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Investigation of Control, Display, and Crew-Loading Requirements for Helicopter Instrument Approach

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A ground simulation experiment was conducted on the Ames Research Center Flight Simulator for Advanced Aircraft to investigate the influence and interaction of flight-control system, flight-director display, and crew-loading situation on helicopter flying qualities during terminal-area operations in instrument conditions. Six levels of control complexity, ranging from angular rate damping to velocity-augmented longitudinal and vertical axes, were implemented on a representative helicopter model. The six levels of augmentation were examined with display variations consisting of raw elevation and azimuth data only and of raw data plus one-, two-, and three-cue flight directors. Crew-loading situations simulated for the control-display combinations were dual-pilot operation (full attention available for control), and single-pilot operation (representative auxiliary tasks of navigation, communications, and decisionmaking). Four pilots performed a total of 150 evaluations of combinations of these parameters for a representative microwave landing system (MLS) approach task. Pilot rating results indicated the existence of a control display trade-off for ratings of satisfactory, whereas ratings of adequate-but-unsatisfactory depended primarily on the control system; the control system required for ratings of adequate-but-unsatisfactory was clearly more complex for the single-pilot situation than that for the dual-pilot situation.

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 to apply new technologies or concepts to resolve them. For example, various government agencies have initiated long-term research efforts for helicopters (e.g., Ref. 1). One area of particular interest is instrument flight at low altitudes in all-weather conditions. 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 ensure a good IFR capability, and with regard to the characteristics that should be required for certification.

To determine these influences, a joint program has been instituted to investigate helicopter IFR certification criteria. This series of investigations has the following two general goals:

1) To provide analyses and experimental data to ascertain the validity of the Airworthiness Criteria for Helicopter Instrument Flight,[2] which have been proposed as an appendix to FAR Parts 27 and 29.[3,4]

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

The first two ground simulation experiments of this series concentrated on the influences of static stability characteristics, and stability and control augmentation system (SCAS) requirements on helicopter flying qualities for a nonprecision VOR (very-high-frequency omnidirectional range) instrument approach task.[5,6] Cooper-Harper pilot rating (CHPR) results indicated 1) the need for some level of SCAS above the bare airframe to ensure a level of adequate performance with tolerable workload (CHPR < 6.5),[5] 2) the requirement for attitude augmentation in pitch and roll to obtain a level of satisfactory (CHPR < 3.5),[5,6] and 3) the acceptability of neutral longitudinal and lateral static stabilities.[6] Because these data were obtained in an experimental environment that did not require auxiliary tasks, these results are applicable only to dual-pilot crew-loading situation. Further, because the proposed IFR Appendix does not consider the influence of displays, only raw data error displays were examined.

With regard to the influence of crew loading, the proposed criteria have different requirements for single-pilot certification of normal category helicopters than for the dual-pilot case, although no distinction is made for transport category. An alternative proposal, in fact, would eliminate the distinction between normal and transport category helicopters, but expand the differences in requirements for single-pilot and dual-pilot certifications.[7] This desired distinction is important because most of the data used to develop the criteria are based on research conducted as in Refs. 5 and 6 (i.e., no auxiliary tasks), and, hence, the influence of the higher cockpit workload inherent in the single-pilot situation needs to be ascertained. For this reason, one objective of the experiment described in this paper was to define this influence in a realistic context.

As was noted above, the proposed IFR Airworthiness Appendix does not address the influence of displays on instrument meteorological conditions (IMC) flying qualities. It has been shown, however, that a trade-off between control complexity and display sophistication exists in a generic sense for VTOL IMC operations[8]; a variety of helicopter applications concerned with this fact is reviewed in Ref. 9, and a recent ground simulation experiment addressed this trade-off

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again in the helicopter context.[10] In terms of certification, the question is whether relaxed flight dynamics requirements might be considered if some "credit" is allowable for display assistance, such as flight directors. For this reason, a second objective of this experiment was to define the control-display trade-off in this context.

In the first two experiments, attitude augmentation in both pitch and roll was found to be necessary to achieve pilot ratings of satisfactory (CHPR < 3.5) when only raw data displays were used.[5,6] In conjunction with determining whether flight directors might modify this conclusion, lower levels of SCAS may be reasonably considered. Further, assuming a baseline helicopter with poor speed-control characteristics (e.g., neutral longitudinal static stability), the influence of more complex augmentations to include velocity loop closures is of interest. Hence, a third objective was an examination of the influence of several levels of SCAS for both single-pilot and dual-pilot applications.

To summarize, based on the considerations outlined above, this experiment had the following three specific objectives:

1) Define, in a realistic context, the difference in required control-display parameters for a single-pilot vs a dual-pilot situation.

2) Define the extent of the control-display tradeoff for a helicopter, assuming several levels of display sophistication (status only, and status plus flight directors).

3) Examine the influence on pilot rating of a range of helicopter SCAS concepts.

The range of parameters designed to achieve these objectives is discussed in the following sections, followed by a description of the results.

Flight-Control Characteristics

Mathematical Model

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.[5,6] The model explicitly includes the three-degree-of-freedom tip-path plane dynamic equations for the main rotor,[11] 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 accomplished 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. All feedback and control gains may be programmed as functions of flight parameters, such as airspeed. This structure permits the construction of typical 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-6A, and BO-105 aircraft, which use teetering, articulated, and hingeless rotor systems, respectively.[5,6] For this experiment, only the generic teetering rotor aircraft model was used to reduce the scope to a manageable level. Because neutral longitudinal and lateral static stabilities had been found adequate (but not satisfactory) in the previous experiment,[6] the generalized feedback structure was again used to achieve these neutral static stabilities for this experiment. Longitudinally, the neutral static stability plus the very low drag damping (X_u) of the model as simulated (hence very flat attitude-to-speed relationship) were expected to emphasize speed-control problems during the approach. The influence of a neutral lateral static stability was shown in the previous experiment to be minor.[6] These baseline characteristics were retained for all the control system designs.

