggles with no moon), an ACAH+HH mode may be selected by the crew.[2]

It is not practical to modify the entire fleet of military helicopters with full authority fly-by-wire SAS to achieve a selectable ACAH+HH mode. One potential alternative is to use a

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[1] The concept of Response-Type as used in ADS-33E is given in Reference 3. In brief, the Response-Type essentially defines the shape of the response to a pilot input. For a Rate Response-Type, the attitude response to a step stick input is a ramp and for an ACAH Response-Type, the response to a step input would be a constant attitude.

[2] The RAH-66 employs a VELSTAB mode that provides Attitude Command Velocity Hold, which meets the requirements for an ACAH+HH Response-Type in ADS-33E.

limited or partial authority SAS to achieve the benefits of ACAH. The advantage of the limited authority SAS is that it is not necessary to provide a multiply redundant fail-operational system. By limiting the series servo to 10% of full authority, it is possible to safely cope with a hardover failure, and hence a single or dual (fail passive) SAS is possible.

Over the past 12 years, the U.S. Army Aeroflightdynamics Directorate has sponsored and accomplished a number of flight tests and simulations (NASA Ames Vertical Motion Simulator or VMS) to investigate ways to achieve the benefits that accrue from a full authority ACAH system using a limited authority implementation. This work was initiated with two VMS simulations that were followed by a series of flight tests using the Canadian Institute of Aeronautical Research/National Research Council (IAR/NRC) variable stability Bell 205. The flight test results have been documented in References 5, and 6. The flight-test results reported in this paper are documented in greater detail in Reference 5.

The results of a VMS simulation intended to extend certain of the Reference 5 flight test results is reported in Reference 7. The flight test and simulation results of References 5 and 7 are generally referred to as the Limited Authority SCAS or LASCAS work.

The results of another VMS simulation to investigate the concept of frequency response matching to minimize the transients associated with limited authority SAS saturation are given in Reference 8. This work is referred to as Partial Authority Flight Control Augmentation (PAFCA).

The objective of this paper is to present an overview of the research on limited authority flight control systems to date, with emphasis on the flight test results from Reference 5.

While this paper is focused entirely on using stability augmentation to improve handling qualities in the DVE, it is important to note that an alternate solution exists. That solution would be to employ improved displays that result in UCE = 1 in the DVE (e.g., on a moonless overcast night). One drawback of this approach is that such a vision aid would probably not be able to maintain UCE = 1 in certain situations. For example, experience has shown that the loss of visibility due to recirculation of sand or snow due to rotor-wash can lead to accidents (referred to as a “brownout” when operating over sand or dust). This phenomenon was simulated during the Reference 5 flight tests, and it was shown that ACAH stability augmentation was highly beneficial for improving safety in brownout conditions. This was even true if the augmentation was limited in authority

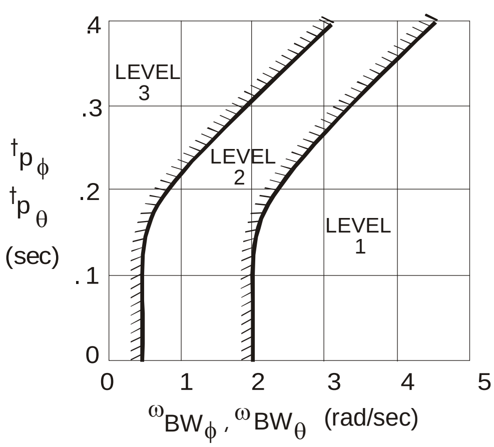
Requirement for Limited Authority ACAH

The primary requirement for the limited or partial authority ACAH+HH SAS, is to achieve an attitude-command-attitude-hold (ACAH) Response-Type without incurring the cost of a multiply-redundant, full-authority flight control system. To make sense of the data, it is important to understand the fundamental reasons that ACAH provides workload relief in the degraded visual environment (DVE), and to identify specifically what features of ACAH must be present to accomplish the reduction in workload (e.g., Reference 1) and enhancement to safety (Reference 9).

The hover task for a normal helicopter is an acquired skill that takes considerable practice. However, if an attitude-command-attitude-hold Response-Type is implemented, this difficult task can be accomplished quite easily by even novice pilots. The reason is that a stable hover requires that the pilot close a very accurate attitude loop, in addition to a translational velocity loop. The ACAH system eliminates the need for the attitude loop closure, thereby lowering pilot workload significantly. The translational velocity loop can be closed at much lower frequency (akin to following the vehicle ahead in an automobile). This is discussed in detail in Section 3.2.7 of the Background Information and User Guide (Reference 3) for ADS-33E, the U.S. Army Rotorcraft Flying Qualities Specification (Reference 4) and in Reference 9.

When fine-grained texture is removed from the field-of-view, it becomes very difficult for even experienced pilots to close the necessary attitude loop. Without fine-grained texture, it is difficult to distinguish between a small change in attitude and a small change in translational rate. Therefore, ACAH augmentation is especially valuable when fine-grained texture cues are absent. This occurs in most simulator visual scenes and with vision aids (e.g., night vision goggles (NVGs) and forward looking infrared (FLIR)). These devices are generally adequate in optimal conditions (e.g., moonlit night for NVGs), but the fine-grained texture cues degrade rapidly under degraded visual environments, such as an overcast night for NVGs or cold soak for FLIR. This is discussed in References 1 and 2, and is the basis for the Useable Cue Environment (UCE) requirements on Response Type in ADS-33E.

A considerable amount of flight-testing in support of ADS-33E was accomplished, prior to this limited authority study, by the U.S. Army in cooperation with the Canadian Institute of Aeronautical Research/National Research Council, using the Variable Stability Bell 205. Much of this testing was to identify the improvement in handling qualities that accrues from ACAH, and the specific characteristics of ACAH that are necessary to achieve Level 1 flying qualities in the DVE. Most of those results are published in Reference 3. For ACAH Response-Types, it was found that Level 1 flying qualities in the DVE required a Bandwidth (ω_{BW}) of 2 (see Figure 1).



e) All Other MTEs - UCE > 1 and/or Divided Attention Operations (pitch and roll)

Figure 1 Bandwidth Requirement from ADS-33E for Flight in the DVE

To summarize, the objective of limited authority ACAH systems is to achieve Level 1 flying qualities in the DVE. To accomplish that, the following conditions must be met.

- The system must meet the requirements for an ACAH Response-Type in ADS-33E.
- The system must have Level 1 Bandwidth in the pitch and roll axes (2 rad/sec).

Limited Authority Control Law Architectures

A schematic of a typical helicopter stability augmentation system is shown in Figure 2.

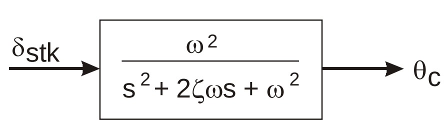
The feedback to the series servo is typically angular rate, a signal that tends to be of relatively small amplitude. As a result, the series servo is not prone to saturation, even though it is limited to 10% of travel for hardover protection. The parallel servo is used exclusively to allow the pilot to trim the aircraft. It is rate-limited to 10%/sec to minimize the effect of a trim runaway.

The most obvious architecture to modify the Figure 2 SAS and achieve an ACAH Response-Type is to add attitude feedback to the series servo. Such a system is illustrated in Figure 3.

As long as the pitch attitude is small, this system will exhibit identical responses as a full authority SAS. However, when the series servo saturates, the response dynamics revert to the unaugmented helicopter.

This can also be mechanized as a model following system, such as used in Reference 8, as shown in Figure 4.

Since the objective is to achieve ACAH, the simplest form of the "model" in the Figure 4 system would be as follows.



The break frequency of the model is nominally set to the Level 1 Bandwidth required by ADS-33E or 2 rad/sec. As shown in Reference 8, it is possible to further refine this model by adding additional equalization, such as a lag-lead network. This can be optimized to minimize the tendency to saturate the system as shown in Reference 8.

