Ground Simulation Investigation of Helicopter Decelerating Instrument Approaches

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A ground simulation experiment was conducted to examine airworthiness requirements for helicopter decelerating approaches in instrument conditions. Major variables of the experiment included three types of stability and control augmentation, two electronic display formats, two approach-profile geometries, and three deceleration profiles. Over 130 piloted evaluations of combinations of these variables were obtained from six pilots for an approach task including a deceleration on instruments from 60 to approximately 15 knots. The evaluations indicated minimal influence of approach geometry, deceleration profiles, or electronic display format for the task considered, and a requirement for attitude command augmentation for ratings of satisfactory.

Introduction

CURRENT and projected expansion of civil helicopter operations has led to increasing efforts to assess problem areas in civil helicopter design, certification, and operation. Of concern are the influences of the helicopter's inherent flight dynamics, flight control system, and display complement on flying qualities for instrument flight rules (IFR) flight, both in terms of design parameters to insure a good IFR capability, and with regard to the characteristics that should be required for certification.

To determine these influences, a research program is in progress at NASA Ames Research Center to investigate helicopter IFR certification criteria. The program consists of a series of experiments and concomitant analyses with the following two general goals:

1) To provide analyses and experimental data to ascertain the validity of the Airworthiness Criteria for Helicopter Instrument Flight,[1] which have been proposed as an appendix to Federal Aviation Regulation (FAR) Parts 27 and 29.[2,3]

2) To provide analyses and experimental data to determine the flying qualities, flight control, and display aspects requird for a good helicopter IFR capability, and to relate these aspects to design parameters of the helicopter.

The experiment described in this paper was the sixth in this series of ground- and flight-simulation investigations. In the previous five experiments, the influence of several characteristics of interest for IFR flight were examined for an instrument approach task representative of current practice; variations were considered in 1) static and dynamic characteristics including instabilities, 2) stability and control augmentation system implementations, 3) the crew-loading situation, and 4) flight director display information.[4-9] The instrument approach task consisted of a constant-speed approach (60 knots) to decision heights of about 300 ft, followed by a missed approach. Such an approach task is consistent with fixed-wing operations and is representative of current helicopter practice.

To exploit fully the unique capabilities of helicopters, however, it is desirable to consider decelerating (rather than constant-speed) approaches on instruments in order to permit operations in reduced-weather minima. In this regard, a variety of ground simulations and flight experiments concerned with manual, decelerating approaches on instruments—which can provide the basis for ascertaining areas of concern for airworthiness certification in this type of operation—has been performed. Recent ground simulation experiments in this context include that of Ref. 10 for VTOL aircraft and that of Ref. 11 for helicopters; flight studies include those of Refs. 12 and 13 for VTOL aircraft and helicopters, respectively. In 1979, summaries and comparisons of most of the studies dealing with decelerating instrument approaches were prepared in three parallel investigations to provide general guidelines for future design and research efforts.[14-16] These summary investigations provided the basis for the design of this experiment.

Following the scheme of Ref. 14, the elements of interest in an investigation of decelerating instrument approaches may be broken into four general areas: task and environment variables, guidance information variables, aircraft dynamics and control system variables, and display presentation variables. As is summarized in Refs. 14-16, a wide variety of these variables has been examined in several programs during the past two decades with the emphasis in general being the development of suitable stability and control augmentation levels. Research investigations span fairly simple rate and attitude systems as examined in Refs. 12 and 13, through velocity-augmented systems,[17] to fully coupled spiral decelerating approaches.[18] Operational military systems have spanned a similar range, from relatively unaugmented aircraft with four-cue flight directors,[19] through velocity-aided hover augmentation,[20] to the control system being incorporated into the HH-65A helicopter, which will permit fully automatic transitions to hover.[21]

For this experiment, the emphasis selected was "minimum safe" control system complexity and the concomitant levels of guidance, display, and task characteristics required to obtain a satisfactory decelerating IFR capability in a civil certification context. For example, the majority of helicopters currently certificated for single-pilot constant-speed IFR operation employ fairly complex augmentation and flight display systems that permit some degree of coupled operation,[22] but the criteria of Ref. 1 do not explicitly require any such augmentation. Similarly, it may be expected that a fairly straightforward expansion of these existing systems can provide a decelerating capability at least down to speeds where velocity measurement becomes difficult. From a certification standpoint, however, it is important to ascertain whether such a capability can be reasonably obtained with

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more basic augmentation levels because of questions involving failure states. For this reason, the augmentation levels selected for this experiment were to be the same as had been previously examined for minimal-complexity constant-speed approaches.

With this background, the specific objectives of this experiment were:

1) Examine the efficacy, as a function of display and deceleration profile, of three simple types of basic stability and control augmentation systems: rate damping in pitch/roll, rate-command-attitude-hold in pitch/roll, and attitude command in pitch/roll.

2) Examine the influence, as a function of control system and deceleration profile, of two levels of displayed information: an electronic analog of a conventional ADI with three-cue flight directors, and an integrated electronic display format, including position and velocity status and command information in addition to three-cue flight directors.

3) Ascertain any influence on the required control-display combinations of the prescribed type of instrument approach and deceleration profile.

The following section of this paper expands on the selection and design of the experimental variables. Following this description is a summary of the experimental apparatus and approach and then a review of the results.

Design of the Experiment

Guidance Characteristics

In the context of this experiment, the term "guidance" is defined as the processing of distance-measuring equipment (DME) information, azimuth information, and elevation information concerning positions and velocities, and to derive from those data the desired command relationships. It was assumed for the experiment that microwave landing system equipment was available, and that a processing of the DME, azimuth, and elevation signals to provide positions and ground velocities in both Earth-referenced and aircraft-carried vertical axes was conducted. No variations in processing or measuring characteristics were considered.

