FLIGHT INVESTIGATION OF BLENDED COMMAND MODEL IN LOW SPEED MANEUVERING

Geoffrey Jeram, geoffrey.j.jeram.civ@army.mil, U.S. Army Combat Capabilities Development Command, Aviation and Missile Center, United States of America

ABSTRACT

This piloted flight investigation with an UH-60 utility helicopter assessed the handling qualities of a blended command response-type alongside attitude command and rate command response-types in longitudinal and lateral axes with three low speed Mission Task Elements (MTEs) of Aeronautical Design Standard ADS-33E-PRF. The Blended Command Model produces an Attitude Response-Type when the cyclic is near center, produces a Rate Response-Type when the cyclic is distant from center, and produces a blended response at intermediate displacements. The investigation assessed three variations of blended command vis-à-vis proportional attitude and rate commands with the Hover, Depart Abort, and Lateral Reposition MTEs. Among the five options, the evaluation pilots ranked blended command best in a Good Visual Environment by an average of 0.5 better than the second ranked attitude command using the Cooper Harper scale. The pilots assessed blended command second best under a Degraded Visual Environment by an average 0.3 worse than the top-ranked attitude command.

1 NOTATION

1.1 Subscripts and Abbreviations

AC	Attitude Command (as a BCM mode)
BC	Blended Command (as a BCM mode)
BCM	Blended Command Model
RC	Rate Command (as a BCM mode)

1.2 Symbols

K	Stick-to-Command conversion	(°/%)
p, q	Roll and pitch rates	(°/sec)
p_{BCM}, q_{BCM}	Rate commands (for roll and pitch)	(°/sec)
δ_{lat}, δ_{lon}	Cyclic position (lateral and longitudinal)	(%)
δ_{+s}	Blending Start position along stick axis on the positive (+) side of cyclic center.	(%)
δ_{-e}	Blending End position along stick axis on the negative (–) side of cyclic center.	(%)
ω_{bw}	Bandwidth	(rad/sec)
ω_{br}	Break frequency	(rad/sec)
ζ	Damping coefficient	non-dimensional
ζ_{AC}	Design damping for AC	non-dim
ω_{AC}	Design bandwidth for AC	(rad/sec)
ω_{RC}	Design bandwidth for RC	(rad/sec)

2 BACKGROUND

The United States Army's ADS-33E Aeronautical Design Standard Performance Specification Handling Qualities for Military Rotorcraft[1] intends, as a minimum, Attitude Command / Attitude Hold for Degraded Visual Environments (DVE), as measured by Useable Cue Environment (UCE) 2 or 3, whereas the specification requires the Rate Response-Type* in Good Visual Environments (UCE 1) (ADS Table IV). Users may infer a compromise between Attitude and Rate Response-Types in terms of precision and aggressiveness. This investigation explores whether a blended response type might provide a "best of both worlds" solution with the stability and precision of the Attitude and the agility and aggressiveness of the Rate Response-Types. The single flexible transfer function, equation (1), may allow seamless transitions between Response-Types.

$$\frac{P}{\delta_{lat}} = \frac{K(s+\omega_{br})}{s^2+2\zeta\omega_{bw}s+\omega_{bw}^2} \quad (1)$$

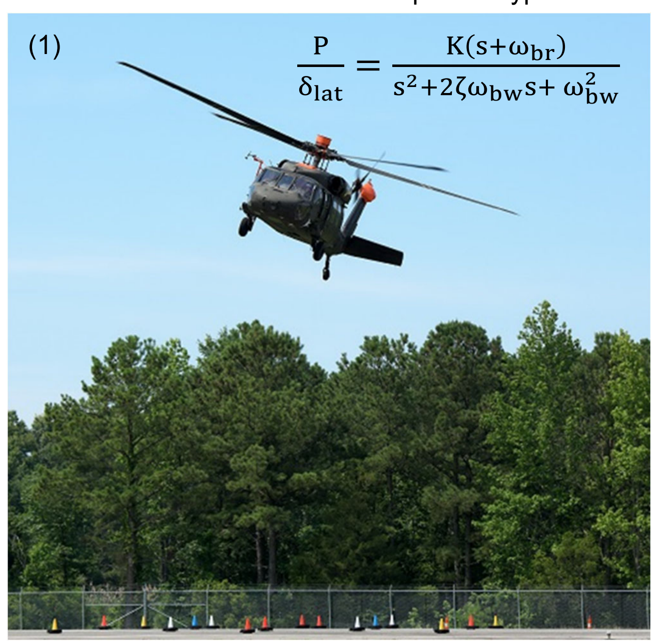


Fig. 1. Flight Evaluation of Blended Command Model with a Flexible Transfer Function

* When capitalized in this work, the term "Response-Type" indicates a type that ADS-33E explicitly identifies.

Preceding this flight portion of the investigation, the author documented the design and analysis of Blended Command Model.[2] It uses the flexible transfer function in equation (1) above, of the kind proposed by Greenfield and Wittmer[3] and couples it with a Parameter Scheduling function that shapes its Response-Type. To affect a Rate Response-Type, a parameter scheduling function sets the parameter values to adopt $\omega_{br} \coloneqq \omega_{bw}$ and $\zeta \coloneqq 1$, which reduces the transfer function to the first order response of equation (2).

(2) $$\frac{p}{\delta_{lat}} = \frac{K}{s + \omega_{bw}}$$

To render an Attitude Response-Type, the scheduling function sets $\omega_{br} \coloneqq 0$, which reduces equation (1) to the second order equation (3).

(3) $$\frac{\phi}{\delta_{lat}} = \frac{K}{s^2 + 2\zeta\omega_{bw}s + \omega_{bw}^2}$$

The distinguishing feature of the Blended Command Model is the use of a single flexible transfer function that can produce a continuum of response-types. This feature differs from an approach[4] that relies on separate transfer functions for each response-type and a switching and synchronizing algorithm (Fig. 2).

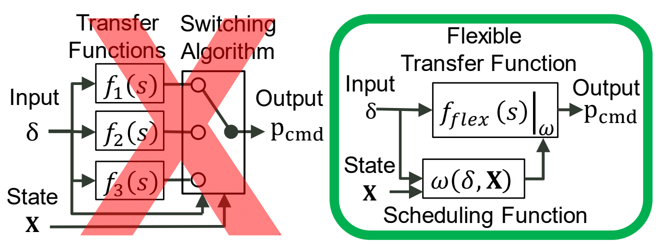


Fig. 2. Replace many transfer functions with one

3 INTEGRATION IN THE RASCAL AIRCRAFT

This flight investigation took place on the Rotorcraft Aircrew Systems Concepts Airborne Laboratory (RASCAL)[5]. The U.S. Army adapted a JUH-60A Black Hawk into a flying laboratory capable of investigating control systems designs and their handling. A full-authority Research Flight Control System (RFCS) accepts control inputs from active inceptors at the right pilot station and, within flight envelope and safety restrictions, follows the trajectory of candidate command models. During flight experiments, the evaluation pilot (EP) flies the candidate control laws from the right seat while a Safety Pilot (SP) remains prepared to disengage the fly-by-wire research system and take control with the aircraft's original limited-authority, mechanically linked flight control system.

3.1 Placement of the Blended Command Model

The Blended Command Model (BCM) resides between the EP's cyclic position and the flight control system's model following architecture. The BCM uses separate flexible transfer functions with identical structures, but with axis-specific parameters, for the pitch and roll axes. The BCM control laws accept the longitudinal and lateral cyclic positions (δ_{lon} and δ_{lat}) and output commanded airframe rates for pitch and roll (q_{BCM} and p_{BCM}) as depicted in Fig. 3

The RASCAL flight control system uses an explicit model following architecture that accepts the commanded rates from the Blended Command Model and manipulates the RASCAL aircraft's control servos on main and tail rotors as required to produce the BCM's commanded rates in the airframe. The Model Following Architecture processes aircraft state feedback from sensors to improve its ability to control the aircraft, mitigate disturbances, processing delays, and plant model inaccuracies. The Blended Command Model, itself, processes only on the cyclic input.

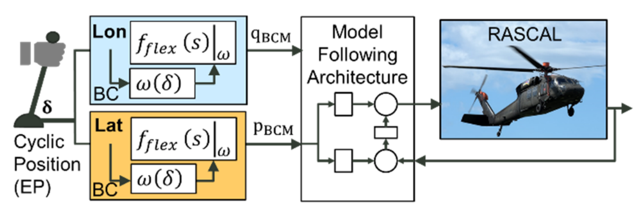


Fig. 3. Pilot Interface to Blended Command Model

In its baseline (or experimental "control") configuration, the RASCAL inherited stability and control parameters from previous research projects, published and unpublished, and refined over time to produce a well performing set of parameters for Attitude Command (AC) and Rate Command (RC) in the low-speed flight regime. In preparation for the flight investigation, test pilots flew RASCAL with the BCM emulating AC and RC and slightly tuned the inherited bandwidths for use in the BCM for those modes. Blended Response did not have a role in the heave and yaw axes. RASCAL provides the heave axis with a pilot selectable height hold and the yaw axes with a stabilized yaw rate and a pilot selectable direction hold.

3.2 Cyclic Position as the Pilot Interface

The pilot varies the effective response-type of the Blended Command Model by his placement of the cyclic from center to either limit. The cyclic position serves as the input domain for the blended command's scheduling function for the break frequency (ω_{br}) and the damping ratio (ζ), which together determine whether the response-type is attitude, rate, or a blend thereof. Additionally, the cyclic position schedules the bandwidth (ω_{bw}) to values that may differ for the attitude and rate command models.