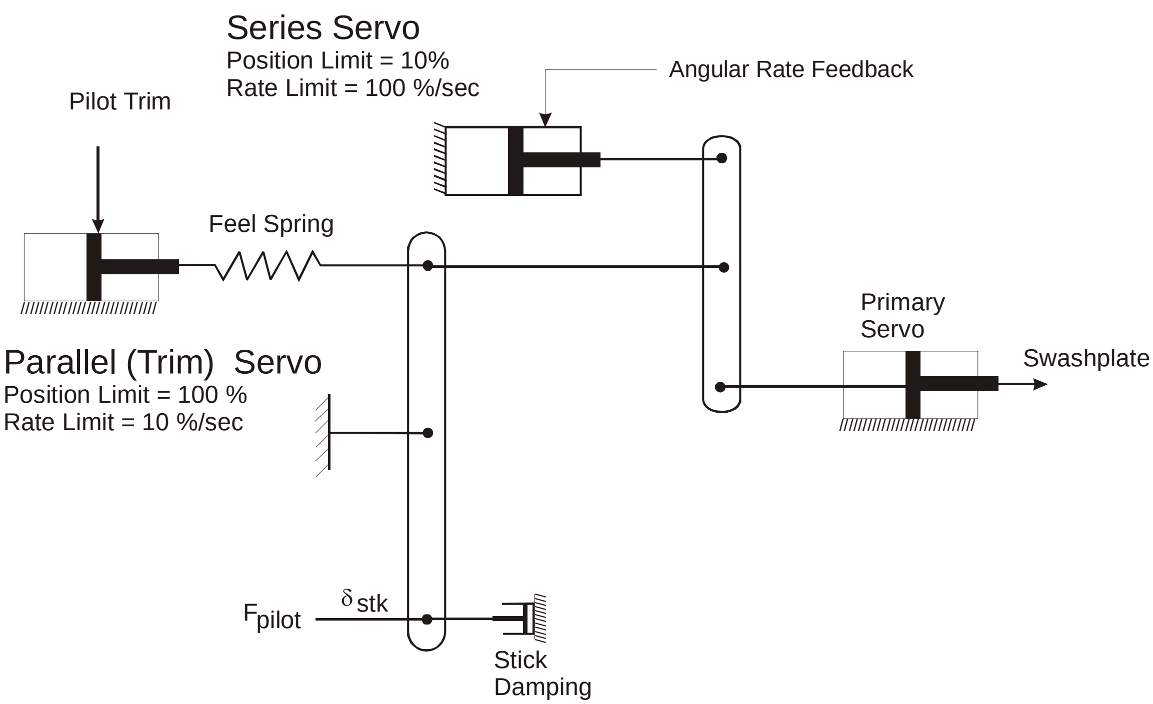


Figure 2 Schematic of Typical Helicopter Stability Augmentation System

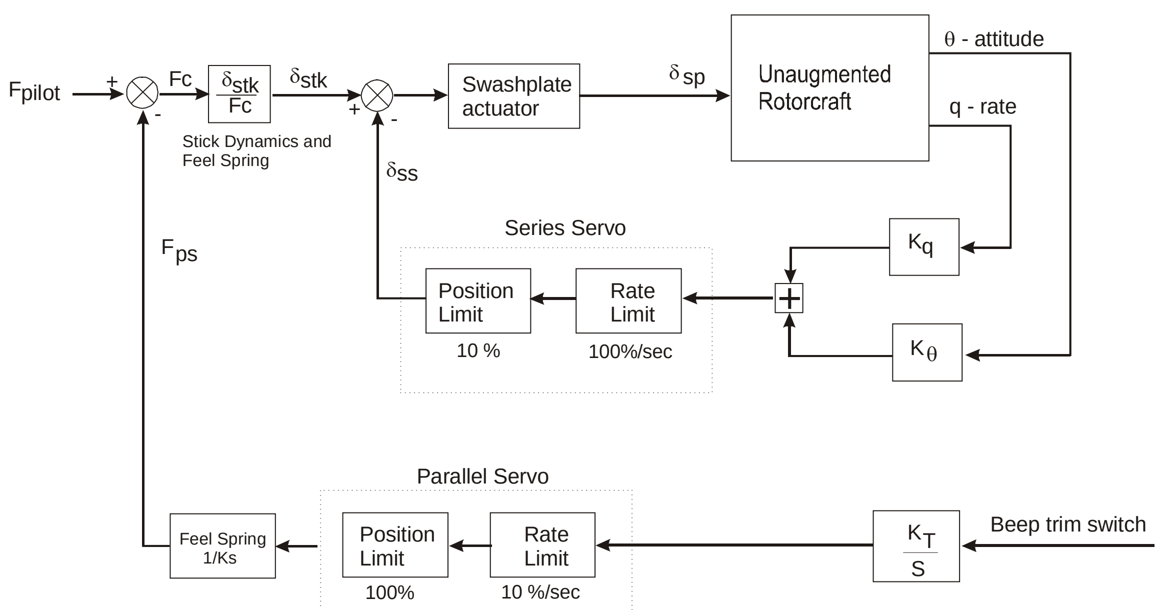


Figure 3 Limited Authority SAS Using Series Servo

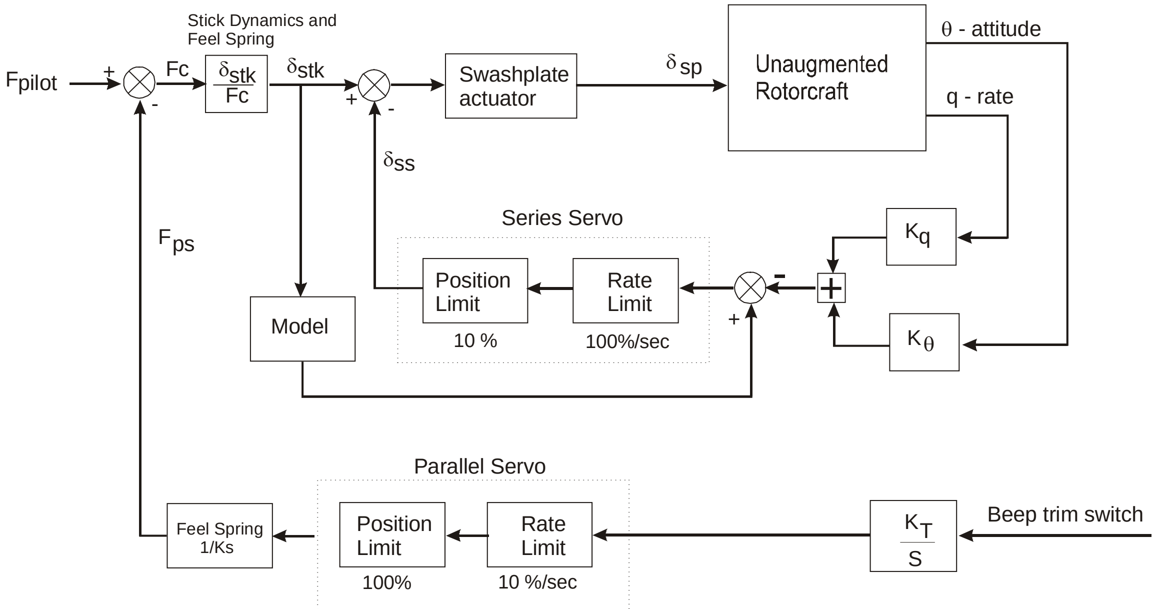


Figure 4 Limited Authority SAS with Model Following Implementation

A brief comparison of Response-Feedback vs. Model Following on the VMS simulator (in support of the Reference 5 flight tests) showed that both systems were saturated for the same amount of time for the Accel/Decel and Sidestep maneuvers. The pilot ratings and comments for each type of augmentation were essentially the same. Reducing the break frequency of the model results in less saturation, but has the negative effect of reducing the Bandwidth, and hence the pilot ratings to below Level 1.

One approach to minimizing the time that the series servo is saturated is to utilize the parallel trim servo as part of the SAS. In this approach the attitude feedback is split between the series and parallel servos. This "Split-Path" augmentation is illustrated in Figure 5.