In addition to providing information concerning the helicopter's current position and velocity, processing of the guidance data is required to develop the necessary commands for these quantities. For this experiment, the vertical-position geometry and longitudinal deceleration profile commands were variables for investigation, and will be discussed subsequently in this paper. Laterally, a straight profile (instead of a curved or spiral one) was used, with the lateral velocity command being proportional to lateral displacement, thereby providing an exponential capture profile.

The longitudinal and lateral velocity commands were air-referenced before the onset of the deceleration, and ground-referenced for the remainder of the approach, with the switchover point being determined by the magnitude of the wind velocity. This switching logic is based on the procedure used in Ref. 12, and is one way of accounting for the fact that the magnitude of the wind velocity can be a significant fraction of the commanded helicopter velocity during deceleration approaches. Although compensating for the wind is fairly easy on the ground simulator (since the "wind" is known exactly), in an actual aircraft a wind estimator and a command procedure are required.[12]

Display Characteristics

One of the variables in this experiment was the manner in which the approach course and velocity-command information for the decelerating instrument task was presented to the pilot. Toward this end, a cathode-ray tube (CRT) display was used to present one of two electronic display formats in place of a conventional electromechanical attitude-director indicator (ADI).

The remainder of the instruments were arranged in a standard "T," with raw azimuth and elevation error plus

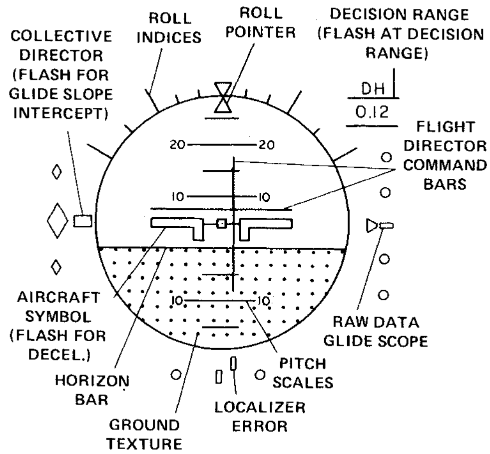
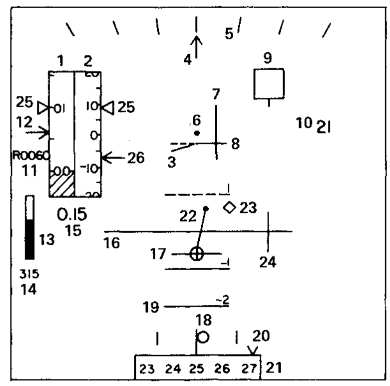


Fig. 1 Electronic display, C-format.



1. ALTITUDE TAPE
2. VERTICAL SPEED
3. THRUST MAGNITUDE CONTROL DIRECTOR
4. ROLL POINTER
5. ROLL INDEX
6. PITCH & ROLL STICK DIRECTOR INDEX
7. LATERAL STICK CONTROL DIRECTOR
8. LONGITUDINAL STICK DIRECTOR
9. LANDING PAD (APPEARS AT DECISION RANGE)
10. AIRSPEED
11. RADAR ALTITUDE
12. ALTITUDE INDEX
13. TORQUE
14. ROTOR RPM
15. RANGE
16. HORIZON BAR
17. AIRCRAFT SYMBOL (FLASH FOR DECEL)
18. SIDESLIP
19. PITCH ATTITUDE
20. WIND DIRECTION
21. HEADING SCALE
22. GROUND VELOCITY STATUS VECTOR (APPEARS AT DECEL.)
23. GROUND VELOCITY VECTOR COMMAND (APPEARS AT DECEL.)
24. LATERAL COURSE OFFSET
25. GLIDE SLOPE (FLASHES AT INTERCEPT)
26. IVSI

Fig. 2 Electronic display, X-format.

DME data shown in all cases on an electromechanical horizontal situation instrument (HSI) located below the CRT. The azimuth error data were scaled to give ± 5 deg full-scale error; the elevation error was scaled at ± 2 deg full-scale error before glide-slope intercept and ± 100 ft thereafter.

The two electronic display formats considered in this experiment are shown in Figs. 1 and 2. The C-format (Fig. 1) was effectively an electronic analog of an electromechanical ADI, and incorporated three-cue flight directors (longitudinal and lateral cyclic and collective) plus azimuth and elevation error. As such, it was representative of current electronic or electromechanical instruments (e.g., the instrument used in the flight experiment described in Ref. 7), although its slightly larger size as drawn permitted an increased scaling of pitch attitude (about 6:1 relative to the real world vs the approximate 8:1 scaling of a conventional 5-in ADI). Following the precepts outlined in Ref. 14, discrete command information was also included via the flashing of selected symbols: initiation of glide-slope intercept (flash collective director), initiation of deceleration (flash aircraft symbol), and attainment of decision height or range (flash preset decision height numerals).

Format "X" is shown in Fig. 2; it represents a possible "advanced" format incorporating a variety of status and command information in an integrated fashion. The particular format selected is taken from Ref. 14, although many aspects of it are similar to the helicopter electronic attitude-director indicator (EADI) proposed in Ref. 15. A complete description of the rationale for the design of this format is beyond the scope of this paper; Ref. 14 should be consulted for a complete discussion.