SCAS Configurations

The six levels of stability and control augmentation, which comprised one of the main variables of this experiment, were implemented on the baseline configuration discussed above. They were designed to address various control aspects of the precision instrument approach as well as to span the range considered in previous experiments. The six levels may be summarized as follows: 1) rate damping pitch/roll/yaw; 2) number 1 plus pilot-releasable wing-leveler (roll attitude stabilization); 3) number 2 plus input decoupling of pitch-collective, yaw-collective; 4) number 3 plus pitch attitude command; 5) number 4 plus pitch/roll integral prefilters to provide rate-command-attitude-hold; and 6) number 4 plus augmented vertical damping (no altitude hold, however), releasable longitudinal velocity hold.

The resulting characteristic roots of the simulated configurations at 60 knots are given in Table 1.

These six levels of SCAS design were selected for the following reasons. The basic rate damping is a minimum level of SCAS found in Ref. 5 to be required to achieve IMC ratings of adequate for the teetering-rotor configuration; the levels of rate damping used in this design are smaller than the Ref. 6 designs and are more consistent with limited-authority implementations. The next level of augmentation added to the rate-damping baseline a roll attitude feedback, implemented through an "SCAS Release" button on the cyclic to disable it for maneuvering. This system is similar to the one investigated in Ref. 12; it was intended to relieve the pilot of roll stabilization requirements once on the localizer. In the Ref. 12 experiment, this simple SCAS addition was considered to provide a noticeable improvement to the IMC capability.

The next three levels of SCAS are consistent with the investigation of Ref. 6, although again the actual levels of feedback used are closer to those of Ref. 5. By using control cross-feed gearings, the off-axis accelerations from a given controller can be minimized; this type of addition has been shown to provide a significant improvement to the IMC capability for some rotor types.[5,6] Attitude augmentation in both pitch and roll, implemented as either attitude command or rate-command-attitude-hold, has been shown in previous ground-simulation experiments to be required to achieve pilot ratings (for a dual-pilot situation) of satisfactory.[5,6] In this experiment, they were designed to achieve undamped natural frequencies of 1.5 rad/s, which was lower than that used previously,[5,6] but the level recommended in Ref. 9. Of interest in this experiment, therefore, was the question of whether these types of augmentation would be sufficient for ratings of satisfactory in the single-pilot case.

The final level of SCAS added translational velocity augmentation to the attitude command control system (Fig. 1). A shortcut approximation to a rate-of-climb-altitude-hold system was made by feeding back vertical velocity to the

Table 1 Characteristic roots in form $(s+\lambda)(s^2+2\zeta\omega s+\omega^2) \Rightarrow (\lambda)(\zeta;\omega)$

SCAS	Characteristic roots
Rate damper	(5.81)(2.80)(0.87; 2.16)(0.06; 0.06) (1.54)(−0.003)
Rate damper, wing leveler	(5.37)(2.80)(0.87; 2.18)(0.06; 0.06) (1.54)(0.38)
Rate, wing level, input decouple	(5.38)(2.78)(0.87; 2.19)(0.07; 0.06) (1.56)(0.38)
Attitude command	(5.37)(0.014)(0.87; 2.18)(0.91; 1.94) (0.78)(0.39)
Rate command attitude hold	Attitude command plus prefilter
Velocity augment, velocity hold	(5.40)(0.88; 2.24)(0.98; 2.14) (0.66;0.61)(0.38)

collective, and increasing the collective control sensitivity; the resulting vertical "time constant" $(1/Z_w)$ was approximately 0.5 s. Longitudinally, velocity was fed back to both the longitudinal cyclic and collective, with the intent being to increase the effective phugoid frequency (M_u) and partially decouple any lift-change due to speed $(Z_u \to 0)$. The longitudinal velocity loops were implemented through the "SCAS Release" switch to enable large velocity changes to be made; hence, the system was velocity-hold rather than velocity-command. This control system, therefore, was investigated to reduce the speed-control workload for the pilot, and to provide improved glide-slope tracking through fairly sophisticated feedbacks.

Guidance and Display Characteristics

Another major variable in this experiment was the manner in which the approach course information for a 6 deg precision microwave landing system (MLS) approach was presented to the pilot. Four levels of display "sophistication" were examined: 1) azimuth angular error, elevation angular error, and DME (see below); 2) number 1 plus collective stick control director (to assist elevation control)—one-cue director; 3) number 2 plus lateral cyclic stick control director (to assist azimuth control)—two-cue director; and 4) number 3 plus longitudinal cyclic stick control director (to assist speed control)—three-cue director.

Figure 2 shows the location of the attitude-director indicator (ADI) incorporating the flight director needles and the horizontal situation indicator (HSI) incorporating the elevation, azimuth, and distance measuring equipment (DME) indicators used in this experiment. The following paragraphs describe the simulated guidance and flight-director information.

As will be described in the next section, four different, but geometrically similar, approaches to an offshore oil rig were considered in this experiment. For all cases, MLS elevation and azimuth-range transmitters were assumed to be colocated on the rig. The MLS guidance was chosen as a simple analog of a modified conventional approach; that is, only a straight centerline with angular error beam was considered. Based on flight tests with a UH-1H helicopter against an MLS,[13] a 6 deg steep approach with ±2 deg full-scale elevation error, and ±5 deg full-scale azimuth error beams were used for the guidance data.