The scheme for the parameter scheduling produces an attitude response when the pilot centers the cyclic and a rate response when he positions the cyclic far from center. With this scheme, a pilot intending a hover would hold the stick steady near center position, which is also the zero-force position of the cyclic spring gradient. In other words, the hands-off stick position settles to the center zero position. For aggressive maneuvering, when the pilot would want to command and regulate high attitudinal rates and accelerations with precision, he would use large stick throws to command large, stabilized rate responses instead of an attitude response. The greater displacement would put the BCM into its RC mode.

The parameter scheduling involves two symmetric pairs of "break points" along the control domain that define as many as five response-type domains (Rate, Blend, Attitude, Blend, Rate as depicted in Fig. 4 and listed in Table 2). The center position defines the zero (0%) position, and the normalized span of the control domain is 1 (100%) with extreme positions of -50% and +50%. Inside the "blend-start" break points on the negative and positive sides (δ_{-s} and δ_{+s}) of center, the Parameter Scheduling Function sets the break frequency to zero ($\omega_{br} \coloneqq 0$) to produce the Attitude Response-Type of equation (2). This center span of the control axis is termed the "Attitude Domain".

Beyond the "blend-end" break points on negative and positive sides (δ_{-e} and δ_{+e}), the Parameter Scheduling Function sets the break frequency equal to bandwidth ($\omega_{br} \coloneqq \omega_{bw}$) and the damping coefficient to 1 ($\zeta \coloneqq 1$) to produce the first order Rate Response-Type of equation (3). These two spans on opposite ends of the control axis are termed "Rate Domains".

When the pilot places the cyclic between the same-side blend-start and blend-end positions (ex. between δ_{+s} and δ_{+e}), the scheduling function linearly interpolates the parameters between their AC and RC set points. These are termed the "Blend Domains." The parameter scheduling function for roll and pitch depends only on cyclic position in the respective axis and is not time dependent. Refer to Fig. 4 for a graphical depiction (not to scale) of the scheduling function described above.

The design of the Blended Command Model accommodates separately optimized or customized dynamics for its Attitude and Rate Command dynamics. The BCM AC and RC modes allow different design bandwidths (ω_{AC} and ω_{RC}) and allows a choice in the AC damping coefficient (ζ_{AC}). The AC and RC modes necessarily have different Stick-to-Command functions (K) due to their different dimensions (degrees and degrees per second respectively).

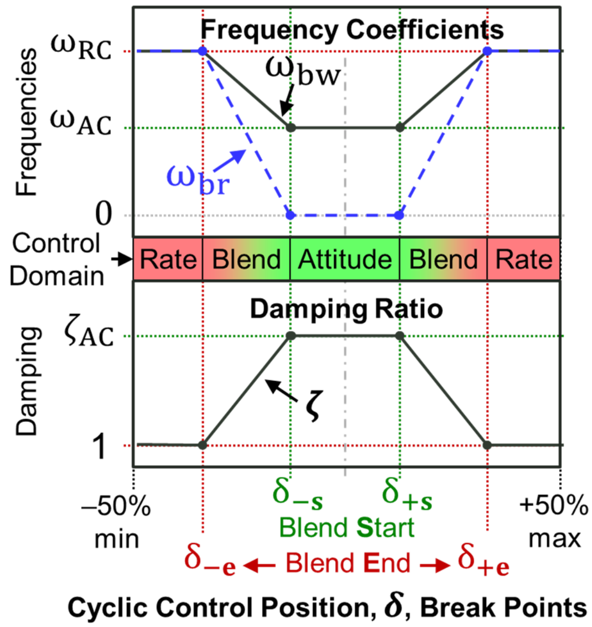


Fig. 4. Parameter Scheduling by Stick Position

In its baseline configuration, the RASCAL had an Attitude Command Model and a Rate Command Model. This investigation adopted the familiar dynamics of those command models into the BCM, and allowed the test pilots the opportunity to tune the BCM AC and RC values. The pilots chose to retain the default parameter values except for the AC bandwidth in the pitch axis, which they increased by 12%, as listed in Table 1.

Table 1. Blended Command Parameter Values

Response-Type	Roll Axis	Pitch Axis
Rate Command, ω_{RC}	4.00 rad/sec	4.00 rad/sec
Attitude Command, ω_{AC}	2.00 rad/sec	2.24 rad/sec
Attitude Cmd damping, ζ_{AC}	1.000	1.000

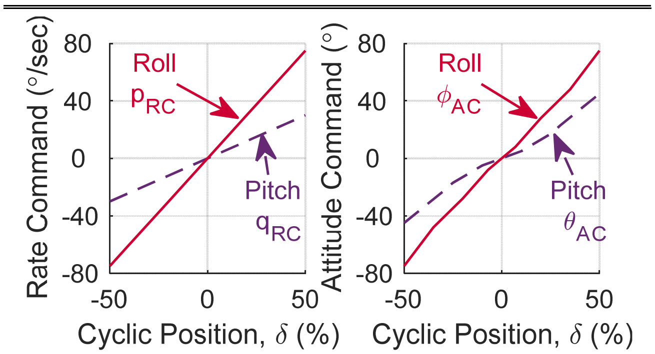


Fig. 5. Stick-to-Command Look Up Table functions

The investigation adopted the RASCAL's baseline Stick-to-Command Look Up Tables depicted in Fig. 5.

Blended Response did not have a role in the heave or yaw axes. As mentioned above, RASCAL provides the pilot a selectable height hold, stabilized yaw rate, and selectable direction hold.

3.3 Terms and Notations for BCM Modes

This first flight investigation of the Blended Command Model involved learning how to exploit the BCM to produce more desirable and effective handling qualities. As described above, it uses cyclic position for the pilot interface, and it uses the blend-start and blend-end positions in the longitudinal and lateral cyclic axes as the controllable variables. This investigation sought to select discriminative test cases from the continuum of potential of BCM settings. The cases included the three full-span modes and a few partial blend modes with offsets.

For the sake of common understanding and concise communication, particularly for the printed flight test cards, the investigation adopted the terms and notation listed in Table 2. The notation for a BCM setting takes the form "BCs##e##" where instances of "##" are the positions (in percent) of the **s**tart and **e**nd of the Blend domain. The BCM parameter scheduling produces its "AC" mode when blend-start and blend-end are 50%. The full notation is BCs50e50, but the term "AC" is used for this canonical ADS-33 response type. The entire span of the control is within the AC control domain.

Table 2. Blended Command Model modes & terms

δ_s%	δ_e%	Response Mode	Notation
50	50	Full Attitude Command	AC
0	50	Full Blended Command	BC
0	0	Full Rate Command	RC
>0		AC offset, ex. δ_s=10%	BCs10…
>0	<50	Partial Blend, ex. 10% & 20%	BCs10e20

Control Input Value	Term
$\delta_{-s} \leq \delta \leq \delta_{-s}$	Attitude Domain
$\delta_{-e} \leq \delta \leq \delta_{-s}$ and $\delta_{+s} \leq \delta \leq \delta_{+e}$	Blend Domain
$\delta \leq \delta_{-e}$ and $\delta_{+e} \leq \delta$	Rate Domain
Subject to: $\delta_{-e} \leq \delta_{-s} \leq 0 \leq \delta_{+s} \leq \delta_{+e}$	

The BCM parameter scheduling produces its "RC" mode when both blend-end and blend-start reside at the center position, 0%. Its full notation is BCs00e00, however the term "RC" will be used as its short name. Notably, BCM's AC and RC domains intersect at the center position, which commands zero for both responses.

The BCs00e50 notation describes the Full Blend "BC" mode with blend-start at 0% and blend-end at 50%. The BCM provides a proportional AC response only at cyclic center and a proportional RC at the extreme positions. It linearly interpolates the BCM parameters between AC to RC by the cyclic position from center to limits.

The term "Partial Blends" refer to settings where blend-start and blend-end bound a positive but not full span of the cyclic span. A BCs10e20 setting provides 10% of cyclic on either side of center for the pilot to exploit canonical Attitude Command. Starting at 10% cyclic either side of center, the BCM begins blending Attitude and Rate until it reaches 20% from center, beyond which the pilot commands a Rate Command to the limit of the cyclic (+/- 50%). During prototyping, the investigation team quickly recognized the importance of the placement of the blend-start and adopted the term "offset", as in "AC offset" or "Blend offset", both meaning a blend-start position offset from center.

In physical execution in simulator and in flight, the investigation limited the blend-end to 45% instead of 50% to avoid potential integration issues at cyclic stops.

3.4 BCM Modes in the Context of ADS-33E

The ADS-33E requirements apply to the Blended Command Model. The specification describes "Blending between Response-Types", but seemingly not through the approach of this BCM design with a flexible transfer function shaped by cyclic position. Still, the specification includes content for Response-Types, requirements, limits, annunciation, and failures that pertain to this BCM. This discussion includes only a few of the most salient requirements where the BCM deserves special interpretation, or where the requirements themselves seem to be ill-posed for the BCM.

3.4.1 Character of Response-Types

The BCM's AC mode satisfies the "Character of Attitude Command Response-Types" described in paragraph 3.2.8 of ADS-33E in which the response for a step force input shall produce a proportional attitude change that follows the input and that remains essentially constant between 6 and 12 seconds after the step input, or if the resulting ground translation is constant or its absolute value asymptotically decreases toward a constant.

The BCM's RC mode satisfies the specification's character of Rate Response-Type (described in para.3.2.6), which is a characterization by subtraction. The BCM's RC mode satisfies neither the character of Attitude Response-Type nor that of Translational Rate Response-Type, therefore it shall be characterized as a Rate Response-Type. More specifically, one may describe the BCM's RC mode as the rate analogue of the specification's Attitude Response-Type because the BCM's RC responds to a step force with a proportional rate response.