Several points are worth noting, however. First, the format was designed to permit decelerating approaches to an instrument hover, and therefore the amount of information (e.g., analog planform velocity and position information from the velocity vector and the landing pad) is probably too much for the task considered in this experiment; the intent was to ascertain whether those information requirements that derived from the most critical aspect (i.e., instrument hover) would be beneficial for other aspects of the approach. Second, note that the flight director and attitude data are separated to reduce clutter near the hover; the influence of this "separation" (even though both pieces of information are on the same display instrument) will be discussed in the Results section. Third, note that altitude and altitude-rate information error and status information are included on this central display. Reference 14 discusses the importance of these data and typical difficulties in presenting them; these moving tapes plus status and command indices are one possible solution.

Finally, this format includes redundant command information in the form of both three-cue control directors and separate velocity command presentations. These latter are: 1) a command diamond for the horizontal velocities, with the guidance being satisfied when the velocity vector tip is in the command diamond, and 2) a linked glide-slope indicator, with the guidance being approximately satisfied when the rate-of-climb is made equal to the value indicated by the linked symbol (Fig. 3). This redundancy implies that the pilot did not need to use the control directors to perform the decelerating task with this format.

For the three flight directors in both formats, the beam error and DME signals were processed to derive command signals as described above; from these, error signals were developed to drive the directors. The general intent in designing flight directors is to provide the pilot with

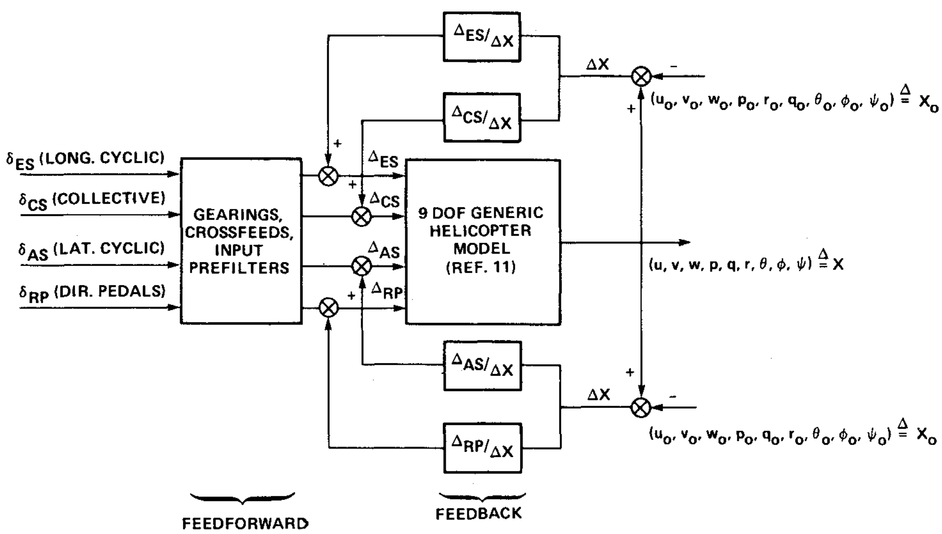


Fig. 3 Control system block diagram.

Table 1 Flight director gains (during deceleration)

Units	Rate damping	Rate command attitude hold	Attitude command
K_E, in./in.	1.0	1.0	1.4
$K_{\dot{x}}$, in./ft/s	−0.025	−0.025	−0.025
K_θ, in./rad	−1.38 (−3.12)	−1.67	−0.55
K_q, in./rad/s	−0.332 (−1.25)	−0.644	−0.210
K_y, in./ft	0.122	0.122	0.122
$K_{\dot{y}}$, in./ft/s	0.025	0.025	0.025
K_ϕ, in./rad	−2.6	−2.7	−0.34
K_p, in./rad/s	−0.45	−0.82	−0.07
K_A, in./in.	0.5	0.5	1.0
K_z, in./ft	−0.01	−0.01	−0.01
$K_{\dot{z}}$, in./ft/s	−0.056/−0.035	−0.056/0.035	−0.056/−0.035
K_{DC}, in./in.	0.34/0.26	0.34/0.26	0.34/0.26
K_C, in./in.	0.5/0.67	0.5/0.67	0.5/0.67
λ_C, 1/s	1.5/0.7	1.5/0.7	1.5/0.7
T_E, s	0.1	0.1	0.1
$T_{\theta_{WO}}$, s	10.0	10.0	10.0
T_A, s	0.1	0.1	0.1
$T_{\Phi_{WO}}$, s	∞ for $V > 20$ knots		
T_C, s	0.1	0.1	0.1

NOTE: CTAB gains functions of velocity; values at 60 knot/0 knot, linear between. EBAR gains for rate damping have second value investigated in parentheses.

"steering" commands that are easy for him to control and that provide good pilot-aircraft-gudiance closed-loop performance. For this experiment, the manual-control-theory approach (as used in Refs. 6 and 12) was again the basis for the design of the logic driving the director bars. Assuming that longitudinal stick (EBAR director) controls primarily speed, that collective stick (CTAB director) controls primarily rate of climb, and that lateral stick (ABAR director) controls primarily lateral course, the general equations driving the directors were

$$\mathrm{EBAR} = K_E\,[K_{\dot{x}}\epsilon_{\dot{x}_H} + K_\theta \theta_{WO} + K_q q]\,\frac{1}{T_E s + 1}$$

$$\mathrm{ABAR} = K_A\,[K_{\dot{y}}\epsilon_{\dot{y}_H} + K_\phi \phi_{WO} + K_p p]\,\frac{1}{T_A s + 1}$$

$$\mathrm{CTAB} = K_C\,[K_z\epsilon_z + K_{\dot{z}}\epsilon_{\dot{z}} + K_{DC}\delta_{C_{WO}}]\,\frac{1}{T_C s + 1}$$

where $\epsilon_{(\ )}$ indicates the difference between command and actual value, the commanded value of $\dot{y}_H$ was proportional to lateral error as noted above ($\dot{y}_{H_C} = -K_y y_H$), and the subscript WO implies a washed-out signal.