For the three flight directors, the beam error and DME signals discussed above were processed to define command and error signals for the director needles. Following the approach used in Ref. 8, generalized velocity and position commands were derived, using the MLS data resolved into a general rectangular coordinate system with origin at the decision height. These commands, as well as the actual velocities, were then resolved into an aircraft-heading referenced vertical frame for presentation on the director needles.[14]

The horizontal velocity command included a deceleration from 80 knots to 60 knots prior to glide-slope intercept, and a correction for wind to provide a constant airspeed for the approach; although done easily on the ground simulator (the "wind" is exactly known), in an actual aircraft a wind estimator and command procedure, as discussed in Ref. 8, would be required. The vertical command consisted of a constant altitude command, rounded-off glide-slope intercept command, and a 6 deg glide-slope command to the decision height; this command was implemented as consistent altitude and altitude-rate commands based on horizontal distance from the decision height. Finally, the lateral (with respect to the approach centerline) velocity command was simply proportional to lateral displacement, thereby providing an exponential capture profile.

The general intent in designing flight directors is to provide the pilot with "steering" commands that are easy for him to control, and that provide good pilot-aircraft-guidance closed-loop performance. For this experiment, the manual control theory approach (as used in Ref. 8) was again the basis for the design of the logic driving the director bars; this design procedure, based on pilot-model considerations, has also been used for STOL and VTOL vehicle experiments.[15,16] Assuming that longitudinal stick (EBAR director) controls primarily speed, 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:

$$\mathrm{EBAR} = K_{\dot{x}}\epsilon_{\dot{x}_H} + K_\theta \theta_{\mathrm{wo}}$$

$$\mathrm{ABAR} = K_{\dot{y}}\epsilon_{\dot{y}_H} + K_\phi \phi_{\mathrm{wo}} = K_{\dot{y}}(K_y y_H - \dot{y}_H) + K_\phi \phi_{\mathrm{wo}}$$

$$\mathrm{CTAB} = K_z \epsilon_z + K_{\dot{z}}\epsilon_{\dot{z}} + K_{\delta_c}\delta_{c_{\mathrm{wo}}}$$

where $\epsilon_{(\,)}$ indicates the difference between commanded and actual values, the commanded value of $\dot{y}$ was proportional to beam error as noted above, and the subscript "wo" implies a washed-out signal of pitch or roll attitude or collective stick position.

Table 2 gives the values of the gains and the washout time constants in the above equations as used in the experiment for

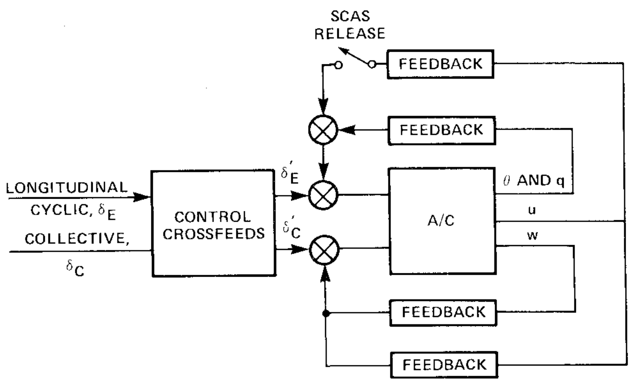

Fig. 1 Schematic of velocity-hold SCAS.

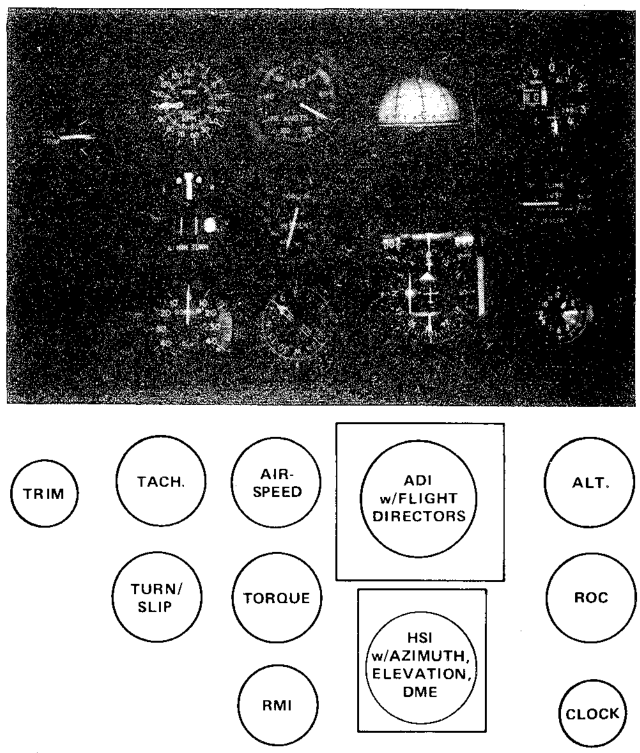

Fig. 2 Flight instrument and radio control panel arrangement.