Because the BCM's BC blends continuously between AC and RC modes, it may result as either the Attitude or Rate Response-Type characterization, depending upon the cyclic position within the Blend domain (Fig. 4). The BCM response would follow the specification's Attitude Response-Type when the force-produced cyclic position is the blend-start position and for cyclic displacements immediately beyond the Attitude domain into the Blend domain. Beyond the blend-start position, where the BC mode has at least an infinitesimal component of RC, the result of a step in force would not asymptotically decrease toward a constant. However, the resulting attitude might remain "essentially constant" for 6 to 12 seconds if it rolls or pitches slowly through the proportional attitude change.

The Partial Blend modes of the BCM manifest the Response-Types of their respective Attitude, Blend, or Rate domains. For practical purposes, with the bandwidths and maneuvers used in this investigation and rotorcraft generally, ADS-33E would characterize the BCM's BC and RC modes as the Rate Response-Type. As will be described below, the RC and BC modes introduce and shift a bias in the attitude response which complicates interpretation of the ADS-33E characterizations. If the path of the control input of a maneuver (as from a step force input) remains entirely within the Attitude domain of the cyclic span, then the resulting response would be the Attitude Response-Type. If not, its character would be the Rate Response-Type.

ADS-33E addresses nonspecified response-types in its paragraph 3.2.12 and lists several examples including "…hybrid responses such as ACAH (Attitude Command /Attitude Hold) for small attitudes that blend to Rate for larger commands or attitudes." That description resembles the BCM in its AC and AC Offset modes. Such response-types shall meet the requirements of the specification and "shall not result in excessive excursions in rotorcraft attitudes or require objectionably complex or unfamiliar control strategies." This last requirement proved relevant to the BCM modes with AC offsets.

3.4.2 Annunciation of Response-Type

The ADS-33E (para.3.8.1) states, "if more than one Response-Type can be selected in a given axis, there shall be a clear and easily interpretable annunciation to the pilot indicating which of the Response-Types are currently engaged or armed." This requirement would be particularly applicable for a BCM setting such as BCs10e10, where an Attitude domain borders with a Rate domain with no intermediate blending. In such a mode, the BCM acts like a switch rather than a blend between Attitude and Rate. With such a setting, the abruptness of the Response-Type transition would depend entirely on the cyclic Stick-to-Command (a.k.a. "stick shaping") function at the blend start position. The Stick-to-Command function appears as K in equation (1) between the cyclic and the BCM. This investigation did not assess such binary modes in flight.

The BCM's BC and Partial Blend modes produce a gradual transition from Attitude and Rate Response-Types across the span of the Blend domain in the control axis. This investigation did not implement stand-alone annunciations of response-type during its flight trials, but one may envision the visual, aural, and tactile annunciations that could communicate transitions through Attitude, Blend, and Rate domains as the cyclic moved. Any such cue design should account for the potential rapidity of transfers among response-types. A single sweep of the cyclic might involve four response-type transitions within a half second during an aggressive maneuver when the pilot's attention would be outside the aircraft. For modes with gradual response-type transitions across sizeable spans of the cyclic, the annunciation requirement is satisfied by the user interface. The cyclic position itself communicates practically, if not precisely, the commanded response-type to the pilot through his grip.

3.4.3 Attitude Quickness

This Attitude Quickness ADS-33E requirement, described starting in paragraph 3.3.3 and in ADS-33 Figure 8 and Table VI, is the ratio of peak attitudinal rate to the peak attitude change that produced it, expressions (4) for roll and pitch, respectively.

$$\frac{p_{peak}}{\Delta\phi_{peak}} \quad \text{and} \quad \frac{q_{peak}}{\Delta\theta_{peak}} \tag{4}$$

The aircraft's physical design and characteristics (ex. rotor control power, airframe inertia, limb-manipulator dynamics) affect the mechanical burden of satisfying this quantifiable specification while the control laws can exploit or constrain what the airframe provides for "responsiveness" or "aggressiveness".

The Blended Command Model, which allows separate design choices for increasing bandwidth and reducing damping for its Attitude domain (ω_{AC} and ζ_{AC}) and Rate domain (only ω_{RC}) may have an advantage satisfying attitude quickness for both small amplitude changes (5° pitch, 10° roll) and large amplitude changes (up to 30° pitch, 60° roll). The blend-start position and the stick-to-command functions also affect the tradeoff of small amplitude precision and large amplitude responsiveness. These design choices could be included in holistic stability and control parameter optimization, and mindful of the constraints of the supporting control system architecture (ex. the RASCAL's Model Following Architecture).

During piloted execution of the Attitude Quickness test maneuver, the character of the Blend domain, especially the full span BC mode and small offset modes, may simplify the Pilot's chore of producing high quickness scores for a wide range of amplitudes because the BC mode provides a more Attitude-like response near center for small amplitudes and a more Rate-like response at large cyclic amplitudes.

This first flight investigation of the BCM did not conduct attitude quickness tests in flight. The handling qualities assessments did include an aggressiveness score through a guided rubric (Fig. 12).

3.4.4 Control System Blending

The ADS-33E para. 3.8.3 addresses blending between Response-Types. It requires that blending "shall be essentially linear with time and shall occur within the time limitations" of 2 to 10 seconds for deceleration and 2 to 5 seconds for acceleration. A switching mode of the BCM, such as the BCs10e10 example above and other modes with small Blend domains, would fail this specification whenever the cyclic moves across the AC/RC boundary.

Inferring from this time-based requirement, the authors of ADS-33E may be addressing the switching method of response-type transitions depicted on the left side of Fig. 2. When a command model maintains multiple parallel transfer functions in order to provide multiple response-types, it must have an algorithm to switch among the transfer functions without producing objectionable control discontinuities. Techniques vary but may include synchronized integrator resets among the transfer functions, the use of hysteresis on the algorithm's input argument signals, and the technique of fading out, over a span of time, the signal output of the current transfer function, while fading in the output from succeeding transfer function. The specification's "time limitations" for blending Response-Types, informs the acceptable timing for the command model transitions.

This ADS-33E requirement may deserve revision and expansion to address command models that pace response-type transitions by control position rather than by time. This time-based requirement for blending Response-Types highlights the potential advantage of a Blended Command Model which relies on a single flexible transfer function coupled with a parameter scheduling function. The single flexible transfer function can produce multiple response-types without the objectionable artifacts of transfer function switching. Instead of time fading between response-types, the command model allows the pilot to deliberately regulate the pace of response-type transitions though his control movements.

4 INTEGRATION AND FAMILIARIZATION

Aside from the author, the investigation team included three flight test engineers and an experimental test pilot of the United States Army's Research In-Flight Laboratory (RIFL) team. Additional Army experimental test pilots participated from an adjacent Army Flight Test Branch. And while all these participated in the integration and familiarization, only two experimental test pilots flew as Evaluation Pilots and provided handling qualities assessments.

Fig. 6. RASCAL Development Facility Pilot Station

4.1 Prototyping in the RASCAL DF

The RIFL team maintains a RASCAL Development Facility (DF) which serves as a limited Hardware-in-the-Loop (HIL), fixed-base, piloted simulation (Fig. 6. RASCAL Development Facility Pilot Station). The RASCAL DF includes much of the full-authority digital flight control system, including the same model Flight Control Computer (FCC) executing the BCM as a component of the aircraft's Research Flight Control System (RFCS). The Pilot Station includes an active cyclic, active collective, and pedals; Control Display Unit; RFCS control panel; and a single forward "outside view" display in front of the pilot seat. A simulation computer runs a NASA Ames version of the Black Hawk General Helicopter (GenHel) model and a sensor simulation to accurately portray the RASCAL aircraft's flight dynamics to the flight control system, including the BCM and model following architecture. These elements communicate through a MIL-STD-1553 bus interface.

The DF serves as a flight simulator with a visual rendering of the forward outside view that allows the EP to maneuver with the BCM through virtual ADS-33E Mission Task Element (MTE) courses set on a visual model of the local airfield. Importantly for BCM prototyping, the DF includes the same Software Safety Monitor for the aircraft's Servo Control Unit. The Software Safety Monitor automatically disengages the full-authority RFCS upon a detection of a fault. These safety aborts protect the aircraft from misbehaving Command Models. Prior to installation and flight in the RASCAL aircraft, the author and RIFL team integrated the Blended Command Model into the RASCAL Development Facility (DF) to verify the proper functioning of the command model in the RASCAL flight control system, to familiarize the flight test engineers and pilots with the BCM and test cases, and to prioritize and down-select which test cases to include in the flight trials.

4.2 Rate Response Introduces Attitude Bias

While verifying in the RASCAL DF that the Blended Command Model behaved as designed, test pilots "flew" the BCM in simulation to familiarize themselves with the BCM modes, particularly the BC and Partial Blend modes. Those accustomed to the Attitude Response-Type quickly noticed and commented that the Attitude Command of the BCM would acquire an attitude bias in center-stick hover after a maneuver into Blend and Rate Domains.

The behavior of the attitude bias of a full span Attitude Command differs from that of a partial blend Attitude Command. A full span Attitude Command, such as the BCM's BCs50e50 (aka AC) mode, or a typical stand-alone Attitude Command Model transfer function, would have a fixed attitude reference point or "Bias". With cyclic centered, a full Attitude Command would command a level (0°) attitude. This not the case when the response includes a component of Rate Command. The BCM with an Attitude Offset would shift the attitude bias while the pilot maneuvered the cyclic beyond the Attitude domain, that is, beyond the blend-start position. To regain a steady level attitude with stick-centered after such an excursion, the pilot must move the cyclic back beyond the opposite Attitude domain to return the Bias to 0° or other attitude as desired.