Table 1 lists some of the values of the gains and the washout time constants in the above equations as used in the experiment. To simplifly the table for the purposes of this paper, the gains for the error signals [$\epsilon_{(\ )}$] are given only for the glide-slope tracking portion of the approaches, where they were constants; these gains varied to give angular sensitivities before glide-slope intercept.

The following points concerning the design philosophy should be noted. First, as is evident in Table 1, the flight director gains vary as a function of control system. This variation is a result of the design objective to have the director commands respond in a constant manner over a wide frequency range (e.g., as an integrator for EBAR and ABAR), thereby requiring differing compensation depending on aircraft response characteristics. The use of angular rate terms in the equations implies increased sensitivity to turbulence[23] and for this reason a first-order filter at 10 rad/s was used on each flight director signal.

Second, note that two values of gains on pitch rate and attitude are given for the rate-damping control system. The smaller gains are consistent with the design philosophy used in Refs. 6 and 12, and imply a low-frequency equalization for the phugoid roots, whereas the higher gains imply an attempt to drive the phugoid roots to much higher frequency and damping; the reason for these two sets of gains will be discussed in the description of the experiment results. Finally, the CTAB director included a washed-out signal of the control input, so that the high-frequency response was proportional to control motion rather than to the integral of control motion. Recent work has appeared to indicate that this type of director response is preferable for noncontinuous control[24]; in Ref. 6, only very high frequencies showed this proportional response, but the design for this experiment resulted in proportional responses for frequencies above approximately 0.2 rad/s.

Aircraft Response and Control System Characteristics

The basic mathematical model used to simulate the flight dynamics of the helicopters investigated in this experiment was the same nine-degree-of-freedom model that was used in the previous studies.[4-6,8,9] The model explicitly includes the three-degree-of-freedom tip-path plane dynamic equations

Table 2 Transfer function charactersistics in form $(S+\lambda)\ (S^2+2\zeta\omega S+\omega^2) \Rightarrow (\lambda)(\zeta;\omega)$ (Δ = characteristic equation, N_j^i = numerator of *i*th state to *j*th control)

	Rate Damping	
$\Delta(s)$	=(5.6)(0.93;2.8)(0.009)(3.79)(1.35)(−0.009;0.21)	
$N^u_{\delta_{long}}$	=(5.6)(0.17;2.4)(0.94;2.8)(0.009)(1.32)	
$N^\theta_{\delta_{long}}$	=(5.6)(0.94;2.8)(1.25)(0.017)(0.007)	60 knots
$N^h_{\delta_{long}}$	=(5.6)(0.12;2.75)(0.93;2.83)(0.58;0.017)	
$N^h_{\delta_{coll}}$	=(5.5)(3.93)(0.01)(0.93;2.80)(0.19;0.24)	
$\Delta(s)$	=(5.9)(3.18)(0.63)(0.078)(3.71)(0.85)(0.051)(−0.048)	
$N^u_{\delta_{long}}$	=(6.0)(3.12)(0.60)(0.079)(0.09;2.3)(0.95)	
$N^\theta_{\delta_{long}}$	=(6.0)(3.17)(0.64)(0.076)(0.88)(0.0022)	30 knots
$N^h_{\delta_{long}}$	=(6.0)(3.17)(0.10;2.38)(0.65)(0.068)(−0.042)	
$N^h_{\delta_{coll}}$	=(5.9)(3.77)(3.17)(0.64)(0.008)(0.08)(−0.044)	
	Rate command/attitude hold[a] and attitude command	
$\Delta(s)$	=(0.72;3.25)(0.94;2.42)(0.68;2.09)(1.13)(0.055)	
$N^u_{\delta_{long}}$	=(0.72;3.24)(0.94;2.40)(1.32)(0.17;2.4)	
$N^\theta_{\delta_{long}}$	=(0.72;3.24)(0.94;2.40)(1.25)(0.0087)	60 knots
$N^h_{\delta_{long}}$	=(0.10;2.80)(0.72;3.24)(0.94;2.41)(0.011)	
$N^h_{\delta_{coll}}$	=(0.71;3.27)(0.67;2.02)(0.94;2.43)(0.06)	
$\Delta(s)$	=(0.73;2.94)(3.20)(0.76)(0.66;1.95)(0.90)(−0.002)	
$N^u_{\delta_{long}}$	=(0.73;2.89)(3.02)(0.74)(0.97)(0.11;2.23)	
$N^\theta_{\delta_{long}}$	=(0.74;2.88)(3.16)(0.76)(0.88)(0.0003)	30 knots
$N^h_{\delta_{long}}$	=(3.13)(0.75;2.89)(0.07;2.48)(0.76)(−0.045)	
$N^h_{\delta_{coll}}$	=(3.19)(0.72;2.95)(0.66;1.95)(0.76)(0.001)	

[a] Rate command attitude hold adds prefilter on δ_{long} of $s+2.0/s$.

for the main rotor,[25] and the six-degree-of-freedom rigid-body equations. The main rotor model consists of several major rotor-system design parameters, such as flapping-hinge restraint, flapping-hinge offset, blade Lock number, and pitch-flap coupling. Simulation of different rotor systems (e.g., hingeless, articulated, and teetering) can be accompanied by appropriate combinations of those design parameters.