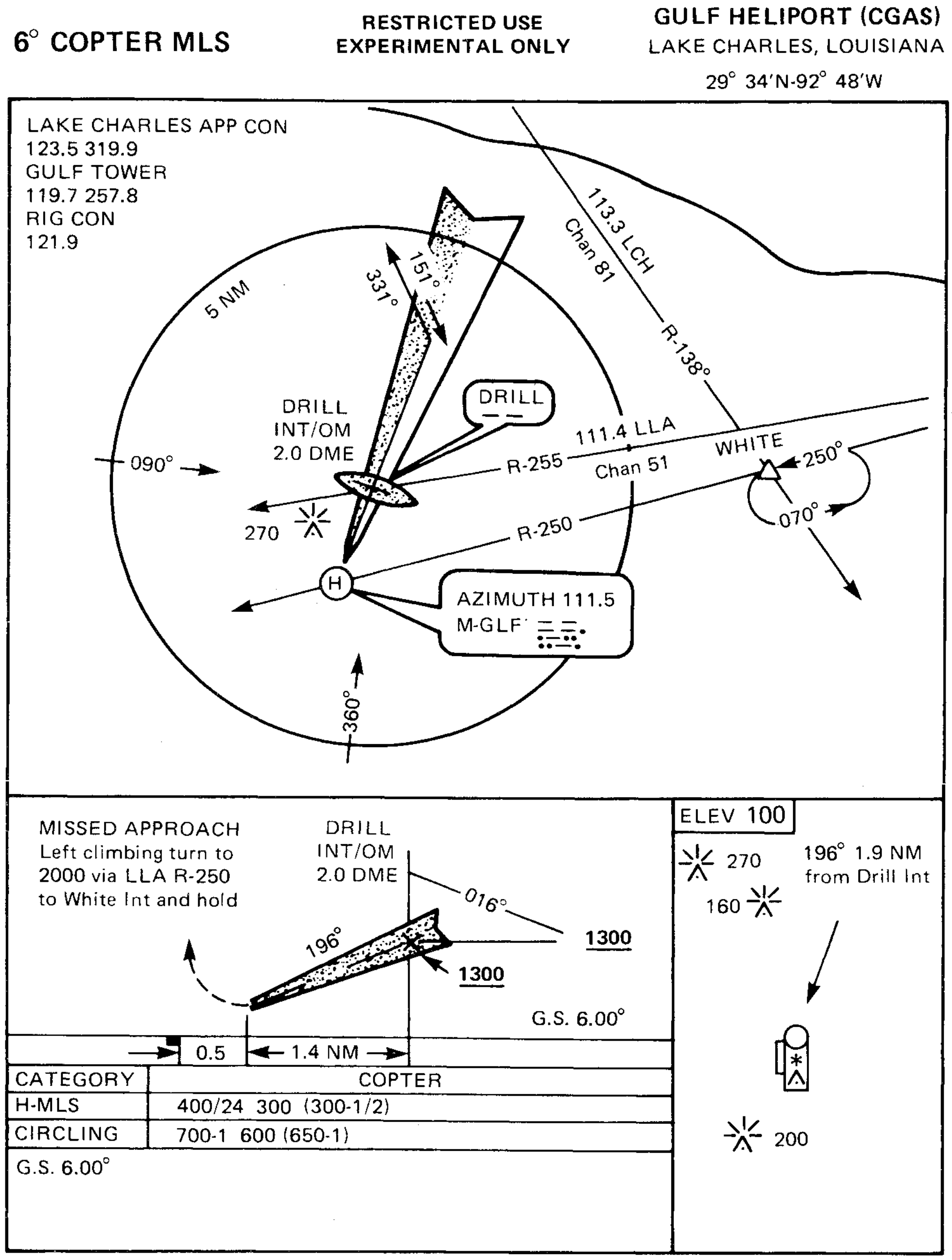

Fig. 3 Example of MLS approach plate.

the approach mode of the flight directors; a more complete description of the design logic and resulting characteristics is given in Ref. 14. Simpler gains commanding a constant 60-knot speed, 10 deg banked turn, and 600 ft/min climb were available as a "go-around" mode for missed approaches. The following differences in philosophy from the previous work[8,15,16] should be noted. First, angular rate signals in EBAR and ABAR were not used in this experiment, even though, as a result, the high-frequency characteristics of the directors therefore departed from the ideal; use of these rate signals was eschewed because of the response to turbulence they introduce.[17] Because the high-frequency characteristics of these directors were permitted to depart from the ideal, the other gains did not have to vary with control-system characteristics, as was done in Ref. 8. Secondly, 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,[18] and the pilots in this experiment agreed. Finally, note in Table 2 that the gains vary linearly with range for the 6 deg glide-slope portion of the approach; hence they produce effectively constant *angular* sensitivities. The technique used in the other work consisted of constant displacement sensitivities,[8,15,16] which maintain constant closed-loop performance; as a result, however, they require a tradeoff in desired performance between the initial and final stages of the approach.

Crew-Loading Characteristics

The third major variable of this experiment was crew loading. To address, in as realistic a context as possible, the influence of auxiliary tasks on the required control-display combinations, each of the control-display configurations defined by the variables described above was evaluated for both simulated dual-pilot and single-pilot situations. The dual-pilot situation was consistent with the scenario of the majority of flying qualities experiments: the pilot's sole task was to track the MLS or flight-director commands, with no auxiliary tasks of communications or navigation. In addition, the pilot knew in advance that a missed-approach maneuver (with no other tasks) would be initiated at the decision height. In single-pilot situations, the pilot always had to communicate with Approach Control and Tower, set a transponder frequency, and switch communication frequencies; for approaches including a missed approach, he also had to switch communication frequencies again, copy a clearance from Departure Control, switch navigation and transponder frequencies, and track to a VORTAC. Radio "chatter" from two other helicopters in the area was simulated. To provide a lack of repetition, four different approach plates to four oil rigs were devised, with different frequencies and alternates for each plate (e.g., Fig. 3); these four possibilities were mixed randomly among the control-display combinations. Finally, on the single-pilot approaches, the pilot did not know whether he would be able to continue the approach or be forced to do a missed approach; the simulated fog was made to start clearing at 100 ft above the decision height and then to either re-fog or continue clearing just below decision height. As a result, the pilot had to make the decision whether to continue.

To summarize, an attempt was made to provide a *realistic* single-pilot situation, in terms of auxiliary tasks, as well as the more usual full-attention (dual-pilot) simulation. In general, each configuration was therefore evaluated by a given pilot three times: 1) dual-pilot with missed approach, 2) single-pilot with missed approach, and 3) single-pilot with continued approach. The single-pilot auxiliary tasks consumed about 60% of the overall time of the approach. No effort was made to vary the auxiliary task loading to ascertain at what point performance would start to deteriorate; instead, a given level, which was assumed high enough to influence performance-workload, was maintained constant for all configurations.