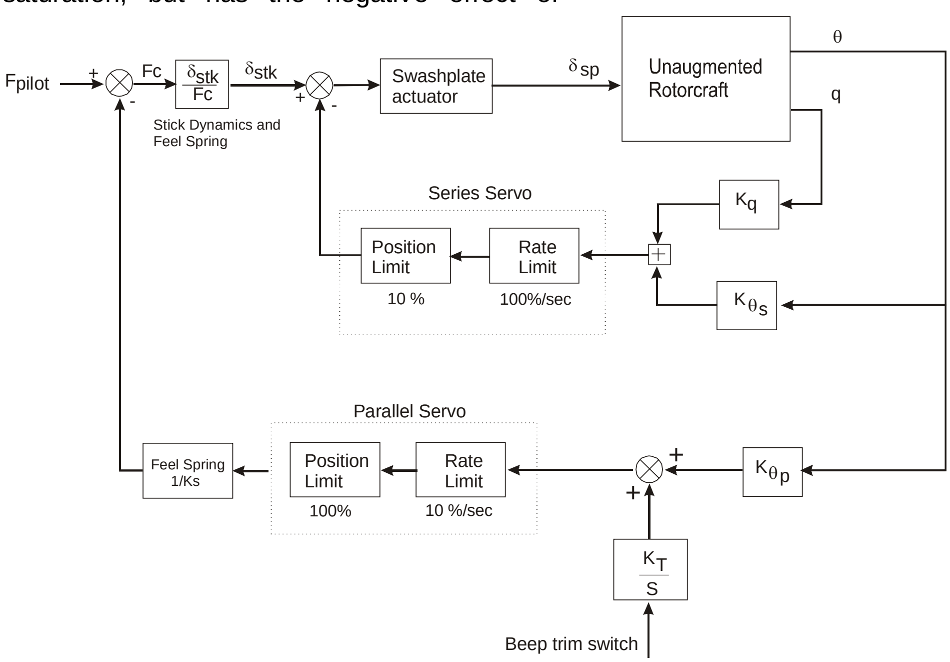


Figure 5 Split-Path (SP) Architecture for Limited Authority ACAH

The concept for this architecture is that the higher frequency pitch-rate signal is passed through the series servo, while a portion of the lower frequency attitude signal is passed through the parallel servo. This offloads the series servo, resulting in less time in saturation. A potential drawback is that the parallel servo is rate limited to approximately 10%/sec, so there is some danger of encountering rate limiting of this path for large amplitude maneuvers.

As long as the series and parallel servos are not saturated, the response of the Split-Path system is identical to the pure Series servo solution (Figure 3). The caveat being that the pilot must allow the stick to move to achieve the advantages of the feedback through the parallel servo. This requires a light touch on the controls.

The Split-Path Architecture would be particularly valuable for helicopters that are highly cross-coupled. For example, in Reference 8 (PAFCA simulation of UH-60 using only series servo), it was noted that the series pitch actuator was saturated during sidesteps, primarily due to the large pitch inputs required to offset coupling during lateral translation. This resulted in pilot ratings in the DVE (average HQR $\approx$ 5) that were no better than with a Rate Response-Type for the Sidestep task. With the Split-Path architecture, the need for longitudinal stick during the sidestep maneuver is automatically handled by the parallel servo. The Reference 7 simulation of Split-Path architecture used the same UH-60 aero model as Reference 8, and series servo saturation was not noted to be a problem during the Sidestep maneuver (average HQR between 3.5 and 4). This is discussed further in the Results section of this paper (Figure 14).

During flight-test development of the Split-Path configurations with the variable stability Bell 205, it was noted that having the system move in and out of saturation while accomplishing the Pirouette maneuver was undesirable. This was most noticeable in a moderate wind, where significant pitch attitude changes were required as the heading changed around the circle. An attitude blend-out function was implemented to minimize the effect of saturation as shown in Figure 6.

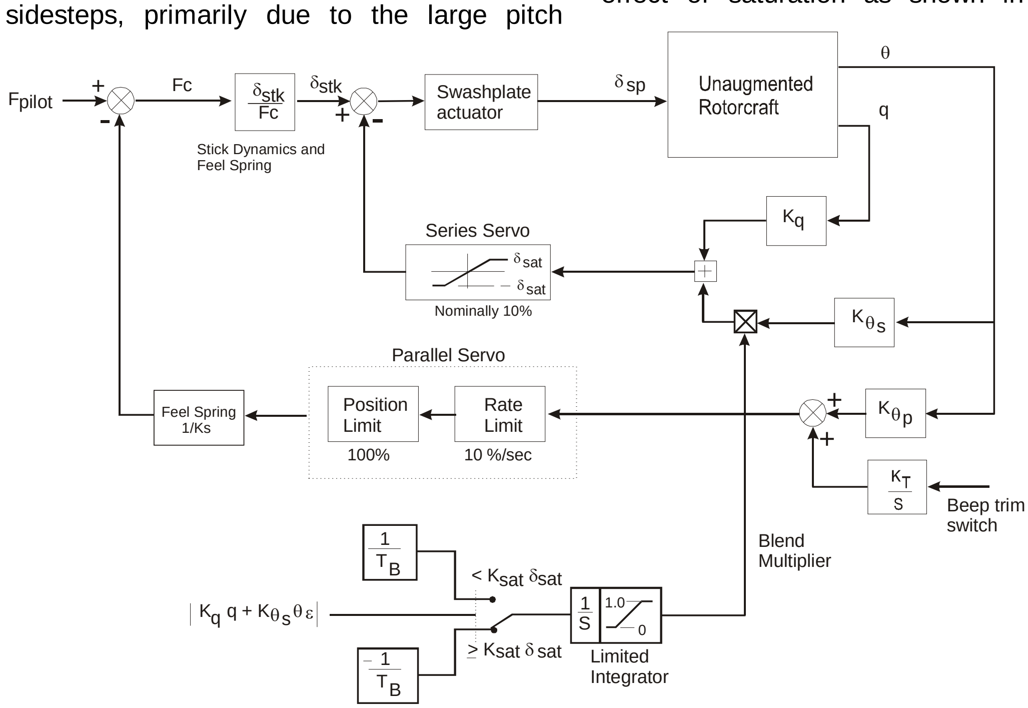


Figure 6 Split-Path Architecture with Blend-Out Function

The blend-out function caused the pitch and roll attitude signals to the series servos to blend out just prior to saturation (start blend-out when input to series servo was 80% of saturation by setting K_{SAT} = 0.80). The advantage of this was that series servo saturation was of shorter duration, and the pitch-rate feedback remained functional most of the time. The net effect of the blend function is to substitute a transition from Attitude augmentation to Rate augmentation in lieu of saturation. Variations in blend time (T_B) showed that the transition was too abrupt at 1 second, and essentially un-noticeable for 5 seconds. A 5 second blend time was used for all formal evaluations.

Another approach to achieving a limited authority SAS is to split the path between the series and parallel servo according to frequency content. The low frequency, large amplitude portion of the signal is routed to the parallel servo, and the high frequency, low amplitude portion to the series servo. This results in a classical complementary filter, and hence this architecture is referred to as the CF configuration. A block diagram of the CF architecture is shown in Figure 7.

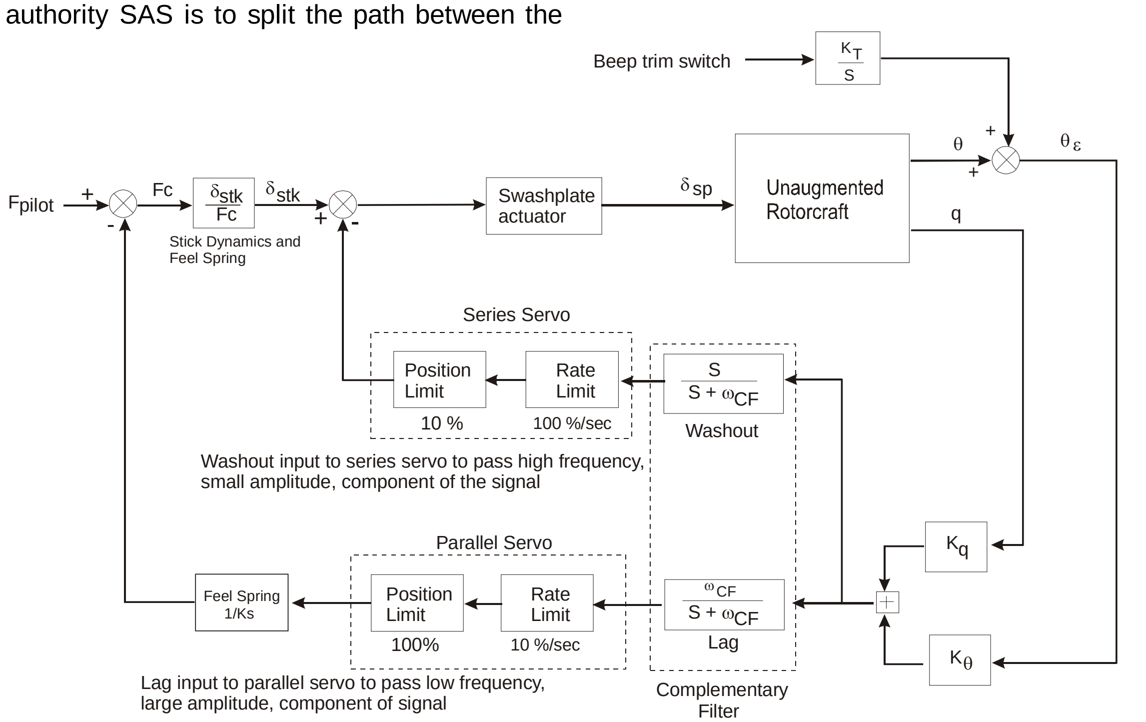


Figure 7 Complementary Filter (CF) Architecture

As will be shown in the Results section of this report, the pilot ratings and commentary for the CF system were not favorable.