Consider a Blended Command Model with BCs10e20 settings and its different trajectories resulting from the three different sinusoidal inputs of Fig. 7. Each maneuver begins at a level attitude (0°). In the first maneuver, depicted with a solid green line, the pilot moved the cyclic from center (0%) to the blend-start position and by 4 seconds, returned the cyclic to 0% and held it at center. Throughout the maneuver, the cyclic remained within the Attitude control domain, its attitude bias remained fixed (at 0°), and the BCM commanded the attitude to 0° when the cyclic returned to center.

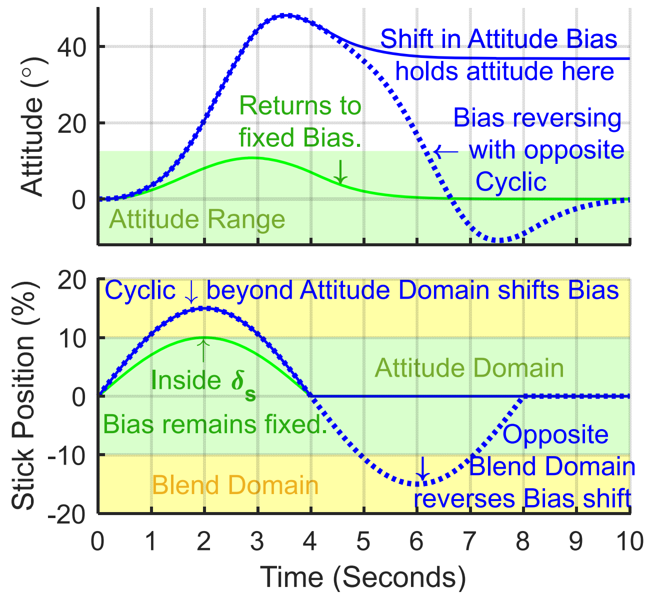


Fig. 7. Bias Behavior Within vs Beyond Blend-Start

In the second maneuver, depicted by the solid blue line, the pilot moves the cyclic beyond the blend-start position to +15% before returning it to 0° at 4 seconds and holding it there. In this case, the pilot entered the Blend domain where the response included a rate component which shifted the attitude bias of the BCM. After the pilot centered the cyclic within the Attitude domain, the BCM commands an attitude of about 37°. The next cyclic placements from center would now command proportional attitude changes relative to the new attitude bias at 37°. As mentioned above, this behavior of the BCM resembles an Attitude Command / Attitude Hold response.

Finally, consider a third maneuver, depicted by the dotted blue line in Fig. 7. The maneuver is identical to the second maneuver through the first 4 seconds, after which the pilot continues to move the cyclic to -15%, on the opposite side of center. Then he returns the cyclic to center (0%) at 8 seconds and leaves it there. During the period of 5 to 7 seconds, while the cyclic passed beyond the opposite blend-start position into the opposite Blend domain, the BCM reverses the Attitude Bias. Because the duration and magnitude of the cyclic's path from 1 to 3 seconds and from 5 to 7 seconds were approximately equal but opposite, the dynamics of the BCM shifted Attitude Bias nearly back to its original value of 0°.

4.3 Considering an "Attitude Reset" Feature

During the familiarization and setup phase of the investigation, a few test pilots voiced concern over the loss of the reliable level-attitude of the Attitude Response-Types they had grown accustomed to. After maneuvering the cyclic into a Blend or Rate domain and returning it the Attitude domain, the BCM seemed to exhibit an uncommanded pitch or roll, due to the shift in attitude bias. The pilot feedback prompted an excursion to create and prototype an "AC Reset" mechanism to enhance the Blended Command Model.

The author designed a functional AC Reset mode which the test pilots exercised in the RASCAL DF with virtual MTEs. In function, the AC Reset mechanism reset the state of the BCM integrator that provided the attitude acceleration command when the aircraft attitude rolled or pitched through 0° or when triggered by the pilot. The mode succeeded in returning the aircraft to within a couple degrees of level attitude at its first zero attitude crossing after large amplitude Rate maneuvers. If the pilot then let the cyclic settle into its center position, the AC Reset mode would level attitude to less than a half degree at a second crossing of 0°. However, the "AC Reset" mode demanded too much from the research flight control system, especially during the Lateral Reposition and Depart Abort MTEs. Intentionally, the design of the AC Reset changed the behavior of the Blended Command Model and would require pilots to adapt to the AC Reset in addition to, or instead of, the Blended Control Model. The author ultimately decided to drop the AC Reset cases from the flight trials for three separately sufficient reasons:

- The AC Reset mode regularly triggered RASCAL's automated safety aborts. The AC reset introduced discontinuities in the BCM integrator's attitude acceleration command. The automatic safety aborts disabled the Fly-by-Wire research system, rendering flight assessments with this mode impossible.

- The complexity of the "AC Reset" clashed with the aesthetic of the existing design. The flexible transfer function elegantly avoids the ugly complications of synchronizing and switching multiple separate transfer functions and handling qualities modes. To add the "AC Reset" mode would compromise the principal advantage of the BCM design over traditional methods.

- The investigation could not afford the flight hours to include test cases dedicated to assessing an "AC Reset" in this first investigation. More fundamental unknowns took priority.

4.4 Selecting Candidate BCM Modes for Study

During the control law integration into the RASCAL DF the author and flight test engineers explored a wide variety of BCM settings while verifying the control laws and paring out settings with obviously objectionable behavior or those with negligible differences in the character of their responses. Among the rejected modes were the switching classes of the BCM, where blend-start equaled blend-end between the cyclic center and limits. With the Stick-to-Command functions used here (Fig. 5) the switching modes produced abrupt Attitude to Rate response transitions that obviously warranted annunciation, as ADS-33E requires. The switching modes were not further developed due to their objectionable abruptness and because the switching modes were not central to the "Blended" intent of this investigation.

Experimentation in the RASCAL DF revealed that the blend-start setting had a more discriminative effect on handling qualities than the blend-end position. Pilots noticed the transition from a steady-state attitude to a slow roll or pitch rate at the blend-start location. But at the end of a blend domain spanning 10 or more degrees, the mode already produces a rate practically indiscernible from a pure rate-response. This observation led to a decision to orient the flight investigation on the placement of the blend-start position.

The nine candidate settings systematically examined in the RASCAL DF before the flight included the canonical RC and AC modes plus BC; four Partial Blend modes with offsets of 5%, 10%, 15%; and 20%; and two modes with an "Attitude Reset". All these modes except the full RC mode placed blend-end at 45% to allow a small margin of Rate span before the cyclic limits to avoid potential execution problems at the extremes.

Every MTE would include AC and RC as benchmarks of the canonical ADS-33E Response-Types. And every MTE flight assessment would include the full span BC mode (with blend-start at 0%). The AC Reset modes were not advanced to flight for any MTE for the reasons described above. Familiarization flight simulations would allow the pilots to devise and practice their control strategies for the blended modes and to make a rough prioritization of the partial blend candidates for assessments in flight.

Despite the DF's poor forward view for the Lateral Reposition MTE, pilots concluded that handling qualities worsened beyond 10% offset. The flight assessment would include the 5% and 10% blend-start settings. During the Depart Abort MTE familiarization, the pilots commented that steeper pitch angles during the deceleration led them to favor the larger AC offsets of 10% and 15%. Unlike the previous two MTEs, the Hover task involved coordinated and simultaneous precision positioning, particularly during the deceleration to stationary hover. The pilots had mixed assessments but no strong opinions. The flight assessment for the Hover MTE would assess the 5% and 10% offsets. The handling qualities assessments in flight would cover the Blended Command Model modes listed in Table 3.

Table 3. Modes Selected for Flight Assessment

BCM Mode	Lateral Reposition	Depart Abort	Hover
RC	√	√	√
AC	√	√	√
BC	√	√	√
BCs05e45	√		√
BCs10e45	√	√	√
BCs15e45		√	

5 HANDLING QUALITIES IN FLIGHT

The flight investigation assessed handling qualities with the RASCAL aircraft in five modes of the Blended Control Model, with three MTEs, and two Visual Environments, making 30 distinct test cases for each pilot. Starting with the study of the BCM candidate modes in the RASCAL DF, the author applied four-digit test case numbers to identify the combinations of BCM modes, MTEs, and Visuals, for each phase of the investigation. Table 4 serves as a legend for the composition or interpretation of a test case and an overall summary of the investigation.

5.1 Data and Metrics

The investigation collected handling qualities performance metrics from aircrew and digitized time history data from the RASCAL data collection systems. For a few flights, the investigation team captured cockpit audio recordings, motion video of the Evaluation Station panel display, and photography of the RASCAL and its aircrew during the flights. The principal metrics and information of interest included the following:

- Cooper Harper Rating (CHR).[8] This rating accounts for controllability, workload, deficiencies, and the overall handling qualities. The rating involves a guided decision flowchart to converge to a CHR integer between 1 to 10 inclusively, and an overall Handling Qualities Level of 1, 2, or 3. The Experimental Test Pilots serving as the EPs during the flight assessments

Table 4. Identification of a Test Case

		Phase	Task	CLAWS	Visuals
Example Case No.->		1	3	2	1
Meaning -->		Setup	Hover	AC	GVE
Code	**Phase**	**First**	**Second**	**Third**	**Fourth**
Num	**Term**	**Digit**	**Digit**	**Digit**	**Digit**
1	Setup				
2	Train				
3	RECORD				
Code	**Task**				
Num	**MTE**				
0	Any				
1	LatRepo				
2	DepAbort				
3	Hover				
Code	**CLAWS**	Blended Command Model			
Num	**Mode**				
0	Any				
1	RC	Rate Command (RC)			
2	AC	Attitude Command (AC)			
3	BC	Blend Command (BC)			
4	BCs05e45	Partial Blend			
5	BCs10e45	Partial Blend			
6	BCs15e45	Partial Blend			
7	BCs20e45	Partial Blend			
8	BCs05e45.rst	Partial Blend w/AC Reset			
9	BCs10e45.rst	Partial Blend w/AC Reset			
Code	**Visuals**				
Num	**Term**				
1	GVE	Daylight, UCE1			
2	DVE	DVE with Filtered NVGs, UCE2			

have the education and experience to provide calibrated, well-reasoned, and defensible ratings.