Table 2 Flight director gains (approach mode)

$K_{\dot{y}}$, cm/m/s	+0.312 at range[a] = 0, +0.088 at range = 5357, linear between
K_{ϕ}, cm/rad	−3.81
$K_{\dot{x}}$, cm/m/s	−0.156
K_{θ}, cm/rad	−3.05
K_z, cm/m	−0.125 at range = 0, −0.0325 at range = 2612, linear between, constant at −0.0325 beyond 2612
$K_{\dot{z}}$, cm/m/s	−0.149 at range = 0, −0.0375 at range = 2612, linear between, constant at −0.0375 beyond 2612
K_{δ_c}, cm/cm	0.188
T_{θ}, s	10.0
T_{ϕ}, s	10.0
T_{δ_c}, s	0.77

[a] Range from decision height location, *m*.

Experiment Equipment and Procedures

The Ames Research Center Flight Simulator for Advanced Aircraft (FSAA) ground-based simulation facility was used for this experiment. It includes a complex movable structure to provide six-degree-of-freedom motion and a visual scene from a terrain board presented through the cab window on a color television monitor with a collimating lens. In this experiment, fog simulation was included, which obscured totally or partially the view of the terrain board except during a brief visual "free run" at the beginning of each evaluation. An actual landing was not included in the evaluation.

Figure 2 shows the flight instruments used in the simulation. All instruments were conventional, with the exception of the attitude indicator, which was a 5-in. ("three-axes ball") unit incorporating heading (through longitudinal lines on the ball) as well as pitch-roll information. The navigation and communication radio-heads were located well to the left of the central instrument cluster, requiring a long reach for the pilot; the transponder head (not visible in the figure) was located in a center console next to the collective stick. Additionally, switches to select "approach" or "go-around" modes for the flight directors were also located to the left of the central instrument cluster.

For this experiment, the evaluations were performed by four pilots from four different government agencies; all were helicopter rated with instrument flight time. The specific tasks to be accomplished for each configuration were as follows:

1) "Free-run" in visual conditions, either at altitude or practice MLS approach.

Table 3 Ratings of pilots A, B, and C

		Pilot ratings								
		Dual-pilot			Single-pilot, missed approach			Single-pilot, continued approach		
Control	Display	A	B	C	A	B	C	A	B	C
Rate damper	Raw data	5	6	5.5	6	7.5	7	5		6
	1-axis	7			8			7		
	2-axis	5	6	4	7	7.5	5.5	6	6.5	5.5
	3-axis	5	5	5.5	6	8	7		7	6
Rate damper, wing leveler	Raw data	4		4	7		4.5	6		4.5
	1-axis	5			6			6		
	2-axis	5.5	4	4	7	7	5	6		
	3-axis	4	6	4.5	6	8	6	6	5	5.5
Rate damper, input decouple, wing leveler	Raw data	4	7	4	5	8	5.5	4	8	5.5
	1-axis	4,5		3	4,6		5	4		5.5
	2-axis	3,4	4.5		8,5.5	6		3	6	
	3-axis	4	5	2	4	6	4	5	6	4
Attitude command	Raw data	4	5	3	4	6.5	4		6	3
	1-axis		4			5.5			5.5	
	2-axis	4.5	3	2.5	5	4	2	4.5	4	2
	3-axis	3	2	2.5	4	2.5	3.5	4	2.5	4
Rate-command-attitude-hold	Raw data		4	1.5		4	2.5			
	1-axis									
	2-axis	3.5	3	1.5	5	3	2.5			
	3-axis	3			3.5					
Velocity hold	Raw data	4.5,5	4	2	4,5	5	2.5	4,4.5		2
	1-axis		3			3.5			3.5	
	2-axis	4	3		4	3			3	
	3-axis	3	2		4	2.5		4	2.5	

2) Dual-pilot IMC approach and missed approach in representative turbulence,[6] assign Cooper-Harper pilot rating,[19] and make comments in response to a comment card.

3) Single-pilot IMC approach in representative turbulence with reference to one of four approach plates, either continue approach or execute missed-approach procedure, assign Cooper-Harper pilot rating, make comments.

4) Same as 3, except the other option at the decision height usually would be provided.

The approach elements consisted of MLS azimuth capture at 80 knots and approximately 1200 ft, a deceleration to 60 knots, capture of a 6 deg glide-slope and tracking at 60 knots, and execution of either a missed approach or the initiation of a deceleration to the hover pad, depending on crew-loading and visual conditions at the decision height. As has been discussed in the single-pilot cases, communications, frequency changing, chart reading, and clearance copying (for missed-approach cases) were included. In addition, for all runs (single- and dual-pilot), a representative level of turbulence (1.5 ft/s rms vertical, 3.0 ft/s rms horizontal) was included plus a 10-knot wind, which changed direction a total of 90 deg from one side of the approach to the other during the final 500 ft.

Pilot Rating Results

Data obtained in this experiment consist of pilot ratings and commentary for each configuration, and measurements of performance indices and control usages for each approach. An example of the performance data, which are standard deviations of selected variables for 35 s of the final approach, is given in Fig. 4. As can be seen, the trend of these performance indices with changing control system or crew loading is minor; the major difference in the example shown is between the raw data and three-axis flight director displays for azimuth and elevation tracking. In all cases, the standard deviations of the tracking errors are within the same "acceptable" limits (e.g., one "dot" for elevation and azimuth, which corresponds to ±1 deg and ±2.5 deg error, respectively). This relative insensitivity is typical of manned flight data (e.g., Ref. 8), emphasizing the pilot's adaptive control behavior to achieve the required performance. For this reason, this paper concentrates on the pilot rating data and their implications; further discussion of the performance-usage data may be found in Ref. 14. The presentation and discussion of the results is primarily in terms of averaged pilot ratings, which is done for simplicity in considering the major trends. It is recognized, however, that the Cooper-Harper scale is ordinal rather than interval,[19] and caution must be exercised when a large spread of ratings is averaged; in this experiment, a total spread of ±1 CHPR was rarely exceeded for a given configuration among the four pilots.