The following abbreviations have been adopted to enhance the discussion of results in testing the SAS architectures presented above.

SP0 = All of feedback is through the series servo (Figure 3).

SP1 = Split-Path Augmentation with most of the attitude signal through the series servo, $K_{\theta p}/K_{\theta s}$ = 0.37 in the Reference 5 tests (Figure 5).

SP2 = Split-Path Augmentation with most of the attitude signal through the parallel servo, $K_{\theta p}/K_{\theta s}$ = 10 in the Reference 5 tests (Figure 5).

SP1b = SP1 with blend-out of attitude (Figure 6)

SP1A = $K_{\theta p}/K_{\theta s}$ = 3.0 (Figure 5, and Reference 8)

SP4B = $K_{\theta p}/K_{\theta s}$ = infinity (Figure 5 and Reference 8)

CF = Complementary Filter architecture (Figure 7)

Description of Flight Tests

The flight tests were conducted in Ottawa Canada using the IAR/NRC variable stability

Bell 205. This facility is described in detail in Reference 6.

The details of the flight test program are presented in Reference 5, including a description of the configuration dynamics, flight test maneuvers, and feel system characteristics. The flight test maneuvers (Precision Hover, Pirouette, Acceleration/Deceleration, and Sidestep) were very close to those specified in ADS-33E (Reference 4).

With the exception of SP0 with model following, all of the flight control system architectures presented above were tested on the IAR/NRC variable stability Bell 205. The feedback gains were adjusted to achieve the following Bandwidths.

	Pitch	Roll
Bandwidth (rad/sec)	2.8	4.5
Phase Delay (sec)	0.18	0.18

A comparison with these values with the Figure 1 boundaries shows that these Bandwidths are well above the minimum required for Level 1 in ADS-33E. In practice, it would be wise to minimize the gains to just barely meet the Bandwidth requirement. This increases the saturation attitude (small $K_{\theta s}$), and minimizes the transient at saturation (Reference 8).

The authority of the series servo was an experimental variable in the Reference 5 flight tests. The magnitude of saturation was specified in terms of the attitude that would cause series servo saturation with zero angular rate (θ_{sat}). This was done so that the results would not be tied to a specific hardware mechanization (e.g., pitch sensitivity, $M_{\delta B}$, and series servo authority). Saturation values of 2.5, 5, and 10 degrees of pitch and roll attitude were tested. These values were always equal for pitch and roll. Using this experimental methodology, the attitude feedback gain, ($K_{\theta s}$) determines where the "effective series servo" saturates, $\delta_{sat} = \theta_{sat} K_{\theta s}$.

For the simulated unaugmented aircraft, the "effective series servo" saturation corresponding to the tested values of θ_{sat} of 2.5 and 10 degrees would be 6.25% and 25% respectively. For a typical series servo with saturation at ±10%, θ_{sat} = ±4 degrees. Hence the data for θ_{sat} = 2.5 degrees is consistent with a more restricted series servo, and the data for θ_{sat} = ±10 degrees is representative of an unrealistically high series servo limit, unless the feedback gain, $K_{\theta s}$, is small. This case is covered by configuration SP2, where most of the attitude gain is passed through the parallel servo.

The variable stability Bell 205 flight-testing was conducted in two phases. Configurations Rate, SP0, SP1, and SP2 were tested in Phase 1 by pilots M, H, Y, and B. Phase 2 focused on optimizing SP1, resulting in configuration SP1b and included pilots V, L, and B (pilot B participated in both phases). In addition to testing in the DVE (UCE=2), a brownout was randomly introduced during the Phase 2 evaluations. This caused the visibility to go to 50 ft as the helicopter approached hover. The evaluation pilot did not have any warning of when a brownout might occur.

Simulation of the degraded visual environment was accomplished by means of a night vision goggle (NVG) simulator that attached to the pilot's helmet in similar fashion to ANVIS-6 NVGs. This device, manufactured by Vision Technologies, Inc., provided a realistic NVG scene that was adjusted to be consistent with an overcast night with no external illumination (i.e., UCE=2). Brownout was simulated by programming the NVG simulator to reduce visibility to less than 50 ft. as a function of altitude, when approaching hover.

The Level 1 Rate configuration was re-evaluated in Phase 2 to ensure that the baseline did not change, and to provide a comparison for the evaluation pilots that did not participate in Phase 1.

Flight Test Results – Full Authority ACAH

As noted above, the flight tests were accomplished on the IAR/NRC variable stability Bell 205. In addition to the limited authority ACAH systems discussed above, two types of Rate systems were simulated. The lowest level of Rate system was designed to represent the unaugmented UH-60. These are the dynamics represented by the block labeled "Unaugmented Rotorcraft" in the block diagrams in Figures 3 through 7. A comparison of these dynamics with ADS-33E showed them to be Level 2. This was confirmed through initial flight tests where Level 2 Cooper-Harper Handling Qualities Ratings (Reference 10) were obtained in the good visual environment (GVE) (average HQR = 4).

A Level 1 Rate system was also simulated. This was done to establish baseline pilot workload when operating in the good visual environment (GVE), and the degraded visual environment (DVE). This Rate Response-Type was designed to meet the Level 1 criteria (e.g., Bandwidth) in ADS-33E. The pilot rating results for this rate system are given in Figure 8.

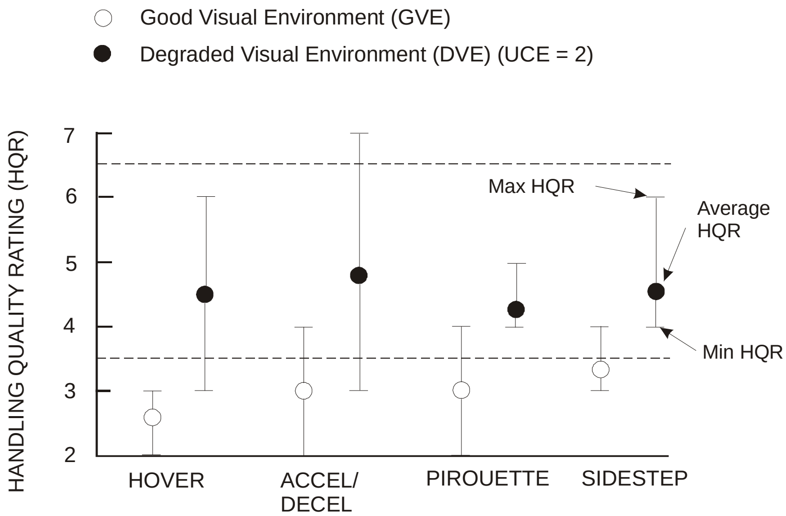


Figure 8. Handling Qualities Ratings for Rate Response-Type with Level 1 Bandwidth in Go and Degraded Visual Environments.

The Figure 8 results indicate that the baseline Rate system is desirable (Level 1) in the GVE but is mid-Level 2 for the DVE. This is consistent with past testing as reported in References (1,2, and 3).

