NASA-TM- 84258 PT.1

NASA Technical Memorandum 84258

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September 1982

NASA

National Aeronautics and
Space Administration

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N83-10049#

A PILOTED-SIMULATOR INVESTIGATION OF STABILITY AND CONTROL, DISPLAY, AND CREW-LOADING REQUIREMENTS FOR HELICOPTER INSTRUMENT APPROACHES

I. TECHNICAL DISCUSSION AND RESULTS

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SUMMARY

A ground-simulation experiment was conducted 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. The experiment was conducted on the Flight Simulator for Advanced Aircraft at Ames Research Center. 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 single-pilot operation 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 and to apply new technologies or concepts to resolve them. For example, both the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA) 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 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.

As a part of their respective research programs, NASA and the FAA have instituted a joint program at Ames Research Center to investigate helicopter IFR certification criteria. This series of investigations has the following two general goals:

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1. To provide analyses and experimental data to ascertain the validity of the Airworthiness Criteria for Helicopter Instrument Flight (ref. 2), which have been proposed as an appendix to FAR Parts 27 and 29 (refs. 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-control augmentation system (SCAS) requirements on helicopter flying qualities for a nonprecision VOR instrument approach task (refs. 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) (ref. 5); (2) the requirement for attitude augmentation in pitch-roll to obtain a level of satisfactory (CHPR < 3.5) (refs. 5, 6); and (3) the acceptability of neutral longitudinal and lateral static stabilities (ref. 6). Because these data were obtained in an experimental environment that did not require auxiliary tasks, these results are applicable only to a 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 dual-pilot certification, although no distinction is made for transport category. This desired distinction is important because most of the data used to develop the criteria are based on research conducted as in references 5 and 6 (i.e., no auxiliary tasks), and hence the influence of the higher cockpit workload inherent in single-pilot operation 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 IMC flying qualities. It has been hypothesized, however, that a trade-off between control complexity and display sophistication exists in the generic sense shown in figure 1, which is taken from reference 7. Such a trade-off has been demonstrated for VTOL IMC operations (ref. 8); a variety of helicopter applications concerned with this fact is reviewed in reference 9, and a recent ground-simulation experiment addressed this trade-off again in the helicopter context (ref. 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 (refs. 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.

Accordingly, the experiment described in this report was designed to focus on these three objectives. Cooper-Harper pilot ratings and comments were obtained from four pilots for a precision 6° MLS approach task in representative wind and turbulence conditions. A variety of control-display parameters were investigated to determine their influence on the pilot's performance and workload under both simulated dual-pilot and single-pilot operation. The Flight Simulator for Advanced Aircraft (FSAA) at Ames Research Center was used in conjunction with a generic nine-degree-of-freedom helicopter mathematical model to implement and examine the experimental configurations.

The remainder of this report is organized into two parts as follows. In the following two sections of part I, the design of the control systems, display characteristics, and auxiliary tasks that comprise the experimental variables, as well as the conduct of the experiment, are described. Flying-qualities results and measured performance and control use indices are discussed in the next two sections; conclusions and recommendations are presented in the final section of part I. Supporting data — data summary, flight-director control laws, pilot comments, and performance and control usage measures — are presented in the appendices. The first two appendices are included in part I; the second two are in part II.

The experiment discussed in this paper was conducted at Ames Research Center as part of a joint program between the National Aeronautics and Space Administration (NASA) and the Federal Aviation Administration (FAA). The authors are grateful to J. Shapley, FAS, and S. Kereliuk, National Aeronautical Establishment of Canada, for their participation as evaluation pilots, and to T. Alderete, NASA, for his contributions to the computer programming.

EXPERIMENTAL DESIGN

This experiment was designed to focus attention on three areas that are of concern in helicopter IFR terminal-area operations. Specifically, as outlined in the Introduction, the experiment had the following three objectives:

1. Define the extent of the control-display trade-off for a helicopter

2. Define, in a realistic context, the difference in required control-display parameters for single-pilot versus a dual-pilot operation

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

The evaluation configurations discussed in this section were designed to address these areas in a manner consistent with the following constraints:

1. The control-system variations were implemented on a baseline helicopter with neutral longitudinal and lateral control position gradients. This decision was made to ensure that the configurations would overlap those investigated in a previous experiment (ref. 6). In other respects, the configurations were designed to meet the criteria of the IFR Appendix for transport-class helicopters (ref. 1).

2. The range of control-display characteristics covered by all the configurations was designed to provide an expected range of Cooper-Harper pilot ratings from approximately 2 to 8 in order to provide a proper flying-qualities experiment.

3. To provide a control task with representative regulatory demands, a wind and simple turbulence model was included for all configurations.

To achieve the experimental objectives, the design of the configurations therefore involved the development of control-system characteristics, flight-director control logic, representative single-pilot task demands, and wind/turbulence characteristics. Aspects of these four design areas are discussed in the remainder of this section; additional details are provided in appendixes A and B.

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 (refs. 5, 6). The model explicitly includes the three-degree-of-freedom tip-path plane dynamic equations for the main rotor (ref. 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 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. 2). 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 to simulate stability and control characteristics of the UH-1H, OH-6A, and BO-105 aircraft, which use teetering, articulated, and hingeless rotor systems, respectively (refs. 5, 6). For this experiment, only the generic teetering-rotor aircraft model was used to reduce the scope to a manageable level; table 1 lists several of the geometric characteristics of this model. Because neutral longitudinal and lateral static stabilities had been found adequate (but not satisfactory) in the previous experiment (ref. 6), the generalized feedback structure was again used to achieve these neutral static stabilities for the baseline aircraft in 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), was 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 (ref. 6). These baseline characteristics were retained for all the control-system designs.

SCAS configurations— The six levels of stability-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

6. Number (4) plus augmented vertical damping (no altitude hold, however), releasable longitudinal velocity hold

The designs of these six levels of SCAS, and the reasons for their selection, are discussed below.

The baseline rate-damping augmentation is the minimum level of SCAS found in reference 5 to be required to achieve IMC ratings of adequate for the teetering-rotor configuration. It consisted of pitch-rate-to-longitudinal cyclic, roll-rate-to-lateral cyclic, and yaw-rate-to-directional control feedbacks plus changes to the control sensitivities. In appendix A are summarized the resulting equivalent stability and control derivatives at 60 knots (tables 5-9, appendix A), and the specific feedback and gearing gains used for the rate-damping control system (table 10, appendix A). The rate-damping feedback levels that were used were smaller than those of reference 6 in order to make them more consistent with limited-authority implementations; the design values, which are approximately the same as those of reference 5, were selected to provide time-constants of about 0.33 and 0.20 sec in pitch and roll, respectively. As shown in table 10 (appendix A), other feedbacks include Δ_{ES}/U and Δ_{AS}/V to provide neutral static longitudinal and lateral control position gradients, respectively, over a velocity range from 40 to 80 knots, plus Δ_{RP}/V to increase the directional stiffness; this latter modification was made to reduce turn-coordination requirements for the pilot, based on the results of reference 6. The feedbacks of vertical velocity shown in the table are "tuning" gains to produce characteristics similar to those of the UH-1H (ref. 5).

The next level of augmentation added a roll-attitude feedback to the rate-damping baseline; it was designed to be pilot-selectable through an "SCAS Release" button on the cyclic stick. This "wing-leveler" system is similar to the one investigated in reference 12, and was intended to relieve the pilot of roll-stabilization requirements, once on the localizer. The additional feedback gain was $\Delta_{AS}/\phi = -4.1$ in./rad to yield an undamped natural frequency of about 1.5 rad/sec. A design flaw of this augmentation system was that the SCAS release button had to be depressed continuously to disable the wing-leveler; the pilots objected to this requirement, and instead flew the aircraft without disabling the wing-leveler, even for maneuvering. A preferable implementation might have been "push-push" logic switching, so that only a momentary depression would have been required to disable or enable the wing-leveler, but this version was not examined.

The next three levels of SCAS were consistent with types examined in the reference 6 experiment, although, again, lower levels of pitch and roll feedback gains that were closer to those of reference 5 were used. For the first of these, input decoupling was added to the rate-damping-plus-wing-leveler discussed above. The gearing and cross-gearing values are shown in table 7 (appendix A); note that the scheduling of longitudinal cyclic from collective with speed required a different Δ_{ES}/U feedback to achieve a neutral longitudinal control position gradient (ref. 6).

For the attitude-command and rate-command-attitude-hold control systems, the roll-attitude gain of the wing-leveler ($\Delta_{AS}/\phi = -4.1$ in./rad) was retained with the

SCAS release disabled, and pitch-attitude augmentation (Δ_{ES}/Θ = -13.24 in./rad) was added so that both pitch and roll axes had undamped natural frequencies of about 1.5 rad/sec. The input decoupling was the same as for the case just described. The rate-command-attitude-hold system has in addition proportional-plus-integral feed-forward prefilters in pitch and roll, so that the attitude responses were of the form

$$\frac{\Theta}{\delta_{ES}} = \underbrace{\left(K_1 + \frac{K_2}{S}\right)}_{\text{prefilter}} \underbrace{\left(\frac{K}{S^2 + 2\zeta\omega_n s + \omega_n^2}\right)}_{\text{attitude-stabilized response}}$$

$$= K_1 \left(\frac{S + K_2/K_1}{S}\right) \left[\frac{K}{(S + \lambda_1)(S + \lambda_2)}\right] \qquad \text{(overdamped)}$$

$$\cong \frac{K_1}{S} \cdot \frac{K}{S + \lambda_2} \qquad \text{for} \qquad \frac{K_2}{K_1} \doteq \lambda_1$$

The ratios K_2/K_1 for this experiment were 0.5 and 0.4 for pitch and roll, respectively. Both of these attitude-augmented types of control system had been shown in previous experiments to be required to achieve pilot ratings (for dual-pilot operation) of satisfactory (refs. 5, 6), and the question of interest here was 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. Figure 3 is a sketch of the implementation, and table 12 (appendix A) summarizes the gains. It was anticipated that the neutral longitudinal static stability of the baseline aircraft in combination with an inherently low attitude-speed gradient ($d\theta/du$) would exacerbate speed-control difficulties for the other configurations, and so the primary intent of this control system was to reduce the speed-control workload for the pilot, with an ancillary objective being assistance to glide-slope tracking through enhanced vertical damping. To enhance speed control, longitudinal velocity was fed back to the longitudinal cyclic at a fairly high gain to increase the effective phugoid frequency through M_u. This feedback implies a very stable longitudinal stick position gradient at a fixed operating point (e.g., about -2.7 in. for a 20-knot change at 60 knots). To provide the full range of speed control down to hover for realistic cockpit control displacement limits, therefore, it is necessary either to increase the control sensitivity significantly or to disable the velocity feedback for large speed changes. The latter option was used in this experiment, with the "SCAS Release" button disabling the velocity feedback when large velocity changes were to be made; hence, the system was velocity-hold rather than velocity-command. As will be noted when the experimental results are discussed, this implementation could cause fairly large pitch transients, if a speed change was initiated with the cyclic before releasing the velocity-hold loop, which was an objectionable feature.

To assist with glide-slope tracking control, this control system also included feedback of both vertical and longitudinal velocity to the collective-pitch control in addition to increased collective-control sensitivity. The vertical velocity feedback provided a heave time-constant of about 0.5 sec at 60 knots; the unaugmented value was about 0.75 sec. The longitudinal velocity feedback was used to decouple partially the lift change due to speed ($Z_u \rightarrow 0$).

Guidance and Display Characteristics

Another major variable in this experiment was the manner in which the approach course information for a 6° precision MLS approach was presented to the pilot. Four levels of display "sophistication" were examined:

1. Azimuth angular error, elevation angular error, and DME

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

4. Number (3) plus longitudinal cyclic stick-control director (to assist speed control:) three-cue director

Figure 4 shows the location of the flight-director needles on the ADI (attitude-director indicator) and the elevation, azimuth, and DME (distance measuring equipment) indicators on the HS1 (horizontal situation indicator) used in this experiment. Table 2 summarizes the configuration identifiers for the combinations of these displays with the control systems discussed previously. The following paragraphs describe the simulated guidance and flight-director information; appendix B provides a detailed derivation of the equations that were used.

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 co-located 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 NASA flight tests with a UH-1H helicopter against an MLS (ref. 13), a 6° steep approach with ±2° full-scale elevation error and ±5° full-scale azimuth error beams was 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 reference 8, generalized velocity and position commands were derived, using the MLS data resolved into a general rectangular coordinate system with the 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, as described in appendix B.

The horizontal-velocity command included a deceleration from 80 knots to 60 knots before glide-slope intercept and a correction for wind to provide a constant airspeed for the approach; although easy to do on the ground simulator (the "wind" is exactly known), in an actual aircraft a wind estimator and command procedure, as discussed in reference 8, would be required. The vertical command consisted of a constant-altitude command, rounded-off glide-slope intercept command, and a 6° 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 (refs. 14, 15). Assuming that longitudinal cyclic (EBAR director) controls primarily speed, that collective stick (CTAB director) controls primarily rate of climb, and that lateral cyclic (ABAR director) controls primarily lateral course, the general equations driving the directors were:

$$\mathrm{EBAR} = K_{\dot{X}}\varepsilon_{\dot{X}_H} + K_\theta \theta_{WO}$$

$$\mathrm{ABAR} = K_{\dot{Y}}\varepsilon_{\dot{Y}_H} + K_\phi \phi_{WO} = K_{\dot{Y}}(K_Y Y_H - \dot{Y}_H) + K_\phi \phi_{WO}$$

$$\mathrm{CTAB} = K_Z \varepsilon_Z + K_{\dot{Z}}\varepsilon_{\dot{Z}} + K_{\delta_C}\delta_{C_{WO}}$$

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

Appendix B gives the values of the gains and the washout time-constants as used in the experiment for the approach mode of the flight directors. Simpler gains commanding a constant 60-knot speed, 10° banked turn, and 600 ft/min climb were available as a "go-around" mode for missed approaches and are also shown there. The following differences in philosophy from the previous work (refs. 8, 14, 15) 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 (ref. 16). Because the high-frequency characteristics of these directors were permitted to depart from the ideal, it was assumed that the other gains did not have to vary with control-system characteristics, as was done in reference 8. As will be discussed in describing the results, this assumption led to some low-frequency problems with the rate-damping control system that might have been alleviated with different flight-director gains for this control system. 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 (ref. 17), and the pilots in this experiment agreed. Finally, the gains varied linearly with range for the 6° glide-slope portion of the approach; hence, they produce effectively constant <u>angular</u> sensitivities. The technique used in the other work consisted of constant-displacement sensitivities (refs. 8, 14, 15), which maintain constant closed-loop performance; as a result, however, they require a trade-off in desired performance between the initial and final stages of the approach.

Simulation Tasks

An instrument approach to a precision 6° elevation MLS installation was simulated for this experiment. The MLS elevation and azimuth-range transmitters were assumed to be co-located on an offshore oil drilling platform. The instrument approaches were conducted to simulate weather conditions approximating Category I and II decision height and visibility.

The basic flight control task was to fly the MLS 6° approach while manually controlling the aircraft and maintaining flight variables to within acceptable tolerances. The task, which began 3-1/3 n. mi. from the platform, consisted of MLS azimuth capture at 80 knots and 1,200 to 1,300 ft, a deceleration to 60 knots, capture of a 6° elevation glidepath and tracking at 60 knots, and execution of either a missed approach or the initiation of a deceleration to the landing platform (landing was not included), depending on crew loading and visual conditions at the decision height. The dual-pilot situation was consistent with the scenario of most flying-qualities experiments; the pilot's sole task was to accomplish the flight-control tasks with no auxiliary tasks. The pilot knew in advance that a missed approach maneuver would be initiated at the decision height (DH). Figure 5 shows an idealized variation of flight parameters (airspeed, altitude, heading, and rate of climb) during the approach.

For single-pilot simulation, auxiliary tasks were added to the basic task to provide a situation that was realistic and representative of helicopter IFR operations in an active close-in but offshore environment. The auxiliary tasks included chart reading, communication and navigation radio-frequency selection, transponder-code selection, voice communication with the tower and air traffic controllers, and clearance copying. As will be discussed in the section on experimental test procedures, the auxiliary tasks were added to examine the influence of higher cockpit workload inherent in single-pilot operation. The charts for the four 6° MLS approaches that were flown are shown in figure 6. Although the four approaches are similar with respect to the geometry of the approach-path trajectory, they required different altitudes, headings, frequencies, and controller identifications (call signs, e.g., Gulf Tower, Pacific Tower, Lake Charles departure control). Also, it was planned that the missed-approach path would differ from the standard procedure depicted on the charts. Radio-frequency and transponder-code selections were made by manipulating knobs on control heads located on the center instrument panel and on the center console, respectively. The VORTAC radial required for tracking after the missed approach was selected by rotation of the course knob on the HSI. It should be noted that aural identification of radio stations and fan markers was not provided and thus this degree of realism in the auxiliary task was lacking. However, communication with other helicopters in the area was simulated; it sometimes interfered with the evaluation pilot's ability to communicate freely with the appropriate controller at the appropriate time, thereby causing additional stress.

An additional task for the pilot on single-pilot approaches was to decide, when reaching decision height, whether to continue the approach or to execute a missed approach. The pilot did not know in advance whether the visual range would be adequate to complete the approach. The simulated fog was made to start clearing at an altitude of 100 ft above the decision height and then to either re-fog or continue clearing just below the decision height. As a result, the pilot had to make the decision whether to continue. The auxiliary tasks and the basic flight-control task are summarized in figure 7.

Wind/Turbulence Characteristics

A simple model for atmospheric turbulence was taken from reference 18, which in turn is a simplification of the model proposed in reference 19. The model as used here provides three linear turbulence components defined in a wind axis system

(U_g, V_g, W_g); the three rotational components (p_g, q_g, r_g) typically used to approximate the first gradient were neglected. The three components are based on a Dryden spectrum with intensities determined either as constants or as a fraction of an assumed wind speed. Scale lengths were 1,000 ft for the longitudinal and lateral components and equal to the current altitude for the vertical component. Although a provision for variations in scale length for altitudes below 200 ft is given in reference 18, this option was not exercised in this experiment. In reference 18, the break frequencies of the Dryden spectra are determined by the ratio of the wind speed to the scale length, but in this experiment the velocity of the aircraft relative to the air mass was used; hence, break frequencies for the longitudinal and lateral spectra ranged from 0.10 to 0.14, depending on speed; for the vertical spectrum they ranged from 0.08 to 0.50, depending on speed and altitude. To avoid compromising the results with an unrealistically high level of turbulence, the intensities were selected at a low level to represent light turbulence: $\delta_{u_g} = \delta_{v_g} = 3.0$ ft/sec and $\delta_{w_g} = 1.5$ ft/sec.

Provision for a wind velocity at a prescribed direction was included in the model. In this experiment the wind velocity was held constant at 10 knots and the wind direction changed from 45° on one side of the final approach course to 45° initially and then to 30° on the other side for the remainder of the approach. The change in wind direction was programmed to occur somewhere during the first two thirds of the approach at "randomized" X distances from the landing platform. The total change in direction occurred over a 1,200-ft interval (about a 12-sec time interval).

CONDUCT OF EXPERIMENT

Simulator Apparatus

The simulation experiment described in this report was carried out at Ames Research Center, using the Flight Simulator for Advanced Aircraft (FSAA) (fig. 8) and a Redifon visual display system. The motion system of the simulator is a six-degree-of-freedom device designed to impart rotational and translational movement to the cockpit. A detailed description is given in reference 20.

For this experiment, the right seat of the cockpit was fitted with conventional helicopter flight controls and a basic set of flight instruments (fig. 4). Turn-slip data were shown on a separate instrument, as is typical of helicopter display presentations. Although not typical, a sideslip instrument was provided to assist in evaluating the lateral-directional characteristics of the configurations. A large ADI provided heading data in addition to pitch and roll; a flight director with a three-cue capability was integrated with this instrument. The remaining flight and nevigational instruments were conventional and arranged in the usual "T" presentation. The collective stick was provided with friction control, but had zero force-displacement gradient. The force-feel characteristics of the cyclic stick and directional pedals were provided by a electrohydraulic unit with adjustable breakout, static gradient, viscous damping, and friction. The force-feel characteristics and control travels for the configurations are shown in table 3.

The navigation and communication radio-heads were located well to the left of the central instrument cluster, thus requiring a long reach for the pilot; the transponder head 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.

MLS instrument approaches to an offshore oil rig were simulated in this experiment. A visual image was generated by the Redifon camera system viewing a model of the rig supported by a board representing the ocean surface. The total field of view encompassed 36° vertically and 48° horizontally. The visual image was displayed through the forward cab window on a color TV monitor with a collimating lens. Figure 9 is a photograph of the image as displayed on the TV monitor but without the collimated lens. Electronic fog was introduced to simulate visibility approximating Category I or II visual range and provided a transition from instrument to visual conditions in the decision height region. Flight in the clouds (IMC) was otherwise simulated by a faded gray monitor.

Test Procedure

The situation simulated in this experiment was the normal operation of a normal-category helicopter in a controlled offshore area under instrument meteorological conditions (IMC) and with moderate traffic density. Simulated approaches were made with reference to a conventional set of flight and navigation instruments, including a flight director; the amount of guidance afforded by the flight director was a variable factor of the experiment as was discussed in the section on design. Each approach was conducted in accordance with one of four specific 6° Copter MLS approach plates (fig. 6).

The pilots were allowed time initially to evaluate each configuration under VMC without being constrained to fly the specific MLS task. The normal procedure was then to conduct three approaches: one dual-pilot and two single-pilot. Representative light turbulence was present for all approaches. An average of three configurations was evaluated in each session, each of which lasted about 1.5 hr. Configurations were selected for evaluation by the project engineer in such a way as to minimize any bias caused by evaluating a series of all good or all bad configurations. During most evaluation sessions the simulator was occupied solely by the evaluation pilot. Copilot assistance during dual-pilot approaches was provided by the project engineer when requested by the evaluation pilot; altitude callouts of "100 ft above" and "decision height" were made on the intercom.

To summarize, the specific runs to be accomplished for each configuration were as follows:

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

2. Dual-pilot IMC approach and missed approach in representative turbulence, assign Cooper-Harper pilot rating (ref. 21) and make comments in response to comment card (table 4)

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), only usually the other option at the decision height would be provided

Evaluation Pilots

Four test pilots participated in the experiment. Pilot A, an Army test pilot, has extensive experimental flight test experience. Pilot B, a NASA research pilot, has extensive experience in V/STOL and rotary-wing aircraft. Pilot C is a test pilot at the Flight Research Laboratory, National Aeronautical Establishment, Canada. Pilot D, an FAA test pilot, has civil certification test experience, including flight approvals for single-pilot IFR. All four pilots had logged high time in rotary-wing aircraft including substantial rotary-wing instrument time.

Evaluation Data

Five categories of data were recorded: (1) numeric pilot ratings based on the Cooper-Harper scale; (2) pilot comments recorded following each approach, using the pilot comment card as a guide; (3) pilot control use determined from time histories of the primary flight-control positions; (4) pilot-vehicle performance determined from the histories of the aircraft state and flight variables; and (5) pilot-simulator environment determined from time-histories of the simulator input command and feedback variables. Variables were recorded on strip charts to permit observation while tests were in progress and on digital tape (sampled 10 times per second) for subsequent analysis. The recorded variables included helicopter body attitudes, helicopter angular and linear rates and accelerations, helicopter flightpath coordinates, helicopter rotor parameters, MLS azimuth and elevation track errors and VORTAC radial track error, turbulence and wind components, pilot control positions, SCAS actuator positions, and simulator input command and feedback signals.