Figures 5-7 are "plots" of the average pilot ratings given to the control-display combinations described earlier for the dual-pilot, single-pilot with missed approach, and single-pilot-with-continued-approach crew-loading precision instrument approaches, respectively. Table 3 lists the actual ratings as assigned. To assist in ascertaining trends, the configuration blocks are shaded according to groups of pilot ratings as indicated in the legend; it is emphasized that any indicated trends apply only to the configurations specifically examined in this experiment.

The two extremes in the data were the dual-pilot loading situation and the single-pilot-with-missed-approach situation. Considering only these two sets of data for simplicity, therefore (Figs. 5 and 6), the first point to note is that the control-display combinations required to achieve pilot ratings of satisfactory (CHPR ≤ 3.5) are substantially the same for both the dual-pilot and single-pilot situations; there is little apparent influence of crew loading on the characteristics required for minimal pilot compensation. Pilot comments indicate that to achieve ratings of satisfactory for single-pilot operation, the pilot must be able to look away from the instruments or release a control and still find the aircraft at approximately the same state when he returns his attention to it. It is apparent that this same stability in all axes in dual-pilot operation permits increased attention to precision compensation in a problem area (e.g., lateral tracking without a flight director) so that *overall* compensation remains minimal.

To achieve ratings of adequate (CHPR ≤ 6.5), however, requires considerably different control-display combinations, depending on crew loading. As shown in Fig. 4, effectively all of the control-display combinations were rated adequate for

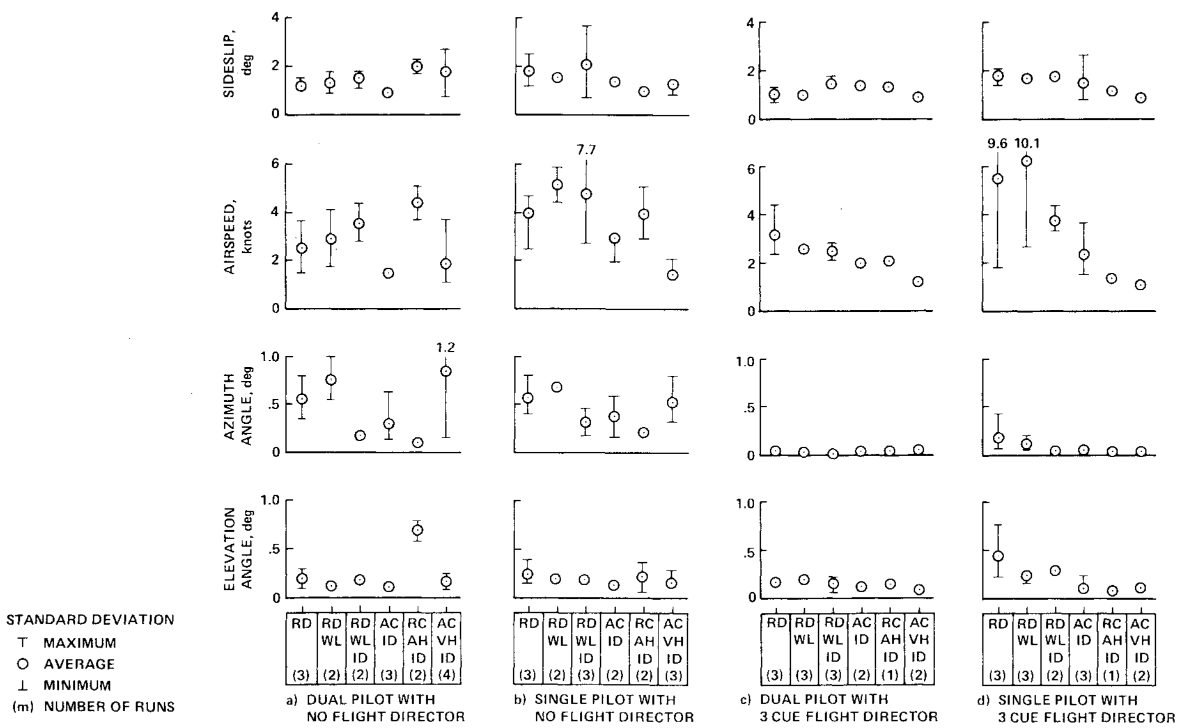

Fig. 4 Standard deviation of flight performance variables.

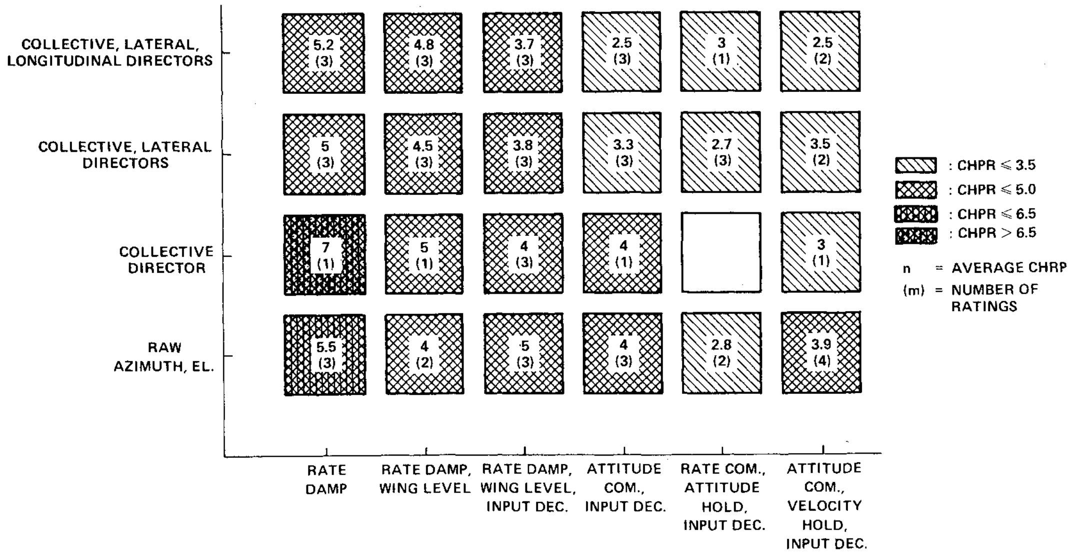

Fig. 5 Average pilot ratings, dual-pilot situation.