The objective of the ACAH Response-Type is to achieve Level 1 in the DVE (UCE = 2). Note that this requires only a moderate improvement in the mean HQR from between 4 and 5 to better than 3.5. Also, it would be desirable to reduce the spread in ratings, which is also a measure of handling qualities problems. It was previously determined that height hold (HH) was required in addition to ACAH to achieve that result (References 1, 2, and 3). A comparison of handling qualities ratings (HQRs) between Rate and full authority ACAH+HH Response-Types for several tasks in the simulated UCE = 2 degraded visual environment is shown in Figure 9.

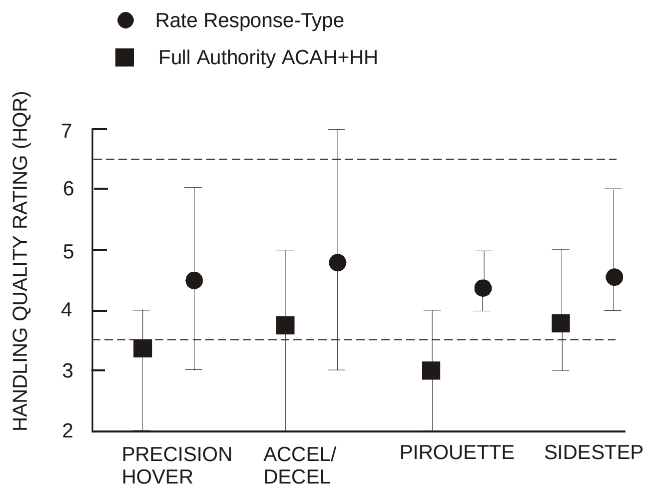


Figure 9 Comparison Between Rate and RCAH+HH in the DVE

The data in Figure 9 indicate that the combination of ACAH and HH (square symbols) comes very close to achieving the desired 3.5 average HQR, albeit the rating spread is still larger than desired for the Accel/Decel maneuver.

While ACAH is highly suitable for operation in the DVE, or for operations where the pilot must divide his or her attention away from flying for a significant portion of time, it is not ideal for aggressive maneuvering in the GVE. The Reference 5 tests showed that the ACAH Response Type was Level 2 (average HQR = 4.5) for the Accel/Decel maneuver in the GVE and that Rate was more desirable than ACAH for the Precision Hover task in the GVE (both Rate and ACAH were Level 1).

Pilot's like the agility that accompanies a Rate Response-Type, and do not like the sluggish response inherent to the ACAH Response-Type when flying in good visibility. This sluggishness is not apparent in the DVE, where the flying strategy is inherently more benign. This is accounted for in ADS-33E in the Attitude Quickness criterion[1] (Paragraph 3.3.3) that includes the following caveat. "It is not necessary to meet this requirement for Response-Types that are designed as applicable only to UCE = 2 or 3", i.e., in the DVE. This indicates a need for selectable modes; Rate in the GVE and ACAH+HH in the DVE, if the helicopter missions require aggressive maneuvering (most military helicopters).

The need for Height Hold with ACAH is shown in Figure 10.

These data indicate that the primary benefit of Height Hold is for moderate maneuvering, i.e., it is not required for Hover.

Flight tests accomplished to determine the effectiveness of height hold without ACAH showed little or no advantage over a pure Rate Response-Type (Reference 5).

Flight Test and Simulation Results – Limited Authority ACAH+HH

Configuration SP0 and SP1 (θsat=2.5 deg)

The handling qualities ratings (HQRs) for configuration SP0 (Figure 3) and SP1 (Figure 5) are compared with the Rate system in Figure11.

Configuration SP0 exhibits an improvement over the Rate system for all tasks except the Sidestep. This is consistent with the VMS simulation results for the PAFCA project (Reference 8) where the Sidestep maneuver was rated Level 2 (avg HQR$\approx$5). As noted above, there tends to be significant pitch coupling during lateral translation that saturates the pitch series servo. Adding a parallel path provides a means to offload the

[1] The "Attitude Quickness" or Moderate Amplitude criterion in ADS-33 is intended to ensure Level 1 handling qualities for aggressive maneuvering.

series servo. This is evidenced by the improved ratings for SP1 on the Sidestep maneuver.

It is clear that some signal to the parallel servo is desirable for the Pirouette and Accel/Decel maneuvers as well (e.g., configuration SP1 is a clear improvement over SP0). The pilots indicated that they did not notice the stick motions associated with the parallel servo feedback with the SP1 architecture ($K_{\theta p} / K_{\theta s}$ = 0.37).

Attitude Blend-out; Configuration SP1b (Phase 2 Flight Test Results)

The Split-Path with Blend-out architecture (Figure 6) results are shown in Figure 12. These results were obtained during the Phase 2 flight-tests. The saturation attitude for these cases was 5 degrees, compared to 2.5 degrees for the Figure 11 results.

The improvement due to the attitude blend-out function was definitely noticeable by the pilots on a back-to-back comparison with and without blend. The formal pilot rating results in Figure 12 show that SP1b resulted in an improvement in workload over the Rate system. Surprisingly, the SP1b HQRs are slightly degraded when compared to SP1 (without blend) in the Phase 1 flight tests (Figure 11). That discrepancy is attributable to the wind, turbulence, and rain conditions encountered during most of the Phase 2 testing - winds averaged 15 kts with gusts to 25 kts. By comparison, the winds during Phase 1 were typically 10 to 15 kts. In addition, the water on the windscreen sometimes degraded the visual cue environment. A check of the UCE with rain on the windscreen and flat light showed that it increased from 2 to 3. A brief evaluation of the full authority system in these conditions produced essentially the same HQRs as SP1b for all tasks.