- Aggressiveness Rating (AGG). The rating asks the EP to estimate his ability to increase pilot gain while maintaining desired performance. Less rigorous than the Cooper Harper Rating, it involves a simpler decision flow chart to arrive at an integer between 1 and 5 inclusively. Each evaluation flight's set of test cards included one reference page with the decision flowcharts for the Cooper Harper and Aggressiveness ratings. (Fig. 12)

- Ranking of BCM Modes ("CLAWS"). For each MTE and Visual Environment pairing, the EP assesses five BCM modes. This metric asks the EP to rank the handling qualities of the five modes from most to least desirable.

- Most Critical Portion of the MTE. For each scored BCM mode assessed, the pilot identifies the most "critical portion" of the MTE maneuver. The pilot chooses his own manner of partitioning the MTE or defining “critical”. Typically, the “critical portion” is the part of the maneuver that constrains the Cooper Harper decision flowchart and the Rating most severely.

The investigation collects metrics and the time history records of sensor and flight data. Among redundant channels, precedence goes to the most immediate source, typically the Evaluation Pilot’s score given verbally through the intercom to the onboard System Operator (SysOp) and captured in writing on his official onboard flight test card. (Table 5)

Table 5. Data Collection Methods

Channel	Pilot Ratings	Time History Data
Primary	SysOp Test Card	Onboard Data Record
Alternate	Telemetry Notes and Test Cards	Telemetry Record & Screenshots
Contingency	Intercom Audio Record	SysOp and Test Cards
Emergency	Post-flight Written Report	Post-flight Written Report

5.2 Visual Environments

The Evaluation Pilots assessed all test cases in a Good Visual Environment (GVE), in daylight, Visual Meteorological Conditions, with no precipitation. No evaluation flights took place in actual Degraded Visual Environments.

Fig. 8. Hood and filtered NVGs produce UCE 2

For the test cases set in Degraded Visual Environments, the EPs artificially created a Useable Cue Environment (UCE) level 2 for themselves and flew the MTEs in that condition. To create UCE 2, the Evaluation Pilot wore hooded Night Vision Goggles (NVGs) (Fig. 8) then further degraded his visual field. The pilot applied a pinhole filter over each tube (left and right) and added one or more neutral density filters depending on the ambient light at the time of the flight. Shortly before or at the start of the flight, the EP defocused the goggles as far as required to reach a calibrated acuity of 20/80. As he did this, he adjusted the focus, until he could barely discern the 20/80 level markings on a nearby Large Size Resolution Test Object, a.k.a. a “3-bar chart”. Refer to the Test Guide for ADS-33E, pp. 29-38, for details and alternate techniques to affect UCE 2 and UCE 3 contitions.[7]

5.3 Execution of a Test Card

To convey the process and rigor of executing this handling qualities flight assessment, the author changes tone in this section and centers the discussion around an annotated post-flight scan (Fig. 9) of one of the System Operator’s actual test cards used onboard the test flight of June 30, 2020.

Prior to executing a handling qualities assessment in flight, the investigation team attends to preflight necessities. About two hours before takeoff, the core team, wearing their protective face masks, meets around a large table in the RIFL’s conference corridor at the airfield. Others participate by phone. They are all eager. Today’s flight has been delayed a week due to weather. Papers, notebooks, kneeboards, clipboards and laptops all compete for space around the table whose chairs now obstruct the door to the RASCAL DF. The RIFL Team’s Experimental Test Pilot (XP) and a second XP from an adjacent flight test organization brief the aviation weather and Notices to Airmen. The Pilot-in-Command and Safety Pilot (SP) for today’s flight, review the preflight, health of the aircraft, and the flight hours available before the next maintenance. They cover the approved Aviation Mission Brief and Risk Assessment. This takes about 10 minutes.

The Principal Investigator (PI) of the Blended Command Model investigation says that today’s objective is the Lateral Reposition MTE in a Degraded Visual Environment. The Flight Test Engineer (FTE) serving as today’s onboard System Operator (SysOp) hands out copies of the PI’s flight test cards and leads a read-through and talking rehearsal of the test cards and their test points. In turn, a second FTE, who will operate the mobile telemetry (TM) van, describes the LatRepo MTE cones and visual markers that he will setup on and around the runway. This test card rehearsal absorbs about 40 minutes. As it culminates, an unnoticed visitor steps forward. He introduces himself as the organization's photographer; says he will photograph the flight. The team disperses to their purposes. The aircrew checks out NVG goggles and gets to the RASCAL to prepare the goggles to emulate DVE and prepare the aircraft to take-off.

The FTE and PI drive off to the runway in a small truck full of traffic cones and visual markers. The RIFL team has runway reserved for the morning. The FTE pre-coordinated with the airfield manager and, this morning, communicates with the control tower for clearance to enter the runway. They place cones at locations on the runway subtly marked with paint spots and tape in a pattern resembling Figure 27 of ADS-33E but modified for Lateral Reposition. On each traffic cone, they place one or two donut-shaped (torus-shaped) weights to prevent the rotorwash from blowing them away. The "LatRepo" setup includes numerous visual markers, on and off the runway, to help the pilot locate the MTE course during the maneuver. The off-runway markers are critical. The EP must face the aircraft perpendicular to the MTE course on the runway. He relies on the markers lined up in-depth in the adjacent fields and certain antennae and edges of buildings on the airfield abreast of the LatRepo start and end points. Those markers and landmarks help the EP judge where to terminate the MTE, because he can't see the target on the runway while decelerating over it. The FTE and PI complete the cone setup within 15 minutes. They drive to the TM van and power up its radios and computers.

Less than hour later, the RASCAL arrives on the runway, having established radio communication with TM and ready to start the first test card. By now, the SysOp and EP have confirmed the onboard software versions, program hashes, configurations, and turned to the first test card (Fig. 9). The SP positions RASCAL near the start point of the MTE while the EP considers test card "07_LatRepoDVE.canon", the first of two test cards for today's flight.

The heading of the testcard (**A**) identifies the investigation and version of control law software that is about to be tested. Beneath the Card Number and Name (**B**), are fields to identify the pilot by number and the Threshold Select (TS). The TS sets the sensitivity of the Software Safety Monitor for the aircraft's Servo Control Unit. This is the safety monitor mentioned above in the context of the RASCAL DF. Its setting affects the lead time the pilots would have in the event of malfunction of a Research Flight Control System. Each TS level has a corresponding minimum altitude restriction as a risk mitigation. The pilots carefully consider the risk of the TS setting vs. the value of relaxing it. The Min Alt affects the difficulty of performing MTEs. The higher (and safer) altitudes make it more difficult for the EP to judge distances and execute precise maneuvers and MTEs properly.

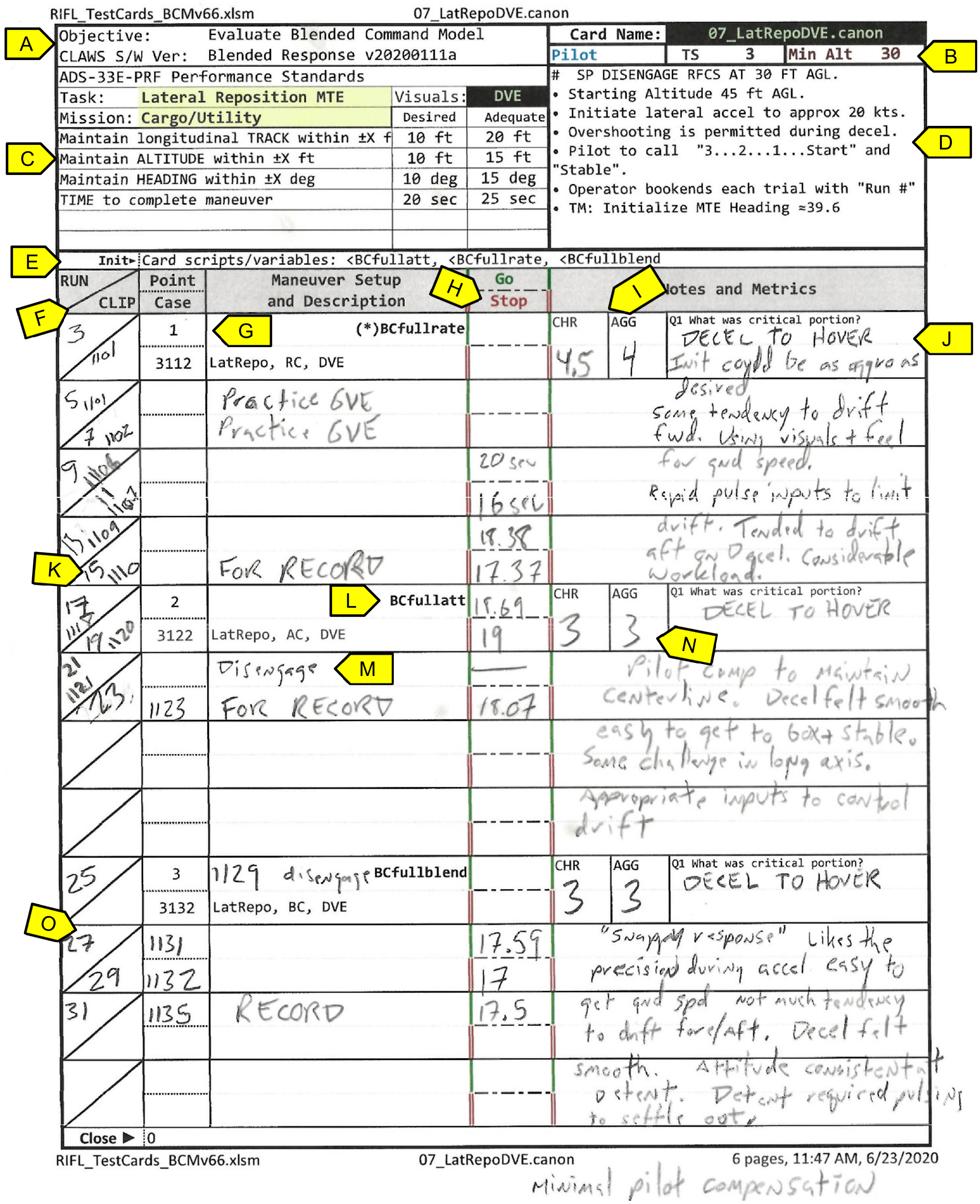
The entire test card is a printed version of the MTE worksheet in a flight test planning spreadsheet. The user had selected the Task ("Lateral Reposition MTE"), Mission ("Cargo/Utility"), and Visuals ("DVE") and the worksheet populated the MTE Standards (**C**) from a reference table of ADS-33E standards.