The model is structured to permit full-state feedback to any of the four controllers (longitudinal and lateral cyclic, collective stick, directional pedals) plus control interconnects and gearings (Fig. 3). All feedback and control gains may be programmed as functions of flight parameters. This structure permits the construction of typical stability and control augmentation (SCAS) networks; it may also be used as a response-feedback, variable stability system to modify the basic characteristics of the simulated helicopter.

In the previous experiments, the rotor design and helicopter geometric parameters of the mathematical model were selected and tuned to simulate stability and control characteristics similar to those of the UH-1H, OH-6, and BO-105 aircraft, which use teetering, articulated, and hingeless systems, respectively.[4,5] For this experiment, only the generic teetering-rotor aircraft model was used with the variable stability aspect of the model employed to provide stable static stabilities in the longitudinal, lateral and directional axes. These baseline characteristics were retained for all the control system designs.

The three levels of SCAS, which comprised one of the main variables of this experiment, were implemented on the baseline configuration discussed previously. The three levels may be summarized as follows: 1) rate damping in pitch/roll/yaw with input decoupling, 2) item 1 plus pitch and roll attitude stabilization to provide pitch/roll attitude command, and 3) item 2 plus proportional-plus-integral prefilters in pitch/roll to provide rate-command-attitude-hold responses to commands. The resulting characteristic roots of the simulated configurations at 60 and 30 knots are given in Table 2.

The characteristics of these three levels of SCAS were designed on the following bases. The rate-damping, input-decoupled control system is the minimal level found in the previous experiments to be required for a clearly adequate constant-speed instrument approach capability.[4-9] Previous investigations of decelerating instrument approaches showed that this type of augmentation might be marginally suitable given a sufficiently good display,[14] although in general more complex types of augmentation appear to be required.[15] The levels of rate augmentation were somewhat higher than in the previous constant speed work.[6-9] Time constants of roughly 0.25 and 0.17 in pitch and roll, respectively, were the design goals (see Table 2).

The next two types of augmentation—rate-command-attitude-hold and attitude-command—were also examined in the previous experiments of this series. These types of augmentation are generally considered to be the minimum complexity necessary for a satisfactory decelerating instrument capability[14-16] and, in addition, were found necessary for ratings of satisfactory during constant-speed approaches.[9] In the previous experiments, the level of augmentation used was predicated on a design goal of undamped natural frequencies of approximately 1.5 rad/s.[6-8] For this experiment, increased levels of augmentation were used, with design guidelines of 2.0 and 3.0 rad/s undamped natural frequencies in pitch and roll, respectively, at 0.7 damping ratio (see Table 2).

As noted above, the levels of augmentation for each SCAS type were selected to be higher than in the previous constant-speed work, particularly laterally. In the lateral axes, the outer-loop control bandwidth is related to the lateral displacement velocity $\dot{y}$, which in turn depends on heading change by $\Delta\dot{y} \doteq V_0 \Delta\psi$. At lower speeds, therefore, larger heading changes are required for equivalent lateral displacement changes, implying a higher inner-loop bandwidth requirement on roll control. Longitudinally, it is not yet clear precisely what bandwidth is required. Ref. 26 hypothesizes inner-loop bandwidths of the order of 1.5 rad/s for a decelerating approach, but previous work has frequently considered higher levels.[14] In order to ensure that the inner-loop bandwidths would be above the minima required for the tasks considered in this experiment, therefore, the levels discussed above were selected. It is important to recognize, however, that further work is necessary to ascertain the minimal levels required.

Task Characteristics

Most of the previous investigations of decelerating instrument approaches considered a constant level of deceleration (usually about 0.05*g*).[14] As is pointed out in Refs. 14 and 15, however, no systematic investigation of the influences of the type of deceleration has been performed, and Ref. 15 summarizes a variety of other possibilities. For this experiment, the typical constant deceleration of 0.05*g* was compared to two other reasonable profiles suggested by the literature. The first, which was investigated in Ref. 27 for instrument decelerations, is a deceleration law of the form $\dot{x}_c = a(x+b)^{1/2}+c$, which is a modification of the constant-deceleration law that can be tailored to provide a nearly constant-pitch-attitude deceleration for helicopters; a constant attitude deceleration was used in Ref. 13 for helicopter instrument decelerations, after an initial look at the constant-*g* deceleration profile, and was found to require less control activity during the deceleration. As implemented in this experiment, this deceleration command was effectively constant-attitude (~4 deg change from 60-knot trim) initially, with a gradual reduction in attitude as range decreased, thereby leading to an exponential type of deceleration for the latter stages of the approach.