FLYING-QUALITIES RESULTS

In this section, the flying-qualities results, in terms of pilot ratings and pilot comments, are presented and discussed. Because of the fairly large quantity of data obtained (about 150 pilot ratings), a summary of the ratings and comments, separated by control-system type, is given initially, followed by the discussion.

Rate-Damping Control System

T30: Raw data display— The T30 configuration included only rate damping in all three axes and had in addition neutral longitudinal and lateral static stabilities. The dual-pilot average rating was 5.5, with a range from 5.0 to 6.0 (three evaluations); the single-pilot average rating including the missed approach was 6.8, with a range from 6.0 to 7.5 (three evaluations); the single-pilot average rating without the missed approach was 6.2, with a range from 5.0 to 7.5 (three evaluations). For the dual-pilot (full-attention) crew-loading situation, pilot comments indicated that the job could be done but it required a lot of concentration. The scan workload was high, with a necessity to concentrate on attitude control and a tendency to overcontrol in pitch attitude and glide slope. One pilot indicated that the deceleration from 80 to 60 knots was a high-workload factor and that azimuth tracking was the biggest problem. When the task including the missed approach was performed in the single-pilot operation, pilot comments indicated that workload saturation had been reached, particularly in the missed approach when clearances could not be copied, and, in fact, one pilot tuned in the wrong new communication frequency. The missed-approach and associated auxiliary tasks were the critical part of the single-pilot task in general, for the comments indicate that without it, the pitch-attitude control task in particular was not as demanding.

T01: Collective director— The T01 configuration had the same control system and one-cue flight-director display. The dual-pilot rating was 7.0 (one evaluation), the single-pilot-with-missed-approach rating was 8.0 (one evaluation), and the single-pilot rating without the missed approach was 7.0 (one evaluation). The dual-pilot comments indicated that the coupling from collective to attitude and speed caused by the collective flight-director commands produced a workload level above the maximum tolerable, and the pilot indicated further that he would have liked at least a wing-leveler. The task performance degraded for single-pilot operation when the missed approach was included, with the pitch axis beginning to present controllability problems. The workload was also excessive without the missed approach, but controllability in pitch was not in question for single-pilot operation.

T02: Collective and lateral cyclic directors— The dual-pilot average rating for configuration T02 was 5.0, with a range from 4.0 to 6.0 (three evaluations); the single-pilot average rating including the missed approach was 6.7, with a range from 5.5 to 7.5 (three evaluations); the single-pilot average rating without the missed approach was 6.0, with a range from 5.5 to 6.5 (three evaluations). For dual-pilot operation, comments indicated that the roll steering command director helped considerably with tracking and compensating for the wind shear, but that the glide-slope control and particularly pitch attitude and airspeed control remained high-workload items. The single-pilot situation including the missed approach was considered significantly degraded over the dual-pilot case, because the aircraft could be inadvertently upset when attention to the instruments was removed; in one case the new transponder frequency was not correctly set. Airspeed control and coupling to the glide slope were major problems in the single-pilot case, both with and without the missed approach.

T03: Collective, lateral, and longitudinal cyclic directors— The average rating for configuration T03 dual-pilot operation was 5.2, with a range from 5.0 to 5.5 (three evaluations). For the single-pilot case including the missed approach the average rating was 7.0, with a range from 6.0 to 8.0 (three evaluations); without the missed approach the average single-pilot rating was 6.5 with a range from 6.0 to 7.0 (two evaluations). The dual-pilot comments indicated that the lateral control director in particular was useful in helping to cope with the lack of roll attitude stabilization, with the pitch workload was still high, even with the director — it was noted that there was wandering in pitch, and that although the pilot could recover from large excursions, he did not like it. The single-pilot operations were considered significantly worse, with the missed approach again being critical. Comments indicated a loss of pitch- and roll attitude control when auxiliary tasks were performed — the auxiliary tasks were considered to have a powerful influence. Speed excursions were again a large problem.

Rate-Damping-Plus-Wing-Leveler Control System

T10: Raw data display— The T10 control system added roll attitude stabilization to the rate-damping control system discussed above. As designed, the wing leveler was intended to be pilot selectable, but in practice it was engaged all the time. For the dual-pilot case, the average rating was 4.0 based on two evaluations which were both a 4.0; for the single-pilot case, including the missed approach, the average rating was 5.8 with a range from 4.5 to 7.0 (two evaluations); the single-pilot average rating for the continued approach case was 5.3 with a range from 4.5 to 6.0

(two evaluations). The dual-pilot comments indicated that the attitude-retention feature of the wing leveler was comfortable, and permitted time to scan other instruments to assist in reducing coupling and improving rate-of-descent control. The single-pilot comments for the missed-approach evaluation differ between the two pilots. One pilot (CHPR = 4.5) chose to ignore "fairly gross excursions" in glidepath in his rating, but the other noted large and "unusual" excursions, particularly in pitch, and had to work hard enough for control that he forgot an auxiliary task. The comments do not show any significant influence of the missed approach.

T11: Collective director— For the only evaluation conducted of the T11 control-display combination, the dual-pilot rating was 5.0 and the single-pilot ratings were both 6.0 for the cases with and without the inclusion of the missed approach. The comments indicated that in the dual-pilot case, coupling of the collective to pitch attitude and airspeed was still a major problem, although the wing leveler helped with azimuth tracking. In the single-pilot case, the comments were similar, with the auxiliary tasks degrading the ability to deal with the pitch-attitude coupling and control problem.

T12: Collective and lateral cyclic directors— The average dual-pilot rating was 4.5, with a range from 4.0 to 5.5 (three evaluations); the average single-pilot rating including the missed approach was 6.3, with a range from 5.0 to 7.0 (three evaluations); the sole single-pilot rating excluding the missed approach was 6.0. The dual-pilot comments noted that with the roll and collective directors to help those axes, more attention could be paid to controlling pitch excursions, although the collective-to-pitch coupling still made the pitch axis difficult. For the single-pilot cases, airspeed control was indicated as deteriorating — the pilots indicated that it was relatively good with their hands on the controls and with a constant scan, but got away when they performed the auxiliary tasks, with the clearance copying for the missed approach being critical.

T13: Collective, lateral, and longitudinal cyclic directors— The average dual-pilot rating for configuration T13 was 4.8, with a range from 4.0 to 6.0 (three evaluations); the single-pilot average rating including the missed approach was 6.7 with a range from 6.0 to 8.0 (three evaluations); without the missed approach, the average single-pilot rating was 5.5, with a range from 5.0 to 6.0 (three evaluations). Dual-pilot comments indicated an incipient pitch pilot-induced oscillation (PIO) in trying to follow the pitch director, although the wing leveler added confidence to the lateral channel. With the missed approach, the single-pilot comments again emphasized a deterioration in pitch control when the auxiliary tasks were performed, with large deviations being encountered and concentration on the ADI being required. In this case, without the missed approach the single-pilot comments indicated a much easier task because of the absence of clearance copying and the capability therefore to concentrate on pitch-attitude control.

Rate-Damping, Input-Decoupling-Plus-Wing-Leveler Control System

T15: Raw data displays— The configuration T15 control system added control cross-gearings to the previous one to minimize off-axis inputs from each controller. The dual-pilot average rating was 5.0, with a range from 4.0 to 7.0 (three evaluations); the single-pilot average rating including the missed approach was 6.2, with a range from 5.0 to 8.0 (three evaluations); the single-pilot continued approach average rating was 5.8, with a range from 4.0 to 8.0 (three evaluations). Comments from the three pilots reflect the fairly wide range of ratings. For one of the pilots, comments for the dual-pilot situation indicated an extreme difficulty with airspeed and glide-slope tracking, which carried over into poor azimuth tracking because of the high workload in the other axes; the other two pilots noted, on the contrary, that localizer tracking was not a big problem, and that there was no difficulty with coupling. In the single-pilot case including the missed approach, all the pilots noted difficulty with airspeed control but to varying degrees; one noted that if he got his control problem stabilized before doing the auxiliary tasks the job became easier. The comments indicated no significant influences of the missed approach for single-pilot operation.

T16: Collective director— The dual-pilot average rating for configuration T16 was 4.0, with a range from 3.0 to 5.0 (three evaluations); the single-pilot average rating including the missed approach was 5.0, with a range from 4.0 to 6.0 (three evaluations); the average single-pilot rating without the missed approach was 4.8, with a range from 4.0 to 5.5 (two evaluations). For the dual-pilot case, one of the pilots noted that the primary advantage of the collective director was in having the glide slope information next to the ADI rather than just down on the HSI, thereby reducing the scan required. The pilots noted some tracking errors on localizer, and once again emphasized the difficulty of tracking airspeed. For the single-pilot case, airspeed control was the main problem, and again it was noted that stabilizing the control situation before performing the auxiliary tasks was useful. No obvious difference as a result of the missed-approach maneuver was pointed out in the single-pilot case; it is also interesting that one of the pilots rated the aircraft better for single-pilot than dual-pilot operation.

T17: Collective and lateral cyclic directors— The average dual-pilot rating for configuration T17 was 3.8, with a range from 3.0 to 4.5 (three evaluations); for the single-pilot case with the missed approach, the average rating was 6.5, with a range from 5.5 to 8.0 (three evaluations). Excluding the missed approach, the average rating was 4.5, with a range from 3.0 to 6.0 (two evaluations). The dual-pilot comments indicate that although the airspeed control was still not too good, the fact that the directors helped the other axes permitted increased concentration on pitch attitude. On one of the single-pilot evaluations including the missed approach, the auxiliary tasks associated with the missed approach led to a large loss of airspeed (CHPR = 8.0); other comments indicated a high sensitivity of configuration T17 to the auxiliary tasks with both airspeed and glide-slope tracking deteriorating. Without the missed approach, one pilot was again able to monitor pitch attitude sufficiently to achieve satisfactory performance single-pilot (CHPR = 3), but the other could not (CHPR = 6.0).

T18: Collective, lateral, and longitudinal cyclic— The average dual-pilot rating for configuration T18 was 3.7, with a range from 2.0 to 5.0 (three evaluations); the average single-pilot rating including the missed approach was 4.7, with a range from 4.0 to 6.0 (three evaluations); without the missed approach, the average single-pilot rating was 5.0, with a range from 4.0 to 6.0 (three evaluations). Comments about the dual-pilot case indicated that azimuth tracking was very good, and that although the pitch workload was high with some director chasing, the pitch director did help with speed control compared with the raw data case. In the single-pilot case including the missed approach, the comments indicated that speed control in the go-around was again a problem if the pilot took his eyes off the director, but that the director helped in telling which way to go when attention was returned to it. The comments and ratings indicated no difference without the missed approach, even though the speed control during this maneuver had been called out as a particular problem.

Attitude-Command, Input-Decoupling Control System

T20: Raw data displays— The T20 control system added pitch attitude stabilization to the previous control system, thereby providing attitude-command augmentation in pitch and roll. With the raw data displays, the average dual-pilot rating was 3.8, with a range from 3.0 to 5.0 (four evaluations); the average single-pilot rating including the missed approach was 4.4, with a range from 3.0 to 6.5 (four evaluations); without the missed approach, the average single-pilot rating was 4.7, with a range from 3.0 to 6.0 (three evaluations). For the first time, comments about the dual-pilot case do not include references to airspeed control problems; instead, the aircraft was considered a little sluggish in response "at the bottom" of the approach, and the workload mentioned had to do with scanning between the ADI and HSI instruments. Comments about the single-pilot case including the missed approach indicated few additional control problems owing to the auxiliary tasks for three of the four pilots; although one indicated continuing control problems with airspeed, his comments are not sufficiently severe to validate the poor rating (CHPR = 6.5) assigned to the aircraft. Without the missed approach, one pilot actually down-rated the aircraft, but the comments do not explain why; for the other pilots the ratings and comments are similar to the missed-approach case.

T21: Collective director— Only one pilot evaluated configuration T21. The dual-pilot rating was 4.0, and the single-pilot ratings with and without the missed approach were 5.5. For the dual-pilot evaluation, the pilot noted that although the aircraft had good attitude loops, the airspeed did not seem to hold well, and the attention required for it detracted from the other axes a little; the collective director was considered to have reduced the workload. In the single-pilot cases, the airspeed wandering was a problem, and the comments indicated a desire for pitch and roll flight directors to reduce the disturbances of the aircraft.

T22: Collective and lateral cyclic directors— The average dual-pilot rating for configuration T22 was 3.3, with a range from 2.5 to 4.5 (three evaluations); the average single-pilot rating including the missed approach was 3.7, with a range from 2.0 to 5.0 (three evaluations); the average single-pilot rating excluding the missed approach was 3.5, with a range from 2.0 to 4.5 (three evaluations). Comments about the dual-pilot case indicated that the two-cue flight director reduced the workload significantly, and, although there was a little trouble with airspeed control, the pitch director was not missed too much, because the pitch characteristics were docile. One pilot, in fact, noted that the missed-approach maneuver was almost "hands-off." With the single-pilot approaches, the speed control in the missed approach was called out as a problem, but the auxiliary tasks were considered easy to perform. No major differences were noted between the single-pilot approaches with and without the missed approach.

T23: Collective, lateral, and longitudinal cyclic directors— The average dual-pilot rating for configuration T23 was 2.5, with a range from 2.0 to 3.0 (three evaluations); the average single-pilot rating including the missed approach was 3.3, with a range from 2.5 to 4.0 (three evaluations); without the missed approach, the average rating was 3.5, with a range from 2.5 to 4.0 (three evaluations). The comments about the dual-pilot case noted again the difficulty in trimming the aircraft; the pitch director reduced the workload although there was still a small tracking problem. The lateral channel was considered very good. In the single-pilot case, one pilot made mistakes in re-tuning the frequencies, whereas a different one indicated that the auxiliary tasks had little effect on the workload. Airspeed control was not considered good, with an inability to track the director well enough. No differences owing to the missed approach were described for the single-pilot case.

Rate-Command-Attitude-Hold, Input-Decoupling Control System

T05: Raw data displays— The T05 control system added proportional-plus-integral prefilters on the pitch and roll commands of the attitude-command control system, thereby providing rate-command-attitude-hold responses to the cyclic inputs. The average dual-pilot rating with the raw data displays was 2.8, with a range from 1.5 to 4.0 (two evaluations); the average single-pilot rating including the missed approach was 3.3, with a range from 2.5 to 4.0 (two evaluations); no single-pilot evaluations excluding the missed approach were conducted. For the dual-pilot operation, one pilot indicated some problem with azimuth, glide slope, and airspeed tracking, and the other considered the configuration very good and did not miss the flight directors. For single-pilot operation, including the missed approach, the comments indicated very little influence on the workload from the auxiliary tasks; one pilot even commented that the approach was often "hands-off."

T06: Collective director— No evaluations.

T07: Collective and lateral cyclic directors— The dual-pilot average rating for configuration T07 was 2.7, with a range from 1.5 to 3.5 (three evaluations); the single-pilot average rating including the missed approach was 3.5, with a range from 2.5 to 5.0 (three evaluations); no evaluations without the missed approach were conducted. The dual-pilot comments indicated minor airspeed control problems, but noted that the roll axis was "great" and the missed-approach performance was good. One pilot was able to fly much of the approach hands-off. For the single-pilot case, two of the pilots indicated that the workload was about the same as dual pilot, and that the aircraft could be flown hands-off while performing the auxiliary tasks; the third pilot noted very large airspeed excursions and a high pitch-axis workload.

T08: Collective, lateral, and longitudinal cyclic directors— Only one pilot evaluated configuration T08. The dual-pilot rating was 3.0, and the single-pilot rating including the missed approach was 3.5. About the only comment was that the pitch director now permitted keeping the speed "right on."

Attitude-Command-Velocity-Hold, Input-Decoupling Control System

T25: Raw data displays— The T25 control system added to the attitude-command system a pilot-releasable high gain longitudinal velocity loop, augmented vertical-velocity damping, and reduced lift-due-to-longitudinal-speed to assist in decoupling. As the comments will indicate, this mechanization required different power settings from the previous configurations, which created some learning problems; in addition, the mechanization of the velocity-hold release created some general difficulties. For the raw data displays, the average dual-pilot rating was 3.9, with a range from 2.0 to 5.0 (five evaluations); the average single-pilot rating including the missed approach was 4.4, with a range from 2.5 to 5.5 (five evaluations); without the missed approach, the average single-pilot rating was 3.5, with a range from 2.0 to 4.5 (three evaluations). The comments about the dual-pilot case are somewhat split among the pilots. One of the pilots indicated that the new power settings made the problem harder and caused "hunting" for glide-slope control; another indicated problems performing the deceleration and acquiring the glide slope; the other two noted a "hands-off" missed-approach capability and indicated that the airspeed hold made the job much easier. For the single-pilot approaches including the missed approach, comments indicated difficulties with azimuth control, perhaps occasioned by having to get used to the way the velocity-hold system worked.

T26: Collective director— The average dual-pilot rating for configuration T26 was 4.0, with a range from 3.0 to 5.0 (two evaluations); the average single-pilot rating including the missed approach was 4.5, with a range from 3.5 to 5.5 (two evaluations); the only single-pilot rating excluding the missed approach was 3.5. For the dual-pilot case, one pilot noted some minor lateral problems, but felt that the speed-hold and collective directors made those axes easy to control; the other pilot got behind the aircraft, partially as a result of not following the collective director. Comments about the single-pilot case indicated no difficulty in performing the auxiliary tasks because the instrument scan could be broken with no adverse effects, so there was no change from the dual-pilot situation. No differences between the missed- and continued-approach cases were discussed or evident in the rating.

T27: Collective and lateral cyclic directors— The dual-pilot average rating for configuration T27 was 3.5, with a range from 3.0 to 4.0 (two evaluations); the single-pilot average rating including the missed approach was also 3.5, with a range from 3.0 to 4.0 (two evaluations); the one single-pilot rating excluding the missed approach was 3.0. Comments about the dual-pilot case indicated a minor workload in following the collective director, because collective inputs were constantly required; there were also complaints about the time required to perform the deceleration. Comments about the single-pilot case correspond to the lack of change in pilot rating. They noted that the additional tasks did not break up the cross-check, and the aircraft could be flown hands-off, so that single- and dual-pilot operations were equally difficult. Similarly, the influence of the missed approach on the workload was negligible.

T28: Collective, lateral, and longitudinal cyclic directors— The average dual-pilot rating for configuration T28 was 2.7, with a range from 2.0 to 3.0 (three evaluations); the average single-pilot rating including the missed approach was 3.3, with a range from 2.5 to 4.0 (three evaluations); without the missed approach, the average single-pilot rating was 3.3, with a range from 2.5 to 4.0 (two evaluations). The dual-pilot comments indicated some difficulties with power tracking at first, but noted that the speed-hold function made it easier. The single-pilot ratings and comments were effectively the same regardless of whether the missed approach was included. The comments indicated that the pilot could let go of the controls to perform the auxiliary tasks and was not near any "limits," although one noted some difficulty while performing the deceleration.

Figures 10-12 are "plots" of the average pilot ratings given to the control-display combinations described earlier for the dual-pilot and single-pilot operations with missed approach, and for the single-pilot-with-continued-approach precision instrument approaches, respectively. Appendix A lists the actual ratings as assigned. To assist in ascertaining trends, the configuration blocks in figures 10-12 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. Further, averaged pilot ratings are used in the discussion only for simplicity in ascertaining such trends. It is recognized that the Cooper-Harper scale is ordinal rather than interval (ref. 22), 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.

The two extremes in the data were generally the dual-pilot loading case and the single-pilot-with-missed-approach case. Initially, for the sake of simplicity, we consider only these two sets of data (figs. 10, 11). The first point to note is that the control-display combinations required to achieve pilot ratings of satisfactory (CHPR ≤ 3.5) were substantially the same for both the dual-pilot and single-pilot cases; 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 to 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 for one control problem (e.g., speed tracking without a flight director) so that overall compensation remains minimal. For example, the comments about dual-pilot operation for the wing-leveler-plus-input-decoupling control system combined with a two-axis director (T17) indicated that the directors permitted increased attention to the pitch-attitude control problem, but that the compensation in this axis was high enough to prohibit assignment of a rating of satisfactory. The comments then note that the pitch workload becomes extensive in the single-pilot case, so that the minor deficiency in pitch becomes very objectionable. When a pitch-attitude augmentation loop is added to this control system with the same display (T22) the dual-pilot comments now note that the third director for pitch was not missed because the pitch characteristics were so docile; with this system in the single-pilot situation, the minimal compensation required for dual-pilot operation translates into a relatively easy performance of the auxiliary tasks in single-pilot operation. To a large extent, therefore, the same aircraft control and display characteristics appear to be required for ratings of satisfactory regardless of crew loading.

However, to achieve ratings of adequate (CHPR ≤ 6.5), considerably different control-display combinations, depending on crew loading, were required. As shown in figure 10, effectively all of the control-display combinations were rated adequate for 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 operations, but broke down badly when attention was diverted in single-pilot operations. For example, the comments indicated that the rate-damper SCAS with three-axis directors (T03) 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 minor control-display trade-off was demonstrated among combinations receiving ratings of satisfactory, but the "boundary" separating adequate from inadequate configurations appears to depend primarily on the stability-control augmentation system, particularly in the single-pilot case. The pilot comments reflected the same type of 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 compensations 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 (T26). 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 (T07).

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 appeared to be relatively ineffective in improving performance, particularly, again, for single-pilot operation. For the two control systems without input decoupling (T30-T03 and T10-T13), in fact, the trend in ratings is almost toward a worse capability with increasing levels of flight directors (fig. 11). As the pilot comments repeatedly indicate, the influence of the auxiliary tasks was to expose aircraft response deficiencies for at least those control systems without pitch-attitude augmentation when attention was diverted from the directors (e.g., T12, T17), resulting in extensive pilot compensation to regain adequate performance. It is interesting to note that the atmospheric disturbances (turbulence, wind) included in this experiment may also have been partially responsible for obviating the efficacy of the flight directors; references 8 and 16 describe the significant degradation of pilot rating for a rate-damper control system in the presence of a crosswind for a VTOL instrument task, for example.

The influence of one aspect of the single-pilot task can be examined by comparing the ratings and comments including and excluding the missed-approach element. In terms of auxiliary tasks, the missed-approach maneuver was a high-workload task, including the necessity to copy a new clearance and change frequencies for both communications and navigation; the control task is also difficult because a large change in aircraft state is required at the critical point of the approach. Comparing the average ratings with and without the missed approach (figs. 11, 12), it can be seen that in general there is very little difference, and the pilot comments also indicate this perhaps surprising result. The control display combinations for which there was a noticeable difference were T13 and T17, both of which highlighted the speed-control problem in the missed approach. However, it appears that the frequency shifting and communications required during the approach phase of the task were sufficient in most of the configurations to point out the influence of the single-pilot environment. On this basis, therefore, conclusions drawn for the single-pilot evaluations that included the missed approach, probably do not need to be qualified as being based solely on the difficulty of the missed 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. 11). 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. As has been discussed, about the same control-display combinations are required for ratings of satisfactory for both dual-pilot and single-pilot operations.