To the right of the MTE Standards, the card offers an abbreviated script (**D**) to coordinate the actions of the EP, the SysOp and the TM during the execution of the MTE. The EP has flown this MTE already, in GVE, but he paraphrases it anyway, to himself and the SysOp over the intercom. "*After the SP transfers control to me, I'll bring the aircraft to 45 ft RADALT, identify my heading and let you know I'm ready. You'll run the "BCfullrate" script and check that the control laws are set. You'll start the data recorder and transmit the Run number to us and TM. Then I'll transmit a '3.2.1.START' for you and TM to start your timers and I'll start accelerating, shooting for 20 knots. I'll decel to a stable hover and transmit 'STABLE' so you can stop your timers. And then YOU will transmit the Run number again before you stop the data record.*"

The SysOp, sitting 6 feet behind the EP on the right side of the RASCAL's cabin, has a small table upon which he set a laptop interfaced to the RFCS network. Already, he checked that the RFCS control computer has the three shell scripts (**E**) needed for this card.

The aircrew works through several practice runs. The test card has 12 major rows but only three test points. The extra rows allow space for three repeat iterations for each test point, but this SysOp chooses to log two iterations in each row. The leftmost column has fields for the Run Number, (**F**), which is the number of the time history data file recorded onboard the aircraft. The adjacent field would hold the Clip Number, which is the Audio/Video file that records the intercom or (for other investigations) video of experimental flight displays.

The second column has fields for the Test Point (TP) (**G**), which is the sequence number (from 1 to 5 in this test card) of the test cases in this set of test cards. And it has the Test Case, which is the unique combination of Control Law (BCM) setting, Visual Environment, MTE, and purpose. This first TP is Test Case 3112 and the third (wide) column spells out its meaning: LatRepo, RC, DVE. (Table 4) The field also lists the "BCfullrate" script that the SysOp runs to initialize the proper BCM settings into the RFCS.



RIFL_TestCards_BCMv66.xlsm 07_LatRepoDVE.canon

Objective:	Evaluate Blended Command Model		Card Name:	07_LatRepoDVE.canon
CLAWS S/W Ver:	Blended Response v20200111a		Pilot / TS 3	Min Alt 30
ADS-33E-PRF Performance Standards				
Task:	Lateral Reposition MTE	Visuals:	DVE	
Mission:	Cargo/Utility	Desired	Adequate	
Maintain longitudinal TRACK within ±X f		10 ft	20 ft	
Maintain ALTITUDE within ±X ft		10 ft	15 ft	
Maintain HEADING within ±X deg		10 deg	15 deg	
TIME to complete maneuver		20 sec	25 sec	

SP DISENGAGE RFCS AT 30 FT AGL.
- Starting Altitude 45 ft AGL.
- Initiate lateral accel to approx 20 kts.
- Overshooting is permitted during decel.
- Pilot to call "3...2...1...Start" and "Stable".
- Operator bookends each trial with "Run #"
- TM: Initialize MTE Heading ≈39.6

Init► Card scripts/variables: <BCfullatt, <BCfullrate, <BCfullblend

RUN / CLIP	Point / Case	Maneuver Setup and Description	Go / Stop	Notes and Metrics
3 / 1101	1 / 3112	(*)BCfullrate LatRepo, RC, DVE		CHR 4.5 AGG 4 Q1 What was critical portion? DECEL TO HOVER. Init could be as aggro as desired
5 1101 / 7 1102		Practice GVE / Practice GVE		Some tendency to drift fwd. Using visuals + feel
9 1106 / 11 1107			20 sec / 16 sec	for gnd speed. Rapid pulse inputs to limit
13 1109 / 15 1110		FOR RECORD	18.38 / 17.37	drift. Tended to drift aft on Decel. Considerable workload.
17 1119 / 19 1120	2 / 3122	BCfullatt LatRepo, AC, DVE	18.69 / 19	CHR 3 AGG 3 Q1 What was critical portion? DECEL TO HOVER
21 1121 / 23	1123	Disengage / FOR RECORD	— / 18.07	Pilot comp to maintain centerline. Decel felt smooth
				easy to get to box + stable. Some challenge in long axis.
				Appropriate inputs to control drift
25	3 / 3132	1129 disengage BCfullblend LatRepo, BC, DVE		CHR 3 AGG 3 Q1 What was critical portion? DECEL TO HOVER
27 / 29	1131 / 1132		17.59 / 17	"Snappy response" Likes the precision during accel easy to
31	1135	RECORD	17.5	get gnd spd not much tendency to drift fore/aft. Decel felt
				smooth. Attitude consistent at detent. Detent required pulsing to settle out.

Close ▶ 0

RIFL_TestCards_BCMv66.xlsm 07_LatRepoDVE.canon 6 pages, 11:47 AM, 6/23/2020

Minimal pilot compensation

Fig. 9. Example Lateral Reposition Test Card from a Record Flight: RC, AC, BC Modes

The fourth column has two field to record the start and stop times for the maneuver (**H**), or (as this SysOp prefers) to log MTE durations with a stopwatch.

The widest rightmost column allows for notes and metrics. It has insets (**I**) specifically for the Cooper Harper Rating and Aggressiveness scores. This test case has one question, "What was the most critical portion?" (**J**) The EP will determine that before his record run. He thinks he knows already, from his GVE trials, but he'll practice several runs to get past the learning curve with this hooded NVG setup.

The EP and SysOp practice the Lateral Reposition a few times without the NVGs. The EP uses the practice to identify the visual markers that the EP will use in his sight picture when approaching the end point. He considers any wind direction, speed, and turbulence.

The EP transfers the flight controls to the SP and puts on his NVG Goggles. He makes three more practice runs with the goggles, noting the altered NVG view of his sight picture. The SysOp backbriefs the EP after each run with relevant observations, and the elapsed time of his runs. The EP calibrates his pace with each run. The MTE is not a race. Shortening the MTE time standard risks distorting the handling qualities assessment by making the MTE more difficult than it should be. The SysOp records the record run (#15 at 11:10 AM) (**K**). Then the EP transfers controls to the SP, removes his hood and flips up his goggles. He jots down his notes and assessments onto his own kneeboard. He will reference them later when he composes his daily fight report. Though he has the Cooper Harper Rating system memorized, he may refer to the Cooper Harper decision tree and the Aggressiveness scale included with the test cards (Fig. 12). He focuses on the meanings of key words: Compensation, Deficiencies, Performance. He uses them to determine his ratings. He includes them when transmitting his rating and describing the MTE. The PI at TM listens through the radio and takes his notes. The SysOP listens through the intercom, takes notes, and adds the record scores beside the test point (**I**) on the first row. One point down. Four to go.

The SP has flown the RASCAL back to the start point and the EP pulls his goggles down into position and reattaches the neoprene hood. SysOp runs the "BCfullatt" script to setup the Blended Control Model for the full span Attitude Command mode. (**L**) The EP initiates his first practice AC run, accelerating rightward. It feels good, well behaved. The EP banks left to decelerate quickly to a hover over the target. Just as he moves his cyclic right to level the aircraft, he feels a thump in the airframe, hears two bells "DONG DONG" through the intercom and a recorded female-ish voice speaks "DISENGAGE" (**M**) The Software Safety Monitor just disengaged the RFCS and the SP took control of RASCAL with the original, mechanically linked flight control system. The EP demanded too much of the research servos in his abrupt leftward roll to a level stop over the LatRepo end point. *Almost a good run*, thinks the EP. *I just need to ease up with the decel and transition to hover*. *That's the critical portion*.