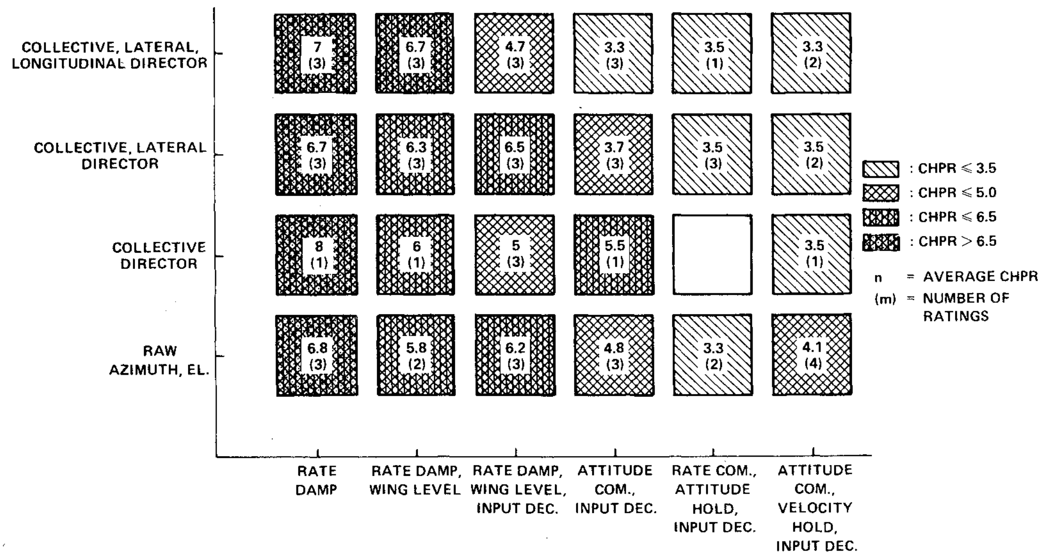

Fig. 6 Average pilot ratings, single-pilot situation with missed approach.

the dual-pilot task; the one anomaly consists of one pilot rating that was not consistent with that pilot's other ratings. For the single-pilot task, however, none of the rate-damper SCAS configurations was rated adequate, regardless of display; further, adding a wing leveler to the rate SCAS was still rated at best as marginally adequate, with no beneficial influences of displays. Pilot comments indicated particularly that the assistance of the flight directors in countering poor control characteristics was noticed in dual-pilot situations, but broke down badly when attention was diverted in the single-pilot cases. For example, comments indicated that the rate damper SCAS with three-axis directors was capable of good tracking performance when the directors could be followed continuously, but that extreme deviations were provoked by inadvertent inputs during the performance of auxiliary tasks.

This latter influence of auxiliary tasks leads into the next result, which is that a control-display trade-off was demonstrated among combinations receiving ratings of satisfactory, but the "boundary" separating adequate from inadequate configurations appears to depend only on the stability-control augmentation system, particularly in the single-pilot situation. The pilot comments reflected the same point as noted above for the influence of task loading. For ratings of satisfactory, if attention could be focused on one axis with none of the others deteriorating, there was some flexibility in maintaining overall compensation at a minimal level. For example, comments indicated that pilot concentration could be on lateral tracking for the velocity-hold SCAS, with only a collective stick control director, because altitude and speed control required no effort; on the other hand, with the rate-command-attitude-hold SCAS and collective-plus-lateral directors, it was noted that some effort was required to maintain airspeed because the directors permitted low effort to perform glide-slope and localizer tracking.

For the ratings of marginally adequate, however, the overall workload was considered sufficiently high that the split-axis assistance offered by the display hierarchy considered in this experiment was apparently ineffective in improving performance, particularly, again, for single-pilot operation. It is interesting to note that the atmospheric disturbances (turbulence, wind) included in this experiment may have been partially responsible for obviating the efficacy of the flight directors; Refs. 8 and 17 describe the significant degradation of pilot rating for a rate-damper control system in the presence of crosswind for a VTOL instrument task, for example.