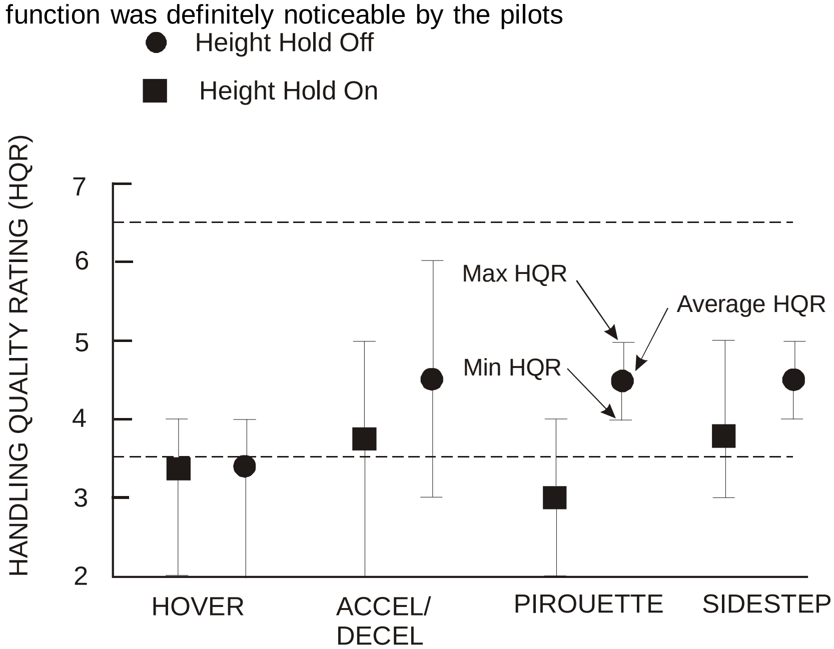


Figure 10 Effect of Height Hold with ACAH Stability Augmentation

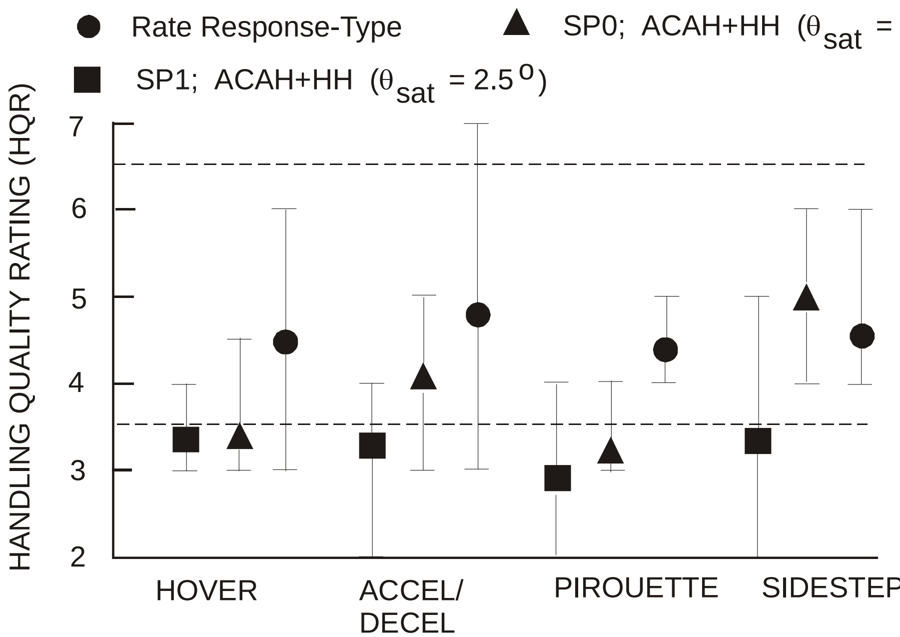


Figure 11 Comparison of HQRs for Rate, SP0 and SP1

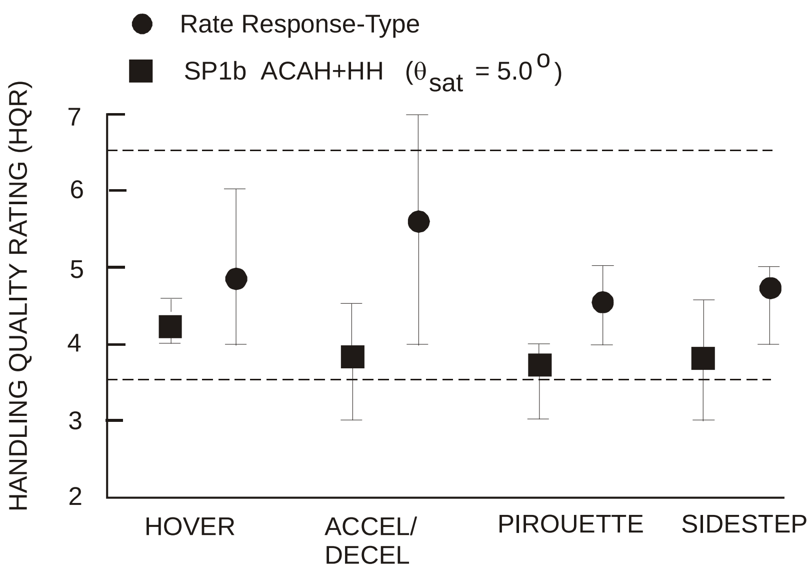


Figure 12 Comparison Between Rate and Split-Path with Blend out.

To put this in context, Level 2 HQRs are expected for ACAH+HH in UCE = 3 (see References 1 through 4).

The overall pilot comments for the DVE and the brownout indicated a consistent opinion that the limited authority ACAH using the SP1b architecture was a significant enhancement.

Effect of Series Servo Saturation for Configuration SP0

The series servo saturation level was systematically varied to determine its effect on pilot opinion. Configuration SP0 was used so that signals through the parallel actuator were not a factor ($K_{\theta p} / K_{\theta s} = 0$). A plot of the average HQRs for each task at four levels of saturation is given in Figure 13.

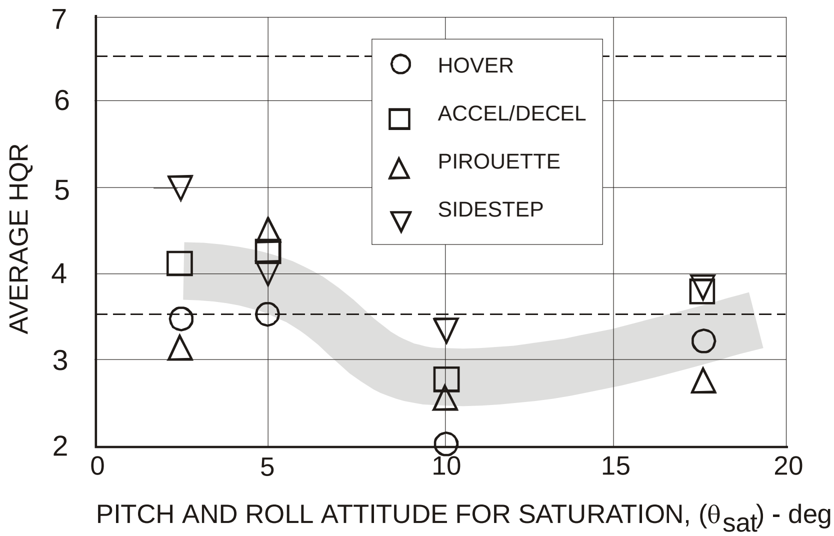


Figure 13 Effect of Series Servo Saturation on Handling Qualities Ratings (SP0), UCE=2

These data indicate little sensitivity to saturation level between 2.5 and 5 degrees, and a reasonably well defined improvement in pilot opinion at 10 degrees. The ratings at 16.5 degrees are for the full authority system and reflect the fact that full stick resulted in that level of pitch attitude. Technically, this is not saturation, but the ratings are shown to illustrate the fact that some series servo saturation was actually found to be desirable.

The fact that 10 degrees of saturation was rated better than full authority may be explained by the fact that the pilots considered series servo saturation an enhancing feature for the aggressive tasks (Accel/Decel and Sidestep). The explanation for this is that with the series servo saturated, the effective dynamics revert to the unaugmented aircraft, which is highly maneuverable, albeit, less stable. Recall that the lack of maneuverability was the primary drawback of ACAH. This deficiency is most obvious in the GVE, but clearly has some impact in the DVE, based on pilot comments that they liked saturation at large attitudes.

The unaugmented aircraft simulated in this flight test was Level 2, but was not severely unstable. Saturation would be more critical if the unaugmented dynamics were highly unstable. However, the SP1b architecture could be used to advantage in that situation since the rate feedback remains intact as the attitude is blended out.

These results suggest that the transition from ACAH to unaugmented dynamics at moderate-to-large pitch attitudes represented a switch from attitude command to "rate" at an ideal time (during the non-precision portion of the maneuver). This might indicate that the Response-Feedback augmentation (Figure 3) is more suitable than Model-Following (Figure 4) as the latter tends to saturate during the initiation and termination of an aggressive maneuver (when the commanded attitude differs significantly from the actual attitude) as opposed to the large attitude portion.

Split-Path Architecture - Effect of $K_{\theta p} / K_{\theta s}$

Using the Split-Path architecture, it is possible to increase the attitude where saturation occurs, by decreasing the gain on the series servo, $K_{\theta s}$, and making up the difference by increasing the attitude feedback gain on the parallel servo, $K_{\theta p}$. The price for this is that the cyclic stick becomes more active because the parallel servo is attached directly to it through the feel spring (Figure 2). The effect of varying $K_{\theta p} / K_{\theta s}$ was studied in the flight-tests of Reference 5, and extended in the VMS simulation of Reference 8. Those results are summarized in Figure 14. They indicate the following:

- Smaller values of parallel servo gain are better accepted by the pilots for the precision hover task.
- Higher values of parallel servo gain are beneficial for the Sidestep.
- $K_{\theta p} / K_{\theta s}$ = 0.37 appears to be the best compromise for all tasks.
- The Split-Path architecture provides a clear benefit over systems that only implement the series servo for the Sidestep and Accel/Decel tasks

The most notable feature of the Split-Path configurations is that the cyclic stick moves considerably during aggressive maneuvering, especially with higher gain on the parallel servo. This means that it is extremely important that the pilot use a light touch on the controls to allow the parallel servo to provide the necessary augmentation. A consequence of this is that the pilot ratings tend to be somewhat dependent on pilot technique. For example for SP2 ($K_{\theta p} / K_{\theta s}$ = 10), Pilot Y gave HQRs of 2 and 3 for all maneuvers, whereas Pilot H gave HQRs of 4 for the same maneuvers. The comments by pilots Y and H are summarized in Table 1, and indicate that H objected to the stick motion and Y did not. A review of the time histories showed that pilot H was considerably more aggressive than pilot Y.

There were no comments related to uncommanded stick activity with $K_{\theta p} / K_{\theta s}$ = 0.37.