The second additional deceleration profile was derived from measurements taken of a large number of *visual* decelerations during flight operations of several helicopters.[28] The deceleration law is of the form $\dot{x}_c = a\{\exp[-b/(x)^{1/2}]\}$, which results in increasing deceleration with decreasing range; this form of deceleration can also be shown to be related to a simple model of pilot behavior involving perceived range.[26] It is frequently thought that a desideratum for instrument flight is to duplicate as nearly as possible conditions in visual flight, and this profile was proposed as one means toward that end.[28]

These three deceleration laws were considered for two vertical approach geometries, as shown in Fig. 4. One of these profiles is a conventional straight-in approach on a glide-slope of 6 deg, which terminates at an altitude of 100 ft at a distance

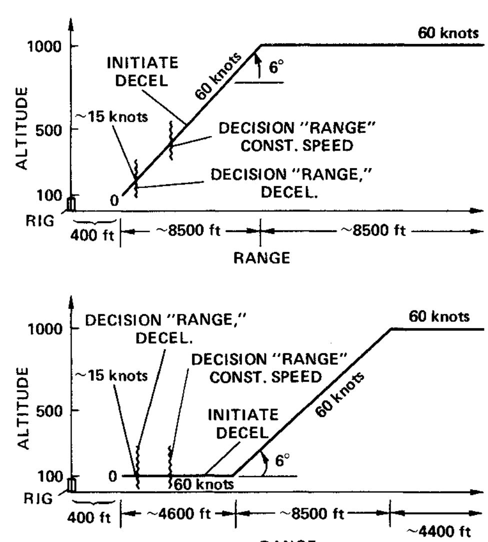


Fig. 4 Approach profile geometries.

of 400 ft from the landing spot. This approach profile is similar to the one used for the constant-speed approaches in the previous experiments of this series[6-9]; it is also representative of profiles used in most previous work.[14-16] The other profile incorporates a 6 deg descent much farther away from the landing pad, and then a long, level approach at 100 ft to the hover point. This approach profile is similar in most particulars to a type of approach being recommended for use in North Sea operations[29]; the question of interest between the two profiles is whether performing the deceleration while holding altitude constant is a simpler control task than performing it while descending.

Experiment Equipment and Procedures

The Ames Research Center Vertical Motion Simulator (VMS) ground-based simulation facility was used for this experiment. This facility includes a complex movable structure to provide six-degree-of-freedom motion, which is characterized by a large vertical travel capability (±30 ft) and hence good fidelity of vertical motion cues of up to 1*g* incrementally. For this experiment, it is likely that this level of motion fidelity was not required, since no large-amplitude maneuvers such as a missed approach were included in the task; the VMS, therefore, was used primarily for consistency in apparatus with the previous experiments. A visual scene from a terrain board was presented through the cab window on a color television monitor with a collimating lens. In this experiment, fog simulation was included for the instrument runs; it totally obscured the view of the terrain board before simulated breakout. An actual landing was not included in the evaluation.

The simulation situation was a two-engine transport category, single-rotor helicopter performing terminal-area operations in instrument meteorological conditions. No failed-condition situations were considered—the configurations represented normal operation of the particular models being simulated. The aircraft was considered to be a dual-pilot operation. Six pilots from four different government agencies performed the evaluations.

For each of the approach geometries discussed above, a constant-speed (60-knot) approach while on instruments (with visual deceleration) and the three types of instrument decelerations to a reduced decision height (corresponding to a velocity of about 15 knots) were examined. In the decelerating instrument approach cases the range at which breakout occurred was about 750 ft from the landing pad, corresponding to a decision height of 140 ft for the straight-in geometry. For each configuration, the pilot was told which geometry would be employed and whether a deceleration on instruments would be included, but not the type of deceleration.

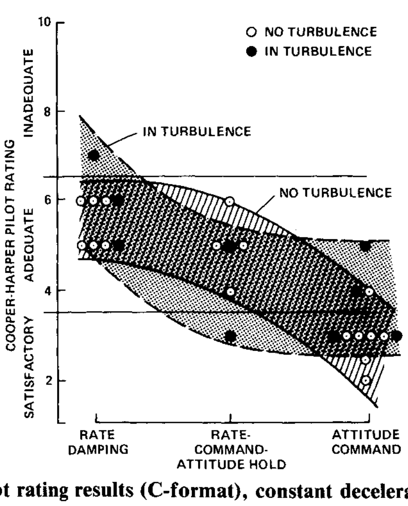


Fig. 5 Pilot rating results (C-format), constant deceleration in level flight.

The approaches were initiated about 3 n.mi. from the landing pad on a simulated oil rig, at a heading simulating radar vector intercept of the localizer, and at an altitude near the commanded altitude of 1000 ft. The evaluation consisted of two complete approaches, the first of which was a "free run" in visual conditions, with the second being the data run on instruments. At the conclusion of the instrument approach, a Cooper-Harper pilot rating[30] was assigned and comments made with reference to a comment card.

A final variable was turbulence level. The evaluations as described above were conducted in calm air during the first part of the experiment. During the latter part, selected configurations were repeated in wind conditions, including a representative level of turbulence (2.25 ft/s rms vertical, 4.5 ft/s rms horizontal) plus a 10-knot wind that sheared both 90 deg in azimuth at about 1 n.mi. out and from 10 to 2 knots between 200 and 0 ft altitude. For the evaluations in wind/turbulence, the pilot did not know what the calm air ratings were.

Pilot Rating Results

Because of the large number of possible combinations of variables and the comparatively small time period available for evaluations, attention was concentrated on the more conventional EADI format (Fig. 2) for most of the control system and approach-profile investigations. Furthermore, to reduce the scope for these investigations to a manageable level, one approach profile (long level-off with constant 0.05*g* deceleration commanded during the level-off) was emphasized for the control system investigation, with two control systems (rate damping and attitude command) used primarily to invesigate the influence of approach geometry and deceleration profile. The influences of these variables as determined by pilot ratings and comments are discussed in the succeeding paragraphs.