As previously discussed, the control-display combinations required for ratings of adequate depend heavily on crew loading. Note, for example, that the average ratings for all the configurations with the rate-damping-plus-input-decoupling-plus-wing-leveler control system differ by at least one pilot rating between the two crew-loading situations. The average ratings of clearly adequate (CHPR < 6.5) for all the dual-pilot configurations correspond to the adequacy for this task, given this crew loading, of neutral longitudinal static stability that was demonstrated in an earlier experiment (ref. 6). The configurations examined here do not include characteristics (e.g., higher interaxis coupling, unstable dynamics or statics) that might have led to ratings of marginally adequate (CHPR ≅ 6.5) for the dual-pilot situation. Although some benefit of flight director displays is evident for the "better" control systems in the dual-pilot situation, no clear trend is apparent for the basic rate-damping system, and it may, therefore, be hypothesized that the marginally adequate combinations would be dependent primarily on the stability and control characteristics. For the single-pilot situation, the data are not completely consistent. Conservatively, however, it appears that at least the wing leveler and probably input decoupling would be required in addition to a basic rate-damping control system, considering the configurations investigated in this experiment. Since the pilot comments indicated an extremely difficult speed-control problem, it is possible that a baseline aircraft with stable longitudinal static stability would also be desirable, but that hypothesis would have to be verified. The rating data indicate on average little if any beneficial influence of the displays for the marginally adequate configurations; accordingly, the requirement appears generally to be for a given level of control complexity irrespective of the display assistance.

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 ≤ 6. Although all of the control-display configurations were rated adequate for the task in the dual-pilot situation, in order 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, 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 was to eliminate the effectiveness of display assistance, once the overall control workload became 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; as has been discussed, speed control was noted as a high-workload item for all the configurations, even with a flight director to assist. The velocity-hold SCAS was designed to alleviate this problem in two ways: increase 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.

SYSTEM PERFORMANCE AND CONTROL USE RESULTS

In this section the system performance and control-use results are presented and discussed. Because of the large quantity of data obtained, attempts have been made to summarize quantitative results in metrics that can be reasonably compared with flying-qualities results (pilot ratings and commentary) for correlation of trends across all test configurations. The use of objective measures of performance and workload in the certification process would be extremely desirable; consequently, correlations were examined for the data from this experiment.

The system (pilot-vehicle) performance measures consist principally of indicators of how well the pilot controls the primary flight performance variables while performing the MLS approach. Control-use measures were chosen to indicate relative changes in the amount of work required of the pilot for the basic flight control task. Standard deviations about mean values of the flight performance and control-use measures were used as gross indicators for these purposes. To establish overall trends, standard deviation values were averaged together during an approach segment and for several segments. An obvious omission that results from the use of standard deviation measures is that they do not reflect the frequency content of the observed variables. These measures were used because of their availability and for comparison with other experiments in this series. Accordingly, the following are discussed in subsequent subsections: (1) the effect of crew-loading and configuration on absolute track error while on MLS final approach, (2) representative single-pilot flight performance and airspace use with some configurations, (3) standard deviation measures of flight performance and control use during final approach with some configurations and, finally, (4) effects of control system, display and crew-loading on the flight performance and control use for all configurations.

MLS Absolute Track Error

An important measure of system performance to consider is the precision with which the aircraft tracks the MLS beam and is positioned at the decision point. This is measured as an absolute angular deviation in azimuth and elevation from the MLS final approach centerline. Data for dual-pilot and single-pilot approaches are summarized in figure 13. All configurations are included in the position cross-plots at three positions on final approach: outer marker, outer marker plus 1,000 ft, and outer marker plus 7,300 ft. All the dual-pilot approaches (fig. 13(a)) included a missed approach whereas the single-pilot approaches (fig. 13(b)) were with and without a missed approach. The figure shows that position accuracy is about the same for dual-pilot and single-pilot at the first two positions on the final approach. However, single-pilot performance is inferior to dual-pilot performance at the final position where measured (typically 1,200 ft before the decision point). It should also be noted that azimuthal tracking was not totally satisfactory in the dual-pilot case since 5 of the 55 runs exceeded 1 dot (2.5°) deviation in azimuth.

The azimuth and elevation tracking errors before decision height are shown in figure 14 for each test configuration; and data are taken from all single-pilot approaches. A clear trend toward improved azimuth tracking with the addition of the lateral flight director (two-axis and three-axis configurations) is shown in the figure. Although the improvement in tracking is not as dramatic in elevation as in azimuth, there may be a slight quantitative improvement, presumably because of an ability to concentrate more on pitch when the lateral control task workload is reduced by the addition of the lateral flight director. The collective director and longitudinal director do not seem to afford a similar measure of improvement in performance. The elevation tracking is poor for the rate-damped (RD) control-system configurations; in particular, the combination of rate damping (RD) with input decoupling (ID) reflects the poorest performance. The attitude-command (AC) and rate-command (RC) control systems reflect degraded tracking performance in some instances on those approaches with low decision height (200 ft). This is because of increasing azimuth and elevation beam displacement sensitivity as the aircraft flies toward the co-located MLS transmitters on the platform. The introduction of decision height as a variable factor in the conditions for evaluating the various configurations did not allow perfect duplication of conditions; it was intended to provide a means to explore in a preliminary way the effects of low visibility and decision height at constant 60-knot approach speed on the capability for completing a satisfactory approach. Pilot comments indicated that there was insufficient distance to decelerate for a landing on the elevated platform with a decision height of 200 ft, since at a distance of 1,000 ft it was practically impossible to keep the platform in view while pitching up to effect a rapid deceleration.

Representative Single-Pilot MLS Approaches

To provide an overview of the complete MLS approach with single-pilot crew loading, data from one approach are shown in figure 15. The figure is a plot of approach position (altitude, x-distance and y-distance to the MLS transmitters), azimuth and elevation tracking, airspeed and rate of climb control. Before the first evaluation period, each pilot was asked to define performance guidelines that were acceptable to him. There was a reasonable agreement among the pilots on the maintenance of airspeed within ±10 knots, of rate of climb within ±200 ft/min, of altitude within ±100 ft, of heading within ±10°, of azimuth tracking ±2.5°, and of elevation tracking within ±1°. For data analysis purposes each approach was divided into segments.

Figure 15(a) for the configuration with rate-damped control system and no flight director (baseline configuration, T30). The approach is well executed overall. The azimuth and elevation track errors vary from beam center but are both within the performance tolerance expected (±2.6° and ±1°). The track errors continue within tolerance down to the decision-height point, although there are some large changes in heading fairly close in (500-ft altitude). Airspeed and rate of climb are continually varying and are indicative of the high workload experienced. Airspeed control exceeds a ±5-knot variation but is within ±10 knots, except during the missed approach when the speed increased to 75 knots momentarily. Rate-of-climb control varies excessively about the desired value, especially during the descent, when it varies from -1,660 ft/min to 100 ft/min (desired nominal rate of climb -637 ft/min).

Figure 15(b) is also for the rate-damped control system configuration but with a three-cue flight control system (configuration T03); it shows better tracking of the MLS beam, although the control of airspeed and rate of climb is not as good as without the flight director. Variations in airspeed and rate of climb occur at a higher frequency. The airspeed dropped to a minimum of 43 knots at the decision height of 200 ft. The decision height for this approach is the lowest of all the approaches flown. The descent was continued to a minimum height of 97 ft, that is, 103 ft below the decision height, passing much closer to the landing platform and oil rig tower than realistic obstacle-clearance constraints would allow.

An approach with a wings leveler and input decoupling system added to the baseline rate-damped control system (configuration T15, RDWLID) shows that (fig. 15(c)) MLS tracking was adequate without a flight director; however, airspeed and rate-of-climb control are inadequate throughout the run and were poorest during the missed approach. The pilot did not feel that he was on the verge of losing control although airspeed decreased to a minimum of 36 knots. The addition of a three-cue flight director (fig. 15(d)) to the RDWLID control system (configuration T18) shows a pronounced improvement in MLS tracking, airspeed, and rate-of-climb control; however, there are some relatively large airspeed and rate-of-climb variations during the transition to a descent.

The last two approaches shown here (figs. 15(e), 15(f)) are with the most sophisticated level of control system installed; it includes attitude command, velocity hold, and input decoupling (ACVHID). Again, one approach (fig. 15(e)) is without a flight director (configuration T25), and the other (fig. 15(f)) is with the three-cue flight director (configuration T28). The performance is satisfactory during both approaches; moreover, there is a significant improvement in MLS tracking (particularly azimuth tracking) and in airspeed and rate of climb control with the guidance provided by the flight director.

Representative Measures of Flight Performance and Control Use

In this subsection some representative measures of flight performance and control use are shown for a 35-sec segment of the final approach for both the dual-pilot and single-pilot crew-loading situations. Fourteen of the 24 test configurations are included in this sample. The configurations included are all six control system types without a flight director and with a three-axis flight director. In addition, configurations with one-axis and two-axis flight directors were included for the rate-damped-with-wing-leveler control system. The flight performance measures over the final approach segment selected were standard deviation values for elevation angle, azimuth angle, airspeed, and sideslip. The control-use measures were standard deviation values of longitudinal and lateral cyclic over the same segment of the final approach. The values from the runs available for each configuration were averaged and are shown with maximum and minimum values in the figures.

As can be seen from the flight performance variables in figure 16, the trends with changing control system or crew loading are minor. The addition of a three-axis flight director does tend to show improved performance — lower average values and less variation between maximum and minimum values — for all control systems and dual-pilot crew loading. For single-pilot operation there is a slight improvement with the addition of the three-axis flight director but only for those configurations with an attitude-command or rate-command attitude-hold control system installed. The single-pilot performance with only a rate-damping system and without input decoupling is worse with the three-axis flight director than with no flight director; note in particular the very large airspeed variations for those configurations. This deficiency will be discussed further in the next paragraph. The major difference seen in this sample of flight-performance data is between the raw data and three-axis flight director displays for azimuth and elevation tracking. This improvement in tracking with the flight director is due primarily to integrating azimuth and elevation commands with the ADI; however, the pilots commented about a requirement to periodically check the raw data display on the HSI.

The trends in control-use variables shown in figure 17 are more apparent than were those in the flight-performance variables shown in figure 16. The trend is toward less control use with more control augmentation installed and with a flight director available. In particular, the use of longitudinal cyclic is significantly reduced with the installation of an attitude-command or rate-command attitude-hold system and a three-axis flight director. However, with the rate-damped wings-leveler control (RDWL) system installed, the trend is to increase longitudinal cyclic use with addition of flight director axes (figs. 17(e), 17(f)). In particular, for the single-pilot situation (fig. 17(f)), the addition of a three-axis flight director to the RDWL control system results in a large increase in longitudinal cyclic use. This is consistent with the deficient longitudinal flight performance noted in the above paragraph and with the pilot comments and pilot ratings given to this configuration. The deficiency may be due to inadequate compensation for the dynamics of the rate-damped control system in the guidance laws of the longitudinal flight director because of the use of one set of director gains for all the control systems (see the section on flight director design). As was noted in the Flying Qualities Results section, the pilot comments indicated an incipient PIO in pitch when trying to follow the longitudinal flight director, as well as a deterioration in pitch control when the auxiliary tasks were performed.

Effect of Control System, Display, and Crew Loading (All Configurations)

As a means of showing for all configurations the effects of control system, display, and crew loading, several measures of flight performance and control use were selected. Values of each selected measure were obtained for three segments of the MLS approach: initial approach, descent, and missed-approach segments. The values for these segments for all configuration evaluations are listed in table 1 of appendix D, part II. Because of the large amount of data obtained, attempts were made to obtain a good composite index of flight performance and control use for each configuration. The composite index for flight performance was obtained by taking the root-sum-square of the standard deviations of airspeed, rate of climb, and sideslip for each segment. The composite index for control use was obtained by taking the root-sum-square of the standard deviations of lateral cyclic, longitudinal cyclic, and directional pedal displacements for each segment. The composite values for all segments flown with each configuration were then averaged to provide an average index for flight performance and an average index for control use. The average plus maximum and minimum values of the indices are plotted for each configuration and for the dual-pilot case (fig. 18(a)), single-pilot case with missed approach (fig. 18(b)), and single-pilot case without missed approach situations (fig. 18(c)).

Consider first the amalgam of data presented in figures 18(a) and 18(b), dual-pilot and single-pilot operations with missed approach, respectively. Since the primary flight-control task is the same in both situations, and the total task differs only in that auxiliary tasks are required in the single-pilot situation, a comparison of these two figures should show the influence of crew loading on the various configurations. The differences are in fact slight, both in average value and range. The average values of control use are slightly greater for the single-pilot loading than for the dual-pilot loading for 20 of the 24 configurations. This trend is also generally true for the average values of flight performance, although it is not as consistent as for control use.

Two indicators were used to compare the cockpit workload between runs with various test configurations and to compare the relative levels of basic task and auxiliary task workload during any one run. The metric chosen for basic task workload is again a composite use of the longitudinal cyclic, lateral cyclic, and directional pedal controls. The numerical value for control use is the root-sum-square value (vector sum) of the standard deviations of each of the three controls about its mean during a segment of the approach. The metric chosen for auxiliary task workload is the relative time required to do the auxiliary task. The value is determined as a percentage of the total time available during the segment in which the auxiliary work is done. An example of the variation of these indicators of pilot workload is shown in figure 19 for a single-pilot approach; the example run is divided into 11 segments. This particular run was with a configuration that was rated unacceptable (CHPR = 8) by the evaluation pilot, principally because of a virtual loss of control situation that developed during the VORTAC tracking (300 sec elapsed time). Although the time required to complete the auxiliary task did vary slightly from run to run and pilot to pilot, the example shown is typical.

There is a noticeable trend of decreasing average control use with increasing control-system complexity for the same flight director, indicating an influence of control system on pilot workload for both crew-loading situations. However, the influence of control system on performance is not apparent. Pilot comments indicated that satisfactory flight performance could be achieved if the task permitted increased attention to deficient handling qualities or guidance information. The addition of flight directors does not show an improvement in flight performance or control use except for the dual-pilot operations with the four control systems that provide input decoupling and for single-pilot operations with the addition of attitude stabilization. These results are in accord with the pilot ratings and comments, which reflect the same insensitivity to flight-director guidance necessary to produce adequate configurations.

All configurations except one were judged adequate for the dual-pilot situation, whereas the determination of adequate in the single-pilot situation depended more on the control system than on the flight-director guidance provided. Overall, the pattern of the control-use index is more consistent with pilot rating for the simulated configurations than is the flight-performance index, a finding that is indicative of the often-demonstrated capability of the pilot to adapt control behavior to achieve the required performance. There was a consensus among the evaluation pilots that the missed-approach segment was the most difficult part of the approach, but they did not appear to weight the performance achieved in this segment as heavily as they did for the descent segment in giving their ratings. In considering all of the segments for all of the dual-pilot and single-pilot runs with missed-approach tabulated in appendix D, the flight performance in 69% of the missed-approach segments is shown to be poorer than the other segments. It would seem reasonable for the airworthiness criteria to require a number of approaches with missed approaches to be completed satisfactorily as part of an operational evaluation before certification for IFR.

In figure 18(c) is plotted the flight performance and control-use data for the single-pilot-without-missed-approach situation. Any trends in this smaller set of data are slight; the variations are not as great as in the single-pilot-with-missed-approach situation. In general the worst configurations in this data set are those without attitude stabilization.

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° slide slope to an offshore oil rig in simulated light turbulence and variable crosswind. 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 $\leq$ 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 $\leq$ 6.5) was evident. All combinations evaluated were rated clearly adequate for dual-pilot operations, 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; the determination of an adequate combination is dependent primarily on stability-control augmentation, although the addition of three-cue flight directors does make these configurations more clearly adequate.

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 single-pilot operation, 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 trade-off of control-system complexity with flight-director sophistication. This trade-off 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.

APPENDIX A

DATA SUMMARY

Pertinent data relative to the evaluation configurations of this experiment are summarized here. Tables 5-9 give the stability and control derivatives of the evaluation configurations at 60-knot, level flight. The elements of the matrices (first-order form of the equations) include the body-axes stability/control derivatives and lumped gravitational/kinematic terms; the L' and N' equations (sixth and eighth, respectively) use the conventional arranging to the eliminate cross-product inertia terms.

Tables 10-12 summarize the feedback and gearing gains used to achieve the evaluation configuration characteristics. These gains are used in a response-feedback fashion around the baseline aircraft described by the mathematical model and characteristics given in table 1.

Table 13 is the master summary of the evaluations conducted in this experiment.

APPENDIX B

FLIGHT DIRECTOR COMMAND LAWS

The axes systems, guidance commands, and flight-director control law designs are described in this appendix. For this experiment, the flight directors must provide the pilot with information to perform the evaluation task described in the body of this report: azimuth capture and tracking at constant-altitude deceleration from 80 to 60 knots and elevation capture and tracking at constant 60 knots down to the decision height; different logic to assist the performance of the missed-approach maneuver is also required. This required information is generated from measurements of the position of the aircraft relative to the desired approach trajectory; the position measurements are used to drive appropriate position and velocity commands which are summed with measured positions, velocities, and aircraft response and control input variables to provide shaped signals that drive the flight directors. Accordingly, in this appendix the appropriate axes systems and desired approach trajectory are described first; the guidance position and velocity commands are then derived; and finally the philosophy used to generate shaped, flight director signals is defined.

In this experiment aircraft position data were assumed to be available relative to an Earth-fixed rectangular XYZ coordinate system. For the microwave landing system that was simulated, this assumption implies the resolution of azimuth, elevation, and range data into such coordinates. The specific system selected has the origin at the decision height point along the commanded glidepath; X_E is aligned with the desired approach course and is positive toward the landing point (i.e., the aircraft approaches along the negative X_E axis); Z_E is vertical and positive down; and Y_E is positive, such that a right-hand triad results. The selection of the origin to be at the decision height rather than at the touchdown point was made to facilitate common implementations for the four approach courses described in the body of this report. With respect to the $X_E Y_E Z_E$ "Earth" axes, the wind components are given by

$$\dot{X}_{W_E} = -V_W \cos \psi_W \tag{B1a}$$

$$\dot{Y}_{W_E} = -V_W \sin \psi_W \tag{B1b}$$

where V_W is positive for headwinds and Y_W is positive for rotations from positive X_E to positive Y_E.

A second reference frame is a vertical-heading coordinate system with instantaneous origin at the aircraft center of gravity, Z_H vertical and positive down, X_H rotated from X_E by the difference between aircraft heading and approach course heading (ψ_R), and Y_H again completing the right-hand triad. Velocities as measured in the two axes systems are therefore rotated by

$$\dot{X}_H = \dot{X}_E \cos \psi_R + \dot{Y}_E \sin \psi_R \tag{B2a}$$

$$\dot{Y}_H = \dot{Y}_E \cos \psi_R - \dot{X}_E \sin \psi_R \tag{B2b}$$

$$\dot{Z}_H = \dot{Z}_E \tag{B2c}$$

The definition of the desired approach trajectory in the "Earth" axes is straightforward. Since X_E was picked to lie along the desired approach course, the X_EY_E portion of the trajectory is $Y_{E_C} = 0$. In the vertical (X_EZ_E) plane, it is desired to have a -6° slide slope for the last part of the approach, a level flight initiation of the approach, and some type of gradual blending between the two to reduce glide-slope overshoot during acquisition. Picking $\Delta Z_E = 900$ ft to be the altitude change during glide-slope tracking defines the "intercept" point to be at $X_E = -8{,}563$ ft; selecting a rate of change of glide slope of 0.5°/sec to smooth the intercept, and using the approach velocity of 60 knots (≅100 ft/sec) leads to the following vertical position commands:

$$\gamma_C = 0° \text{ for } X_E \text{ beyond } -9{,}163 \text{ ft} \tag{B3a}$$

$$\gamma_C = -\frac{X_E + 9163}{200} \text{ deg for } X_E \text{ between } -9{,}163 \text{ and } -7{,}963 \text{ ft} \tag{B3b}$$

$$\gamma_C = -6° \text{ for } X_E \text{ between } -7{,}963 \text{ and } 0 \text{ ft} \tag{B3c}$$

and

$$Z_{E_C} = -900 \text{ ft for } X_E \text{ beyond } -9{,}163 \text{ ft} \tag{B4a}$$

$$Z_{E_C} = -900 - \frac{X_E + 9163}{2} \tan \gamma_C \text{ for } X_E \text{ between } -9{,}163 \text{ and } -7{,}963 \text{ ft} \tag{B4b}$$

$$Z_{E_C} = -X_E \tan \gamma_C \text{ for } X_E \text{ between } -7{,}963 \text{ and } 0 \text{ ft} \tag{B4c}$$

With the $X_{E_C}Y_{E_C}Z_{E_C}$ desired approach trajectory defined by equations (B3) and (B4) plus $Y_{E_C} = 0$, and assuming measurements $X_EY_EZ_E$ of the position of the aircraft to be available, it is now necessary to derive velocity commands that will eliminate the position error and define the aircraft state. Consider initially the longitudinal airspeed, and recall that the evaluation task for this experiment includes a deceleration from 80 to 60 knots before glide-slope intercept. If the command is written in terms of groundspeed (feet per second), a constant 0.05-g deceleration is assumed, and ψ_R is assumed effectively zero,[1] the commands are:

$$\dot{X}_{E_C} = 135 - V_W \cos \psi_W \qquad X_E \text{ beyond } -13{,}583 \text{ ft} \tag{B5a}$$

$$\dot{X}_{E_C} = 1.8\sqrt{-7888 - X_E} - V_W \cos \psi_W \qquad X_E \text{ between } -13{,}583 \text{ and } -11{,}000 \text{ ft} \tag{B5b}$$

$$\dot{X}_{E_C} = 101 - V_W \cos \psi_W \qquad X_E \text{ between } -11{,}000 \text{ and } 0 \text{ ft} \tag{B5c}$$

---

[1]The assumption $\psi_R = 0$ is not required, and in fact the correct way to write equations (B5) is as the heading-system commands ($\dot{X}_{H_C}$). These equations document the actual design; as will be discussed, when they were implemented the above mistake was in effect corrected.

Consider next the command to achieve azimuth tracking ($Y_{E_C} = 0$). In order to provide a smooth capture of the azimuth center, a velocity toward the centerline that is linearly proportional to the error is desirable; this type of command is consistent with most previous work (ref. 8), and results in an exponential capture profile:

$$\dot{Y} = KY \rightarrow Y = Y_0 \, e^{+kt} \tag{B6}$$

assuming an initial lateral deviation from the azimuth center of Y_0 at time $t = 0$. If K is constant in equation (B6), equally tight tracking is required far out on the approach as close in — that is, it is equivalent to a linear error sensitivity. To permit less stringent acquisition demands far out on the approach (i.e., a longer time-constant for large $|X_E|$ than for small $|X_E|$), the proportionality constant was made a linear function of range, thereby yielding an angular rather than a linear sensitivity. The resulting command is:

$$\begin{aligned} \dot{Y}_{E_C} &= -K_Y Y_E \\ K_Y &= 0.125 \text{ 1/sec} \quad \text{at} \quad X_E = 0 \text{ ft} \\ &= 0.089 \text{ 1/sec} \quad \text{at} \quad X_E = -17{,}560 \text{ ft} \end{aligned} \tag{B7}$$

(with linear interpolation between)

Finally, for the vertical-plane commands, a velocity command in addition to the profile-position command given in equation (B4) is required to assist in shaping the flight-director control law, as will be described. For consistency with the position command, the vertical-velocity command is

$$\dot{Z}_{E_C} = \dot{X}_{E_C} \tan \gamma_C \tag{B8}$$

where γ_C is given by equation (B3).