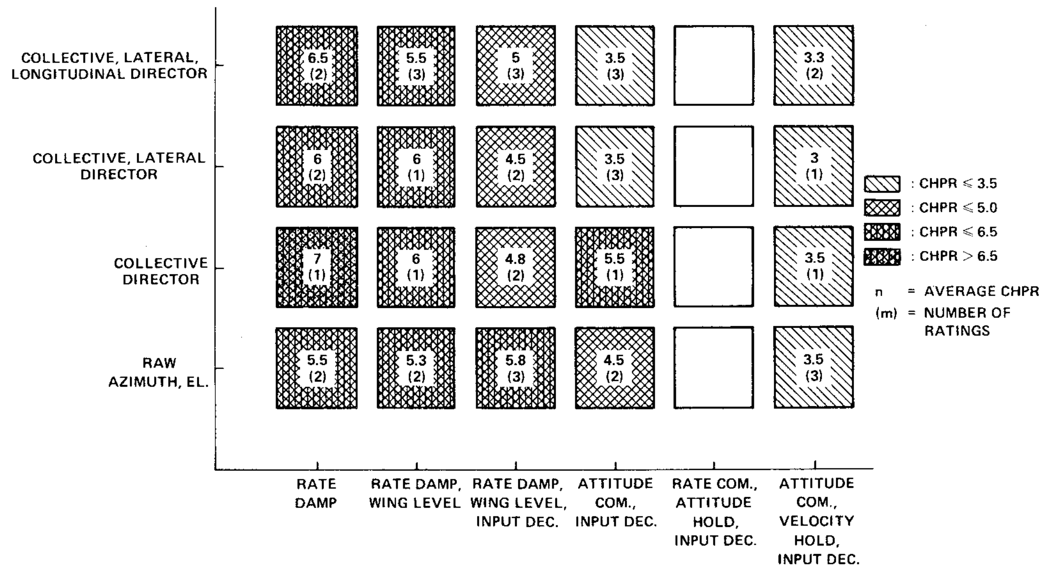

Fig. 7 Average pilot ratings, single-pilot situation with continued approach.

It is of interest, also, to consider the actual control-display combinations required for a given level of pilot ratings as a function of crew loading. For ratings of satisfactory, it appears that at least attitude augmentation in pitch-roll and flight directors for elevation and localizer tracking are required, with some permissible trade-off on the directors if velocity augmentation is included (Fig. 5). Note that the average rating for the rate-command-attitude-hold SCAS with raw data appears to contradict this statement, but the validity of one of the two ratings that made up the average is questionable (last rating of last day of experiment), and the other rating was a "4," both for single-pilot and dual-pilot operations.

To interpret these data in terms of airworthiness acceptance, this type of judgment is likely to center on those configurations whose flying qualities ratings fall between satisfactory and inadequate; that is, those configurations receiving ratings of $4 \leq CHPR \leq 6$. As discussed above, for dual-pilot situations, effectively all of the control-display configurations investigated in this experiment were rated adequate for the task. To provide some margin from "extensive" pilot compensation (CHPR = 6), one might consider that either three-axis directors or a wing leveler in addition to the rate-damper SCAS would be necessary. For the single-pilot case, although the data are not completely consistent, it appears that providing a similar margin leads to the need for pitch and roll augmentation, more or less independent of the display. As the pilot comments indicated, the influence of the auxiliary tasks in a realistic single-pilot situation is to eliminate the effectiveness of display assistance, once the overall control workload becomes more than moderate (CHPR = 4).

Finally, it was noted earlier that the neutral longitudinal static stability plus very flat attitude-speed relationship of the baseline helicopter model was expected to emphasize speed-control problems for all the SCAS configurations except the velocity-hold SCAS. This emphasis on speed control did in fact occur; speed control was noted as a high-workload item for all the configurations, even with a flight director to assist. The velocity-hold SCAS alleviated this problem in two ways: increased static stability through increased M_u, and a steeper attitude-speed relationship because of a concomitant increase in drag damping (X_u). According to the pilot comments, the velocity-hold SCAS did result in considerably less workload in this axis during constant-speed tracking; however, the implementation required the pilot to switch out the hold function (and thereby eliminate the velocity stability) during the deceleration from 80 to 60 knots, and this feature plus some control harmony problems in pitch-roll were considered moderately objectionable unless some flight-director assistance was provided. It is possible that a more refined implementation would have resulted in ratings of satisfactory for this SCAS for all the display variations examined.

Conclusions

This piloted simulator experiment was conducted to investigate the influence of stability-control augmentation, flight-director displays, and crew-loading auxiliary task effects on helicopter flying qualities for terminal-area operations in instrument meteorological conditions. Simulated test configurations were evaluated for a precision microwave landing system approach with 6 deg glide-slope to an offshore oil rig in simulated light turbulence and variable cross-wind. The baseline helicopter model included neutral longitudinal and lateral static stabilities in conjunction with an almost flat steady-state speed-to-attitude relationship for the flight conditions investigated, and the results should be qualified in this regard.

Predicated upon the characteristics of the baseline helicopter and stability-control augmentation systems as designed plus the extent to which an actual single-pilot operation was realistically simulated, the following conclusions may be drawn from the results, analyses, and interpretations of this experiment:

1) The difference in auxiliary tasks between dual- and single-pilot crew-loading situations had a negligible effect on the control-display combinations required to achieve pilot ratings of satisfactory (Cooper-Harper pilot rating ≤ 3.5).

2) A strong influence of auxiliary tasks on the control-display combinations required to achieve pilot ratings of adequate (Cooper-Harper pilot rating ≤ 6.5) was evident. All combinations evaluated were rated clearly adequate for a dual-pilot situation, but augmentation including at least a wing leveler was required for single-pilot operation.

3) The hypothesized trade-off between display sophistication and control complexity was evident for combinations rated satisfactory, but the determination of an adequate combination is dependent primarily on stability-control augmentation.

4) Considerations for airworthiness acceptance are likely to center on those configurations whose flying qualities are assessed to fall between satisfactory and adequate. In this regard, for the single-pilot situation, attention is thus likely to be directed toward control systems that provide pitch and roll

attitude stabilization. The flight director configuration is unlikely to be a factor in this judgment.

5) For dual-pilot operations, airworthiness assessments may be influenced to some extent by a tradeoff of control-system complexity with flight-director sophistication. This tradeoff could be expected to range from a rate-damper SCAS and wing leveler with raw position error deviations displayed to a rate-damper SCAS alone with a three-axis flight director.

6) The use of velocity augmentation in addition to pitch-roll attitude augmentation alleviated speed-control difficulties inherent to the baseline helicopter, although implementation difficulties precluded uniformly satisfactory ratings.

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