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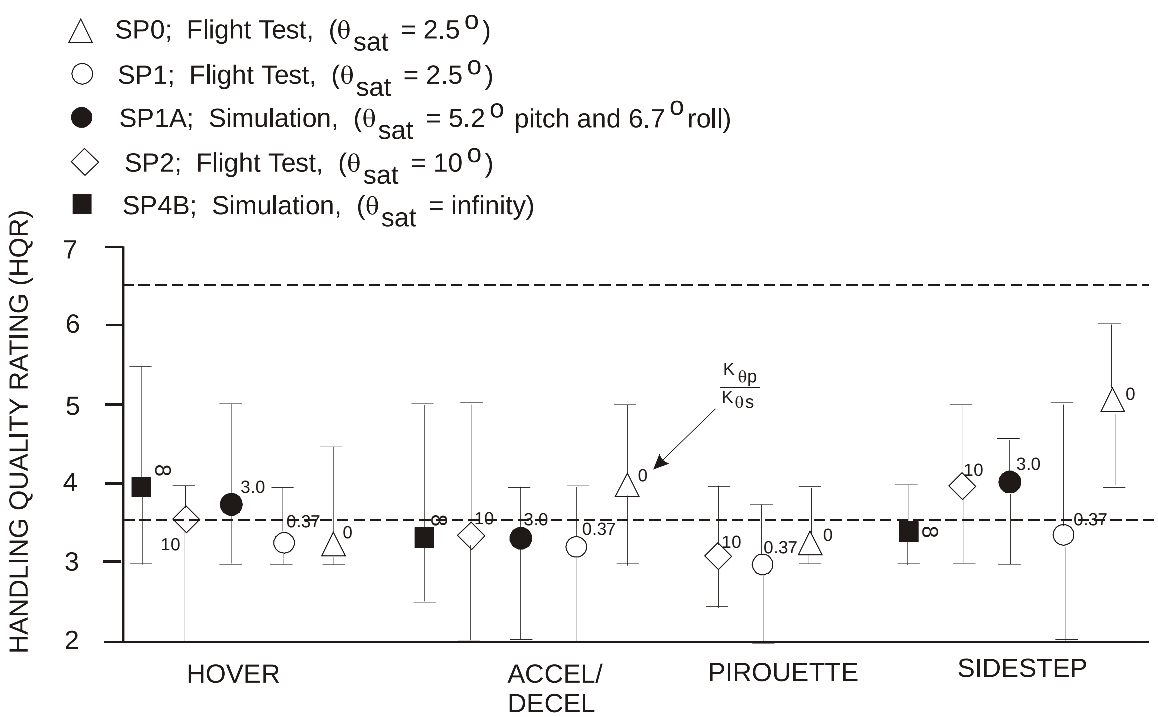

Figure 14 Effect of varying $K_{\theta p} / K_{\theta s}$ with Split-Path Architecture

Table 1 Pilot Commentary and HQRs for Limited Authority Configuration SP2 in the DVE (θ_{sat}=10 deg)

Maneuver	Pilot H	Pilot Y

Hover	Did not see any saturation, but did not like opposing stick inputs. HQR=4	Not much control required. HQR=2
Accel/Decel	Annoying deficiency is stick motion, and the opposing force while trying to hold pitch attitude on the decel. Still found saturation which seemed good. HQR=4.	Good aggressiveness (near UCE=1). HQR=2
Pirouette	Desired performance, but stick motion caused additional workload while trying to hold trim pitch attitude - HQR=4.	Easily controllable. HQR=2
Sidestep	Opposing force on the accel portion, made holding the desired attitude difficult. HQR=4.	Very predictable (HQR=2).
Other Comments	Forces induced by parallel actuator confuse perception of corrective inputs - worse for precision maneuvers. System fights me on larger maneuvers.	Flown with trim lead into maneuver. Predictable - okay.

Configuration CF

This configuration was evaluated in the Reference 5 flight tests and in unpublished results from an interim VMS simulation. The flight test results were inconclusive in that Pilot H did not like CF for any task and gave HQRs of 5 for Hover, Accel/Decel, and Sidestep. His primary complaint was that it was too easy to saturate the system, and that it did not handle well when saturated. Pilot Y gave HQRs of 2 for all tasks except Sidestep where she rated it a 3. She noted the early saturation but did not feel that was a problem and liked the resulting agility. The washout frequency for the complementary filter was 0.25 rad/sec in the Reference 5 flight tests. This low washout frequency resulted in passing most of the attitude through the series actuator and hence the rapid saturation during maneuvering.

The VMS simulation trials with CF were flown by 3 pilots per task. The results are shown in Figure 15.

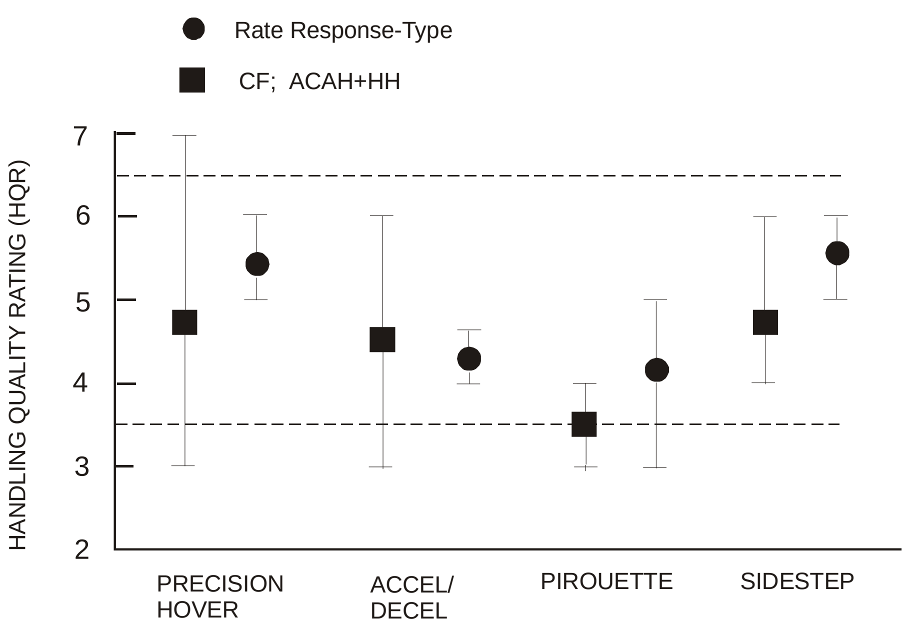

Figure 15 Simulator Evaluation of Configuration CF and Rate

These results are consistent with the HQRs and comments received from Pilot H in the Reference 5 flight tests, i.e., the CF system has significant deficiencies. The complementary filter break frequency was initially set to 1.4 rad/sec to minimize the early series servo saturation noted in the Reference 5 flight tests. This resulted in comments of excessive stick activity. Decreasing ω_{CF} to 1.0 rad/sec resulted in "a little less stick motion". The results in Figure 15 were with ω_{CF} = 1.0 rad/sec.

Is Stick Motion a Problem?

The ACAH flight control system architectures that pass attitude feedback through the parallel servo (e.g., SP and CF) inherently involve motion of the cyclic stick. At the outset of this work, it was assumed that this would be undesirable, and the initial testing was accomplished primarily to verify that assumption. Surprisingly, the pilot rating and performance results with such systems were mostly favorable, which led to further testing of the SP and CF configurations. Those simulation and flight-test studies provided further insights. The most significant of these is that most pilots that flew CF commented that the stick motions were not acceptable. There were far fewer negative comments regarding SP2 and SP4B, both of which had most of the attitude feedback through the parallel servo ($K_{\theta p} / K_{\theta s}$). In fact, there were numerous comments that indicated that the stick motion was noticeable but not objectionable for SP2 and SP4B.

What is unique about CF is that the feedback path to the cyclic stick is lagged pitch attitude (Figure 7). It is strongly suspected that the pilots are sensitive to the phasing of the stick compared to the aircraft motions. If the stick motions are consistent with what the pilot needs, they are judged acceptable. Some pilots that flew CF noted that it was okay if they got out of the loop during the precision part of the task. The following comment summarizes this. "If the stick is allowed to do its thing, it settles out very nicely, but the slightest, interaction by the pilot to stop that stick movement results in undesirable oscillations." Based on such comments, and degraded HQRs, the lagged pitch attitude to the stick is judged a primary deficiency that eliminates CF as a viable architecture for limited authority ACAH.