Consider initially the results shown in Fig. 5, which are for one display format (C-format), one approach geometry (deceleration during constant-altitude tracking at 100 ft), and one deceleration type (constant-0.05*g* deceleration). Starting with the ratings in no turbulence, rate damping only in pitch and roll was rated as adequate but not satisfactory. Pilot comments indicated considerable workload in pitch, with concomitant chasing of the speed director (EBAR), particularly during the deceleration, which in turn led to large altitude excursions. The use of attitude augmentation in pitch and roll, implemented to be an attitude-hold function, did not significantly improve the system capability. Although the concept of the attitude hold was to aid the long-term stability, the pilot comments (with one exception) did not indicate any awareness of this function; instead, the constant inputs to initiate the deceleration and track the speed director were commented upon as being similar to the overcontrol problems evident with rate damping only. To achieve ratings in the satisfactory category, pitch and roll attitude augmentation implemented as attitude-command charactersitics was required. The comments indicated good speed control before the deceleration and excellent tracking of the altitude and azimuth. As was suggested in Refs. 12 and 17, one of the advantages of attitude-command augmentation is the direct relationship between control force and aircraft attitude, which reduces the compensation required to command precise attitude changes to vary speed.

As can be seen in Fig. 5, the addition of the wind/turbulence level considered in this experiment led to a minor degradation in capability for these control systems. For the rate-damping system, the degradation is not as much as had been observed for constant-speed approaches, but the pilot comments indicate a larger decrease in performance and increase in compensation than is reflected in the ratings. It is possible that the lack of degradation is due in part to the low inherent gust sensitivity of the baseline teetering-rotor helicopter model and in part to the turbulence model used,[31] which scaled the gust filter break point with airspeed and may, therefore, have resulted in an unrealistically low spectral power at low airspeed. This latter possibility should be examined in the future with a turbulence model more directly oriented toward low speed flight. It is also worth noting that the crosswind did not result in ratings of inadequate, as was found in Ref. 12, probably because instrument hover was not included in the task. In this regard, pilot comments did describe heading control problems for all the configurations through the deceleration, irrespective of wind/turbulence. Reference 14 suggested that directional augmentation, including a heading-hold control system would be necessary; such directional augmentation, which might have improved the system capabilities, was not investigated in this experiment.

These results are generally consistent with those of previous helicopter and VTOL programs in which decelerating instrument approaches were investigated,[11-14] keeping in mind that previous results requiring display of translational velocities for instrument hover would not apply here because of the breakout to visual conditions. In fact, the results for the rate and attitude systems are in the same catgories (adequate-but-not-satisfactory and satisfactory, respectively) as the results of previous experiments in this series considering *constant-speed* approaches.[4-9] The rate-damping and attitude-command systems investigated in this experiment were evaluated also for a check-case constant-speed approach, and received average ratings in turbulence of 5.0 and 3.3, respectively; these ratings are consistent with the earlier work, and are about 0.5 to 1.0 rating better than the average of the decelerating approach results.

By comparing the ratings assigned to the rate-damping and attitude-command SCAS configurations for the two approach geometries and three types of deceleration profiles considered, the influence of these task characteristics can be investigated. This comparison is shown in Fig. 6, again for the C-format display and considering the data obtained in no turbulence; the check cases for a constant-speed instrument approach using the straight-in profile are also shown for comparison. Consider initially the influence of the approach-profile geometry. On the basis of the pilot ratings shown in Fig. 6, no significant difference between the acceptabilities of the two profiles considered is apparent. The level deceleration was modeled after a proposed procedure for operations in the North Sea, the hypothesis being that separating the deceleration from the descent task would simplify the pilot's control task and hence this profile would be preferable. According to the pilot comments, however, the requirement to maintain constant altitude close to the ground was at least as demanding a task as maintaining glide slope through the deceleration. Although the selection of a higher altitude for the deceleration might have ameliorated this problem, the goal of reduced weather minima would then be compromised.

Similarly, little significant difference was found among the three deceleration profiles considered (Fig. 6). Pilot comments indicated that a difficulty with the constant-level and constant-attitude-exponential profiles as implemented was the rapid onset of the commanded attitude change. As a result, the initial attitude change was often overshot, with the effective command appearing to the pilot as requiring two or three attitude changes initially. The more gradual onset of the commanded deceleration for the increasing-deceleration profile alleviated this difficulty, and the requirement for an increasingly nose-high attitude near the end of the approach did not receive any adverse comments. For an operational system, therefore, careful tailoring of the initial deceleration command is implied, but some latitude in the selection of the overall profile appears possible.

Another question of interest in this experiment was the influence of the display format. As was discussed earlier, the X-format was an attempt to add further data to the conventional EADI information in an integrated fashion; specifically, data concerning heading, altitude and altitude

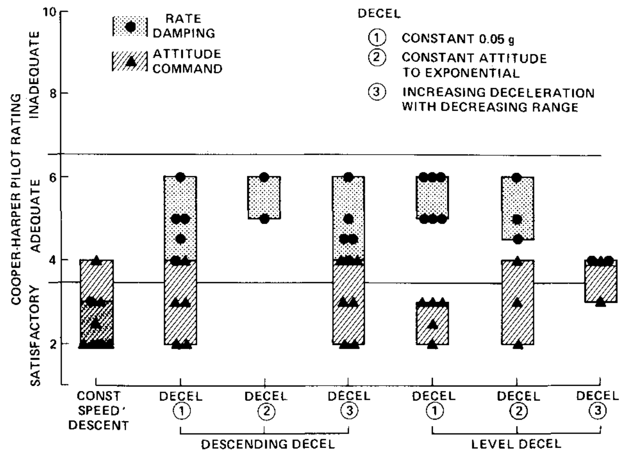


Fig. 6 Pilot rating results as functions of task (C-format).