Given the commands as defined above, the flight-director control laws are derived by comparing these commands with measured actual values and adding shaping. A variety of methods for deriving the shaping are available, depending generally on assumed forms of pilot behavior and desired pilot-vehicle closed-loop tracking performance. For this experiment, following reference 8, it was assumed that a director bar motion proportional to the integral of the appropriate controller input (e.g., $FD_i = K/s\delta_i$) over some frequency range is desirable for "primary" controlled elements (pitch and roll); on the other hand, recent STOL experience has indicated that a proportional response ($FD_i = K\delta_i$) is preferable for "secondary" elements (collective) (ref. 17). For a typical aircraft problem in which the transfer function of a response to a control input is fourth order, the K/s desideration implies that the flight-director signal should be a weighted sum of linear velocity, aircraft attitude, and attitude rate; for example,

$$FD_{\dot{X}} \sim K_{\dot{X}}\dot{X} + K_\theta \Theta + K_q q \tag{B9}$$

With such a relationship, the flight-director transfer function is, for the same example,

$$\frac{FD_{\dot{X}}}{\delta_{ES}} = \frac{1}{\Delta(s)}\left[K_{\dot{X}}N^{\dot{X}}_{\delta_{ES}}(s) + K_{\theta}N^{\theta}_{\delta_{ES}}(s) + K_{q}N^{q}_{\delta_{ES}}(s)\right]$$

$$= \frac{N^{FD_{\dot{X}}}_{\delta_{ES}}(s)}{\Delta(s)} \tag{B10}$$

where

$\dfrac{N^{\dot{X}}_{\delta_{ES}}(s)}{\Delta(s)}$ is the $\dot{X}/\delta_{ES}$ transfer function of the aircraft, etc.

The design problem is essentially to choose the $K_{\dot{X}}$, K_{θ}, and K_q in equation (B10) so that $N^{FD_{\dot{X}}}_{\delta_{ES}}(s)/\Delta(s)$ exhibits K/s behavior over a wide frequency range. In the event that a proportional rather than integral response is desired ($FD_i = K\delta_i$), the controller itself may be added to equation (B10), namely,

$$\frac{FD_{\dot{X}}}{\delta_{ES}} = \frac{1}{\Delta(s)}\left[K_{\dot{X}}N^{\dot{X}}_{\delta} + K_{\theta}N^{\theta}_{\delta_{ES}} + K_{q}N^{q}_{\delta_{ES}} + K_{\delta}\ \Delta(s)\right] \tag{B11}$$

Although, as was discussed above, the use of attitude rate signals in the flight-director equation may be required to achieve a K/s response, the use of these signals also makes the director commands sensitive to turbulence inputs to the aircraft, particularly for aircraft without much stability augmentation (ref. 16). For this reason, it was decided at the outset to use only translational rate and aircraft attitude signals in the commands for this experiment, thereby sacrificing the potential for K/s behavior at high frequencies as a trade-off for reduced sensitivity. Because of this inability to provide overall K/s behavior, it was further assumed that one set of flight director gains for each command would be designed, rather than designing gains that vary with aircraft characteristics as equation (B10) implies and as was done in reference 8. This simplifying assumption resulted in flight-director laws that may not have been sufficiently tailored to the controlled element characteristics, as will be discussed below. Finally, to avoid standoff errors, the attitude signals (eq. (B10)) and controller signals (eq. (B11)) were run through washout filters.

On the bases discussed above, and assuming that longitudinal cyclic (EBAR director) controls primarily speed, that collective pitch (CTAB director) controls primarily rate of climb, and that lateral cyclic (ABAR director) controls primarily lateral course, the general equations driving the directors were

$$EBAR = K_{\dot{X}}\varepsilon_{\dot{X}_H} + K_{\theta}\theta_{WO} \tag{B12}$$

$$ABAR = K_{\dot{Y}}\varepsilon_{\dot{Y}_H} + K_{\phi}\phi_{WO} \tag{B13}$$

$$CTAB = K_Z\varepsilon_Z + K_{\dot{Z}}\varepsilon_{\dot{Z}} + K_{\delta_C}\delta_{C_{WO}} \tag{B14}$$

In these equations, $\varepsilon_{(\ )}$ indicates the difference between commanded and actual values, and the WO subscript implies a washed-out signal of pitch or roll attitude or collective stick position, as discussed above.

Consider initially the longitudinal cyclic command, EBAR. Approximate transfer functions for the rate-damping control system are, from appendix A,

$$\frac{U}{\delta_{ES}} \doteq \frac{-1.92(0.18;\ 2.4)}{(2.8)(0.06;\ 0.06)} \cong \frac{-11}{(2.8)(0;\ 0.06)} \tag{B15}$$

$$\frac{\Theta}{\delta_{ES}} \doteq \frac{0.36(0.011)}{(2.8)(0.06;\ 0.06)} \cong \frac{0.36(0)}{(2.8)(0;\ 0.06)} \tag{B16}$$

Using equations (B12), (B15), and (B16), and writing $\Theta_{WO} = (S/S + 1/T_{WO})\Theta$, the expression for EBAR at 60 knots is

$$\frac{\text{EBAR}}{\delta_{ES}} \doteq \frac{0.36K_\theta[S^2 - 30.6(K_{\dot{X}}/K_\theta)S - 30.6(K_{\dot{X}}/K_\theta)(1/T_{WO})]}{(S + 1/T_{WO})(S + 2.8)(S^2 + 0.06^2)} \tag{B17}$$

A region of K/s-like behavior between $S = 1/T_{WO}$ and $S = -2.8$ can be obtained in principle by selecting the flight director gains such that the numerator quadratic "cancels" the denominator poles at $S = \pm 0.24$. As discussed in reference 8, however, this procedure might still lead to a lightly damped low-frequency characteristic if the cancellation is imperfect, and a preferable concept is to provide zeroes, at approximately the same frequency, that are well damped. Selecting as desired numerator characteristics, therefore, $\zeta = 1.0$ and $\omega_N = 0.2$ leads to

$$\frac{K_{\dot{X}}}{K_\theta} = -0.013 \tag{B18a}$$

$$\frac{1}{T_{WO}} = 0.1 \tag{B18b}$$

With these relationships, selecting a ±40 ft/sec full-scale error (1-in. deflection of the command bar) as reasonable for desired speed tracking leads to

$$K_{\dot{X}} = -0.025 \text{ in./ft/sec}$$

$$K_\theta \doteq +2.0 \text{ in./rad}$$

$$T_{WO} = 10 \text{ sec}$$

During initial piloted checkout in the simulator, these gains were reduced on the basis of pilot comments to $K_{\dot{X}} = -0.0188$ and $K_\theta = 1.2$, yielding numerator characteristics of $\omega_N = 0.22$ rad/sec and $\zeta = 1.08$. In addition, as mentioned earlier, the $\dot{X}_{EC}$ of equation (B5) was used as the command in the error equation, so that $\varepsilon_{\dot{X}_H} \triangleq \dot{X}_{E_C} - \dot{X}_H$ in equation (B12).

Consider next the lateral cyclic command, ABAR. Assuming that the pilot or control system provides good turn coordination characteristic ($\beta \doteq 0$, $\dot{Y}_H \doteq 0$), the approximate transfer functions of interest for the rate damping control system are

$$\frac{\phi}{\delta_{AS}} \doteq \frac{0.91(0.87)(2.09)}{(5.8)(-0.0032)(0.87)(2.16)} \cong \frac{0.91}{(5.8)(0)} \tag{B19}$$

$$\frac{r}{\delta_{AS}} \doteq \frac{g}{U_o} \cdot \frac{\phi}{\delta_{AS}} \doteq \frac{0.29}{(5.8)(0)} \tag{B20}$$

$$\frac{\psi_R}{\delta_{AS}} \doteq \frac{1}{S} \frac{r}{\delta_{AS}} \doteq \frac{0.29}{(5.8)(0)^2} \tag{B21}$$

$$\frac{\dot{Y}_E}{\delta_{AS}} \doteq U_o \frac{\psi_R}{\delta_{AS}} \doteq \frac{29.3}{(5.8)(0)^2} \tag{B22}$$

$$\frac{Y_E}{\delta_{AS}} = \frac{1}{S} \frac{\dot{Y}_E}{\delta_{AS}} = \frac{29.3}{(5.8)(0)^3} \tag{B23}$$

Substituting equations (B19) through (B23) into equation (B13) and assuming, for simplicity, that the difference between aircraft and course headings is small (ψ_R small, $\cos \psi_R \doteq 1$ $\varepsilon_{\dot{Y}_H} \doteq \varepsilon_{\dot{Y}_E}$ when longitudinal velocity tracking is good so the $\varepsilon_{\dot{X}_E} \doteq 0$) leads to (recalling that $\dot{Y}_{E_C} = -K_Y Y_E$) the following:

$$\frac{ABAR}{\delta_{As}} = 0.91K_\phi \left[\frac{s^3 - (K_{\dot{Y}}/K_\phi)(s + K_Y)(s + 1/T_{WO})32.2}{(s + 1/T_{WO})(s + 5.8)s^3}\right] \tag{B24}$$

Since K_Y is picked already, the flight-director design problem is to select $K_{\dot{Y}}/K_\phi$ and $1/T_{WO}$ to give a K/s-like behavior between some low frequency and $s = -5.8$. Using the $X_E = 0$ value for K_Y, the numerator of equation (B24) is

$$N^{ABAR}_{\delta_{As}} = s^3 - 32.2 \frac{K_{\dot{Y}}}{K_\phi} s^2 - 32.2 \frac{K_{\dot{Y}}}{K_\phi}\left(0.125 + \frac{1}{T_{WO}}\right) s - 4.03 \frac{K_{\dot{Y}}}{K_\phi} \frac{1}{T_{WO}} \tag{B25}$$

At this point, unfortunately, both "art" and iteration are required. It is clear from equation (B24) that one closed-loop root will be near the washout, and from equation (B25) it can be seen that the frequency and damping of the other two roots are determined primarily by $K_{\dot{Y}}/K_\phi$. For $1/T_{WO} = 0$, in fact,

$$N^{ABAR}_{\delta_{As}} = S\left(S^2 - 32.2 \frac{K_{\dot{Y}}}{K_\phi} - 4.03 \frac{K_{\dot{Y}}}{K_\phi}\right) \tag{B26}$$

Then possible solutions are:

$$\frac{K_{\dot{Y}}}{K_\phi} = -0.015 \quad : \quad \omega_N = 0.25 \ , \quad \zeta = 0.97$$

$$\frac{K_{\dot{Y}}}{K_\phi} = -0.020 \quad : \quad \omega_N = 0.28 \ , \quad \zeta = 1.15$$

$$\frac{K_{\dot{Y}}}{K_\phi} = -0.025 \quad : \quad \omega_N = 0.32 \ , \quad \zeta = 1.26$$

The effect of the selected time-constant on the resulting roots is then:

$$\frac{K_{\dot{Y}}}{K_\phi} = -0.025 \ , \quad T_{WO} = 4.0 \quad : \quad \lambda = -0.11 \ , \quad \omega_N = 0.47 \ , \quad \zeta = 0.74$$

$$\frac{K_{\dot{Y}}}{K_\phi} = -0.025 \ , \quad T_{WO} = 10.0 \quad : \quad \lambda = -0.08 \ , \quad \omega_N = 0.35 \ , \quad \zeta = 1.036$$

This latter set of gains appears to offer a reasonable set of numerator dynamics for the $X_E = 0$ case. In addition, the value of $K_{\dot{Y}}$ is reasonable (for $K_\phi = -1.0$) on another basis. For the assumed co-located MLS and ±5° error sensitivity on azimuth, the full-scale error in Y_E is ±250 ft at an altitude of 300 ft; assuming a 1-in. full-scale flight-director deviation, a lateral error of $1/K_Y K_{\dot{Y}}$ ft causes full-scale deflection. For the example:

$$\frac{1}{K_Y K_{\dot{Y}}} = \frac{1}{(0.125)(0.025)} = 320 \text{ ft} \tag{B27}$$

Although equation (B27) indicates that a more sensitive value of $K_{\dot{Y}}$ (for $K_\phi = 1$) can be used to be consistent with the selected MLS sensitivity, $K_{\dot{Y}} = +0.025$ is reasonable at $X_E = 0$. For X_E large, the value of $K_{\dot{Y}}$ needs to be different because K_Y varies and because a reduced flight-director sensitivity is desirable for acquisition. On the basis of equation (B27), looking for a full-scale deflection of approximately 1,600 ft yields,[2] for $K_\phi = -1.0$,

$$K_{\dot{Y}} = \frac{1}{K_Y \cdot 1600} = \frac{1}{(0.089)(1600)} = +0.007 \text{ in./ft/sec} \tag{B28}$$

The dynamics of the flight-director numerator at this range are then

$$N_{\delta_{AS}}^{ABAR} = (S + 0.06)S^2 + 2(0.46)(0.18)S + (0.18)^2 \tag{B29}$$

[2]This 1,600-ft deflection value is a result of an arithmetic error; using a decision height of 300 ft, at $X_E = 17{,}560$, the full-scale value of Y_E should have been 1,785 ft.

As can be seen from equation (B29), the design procedure has resulted in slower dynamics for the numerator during the acquisition phase, which is probably reasonable. However, there probably should have been further tuning to improve the damping ratio.

During the piloted checkout, these gains were all increased by 50% on the basis of pilot comments and observed performance. The final gains for the lateral director were therefore:

$$K_{\dot{Y}} = +0.0375 \text{ in./ft/sec} \quad \text{at} \quad X_E = 0 \text{ ft}$$

$$= +0.0105 \text{ in./ft/sec} \quad \text{at} \quad X_E = -17{,}560 \text{ ft} \tag{B30}$$

(with linear interpolation between)

$$K_\phi = -1.5 \text{ in./rad} \tag{B31}$$

$$T_{WO} = 10 \text{ sec} \tag{B32}$$

Finally, consider the collective-stick director, CTAB. The critical assumption made in the derivation of the control law for this director is that at the approach speed of 60 knots considered in this experiment, rate of climb is controlled through aircraft body vertical velocity instead of through pitch attitude; that is,

$$\dot{h} \doteq U_o\theta - w \doteq -w \tag{B33}$$

For the rate-damping control system, the important transfer function is therefore,

$$\frac{\dot{Z}}{\delta_{CS}} = -\frac{\dot{h}}{\delta_{CS}} \doteq \frac{10.3(5.7)(2.65)(0.88;\ 2.11)(-0.008)(0.13;\ 0.06)}{(5.8)(2.8)(0.87;\ 2.16)(-0.003)(0.06;\ 0.06)(1.54)} \tag{B34}$$

Assume initially that K/s-like behavior is desirable for altitude control with the collective director. Substituting equation (B34) into equation (B14) with $K\delta_C = 0$ leads directly to

$$\frac{CTAB}{\delta_{CS}} \doteq 10.3K_{\dot{Z}} \frac{s + K_Z/K_{\dot{Z}}}{s(s + 1.54)} \tag{B35}$$

The ratio of $K_Z/K_{\dot{Z}}$ is then selected to cancel approximately the real root in the denominator. In this experiment, the design was conducted using an approximate value of this root of $s = -1.3$ (based on the value of Z_W); the ratios given below reflect this assumption.

The values of the gains were selected by assuming full-scale deflection to correspond to full-scale angular deflection of the selected MLS sensitivities. At the decision height point ($X_E = 0$), the selected ±2° sensitivity on elevation corresponds to approximately ±100 ft. Therefore,

$$K_Z = -0.01 \text{ in./ft} \qquad \text{at} \quad X_E = 0 \text{ ft} \tag{B36a}$$

$$K_{\dot{Z}} = -0.0077 \text{ in./ft/sec} \tag{B36b}$$

At glide-slope intercept, these sensitivities correspond to about ±385 ft. Therefore,

$$K_Z = -0.0026 \text{ in./ft} \qquad \text{at} \quad X_E = -8{,}560 \text{ ft} \tag{B37a}$$

$$K_{\dot{Z}} = -0.0020 \text{ in./ft/sec} \tag{B37b}$$

Linear interpolation between $X_E = 0$ and $X_E = -8{,}560$ was used, but the values were held constant beyond $X_E = -8{,}560$ ft (a linear sensitivity) to retain reasonable attitude-hold performance.

As was discussed earlier, recent work appears to indicate the desirability of the third-cue director exhibiting K-like instead of K/s-like behavior over at least some frequency range. Toward this end, equation (B35) becomes

$$\frac{CTAB}{\delta_{CS}} = -10.3K_{\dot{Z}} \frac{(s + K_Z/K_{\dot{Z}})}{s(s + 1.54)} + K_{\delta_C} \frac{s}{(s + 1/T_{WO})} \tag{B38}$$

If the washout time-constant is selected to correspond to the real root in the vertical velocity transfer function, then

$$N_{\delta_{CS}}^{CTAB} = K\delta_C\left(s^2 - 10.3 \frac{K_{\dot{Z}}}{K\delta_C} s - 10.3 \frac{K_Z}{K\delta_C}\right) \tag{B39}$$

The design assumption is that one root of the numerator is selected to cancel the real root in the denominator (recall that this root was assumed to be -1.3), and then the gains are varied to provide an additional numerator zero that selects the break frequency between K/s and K behavior. Using the $X_E = 0$ value of $K_Z = -0.01$ leads to, for break points at 0.2, 0.5, and 1.0 rad/sec:

$$\lambda_\beta = 0.2 \ : \ K_{\dot{Z}} = -0.059 \ , \quad K_{\delta_C} = 0.40 \tag{B40a}$$

$$\lambda_\beta = 0.5 \ : \ K_{\dot{Z}} = -0.028 \ , \quad K_{\delta_C} = 0.16 \tag{B40b}$$

$$\lambda_\beta = 1.0 \ : \ K_{\dot{Z}} = -0.018 \ , \quad K_{\delta_C} = 0.08 \tag{B40c}$$

As can be seen from equation (B40), the lower the desired break frequency, the higher the gains required for the error rate and stick position terms. In order to maintain the K_Z and $K_{\dot{Z}}$ gains designed on the K/S behavior basis, therefore, the $K\delta_C$ gain from equation (B40c) was selected for initial evaluation.

During piloted checkout, the following changes were made to the collective director gains on the basis of pilot comments. The altitude error gain was increased by 50% over the entire range; the altitude rate error gain (eqs. (B36b) and (B37b)) was multiplied by 2.25; and the collective stick gain was multiplied by 2.35. In addition, and very important, a lead-lag filter of the form $(S + 1)/(0.1S + 1)$ multiplied the entire CTAB signal to compensate for an instrument lag. The final gains were, therefore,

$$K_Z = -0.015 \text{ in./ft} \quad \text{at} \quad X_E = 0 \text{ ft}$$

$$= -0.0039 \text{ in./ft} \quad \text{at} \quad X_E = -8{,}560 \text{ ft} \tag{B41a}$$

(linear interpolation between)

$$K_{\dot{Z}} = -0.0173 \text{ in./ft/sec} \quad \text{at} \quad X_E = 0 \text{ ft}$$

$$= -0.0173 \text{ in./ft/sec} \quad \text{at} \quad X_E = -8{,}560 \text{ ft} \tag{B41b}$$

(linear interpolation between)

$$K_{\delta_C} = 0.188 \text{ in./in.} \tag{B41c}$$

$$T_{WO} = 0.77 \text{ sec} \tag{B41d}$$

The guidance and flight-director laws described in the preceding paragraphs were for acquisition and tracking phases of the approach. Because the evaluation task also included a missed-approach maneuver for most of the evaluations, simplified go-around-mode flight directors were selectable by the pilot. The commands were to hold airspeed constant at 60 knots (EBAR), achieve a 600 ft/min rate of climb (CTAB), and hold a bank angle of +10.0°, 0.0°, or -10.0°, the latter being pilot-selectable, depending on the called-for missed-approach direction. Because the missed-approach maneuver is nonprecision, no signal shaping was used for the CTAB and ABAR directors, with just the error between the command and actual value driving the director; for EBAR, the shaping using washed-out pitch attitude was retained. The go-around-mode director commands were, therefore,

$$EBAR = -0.0187(100 - V_T) - 1.50\theta_{WO} \; ; \quad V_T \text{ ft/sec} \; , \; \theta_{WO} \text{ rad} \tag{B42}$$

$$ABAR = -3.0(0.175 - \phi) \; ; \quad \phi \text{ rad} \tag{B43}$$

$$CTAB = -0.050(-10 + \dot{Z}) \; ; \quad \dot{Z} \text{ ft/sec} \tag{B44}$$

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TABLE 1.- GEOMETRIC CHARACTERISTICS OF BASELINE HELICOPTER CONFIGURATION

Weight, lb	8,000
Main rotor	
x, z, ft	-0.29, 7.02
rpm, rad/sec	33.9
Diameter, ft	48.0
Chord, ft	1.75
Number of blades	2
Lock number	6.45
Solidity	0.046
Offset	0
Restraint, ft-lb/rad	0
δ_3, deg	0
Horizontal tail	
x, z, ft	18.85, 6.87
Area, ft^2	16.4
Vertical tail	
x, z, ft	26.90, 45.20
Area, ft^2	12.0
Tail rotor	
x, z, ft	28.5, 6.67
rpm, rad/sec	174
Diameter, ft	8.50
Control throws	
Pitch/roll/yaw, in.	±6/±6/±3.25
Collective, in.	10

TABLE 2.- CONFIGURATION IDENTIFIERS

	RATE DAMP	RATE DAMP, WING LEVEL	RATE DAMP, WING LEVEL, INPUT DEC.	ATT. CMND, INPUT DEC.	RATE CMND, ATT. HOLD, INPUT DEC.	ATT. CMND, VEL. HOLD, INPUT DEC.
COLLECTIVE, LATERAL, LONGITUDINAL DIRECTOR	T03	T13	T18	T23	T08	T28
COLLECTIVE, LATERAL DIRECTOR	T02	T12	T17	T22	T07	T27
COLLECTIVE DIRECTOR	T01	T11	T16	T21	T06	T26
RAW AZIMUTH, EL.	T30	T10	T15	T20	T05	T25

TABLE 3.- FORCE-FEEL CHARACTERISTICS FOR ALL CONFIGURATIONS

	Gradient, lb/in.	Breakout, lb/in.	Travel, in.
Pitch	0.5	0.5	±6.0
Roll	0.5	0.5	±6.0
Directional	3.0	1.5	±3.25
Collective	0.0	Adjustable	10.0

TABLE 4.- COMMENT CARD

PILOT RATING (COOPER-HARPER)

1. Record dichotomous decision process, adjectives best suited and why

SPECIFIC COMMENTS

1. Task Performance
   a) Intercept and Tracking
   b) Breakout or Missed Approach Maneuver

2. Aircraft Response
   a) Pitch/Roll (sensitivity/predictability)
   b) Collective (predictability, coupling)
   c) Yaw

3. Displays
   a) Flight Director (when applicable) — sensitivity, response
   b) Raw data, scan

4. Auxiliary Tasks (when applicable)
   a) Influence on control tasks

5. Any special problems?

TABLE 5.- STABILITY AND CONTROL DERIVATIVES FOR RATE-DAMPING CONFIGURATIONS (60 knots)