And he does. He completes the next run (# 23) and uses it for his record run. He takes notes. Transmits his assessment of AC. SysOp writes the record assessment abreast of Test Point 2 on the fifth row. (**N**)

The aircrew has established test momentum and the rest of the flight proceeds apace, despite a few more RFCS disengagements. The SysOp has been recording all the runs, even the practice runs. And why not? Something might abort the flight without notice. It would be good to have at least one clean practice run just in case it's needed as a record run, or for control law troubleshooting, or for troubleshooting RASCAL's research systems. SysOp records every rightward LatRepo onto his test cards because the EP sits on the right side of the aircraft and flies record flights rightward. But the EP also practices the LatRepo leftward, looking cross-cockpit, past the SP, though the left door's window, toward the target endpoint. During one of these more awkward, off-side, practice runs (Run # 27, **O**), the forgotten visitor with the camera took a series of photographs that the PI later assembled into a composite panorama of the RASCAL executing an MTE on a sunny, severe clear, blue-sky, summer day. (Fig. 10)

Fig. 10. Positions of RASCAL while Maneuvering a Lateral Reposition MTE (toward the Aircraft's left)

6 RESULTS

This investigation assessed the handling qualities of the Blended Command Model in flight through the Cooper Harper and Aggressiveness ratings of two Evaluation Pilots. The CHR assessments indicate that the full-span Blended Command (BC) mode performed generally better than Rate Command. The BC mode also performed generally as well as the canonical Attitude Response-Type, and better than AC in the GVE. If the Cooper Harper Ratings of all three MTEs ratings in GVE were averaged together, the BC mode rating (at 2.7) is less (better) than the AC mode average (3.2) by 0.5. In DVE, the AC average (3.7) is only 0.3 less (better) than the BC average (4.0). The ratings, averaged from the assessments of the evaluation pilots, appear below (Fig. 11) and in Table 7 and Table 8 at the end of this Results section.

The surprising finding of this investigation is the peculiarly worse assessment of the 5% Offset (the BCs05e45 setting) relative to all other modes except the Rate Command (RC) mode. Relative to its blended neighbors, the 0% and 10% offsets (BC and BCs10 modes), the 5% offset average CHR is more than 1 rating greater (worse) than its blended neighbors. The 5% mode was not assessed in the Depart Abort MTE, which assessed 15% instead. The ratings of the 15% offset appear consistent with the ratings of 10% offset.

Evaluation Pilots ranked the BC and AC modes about equal in their Desirability rankings. They slightly favored BC in GVE and AC in DVE. (Table 6)

Table 6. Compiled Rankings of Desirability

Visual Env	GVE			DVE		
Pilot HQ Rankings	Lateral Repo	Depart Abort	Hover *	Lateral Repo	Depart Abort	Hover
Best	BC	BC	AC	AC	AC	AC
2nd	AC	BCs10	BCs10	BC	BC	BCs10
3rd	RC	BCs15	BC	BCs10	BCs10	BC
4th	BCs10	AC	BCs05	BCs05	RC	BCs05
5th	BCs05	RC	RC	RC	BCs15	RC

*Averaged rankings resulted in a tie for first choice.

Incidentally, the pilots also assessed CHR of the AC better than those of RC across three MTEs in both the GVE and DVE. This finding reinforces the finding of a 2011 study[9] exploring whether the application of the Attitude Response-Type in aggressive maneuvering in the GVE imposes a handling qualities penalty vis-a-vis the Rate Response-Type. The finding here also shares the same caveat of the 2011 study: the evidence only pertains to the cargo/utility mission standards.

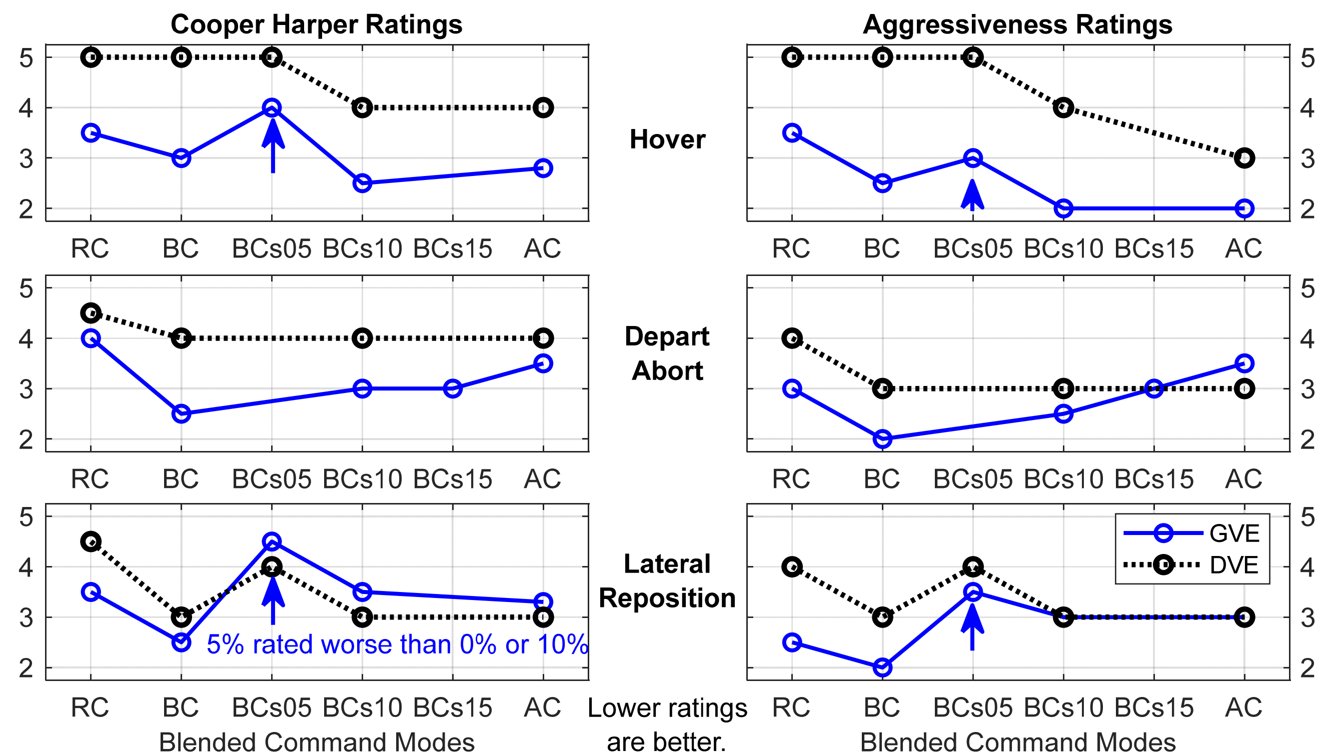


Fig. 11. Handling Qualities Assessments

6.1 Interpretation of Partial Blend Assessments

The evaluation pilots assessed the CHR of BCs10e45 equal to AC in every DVE assessment and two of three GVE assessments. The EPs assessed the BC better in GVE, but the mode lost its advantage in the DVE. And as mentioned above, the 5% offset performed the worst of these.

The full Attitude Command offers the safety of a wings-level condition by letting the cyclic settle into its center position. But when the aircraft carries a load that shifts it center of mass, or when it needs a stationary hover in stiff crosswind, or in some other imperfect flight condition the Attitude Command may require constant attention. The pilot's experience with the AC mode in the Hover MTE may be an example. With the blended command model, the pilot could maneuver the aircraft into a non-level attitude if desired, and would shift the attitude bias in that direction, allowing a relaxed cyclic position once the attitude bias is set.

In a Degraded Visual Environment, a pilot lacks the visibility to quickly perceive and correct small angles, rates, and drifts. He may discover them late, after slow rates have built large errors. A blended command with a sizeable offset, allows the pilot to execute rapid gross corrections with cyclic displacements well into the Blend and Rate Domains, to quickly reach an approximate target attitude. Once close to the target attitude, the pilot centers the cyclic, returning the aircraft to an Attitude Response-Type. The pilot can then exploit the precision of Attitude Response and control attitude with small displacements of the cyclic. In effect, he has shifted the attitude bias near to his target and caught it in an Attitude Command "bucket" as wide as the offset on either side of center.

Too small an offset would not allow the pilot to "fine tune" a target attitude using Attitude command without exceeding the tighter blend-start position and shifting the attitude reference bias.

The advantage of the large offset, like the 10% used here, is that the pilot need not be precise when making gross aggressive maneuvers with a Rate-Response – a good example is the terminal maneuver of Lateral Reposition where the pilot executes an aggressive roll from a decelerating banked attitude to a level hover. The pilots consistently identified the terminating deceleration to hover as the critical portion of the Lateral maneuver MTE. With the blend-offset modes, the pilot need only be precise enough to end the maneuver within the mode's Attitude Command "bucket." Afterward, he uses the precision of the Attitude Response Type for station keeping. This could be the "best of both worlds" solution mentioned in the introduction.

With the stick-to-command functions of this BCM design, the 5%, 10%, and 15% offsets map to pitch attitudes of 2.5°,5°, and 9° and roll attitudes of 5.7°, 12.6°, and 20°. The lateral 10% offset mode commands attitudes up to 12.6° either side of the center stick attitude bias, about 25° of roll. In the Lateral Reposition termination maneuver, the pilot need only move the attitude bias within 25° of the target attitude for hover. With that, the pilot can exploit the precision of the Attitude Response-Type for stable hover. Based on these assessments, the 10% offset satisfies the pilot, whereas the narrower 5% offset performs decidedly worse.

The AC mode also provides this precision, and its higher aggressiveness scores suggest that it should perform perhaps better than the 10% offset for aggressive maneuvers like the LatRepo termination. The pilots did assess the AC CHRs equal to the 10% Blend offset in the DVE, but slightly worse for the GVE.

The shortcoming of small offsets, like the 5% BC mode, is that the pilot may not have the accuracy to terminate a maneuver within its attitude bucket, or that the span of Attitude Command might be breached by crosswind or turbulence. In those situations, the pilot can only correct his attitude by departing the Attitude Domain, suffering frequent shifts in the attitude bias and changes to the cyclic solution.

6.2 General Execution and Exogenous Factors

The flight assessments of this investigation spanned four months between its first flight assessment on March 4, 2020 and its ninth and final on July 1, 2020. The test flights consumed 11.3 dedicated flight test hours. These exclude a couple of integration and familiarization flights during the preceding three months. The two Experimental Test Pilots who flew as Evaluation Pilots completed 45 test cases. Of the 30 distinct test cases, 29 received at least one assessment. The first pilot needed to cut short his DVE, Depart Abort flight, resulting in the omission of its 15% Offset record assessment. The second pilot could not complete any of his 15 DVE cases before RASCAL's final flight, so every DVE assessment came from the same XP.