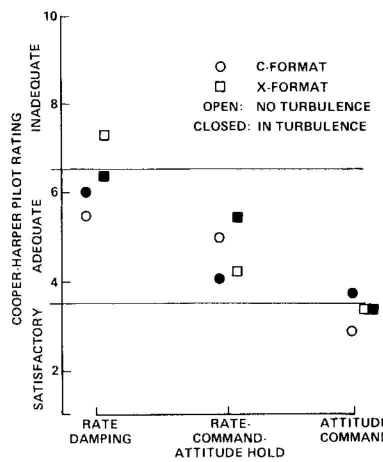


Fig. 7 Average pilot ratings, constant deceleration in level flight.

rate, and ground velocity were added to the flight director, attitude, and tracking-error data of a baseline EADI. Because of the limited time available, the X-format was examined almost entirely for only one approach geometry/deceleration profile: level deceleration, constant 0.05g deceleration level. The pilot ratings for this investigation are shown in Fig. 7, where they are compared with the ratings for the conventional C-format. As can be seen, the average rating with the integrated format when compared with that for the conventional format is somewhat worse for the rate-damping control system and approximately equivalent for the attitude-command system. Pilot comments generally indicated a preference for the conventional C-format with the rate damping SCAS because of the coincident display of attitude reference and flight director information; the separation of these two inner-loop information presentations in the integrated X-format was considered a serious drawback when the aircraft attitude control was difficult. For the task considered in this experiment, the display of analog velocity and landing-pad position data was not considered particularly useful, and the scan from the director bars to sideslip and heading information was considered too large. The manner of presenting altitude-rate information was considered good, with the data easy to assimilate. It is important to note that a learning process was evident for the X-format, with comments and performance improving with increased exposure. In this regard, the pilot comments indicated that, initially, the flight directors were used almost entirely in lieu of the other velocity-command information given on this format; in effect, therefore, the pilots initially flew this format as they had the C-format, thereby accentuating the difficulty caused by the separated displays of director and attitude information. With more exposure to the format, the comments changed to include more awareness and appreciation of the velocity-command information, particularly for height control. Nonetheless, for the task considered in this experiment, which included a breakout to the visual conditions before the hover, the conventional C-format display with three-cue flight directors but limited velocity and position status information was found to be suitable.

One final aspect of the display information as examined in this experiment is worth noting. As was discussed earlier, most of the evaluations with the rate-damping control system were conducted using a pitch flight director that included low-frequency equalization to stabilize the phugoid. With this design technique, a low-frequency oscillation in speed was evident for most of the evaluations of this control system, and pilot comments noted that the director appeared to be oscillatory and to require significant pitch inputs. A very limited investigation of a philosophy using a much higher ratio of attitude-to-speed information in the pitch director was conducted at the end of the experiment. This latter philosophy eliminated the low-frequency tracking oscillation, and resulted in pilot rating changes varying from no change to two pilot rating units, depending on the pilot. The important point is that the performance of those systems that have stability or control difficulties is much more sensitive to the details of the flight director design than is the performance of benign systems (e.g., attitude command), and the results of this and other experiments for such systems should be considered in this light.

Concluding Remarks

This piloted-simulator experiment was conducted to examine the influence of stability-control augmentation, display information format, and approach-task effects on helicopter flying qualities for terminal-area operations incorporating a deceleration in instrument meteorological conditions. Simulated test configurations were evaluated for precision approaches with an instrument deceleration from 60 to about 15 knots in both calm air and simulated moderate turbulence and wind shear.

Predicated upon the characteristics of the simulated helicopter with the stability-control augmentation systems as designed, the following conclusions may be drawn from the results and interpretations of this experiment:

1) Attitude-command augmentation in pitch and roll was rated marginally satisfactory for the decelerating task in wind and turbulence. Rate-damping augmentation was rated marginally adequate for the decelerating task. These results are consistent with those of earlier experiments in which decelerating approaches were considered. Further, although the pilot ratings indicate a reduced capability relative to the constant-speed approaches considered previously, these results are consistent with the general conclusions for constant-speed helicopter instrument operations, thereby indicating that the decelerating task considered in this experiment was not significantly more difficult for a pilot to perform than a precision constant-speed appraoch.

2) No advantage, in terms of pilot rating, was shown for approaches in which the deceleration occurred during a long level-off at the end of the approach. Decelerating while tracking a 6 deg glide slope was rated to be equally easy.

3) In terms of task difficulty, there was very little difference among the three deceleration profiles considered.

4) For the task considered in this experiment, which did not include instrument hover, no significant advantage was shown for an integrated display format that included velocity and position status information. An electronic analog of a conventional attitude indicator with tracking error and three-cue flight direction information was found to be suitable for decelerating instrument approaches with a breakout before hover.

Because the type of stability-control augmentation system had the dominant influence on the pilot ratings obtained for the tasks and displays considered in this experiment, it is important to emphasize that the dynamic characteristics of these types of control systems require further examination. These characteristics also have an impact on the requisite guidance design, since in many cases the flight director laws effectively require the pilot to supply compensation for insufficient inner-loop aircraft bandwidths; in this experiment, the acceptability of lower levels of augmentation was found to be very sensitive to the director design, implying that only a limited tradeoff between the aircraft dynamics and display compensation exists. Since the bandwidths of the inner-loop control channels depend on the outer-loop requirements dictated by the details of the task, a careful investigation of the minimum required levels as a function of the task, as well as a similar determination of minimal outer-loop bandwidths provided by other types of control systems incorporating velocity augmentation, is warranted.

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