F matrix			
U	W	Q	θ
-0.11152E-01	0.28576E-01	0.11423E 02	-0.32176E 02
-.21634E-01	-.12794E 01	.13940E 03	-.12532E 01
.37455E-03	-.27030E-02	-.30288E 01	.00000E 00
.00000E 00	.00000E 00	.10000E 01	.00000E 00
.38247E-02	-.19564E-02	-.84063E-01	.00000E 00
.90874E-03	-.29638E-02	-.70551E-02	.00000E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.35107E-02	-.48817E-02	.10067E 00	.00000E 00
V	P	ϕ	R
0.22405E-03	-0.90840E 00	0.00000E 00	0.11397E 01
-.25125E-01	-.27246E 01	.00000E 00	-.15675E-01
.85460E-04	.14369E 00	.00000E 00	.57833E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.95096E-01	-.54893E 01	.32176E 02	-.96564E 02
-.15263E-01	-.60282E 01	.00000E 00	.11158E 01
.00000E 00	.10000E 01	.00000E 00	.38948E-01
.40051E-01	-.97333E 00	.00000E 00	-.34546E 01
G matrix			
δ_E	δ_C	δ_A	δ_P
-0.19203E 01	0.36606E 00	-0.23977E-02	0.29254E-01
-.54731E 01	-.10255E 02	.44967E-01	-.22012E-02
.36149E 00	.39228E-01	-.43057E-04	-.34322E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.12178E 00	-.20770E 00	.14290E 01	-.11827E 01
-.11020E 00	-.48771E-01	.90278E 00	-.29980E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.88037E-01	.17553E 00	.11952E 00	.86565E 00

TABLE 6.- STABILITY AND CONTROL DERIVATIVES FOR ATTITUDE-COMMAND AND RATE-COMMAND-ATTITUDE-HOLD CONFIGURATIONS (60 knots)

F matrix

U	W	Q	θ
-0.10543E-01	0.29069E-01	0.11422E 02	-0.20184E 02
-.21603E-01	-.12781E 01	.13940E 03	.32928E 02
.30190E-03	-.27956E-02	-.30286E 01	-.22574E 01
.00000E 00	.00000E 00	.10000E 01	.00000E 00
-.18630E-01	-.28653E-02	0.83939E-01	.76060E 00
-.47798E-02	-.31748E-02	-.70698E-02	.68821E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
.12932E-01	-.41733E-02	.10046E 00	.54967E 00
V	**P**	**φ**	**R**
0.40879E-03	-0.90836E 00	0.60469E-02	0.11390E 01
-.24622E-01	-.27224E 01	-.11242E 00	-.15675E-01
.51962E-04	.14349E 00	.10126E-03	.57805E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.95459E-01	-.54895E 01	.28603E 02	-.96564E 02
-.15348E-01	-.60277E 01	-.22568E 01	.11158E 01
.00000E 00	.10000E 01	.00000E 00	.38939E-01
.40332E-01	-.97329E 00	-.29880E 00	-.34548E 01

G matrix

δ_E	δ_C	δ_A	δ_P
-0.19117E 01	0.52993E 00	-0.24567E-02	0.29578E-01
-.54653E 01	-.97768E 01	.44652E-01	-.23584E-02
.36042E 00	.80638E-02	-.31786E-04	-.34466E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.20740E 00	-.82410E-01	.14290E 01	-.11828E 01
-.30052E-01	-.39059E-01	.90273E 00	-.29983E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
.19423E 00	.36841E-01	.11953E 00	.86572E 00

TABLE 7.- STABILITY AND CONTROL DERIVATIVES FOR RATE DAMPING, WING LEVELER CONFIGURATIONS (60 knots)

F matrix

U	W	Q	θ
-0.11146E-01	0.28580E-01	0.11423E 02	-0.32176E 02
-.21713E-01	-.12794E 01	.13940E 03	-.12532E 01
.37451E-03	-.27037E-02	-.30288E 01	.00000E 00
.00000E 00	.00000E 00	.10000E 01	.00000E 00
.38293E-02	-.19515E-02	-.84105E-01	.00000E 00
.91070E-03	-.29602E-02	-.71010E-02	.00000E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.35122E-02	-.48803E-02	.10062E 00	.00000E 00
V	**P**	**ϕ**	**R**
0.22798E-03	-0.90843E 00	0.61370E-02	0.11397E 01
-.25046E-01	-.27239E 01	-.11224E 00	-.15675E-01
.84176E-04	.14366E 00	.86280E-04	.57831E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.95096E-01	-.54893E 01	.28603E 02	-.96564E 02
-.15263E-01	-.60282E 01	-.22570E 01	.11158E 01
.00000E 00	.10000E 01	.00000E 00	.38948E-01
.40051E-01	-.97332E 00	-.29882E 00	-.34547E 01

G matrix

δ_E	δ_C	δ_A	δ_P
-0.19203E 01	0.36609E 00	-0.24567E-02	0.29293E-01
-.54732E 01	-.10255E 02	.44967E-01	-.23584E-02
.36149E 00	.39223E-01	-.33364E-04	-.34337E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.12181E 00	-.20770E 00	.14290E 01	-.11828E 01
-.11021E 00	-.48770E-01	.90278E 00	-.29981E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.88030E-01	.17554E 00	.11954E 00	.86566E 00

TABLE 8.- STABILITY AND CONTROL DERIVATIVES FOR RATE DAMPING, INPUT DECOUPLING, WING LEVELER CONFIGURATIONS (60 knots)

F matrix

U	W	Q	θ
-0.10536E-01	0.29080E-01	0.11422E 02	-0.32176E 02
-.21619E-01	-.12781E 01	.13940E 03	-.12529E 01
.30093E-03	-.27975E-02	-.30286E 01	.00000E 00
.00000E 00	.00000E 00	.10000E 01	.00000E 00
-.18629E-01	-.28635E-02	-.83961E-01	.00000E 00
-.47795E-02	-.31729E-02	-.70840E-02	.00000E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
.12931E-01	-.41714E-02	.10046E 00	.00000E 00
V	**P**	**ϕ**	**R**
0.41370E-03	-0.90839E 00	0.61145E-02	0.11390E 01
-.24622E-01	-.27251E 01	-.11224E 00	-.15675E-01
.51150E-04	.14350E 00	.89122E-04	.57823E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.95461E-01	-.54895E 01	.28603E 02	-.96564E 02
-.15350E-01	-.60277E 01	-.22568E 01	.11158E 01
.00000E 00	.10000E 01	.00000E 00	.38939E-01
.40331E-01	-.97329E 00	-.29882E 00	-.34548E 01

G matrix

δ_E	δ_C	δ_A	δ_P
-0.19117E 01	0.52985E 00	-0.23977E-02	0.29578E-01
-.54653E 01	-.97768E 01	.44810E-01	-.23584E-02
.36041E 00	.80769E-02	-.42832E-04	-.34468E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.20740E 00	-.82428E-01	.14290E 01	-.11828E 01
-.30060E-01	-.39074E-01	.90273E 00	-.29983E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
.19421E 00	.36826E-01	.11952E 00	.86572E 00

TABLE 9.- STABILITY AND CONTROL DERIVATIVES FOR VELOCITY-HOLD CONFIGURATIONS (60 knots)

F matrix

U	W	Q	θ
-0.18289E 00	0.51586E-01	0.11426E 02	-0.20179E 02
.41303E-01	-.19111E 01	.13940E 03	.32927E 02
.27436E-01	-.36168E-03	-.30295E 01	-.22581E 01
.00000E 00	.00000E 00	.10000E 01	.00000E 00
-.13733E-01	-.15508E-01	-.83751E-01	.76089E 00
-.10102E-01	-.61465E-02	-.69256E-02	.68849E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.60403E-02	.65179E-02	.10054E 00	.54993E 00
V	**P**	**ϕ**	**R**
0.37145E-03	-0.90848E 00	0.61145E-02	0.11395E 01
-.24685E-01	-.27257E 01	-.11242E 00	-.15675E-01
.58386E-04	.14350E 00	.90413E-04	.57880E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.95393E-01	-.54904E 01	.28602E 02	-.96564E 02
-.15335E-01	-.60299E 01	-.22576E 01	.11158E 01
.00000E 00	.10000E 01	.00000E 00	.38963E-01
.40274E-01	-.97362E 00	-.29889E 00	-.34548E 01

G matrix

δ_E	δ_C	δ_A	δ_P
-0.19124E 01	0.62169E 00	-0.25254E-02	0.29598E-01
-.54653E 01	-.12341E 02	.44810E-01	-.23584E-02
.36053E 00	.17841E-01	-.22543E-04	-.34470E-02
.00000E 00	.00000E 00	.00000E 00	.00000E 00
-.20731E 00	-.13451E 00	.14295E 01	-.11828E 01
-.30014E-01	-.51331E-01	.90307E 00	-.29983E 00
.00000E 00	.00000E 00	.00000E 00	.00000E 00
.19420E 00	.80788E-01	.11956E 00	.86573E 00

TABLE 10.- FEEDBACK AND GEARING GAINS FOR RATE-DAMPING CONTROL-SYSTEM CONFIGURATIONS

Units	Gains	Value (V in knots)
in./in.	Δ_{ES}/δ_{ES}	2.12
in./in.	Δ_{AS}/δ_{AS}	1.64
in./in.	Δ_{CS}/δ_{CS}	1.00
in./in.	Δ_{RP}/δ_{RP}	0.70
in./ft/sec	Δ_{ES}/u	0 for $V_o = 0$
		0 for $V_o = 30$
		-0.00562 for $V_o = 40$
		-0.00391 for $V_o = 60$
		-0.00297 for $V_o = 80 \rightarrow 100$
in./ft/sec	Δ_{ES}/w	0.028
in./rad/sec	Δ_{ES}/q	-14.79
in./ft/sec	Δ_{AS}/w	0.0287
in./ft/sec	Δ_{AS}/v	0 for $V_o = 0 \rightarrow 40$
		-0.00574 for $V_o = 60$
		-0.00995 for $V_o = 80 \rightarrow 100$
in./rad/sec	Δ_{AS}/p	-8.25
in./ft/sec	Δ_{CS}/w	0.0383
in./ft/sec	Δ_{RP}/v	0.011
in./rad/sec	Δ_{RP}/r	-2.00

TABLE 11.- INPUT DECOUPLING GAINS

Units	Gains	Value (V in knots)
in./in.	Δ_{ES}/δ_{CS}	0 at V = 0
		-0.093 at V = 30
		-0.186 at V = 60
		-0.240 at V = 80
in./in.	Δ_{RP}/δ_{CS}	-0.3247 at V = 0
		-0.2397 at V = 30
		-0.1132 at V = 60
		-0.1053 at V = 80
in./in.	Δ_{AS}/δ_{CS}	-0.088
in./in.	Δ_{AS}/δ_{ES}	0.309
in./in.	Δ_{RP}/δ_{ES}	0.210
in./ft/sec	Δ_{ES}/u	0 at V = 0 $\rightarrow$ 30
		0.00768 at V = 40
		0.00939 at V = 60

TABLE 12.- VELOCITY-HOLD AUGMENTATION GAINS

Units	Gains	Value
in./ft/sec	Δ_{ES}/u	+0.177
in./ft/sec	Δ_{CS}/u	-0.049
in./ft/sec	Δ_{CS}/w	+0.10
in./in.	Δ_{CS}/δ_{CS}	1.25

TABLE 13.- MASTER DATA SUMMARY

ID	SCAS	Display	Pilot	Pilot rating			Run No.
				Dual-pilot, missed approach	Single-pilot, missed approach	Single-pilot, continued approach	
T30	Rate damping	Raw data	M	5	6	5	83-85
			K	5-1/2	7	6	190-192
			G	6	7-1/2	7-1/2	213-215
T01	Rate damping	Collective dir.	M	7	8	7	139-141
T02	Rate damping	Collective, azimuth dir.	M	5	7	6	172-174
			G	6	7	6	210-212
			K	4	5-1/2	5-1/2	261-263
T03	Rate damping	Collective, azimuth, elevation dir.	M	3	4	--	13-14
			G	5	8	7	67-69
			K	5-1/2	7	6	147-149
			M	5	6-1/2	--	281-282
T10	Rate damping, wing leveler	Raw data	M	4	7	6	94-96
			K	4	4-1/2	4-1/2	186-188
T11	Rate damping, wing leveler	Collective dir.	M	5	6	6	136-138
T12	Rate damping, wing leveler	Collective, azimuth dir.	M	5-1/2	7	6	169-171
			G	4	7	--	286-287
			K	4	5	--	295-296
T13	Rate damping, wing leveler	Collective, azimuth, elevation dir.	M	4	6	6	9-11
			G	6	8	5	23-25
			K	4-1/2	6	5-1/2	150-152
			S	7	8	8	197-199
T15	Rate damping, input decoupling, wing leveler	Raw data	M	4	5	4	40-42
			G	7	7-1/2	7	57-59
			K	4	5-1/2	5-1/2	236-238
T16	Rate damping, input decoupling, wing leveler	Collective dir.	M	4	6	--	34-35
			M	5	4	4	43-45
			K	3	5	5-1/2	239-241

TABLE 13.- Continued.

ID	SCAS	Display	Pilot	Pilot rating: Dual-pilot, missed approach	Pilot rating: Single-pilot, missed approach	Pilot rating: Single-pilot, continued approach	Run No.
T17	Rate damping, input decoupling, wing leveler	Collective, azimuth dir.	M	3	8	3	30-32
			G	4-1/2	6	6	207-209
			M	4	5-1/2	--	302-303
T18	Rate damping, input decoupling, wing leveler	Collective, azimuth, elevation dir.	M	4	5	--	46-48
			G	5	6	6	60-65
			K	2	4	4	242-244
T20	Attitude command	Raw data	G	5	6	6	165-167
			K	3	4	3	182-184
			S	3	3	5	200-202
			M	4	4	--	278-279
T21	Attitude command	Collective dir.	G	4	5-1/2	5-1/2	161-164
T22	Attitude command	Collective, azimuth dir.	M	4-1/2	5	4-1/2	176-180
			G	3	4	4	224-227
			K	2-1/2	2	2	258-260
T23	Attitude command	Collective, azimuth, elevation dir.	M	3	4	4	5-7
			G	3	6	4	18-21
			K	2-1/2	3-1/2	4	143-145
			S	3	5	5	194-196
			G	2	2-1/2	2-1/2	231-233
T05	Rate-command-attitude-hold	Raw data	G	4	4	--	292-293
			K	1-1/2	2-1/2	--	299-300
T07	Rate-command-attitude-hold	Collective, azimuth dir.	G	3	3	--	290-291
			K	1-1/2	2-1/2	--	297-298
			M	3-1/2	5	--	305-306
T08	Rate-command-attitude-hold	Collective, azimuth, elevation dir.	M	3	3-1/2	--	307-308

TABLE 13.- Concluded.

ID	SCAS	Display	Pilot	Pilot rating: Dual-pilot, missed approach	Pilot rating: Single-pilot, missed approach	Pilot rating: Single-pilot, continued approach	Run No.
T25	Velocity-hold	Raw data	M	5	4	4	79-81
			G	4	5	--	90-91
			M	4-1/2	5	4-1/2	97-99
			K	2	2-1/2	2	266-268
			S	4	5-1/2	--	220-221
T26	Velocity-hold	Collective dir.	G	3	3	3	87-89
			S	5	5-1/2	--	222-223
T27	Velocity-hold	Collective, azimuth dir.	G	3	3	3	228-230
			M	4	4	--	283-284
T28	Velocity-hold	Collective, azimuth, elevation dir.	G	2	2-1/2	2-1/2	71-73
			M	3	4	4	75-78
			S	3	3-1/2	--	217-218

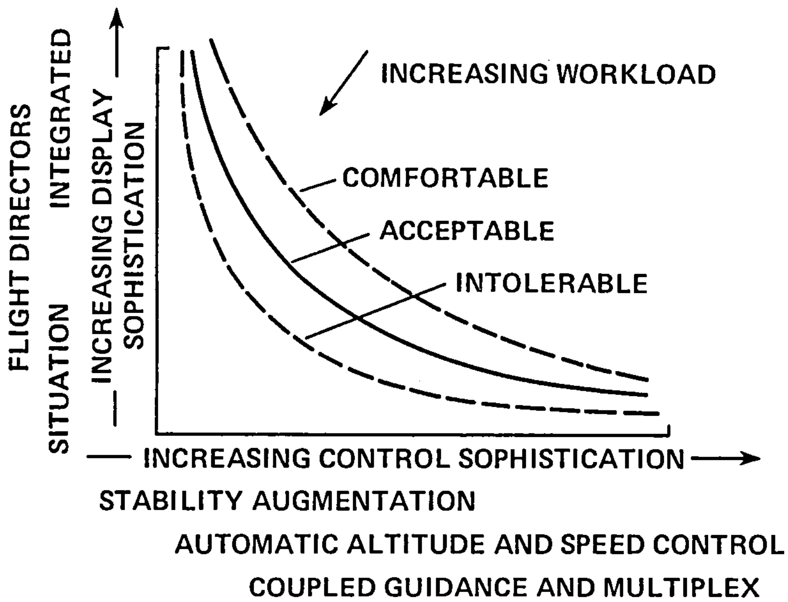


Figure 1.- Trade-off between display and control sophistication (from reference 7).

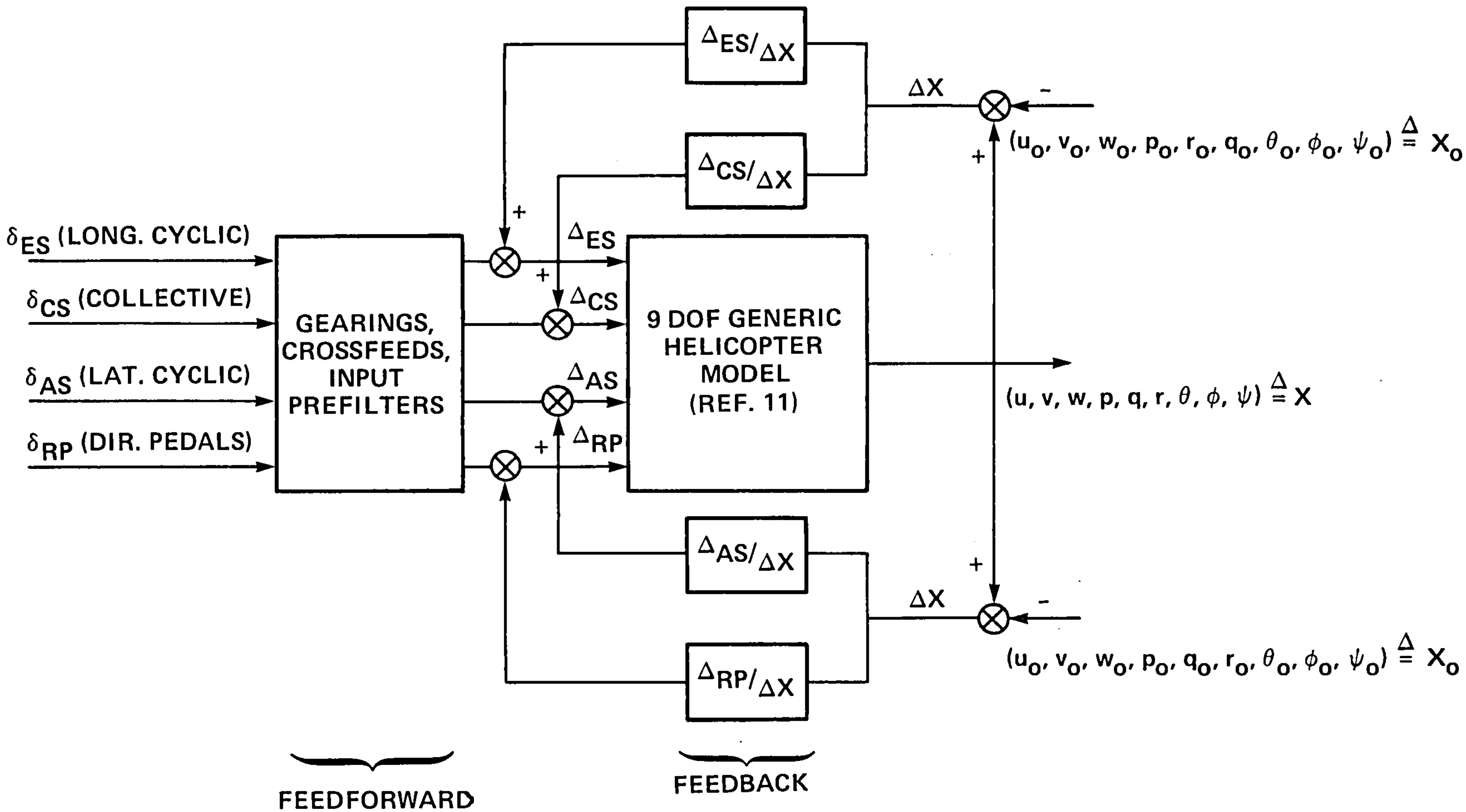


Figure 2.- Mathematical model schematic diagram.

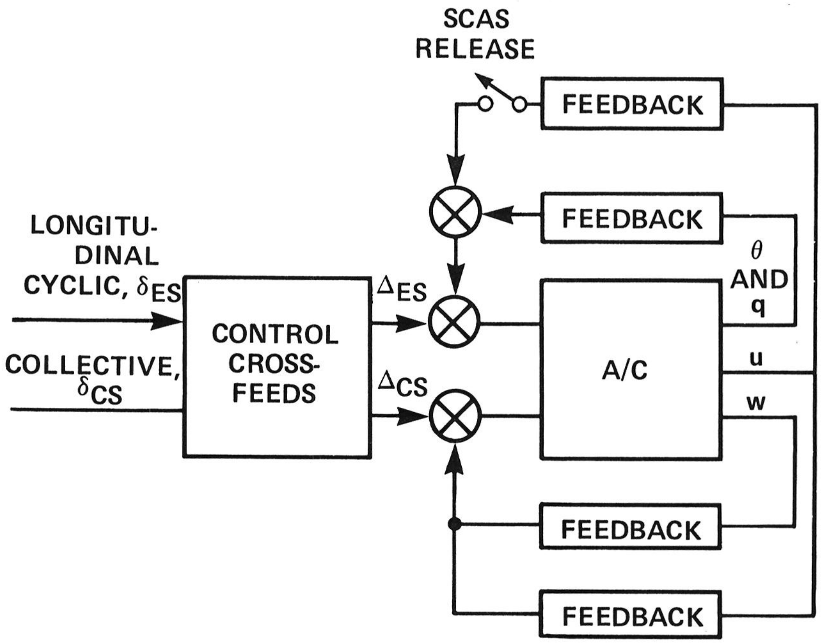


Figure 3.- Velocity-hold system implementation.

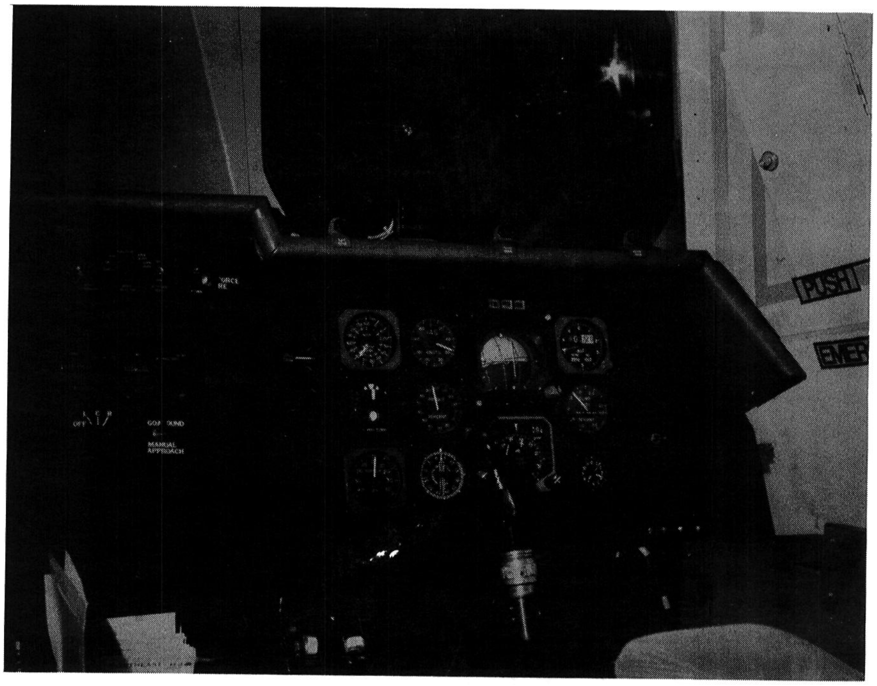


Figure 4.- Flight instrument panel layout.