Two exogenous factors that dramatically affected this investigation deserve mention. The first arrived soon after the first flight of record assessments. The COVID-19 Pandemic forced the organization to suspend flights. Three months passed. Starting with the second flight on June 9, the RIFL Team applied strict health protection protocols to limit the likelihood of COVID transmission. Preflight briefings took place by teleconference. Sometimes, the pilots and system operator went to the aircraft without intersecting with the principal investigator, who went directly to the mobile telemetry facility. Adding to common delays such as poor weather and maintenance, later flights rarified for reasons related to the pandemic.

The second factor was the RASCAL Aircraft's long planned retirement. The RIFL team needed to remove the RASCAL from flight status in early July for intensive maintenance and movement. This forced the investigation to curtain its flights. Thus, this first Blended Command Model investigation became the final flight research project of the RASCAL's two-decade career.

Table 7. Average Assessed Cooper Harper Ratings

Visual Env	GVE			DVE		
Response Type	Lateral Repo	Depart Abort	Hover	Lateral Repo	Depart Abort	Hover
RC	3.5	4.0	3.5	4.5	4.5	5.0
BC	2.5	2.5	3.0	3.0	4.0	5.0
BCs05e45	4.5	NA	4.0	4.0	NA	5.0
BCs10e45	3.5	3.0	2.5	3.0	4.0	4.0
BCs15e45	NA	3.0	NA	NA	NA	NA
AC	3.3	3.5	2.8	3.0	4.0	4.0

Lower values are better, Best scores are shaded blue
NA = Not Assessed

Table 8. Average Aggressiveness Ratings

Visual Env	GVE			DVE		
Response Type	Lateral Repo	Depart Abort	Hover	Lateral Repo	Depart Abort	Hover
RC	2.5	3.0	3.5	4.0	4.0	5.0
AC	3.0	3.5	2.0	3.0	3.0	3.0
BC	2.0	2.0	2.5	3.0	3.0	5.0
BCs05e45	3.5	NA	3.0	4.0	NA	5.0
BCs10e45	3.0	2.5	2.0	3.0	3.0	4.0
BCs15e45	NA	3.0	NA	NA	NA	NA
AC	3.0	3.5	2.0	3.0	3.0	3.0

Lower values are better. NA = Not Assessed

7 CONCLUSIONS

Conclusions about Performance

1. In general, for Good Visual Environments, the blended command model provided more desirable handling qualities than the full domain Attitude Command (AC) or full domain Rate Command (RC) modes. The average Cooper Harper Rating of the pilot assessments for blended command was 0.5 below (better than) the average for attitude command, the second best assessed command model. This finding alone justifies additional research to confirm the finding and to determine the best performing variant of blended command.

2. In Degraded Visual Environments, blended command lost its relative desirability. Pilots assessed its Cooper Harper rating marginally worse than attitude command by 0.3 average.

3. The Blended Command mode with a 5% blend-start position (a 5% offset, BCs05 settings) performed at least 1 Cooper Harper Rating worse than both the 0% blend-offset (the full-span BC mode) or the 10% offset (the BCs10 mode). This assessment was unexpected, and its root causes are not well understood.

4. In either visual environment, the blended command assessed better for the Lateral Reposition and Depart Abort MTEs than it did for Hover. Its advantage shows best when one axis is dominant and dynamic while the other remains relatively static and centered. The blended response behaves most like attitude command for the centered, non-dominant, axis, with a low workload in the non-dominant axis, and allows the pilot to focus on aggressively maneuvering along the dominant axis. The pilots credited no advantage to blended command in the Hover MTE, where they exercised dynamic displacements in both lateral and longitudinal axes.

5. In general, pilots assessed the full domain blended command best relative to its variants. That is, the blended command variants (ex. BCs10e45) that had an off-center blend-start position (termed an "offset"), usually performed worse than the full blend where the blend-start position is zero (at stick center).

6. The Attitude Response-Type as applied to this utility helicopter does not impose a penalty to handling qualities relative to a Rate Response-Type under either the GVE or the DVE. Attitude Response-Type is the better of the two canonical ADS-33E Response-Types in GVE and DVE.

Suggestions for Future Research

7. An "Attitude Reset" mechanism would likely improve the desirability and safety of Blended Command. While piloting the blended command variants with a blend-start offset, the Blended Command Model could accrue an "attitude bias" which would not be evident to the Pilots until returning the

cyclic to center position and finding an apparent uncommanded attitude.

8. Continuing research should explore situational cueing possibilities to communicate the precise blended domain boundaries. A tactile example of such a cue would be a noticeable change in cyclic force gradient at attitude command's boundary with blended command.

9. Continuing research should assess the blended response in other maneuvers requiring large or dynamic inputs in both lateral and longitudinal axis, such as the Pirouette MTE and forward flight.

10. A Blended Command Model's tractability with holistic optimization should be explored. By the nature of its design, the Blended Command Model accommodates both Attitude Response-Type dynamics and Rate Response-Type dynamics. These have separate design parameters for their bandwidths and Attitude Command damping. Possibly, the blend-start and blend-end mode settings could also be considered as design parameters for optimization.

Regarding ADS-33

11. The ADS-33 requirement for "Annunciation of Response Type to the Pilot" (para.3.8.1) is superfluous for Response-Type control by means of the pilot's cyclic position. This investigation did not dedicate a visual, aural, or tactile annunciation to the pilots, yet they maintained a practical cognizance of the Response-Type because they commanded it through their deliberate steering of the cyclic.

12. The Control system blending time-based requirement of para. 3.8.3 should be revised to accommodate the cyclic-based blending of Response-Types.

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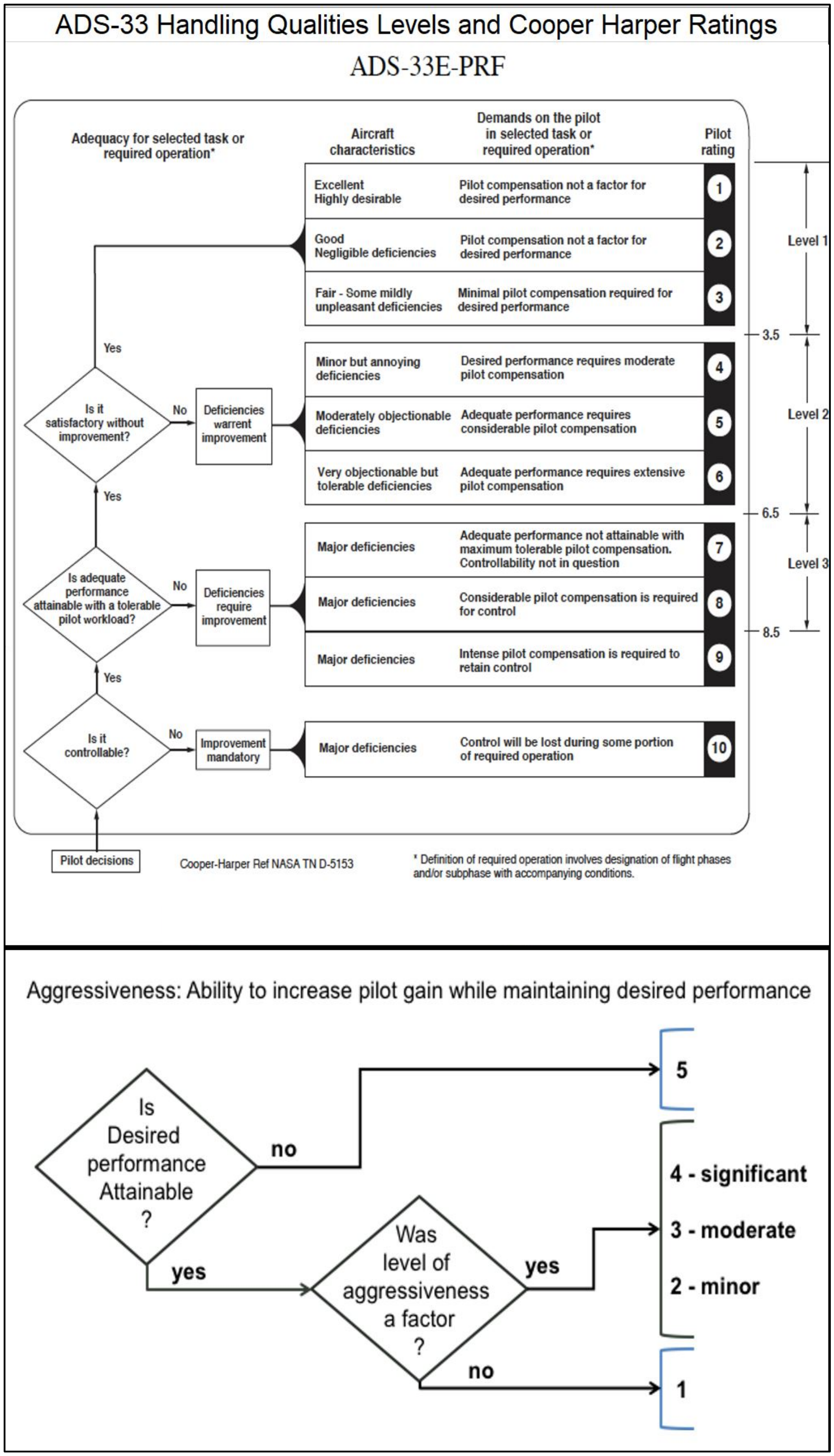

Fig. 12. Cooper Harper Rating and Aggressiveness Handout Included with Test Cards