The attitude feedback through the parallel servo to the stick for the SP configurations is not lagged, but is subject to two potential problems. The most obvious is rate limiting. A rate-limited signal to the cyclic stick would certainly not feel natural. The compensating factor is that such rate limiting always occurs during the large amplitude portion of the maneuver where a high level of precision attitude control is not required. This may explain why most pilots did not complain about the stick dynamics for SP2 and SP4B, even though rate limiting did occur during the aggressive maneuvers. A more subtle potential deficiency related to the SP stick dynamics is that pure pitch attitude feedback is not adequate to stabilize most helicopters. Some rate feedback is necessary. Hence, the pilot may notice that the phasing of the stick is a little behind what is required.

One way to analyze the dynamics of the stick motion is to look at a root locus plot of the ACAH system loop closure with and without the feedback through the series servo. The locus without feedback through the series servo indicates two physically insightful phenomena. First it shows what the ACAH stability would be if only the parallel servo path through the stick were active, and second it illustrates the dynamics of the SAS with the series servo saturated. The root loci in Figure 16 illustrate three cases.

Case 1 illustrates the dynamics of the augmented rotorcraft without saturation for all configurations. This is what occurs for SP0 when not saturated and SP and CF if the pilot flies with a loose grip on the stick.

Case 2 illustrates the dynamics of SP1 that result during series servo saturation. The pilot comments indicate that the stick motions were negligible so the stick dynamics during unsaturated operation are probably not important.

Case 3 illustrates the dynamics of SP2 that result during series servo saturation. In addition, this is the dynamics that would result from motions of the cyclic stick that the pilot feels during normal unsaturated operation.

Case 4 illustrates the Dynamics of CF that result during series servo saturation. In addition, these highly unstable dynamics would result if the only feedback was due to the motions of the cyclic stick. That is, what the pilot feels, would produce a highly unstable system. The pilot commentary and ratings for CF verify that pilots are able to sense that fact.

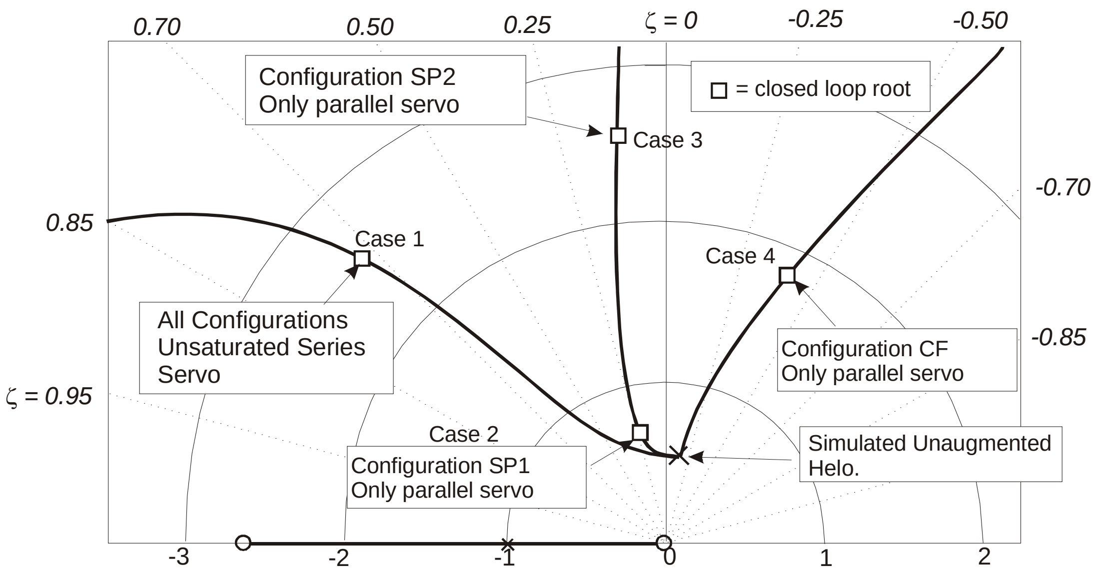

Figure 16 Root Loci Showing the Effect of Feedback Through the Series and Parallel Servos.

Conclusions

The Split-Path with attitude blend-out (SP1b) was judged to be the best overall limited authority configuration. The Phase 2 testing in Reference 5 focused on optimizing that configuration. Those results are best summarized by the post-flight report provided by one of the U.S. Army evaluation pilots. He wrote the following.

Under clearhood conditions (GVE), the blended limited authority ACAH+HH (SP1b) performed almost as well as the full authority ACAH+HH and was as good as or better than the Rate system.

Under degraded visual conditions (DVE), the limited authority system (SP1b) performed almost as well as the full authority ACAH+HH and better than the Rate system or the Rate system with height-hold.

Under brown-out conditions, the limited authority (SP1b) and full authority ACAH+HH systems performed equally well, and were superior to the Rate or Rate with HH systems.

Several flight control system architectures have been tested. Each of these represents a different approach to resolve the compromises that result from limiting the authority of the series servo. The results of testing each of the flight control system architectures are summarized below.

Using only the limited authority series servo for feedback of attitude and angular rate was the least effective solution, unless the series servo authority resulted in saturation at 10 degrees of pitch attitude or greater.

The Split-Path architecture improved the pilot ratings for large amplitude maneuvers. The best overall compromise was to introduce a low gain feedback through the parallel servo (e.g., configuration SP1 where $K_{\theta p} / K_{\theta s}$ = 0.37).

Adding an attitude blend-out function to SP1 was found to be very desirable in back-to-back flight-test comparisons. This caused the rate feedback to remain functional during aggressive maneuvering. The best blend-out parameters caused the attitude input to the series servo to phase out when it exceeded 80% of the series servo authority. The blend time was optimized to 5 seconds.

During flight test trials, the pilots considered series servo saturation an enhancing feature for most runs. That is because the Attitude Command Response-Type is ideal for precision maneuvering in the DVE, but not for aggressive maneuvering (e.g., Accel/Decel maneuver). However, in a few cases the same pilots noted that the aircraft tended to "dig in" at saturation, which could (but never did) result in an excessive pitch attitude. The use of the attitude blend-out function (SP1b) was developed to minimize this effect by retaining pitch damping at large attitudes.

The use of a larger proportion of the gain to the parallel servo (e.g. SP2 with $K_{\theta p} / K_{\theta s}$ = 10) results in increased stick motion. Pilots did not object to such motion when it was in phase with the aircraft motions (i.e., consistent with what the pilot would do). SP with large $K_{\theta p} / K_{\theta s}$ is only effective if the pilot does not grip the stick tightly, as a tight grip defeats the portion of the augmentation through the parallel servo.

The Split-Path architecture might be necessary for configurations with significant cross-coupling. For example, in one limited authority simulation that used only the series servo, the UH-60 saturated the pitch servo during the Sidestep maneuver resulting in Level 2 pilot ratings that were no better than a Rate SAS. In a subsequent simulation of the UH-60, the SP architecture was successfully employed to allow the parallel servo to provide the control power to regulate against moments in the off axis due to cross coupling.

Model following (or command augmentation) causes saturation to occur at the beginning and end of the Accel/Decel and Sidestip maneuvers, where precision of control may be important. Back to back comparison of model following and response feedback architectures produced the same percent of time in saturation, and the pilots did not favor one over the other. It is not practical to implement a Split-Path architecture using model following, as it results in a loop where the stick commands itself through the model.

Keeping the gains as low as possible (sometimes referred to as frequency response matching) maximizes the attitude where saturation occurs and minimizes the transient when saturation does occur. It is important that the gains be sufficiently high to achieve an Attitude Response-Type and to meet the Bandwidth criterion in ADS-33E. It is not necessary to meet the Attitude Quickness criterion unless a Rate system is not available.

The use of a complementary filter (CF) to pass washed-out attitude to the series servo and lagged attitude to the parallel servo is not recommended. The primary deficiency of the CF architecture is that the stick motion that results from the lagged attitude feedback is not consistent with pilot control behavior. The pilots are sensitive to this and feel that the system is fighting them. When the series servo in the CF system is saturated, the system is highly unstable due to lagged attitude feedback to the parallel actuator.

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