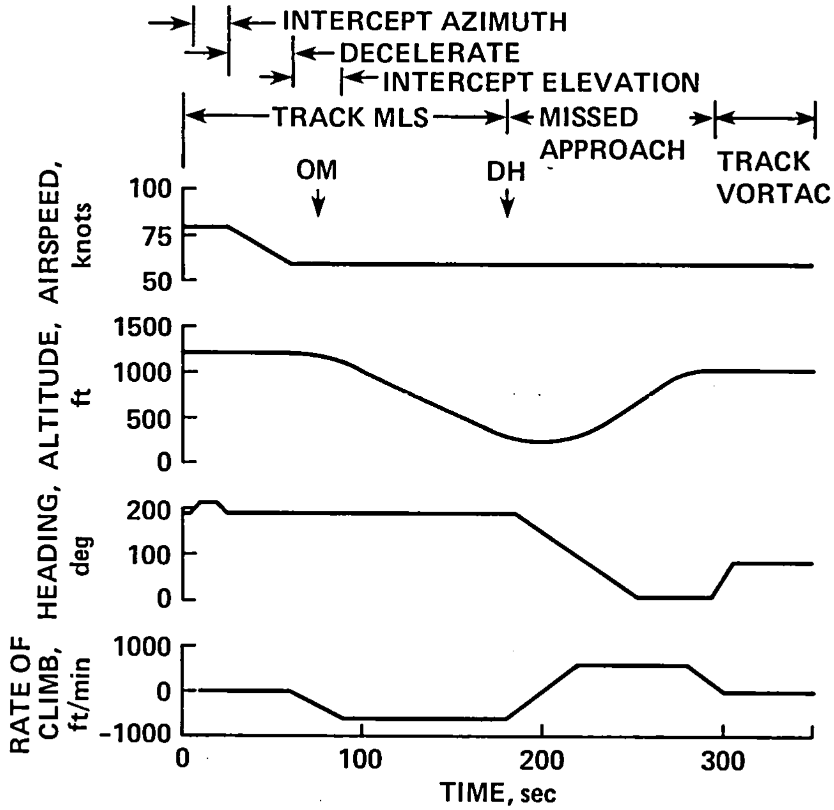
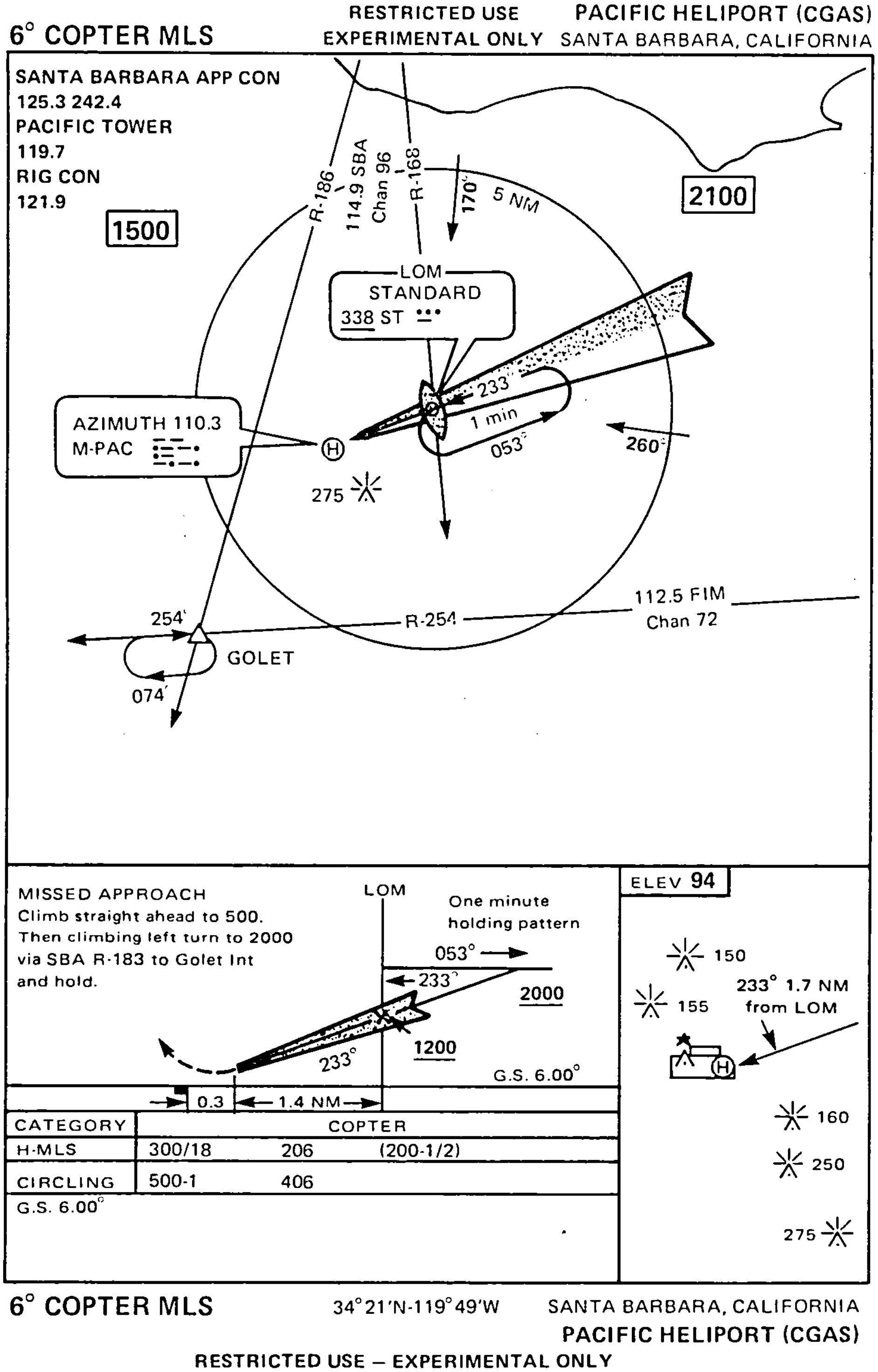


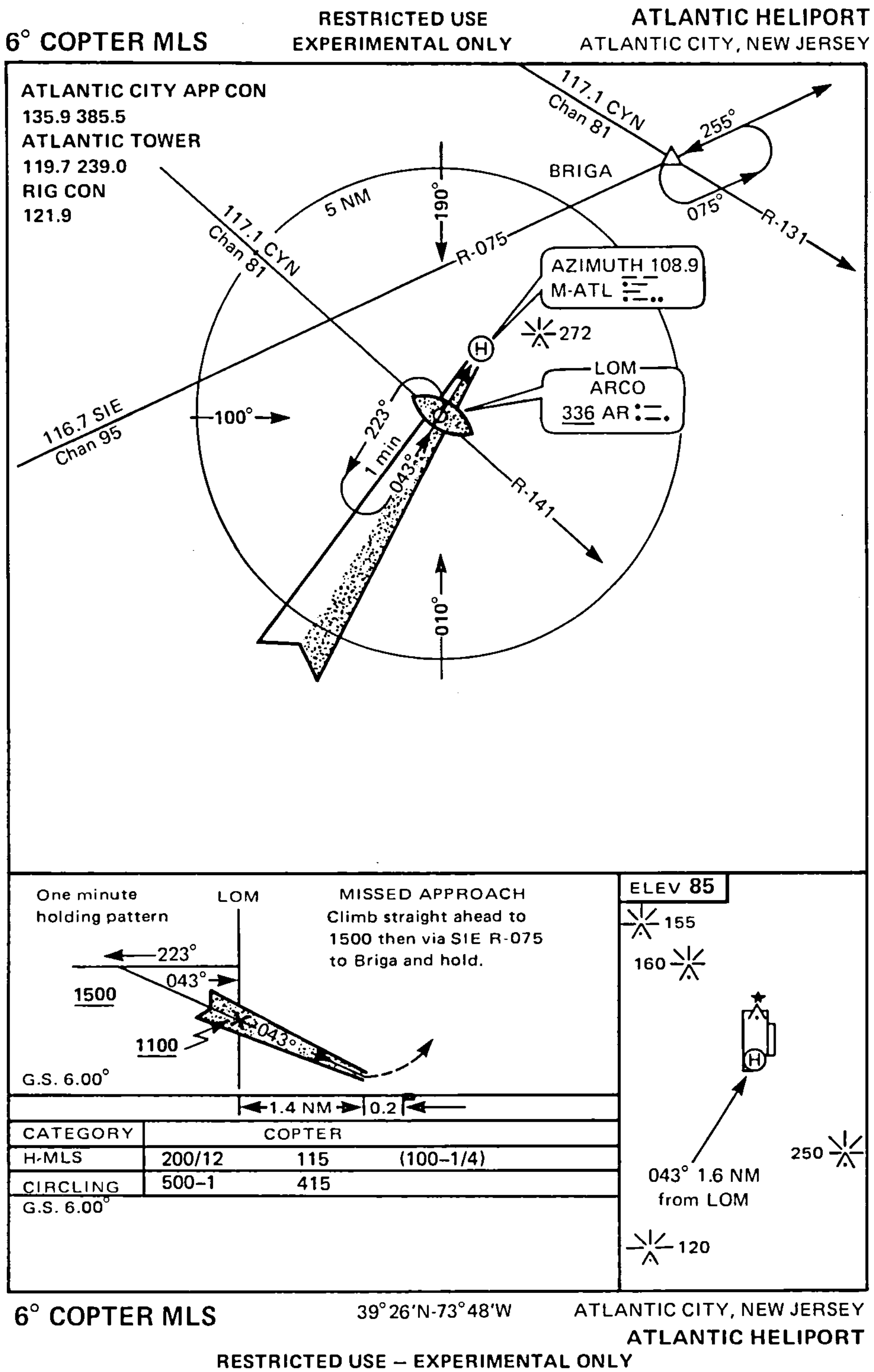
Figure 5.- Idealized variation of flight parameters on MLS approach.



(a) Approach No. 1.

Figure 6.- 6° MLS approach plates.

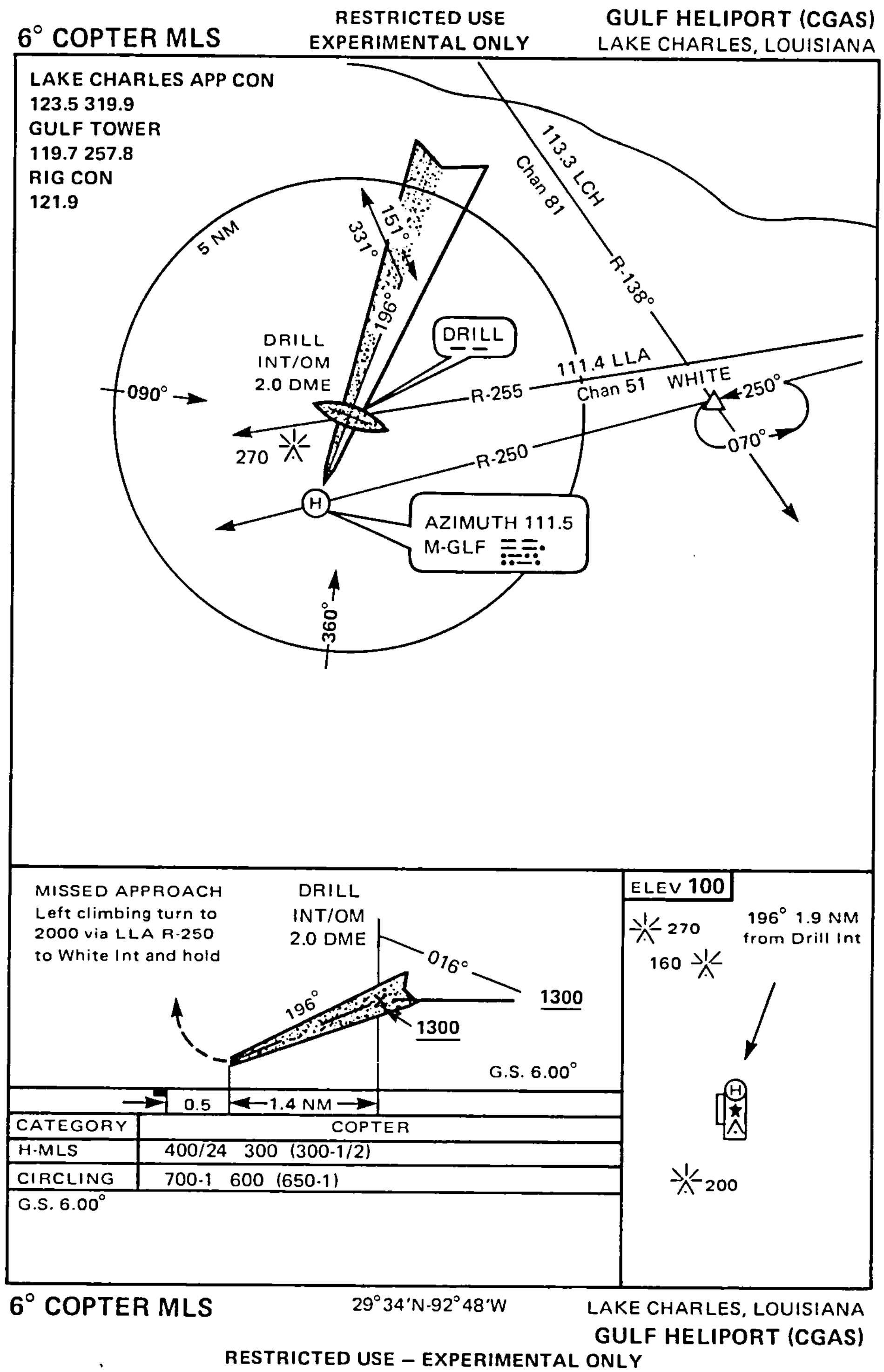
Note: Restriction not applicable to this paper.



(b) Approach No. 2.

Figure 6.- Continued.

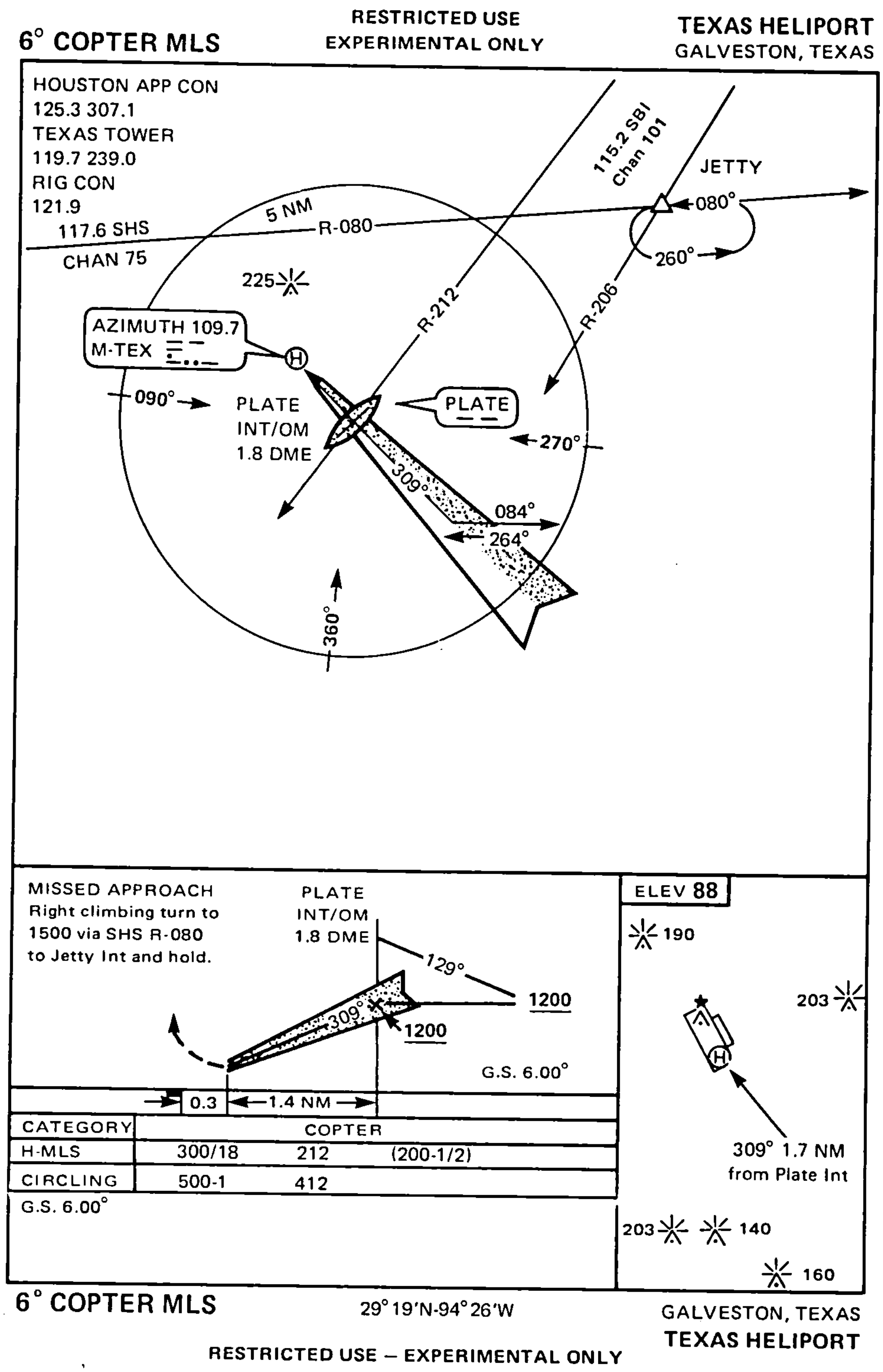
Note: Restriction not applicable to this paper.



(c) Approach No. 3.

Figure 6.- Continued.

Note: Restriction not applicable to this paper.



(d) Approach No. 4.

Figure 6.- Concluded.

Note: Restriction not applicable to this paper.

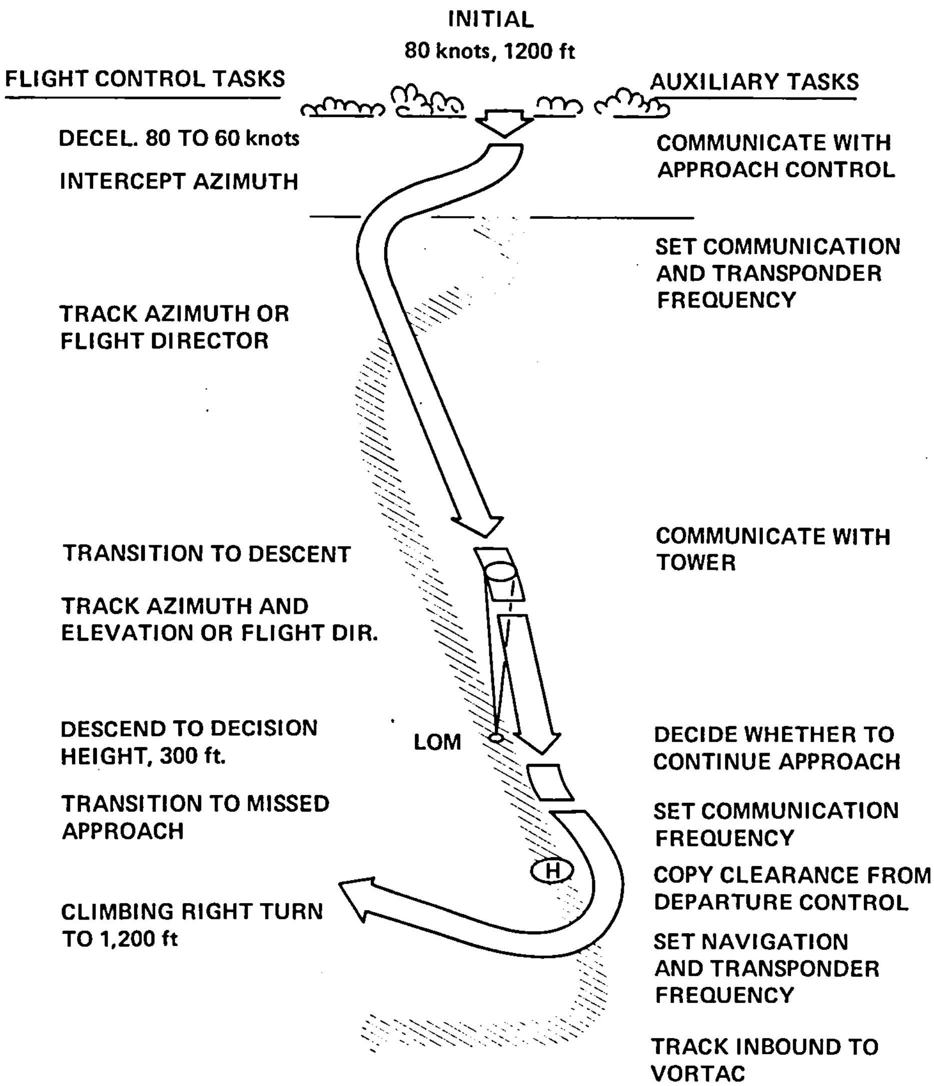


Figure 7.- MLS 6° approach task.

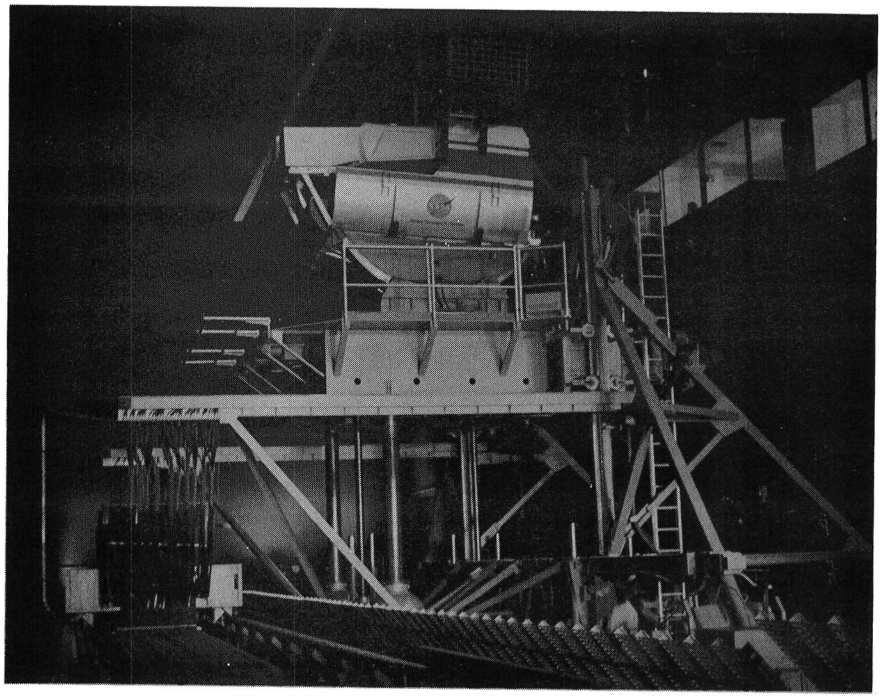


Figure 8.- Flight simulator cab and motion system.

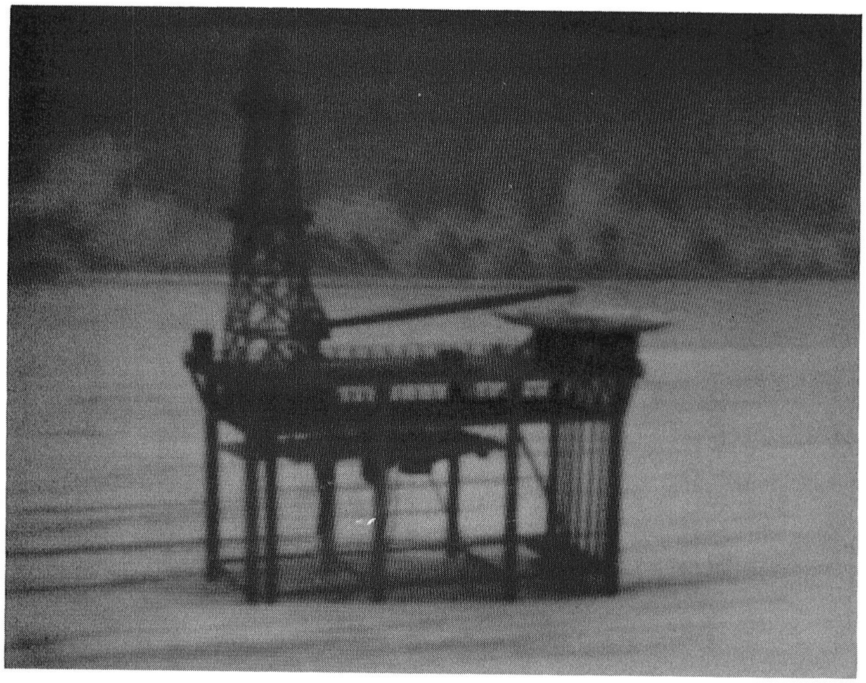


Figure 9.- Image displayed on TV monitor.

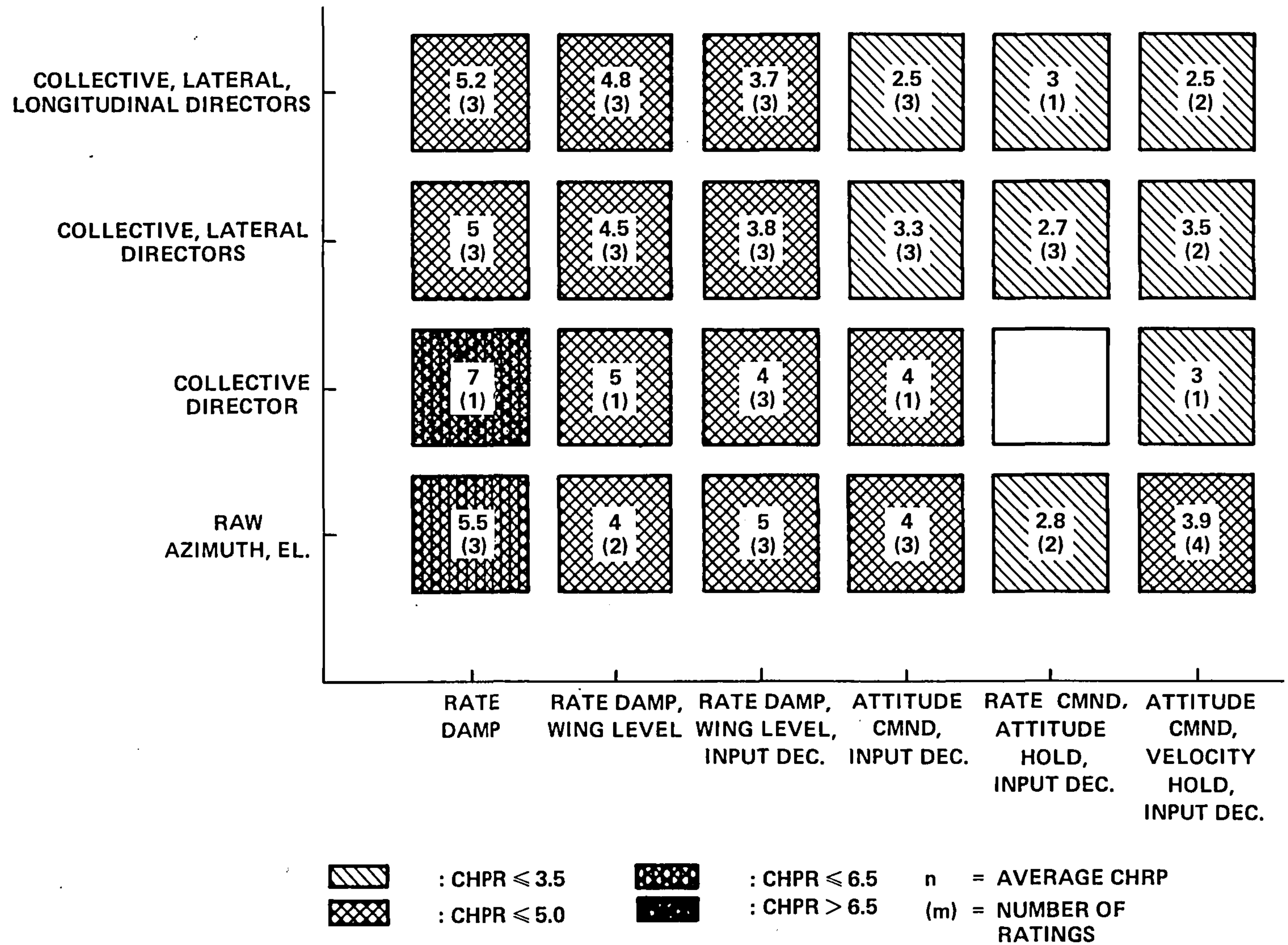


Figure 10.- Average pilot ratings: dual pilot case.

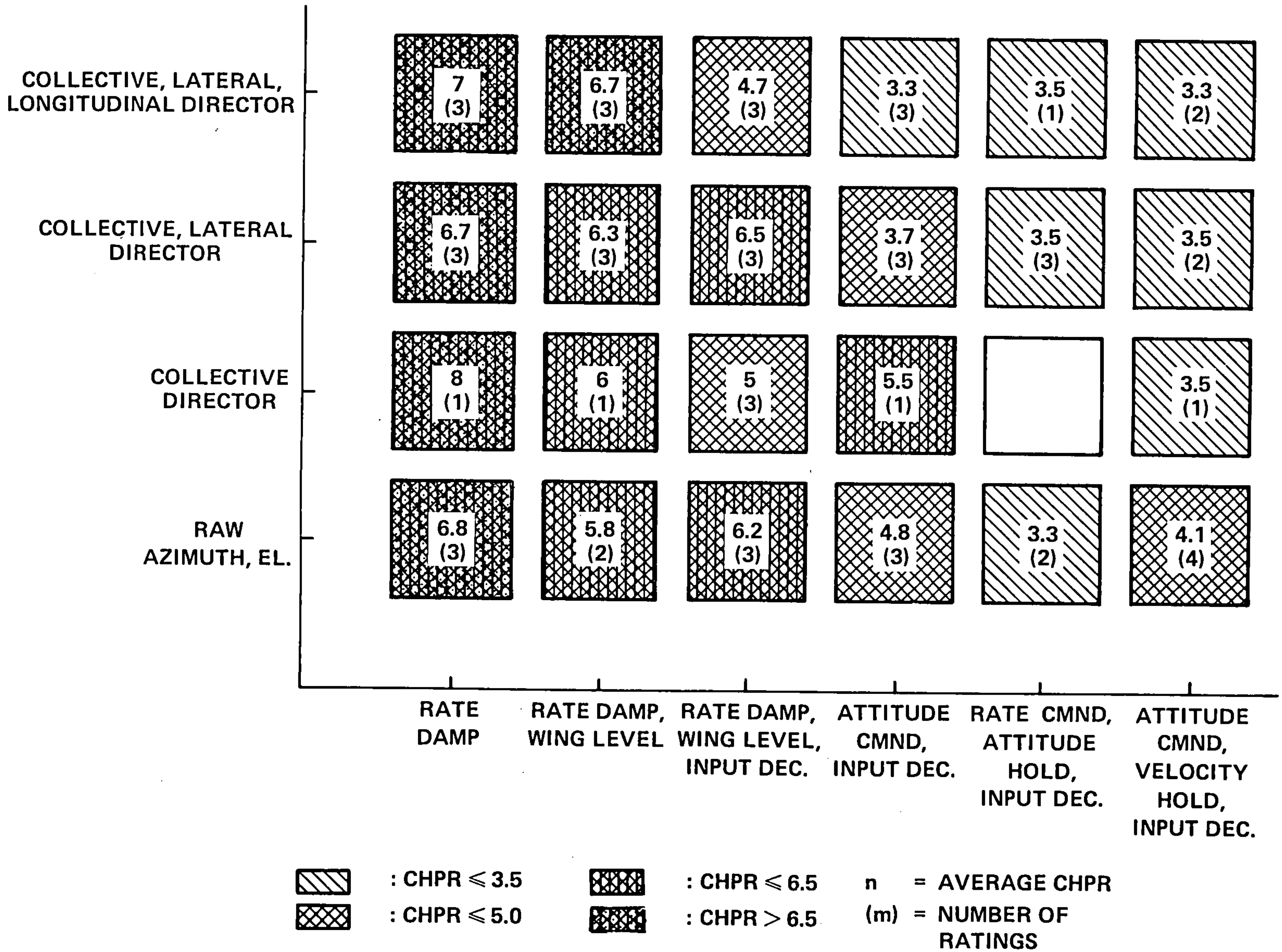


Figure 11.- Average pilot ratings: single-pilot case with missed approach.

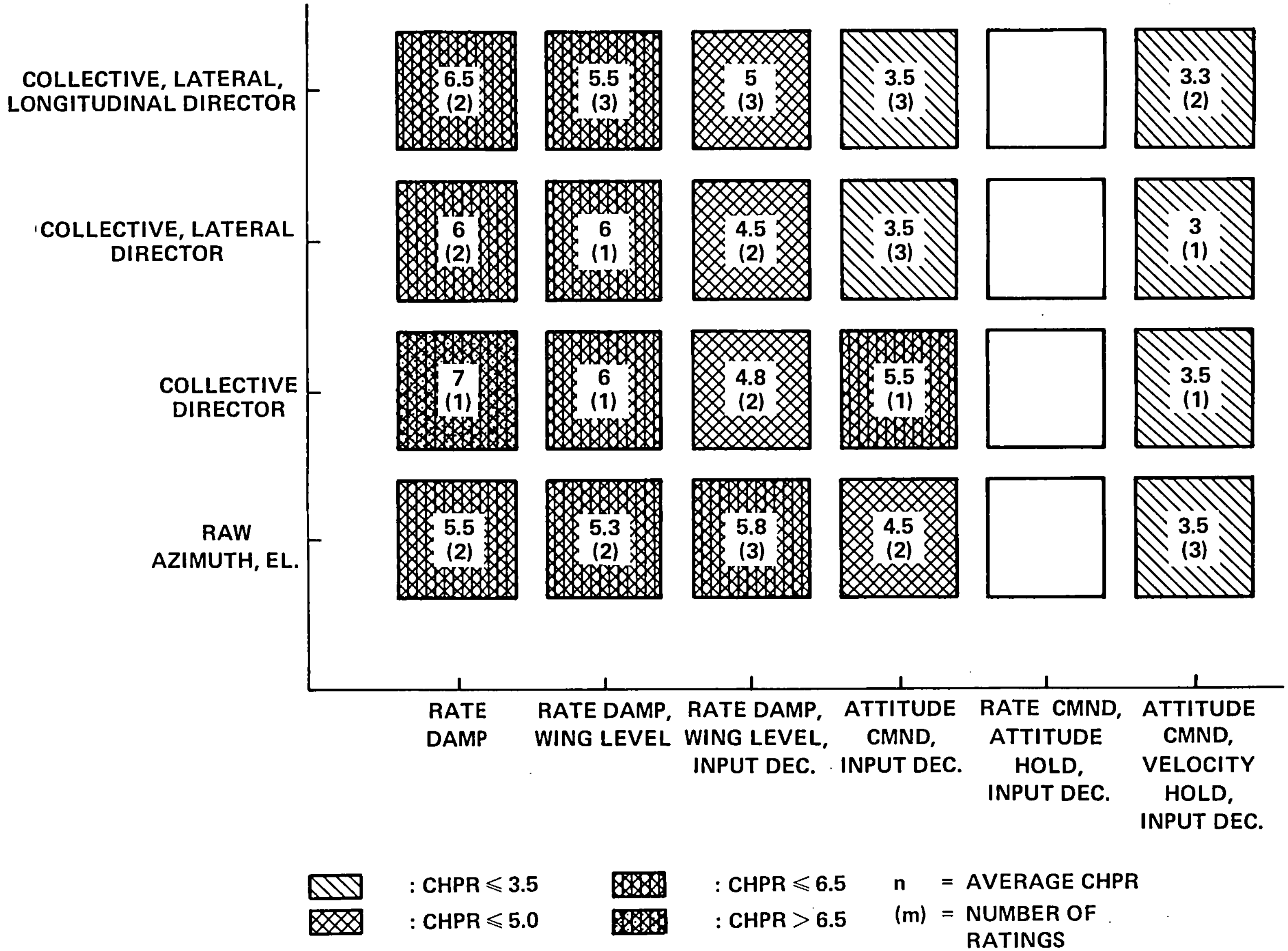


Figure 12.- Average pilot ratings: single-pilot case with continued approach.

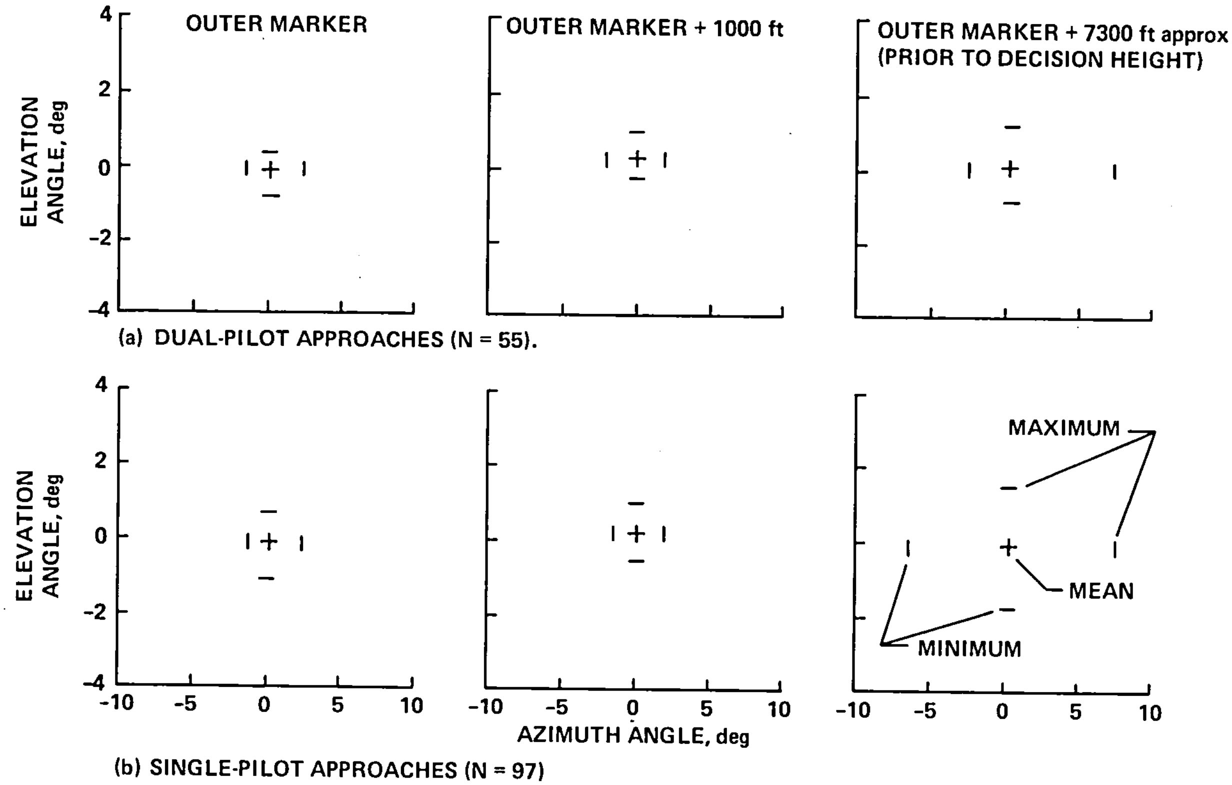
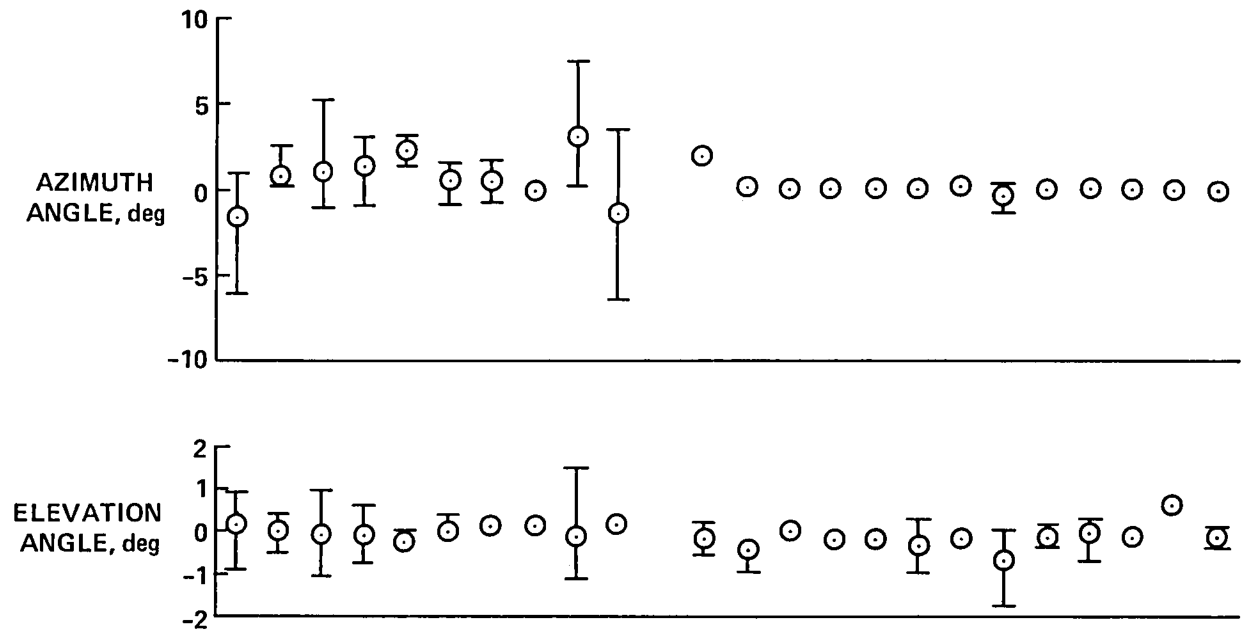


Figure 13.- Effect of crew loading on MLS tracking error, all configurations.



CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	6	4	6	5	2	7	2	2	5	2	0	2	6	4	5	6	3	3	5	6	5	6	1	4
DECISION HEIGHT, ft x 10^2	3	4	3	3	3	3	3	4	3	2		2	4	3	4	4	3	3	2	4	3	4	2	4
FLIGHT DIRECTOR	NONE						1-AXIS						2-AXIS						3-AXIS					

Figure 14.- Effect of configuration on MLS tracking error, single-pilot approaches, error measured before decision height.

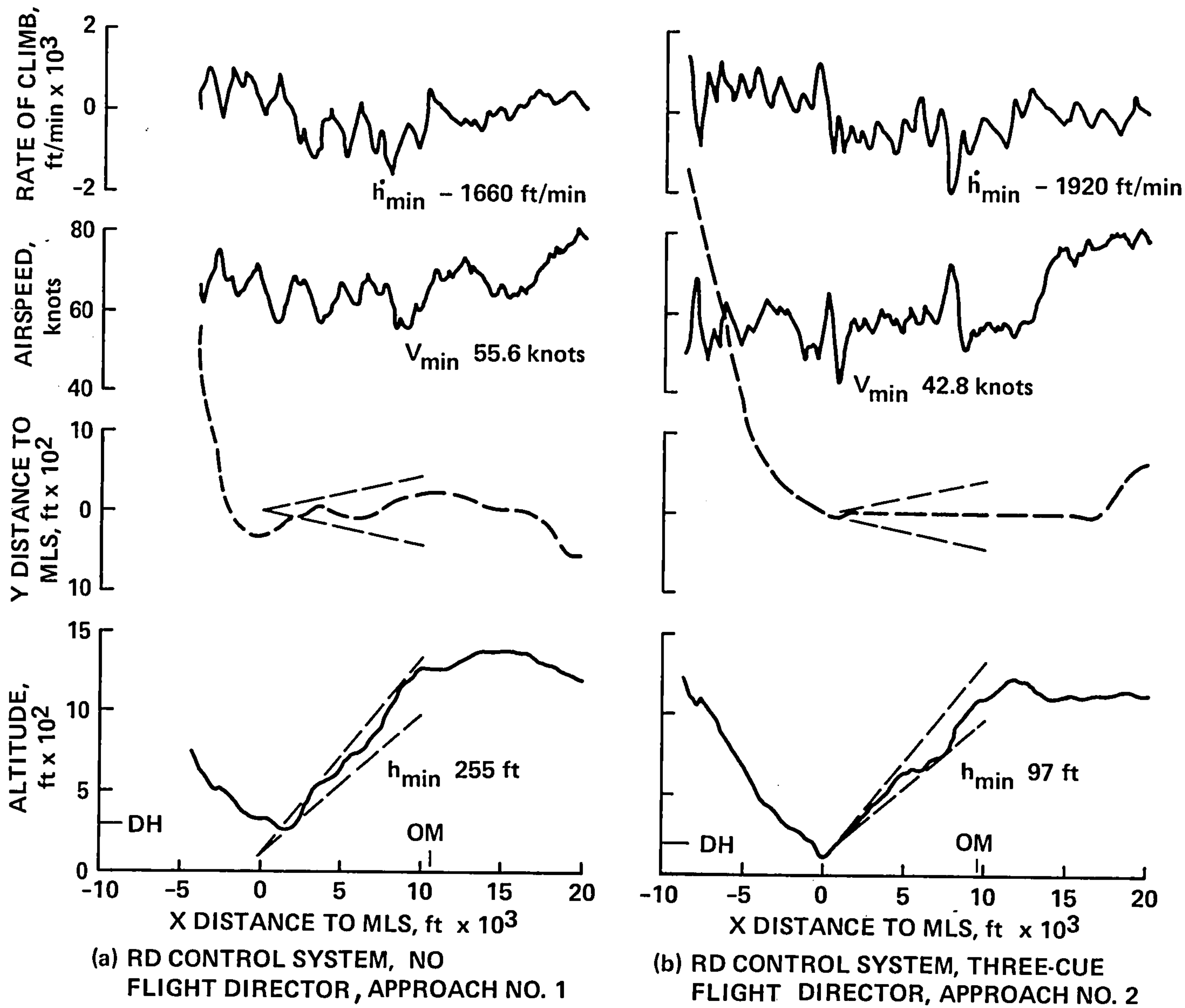
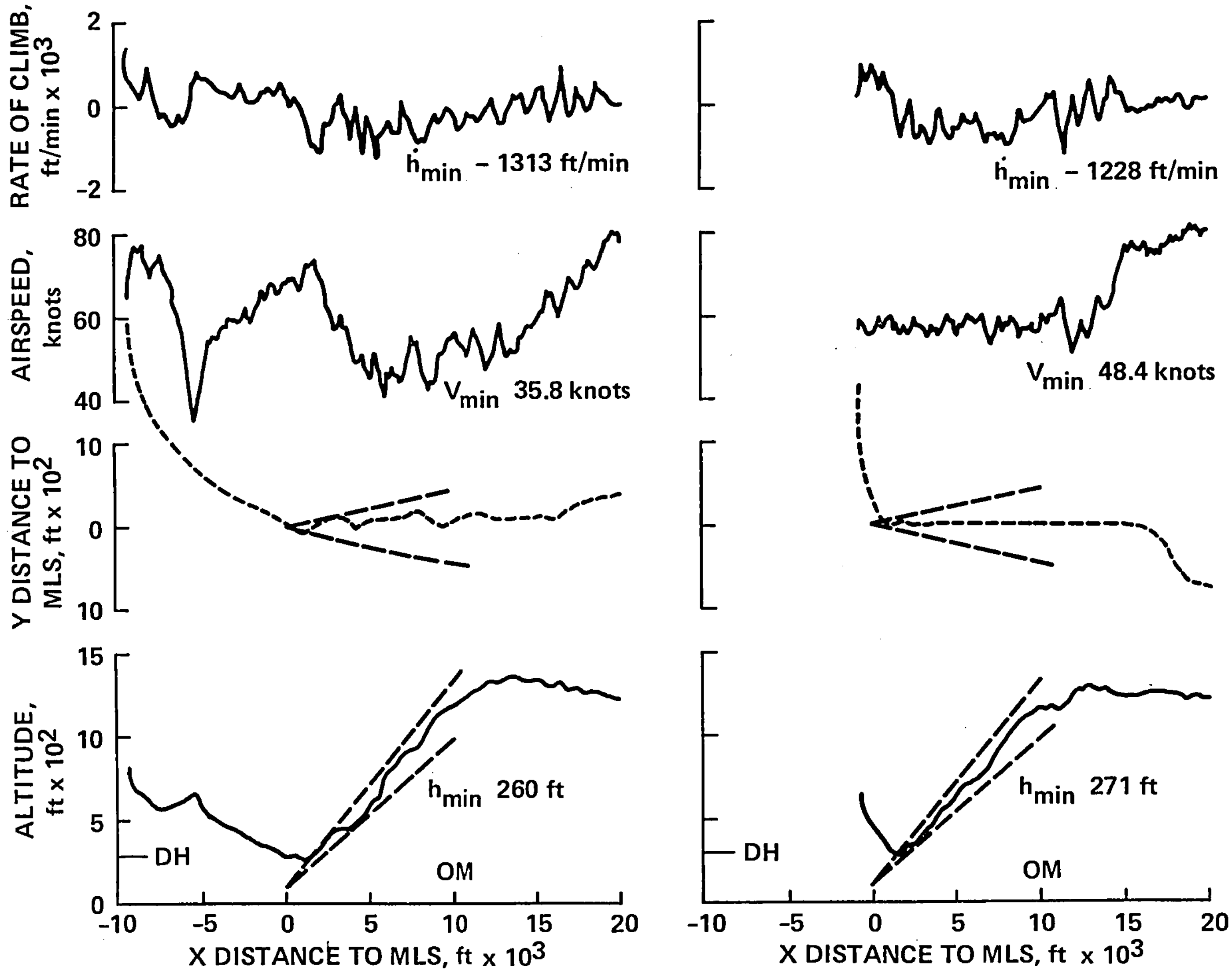


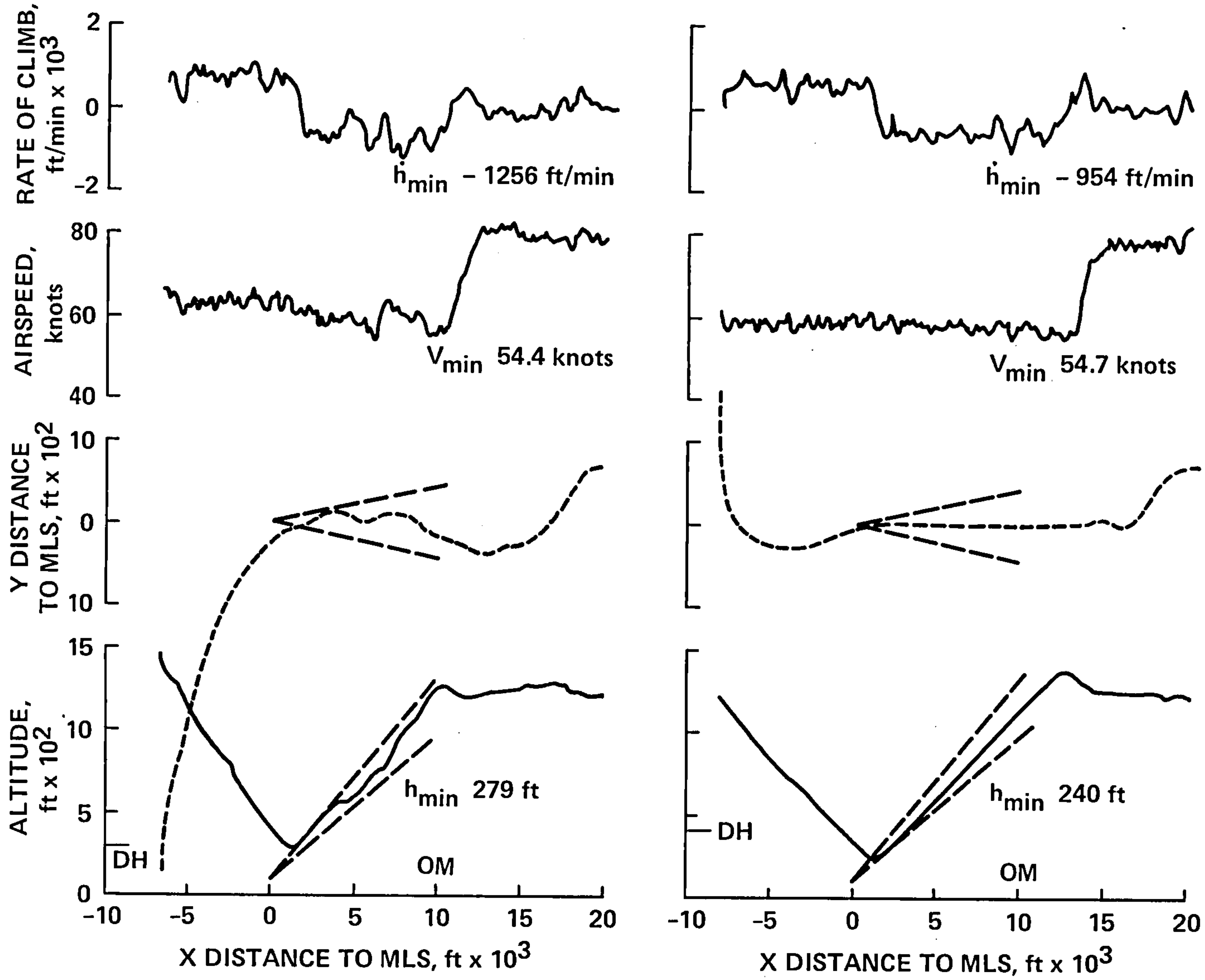
Figure 15.- MLS approach performance, single-pilot loading.



(c) RDWLID CONTROL SYSTEM, NO FLIGHT DIRECTOR, APPROACH NO. 1

(d) RDWLID CONTROL SYSTEM, THREE-CUE FLIGHT DIRECTOR, APPROACH NO. 4

Figure 15.- Continued.



(e) ACVHID CONTROL SYSTEM, NO FLIGHT DIRECTOR, APPROACH NO. 1

(f) ACVHID CONTROL SYSTEM, THREE-CUE FLIGHT DIRECTOR, APPROACH NO. 3

Figure 15.- Concluded.

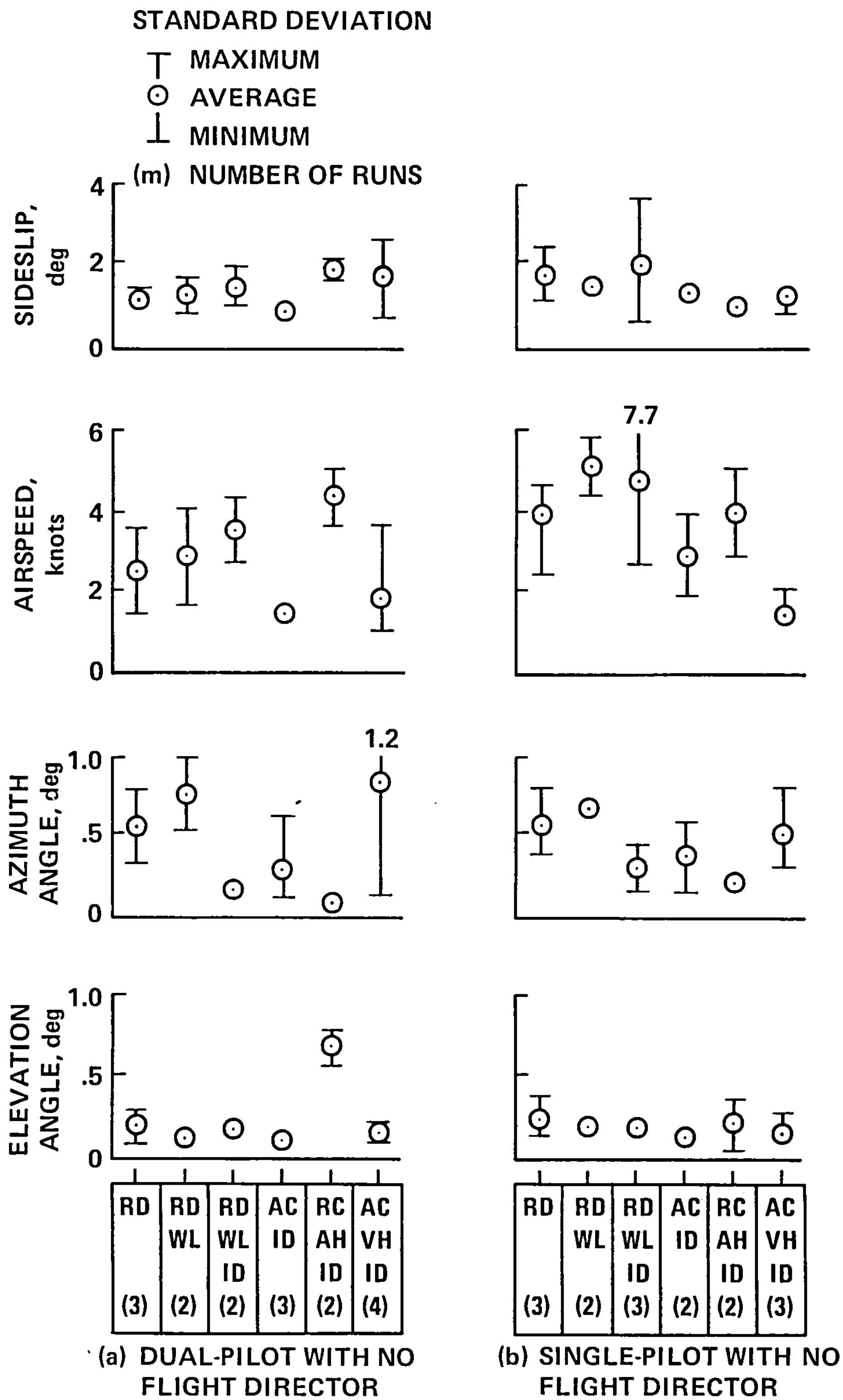


Figure 16.- Standard deviation of flight performance variables, 35-sec interval during final approach.

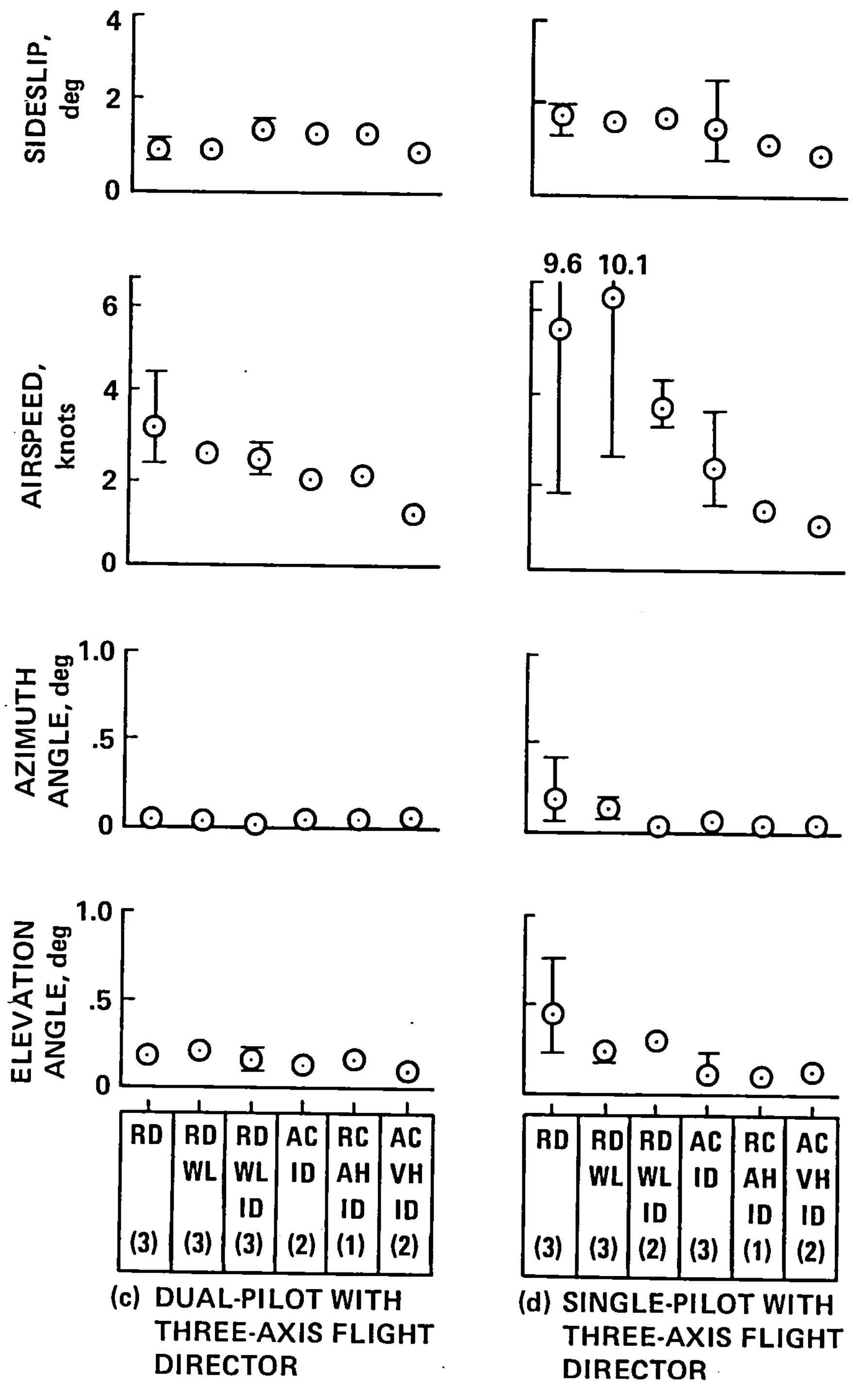


Figure 16.- Continued.

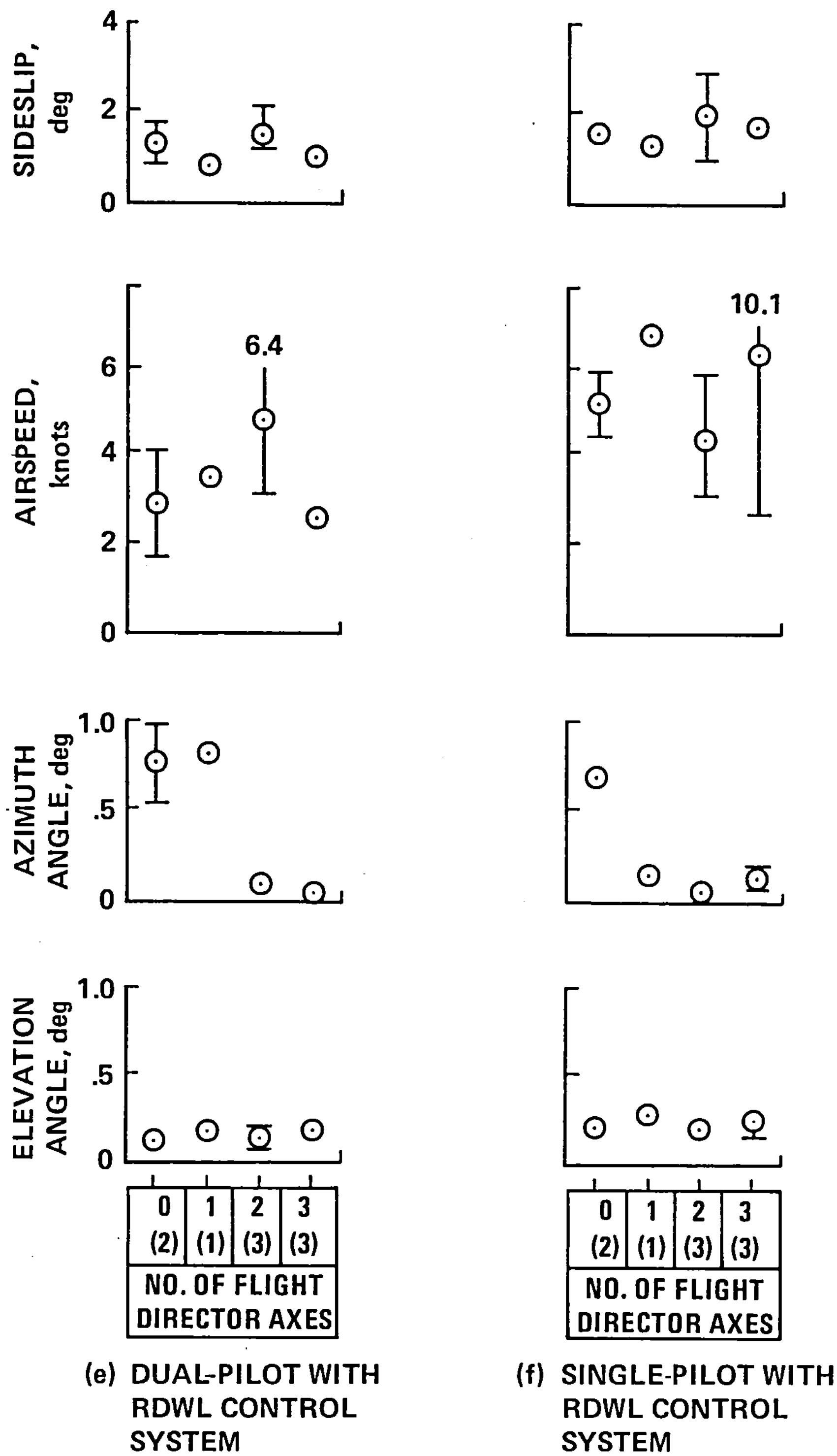


Figure 16.- Concluded.

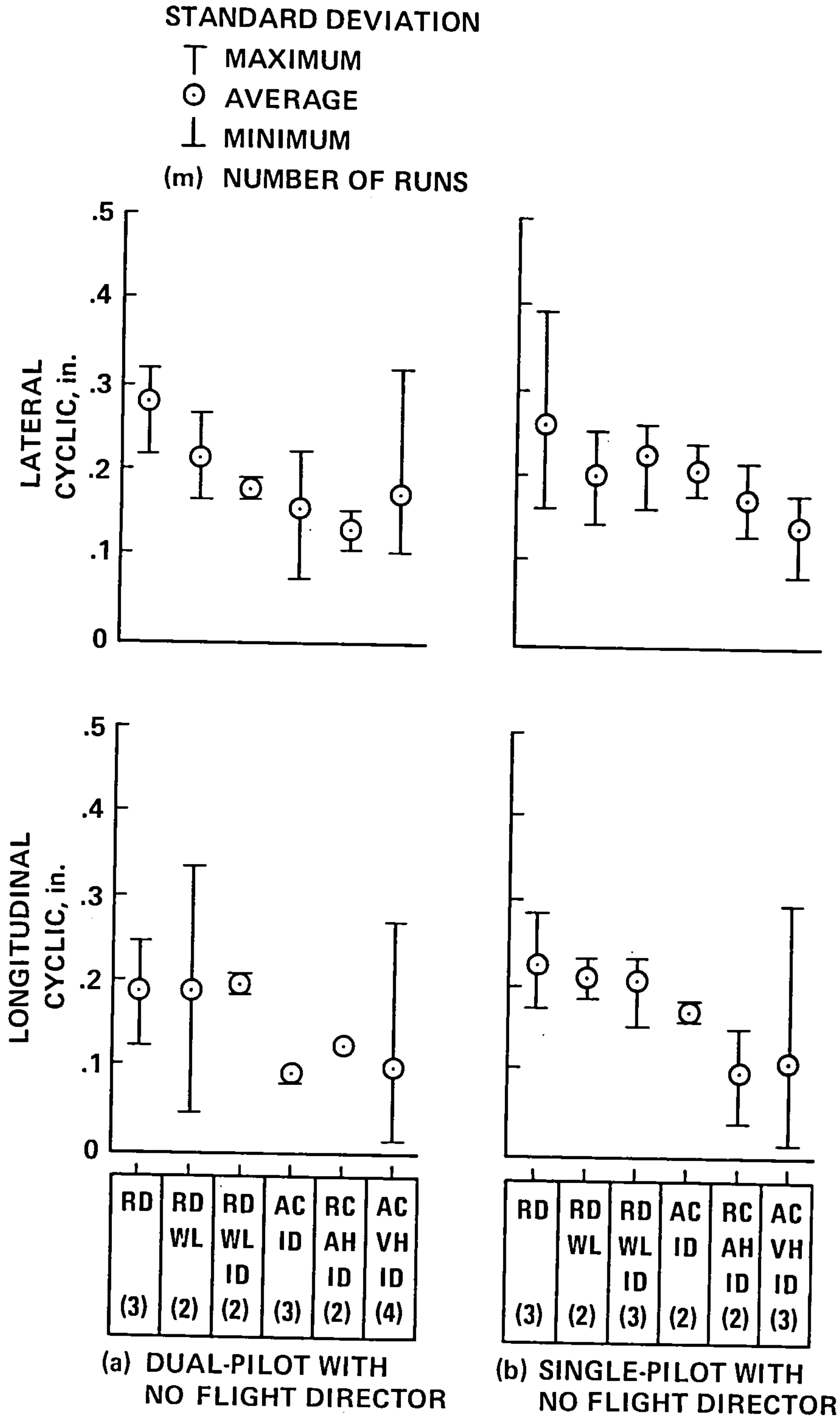


Figure 17.- Standard deviation of cyclic control deflection, 35-sec interval during final approach.

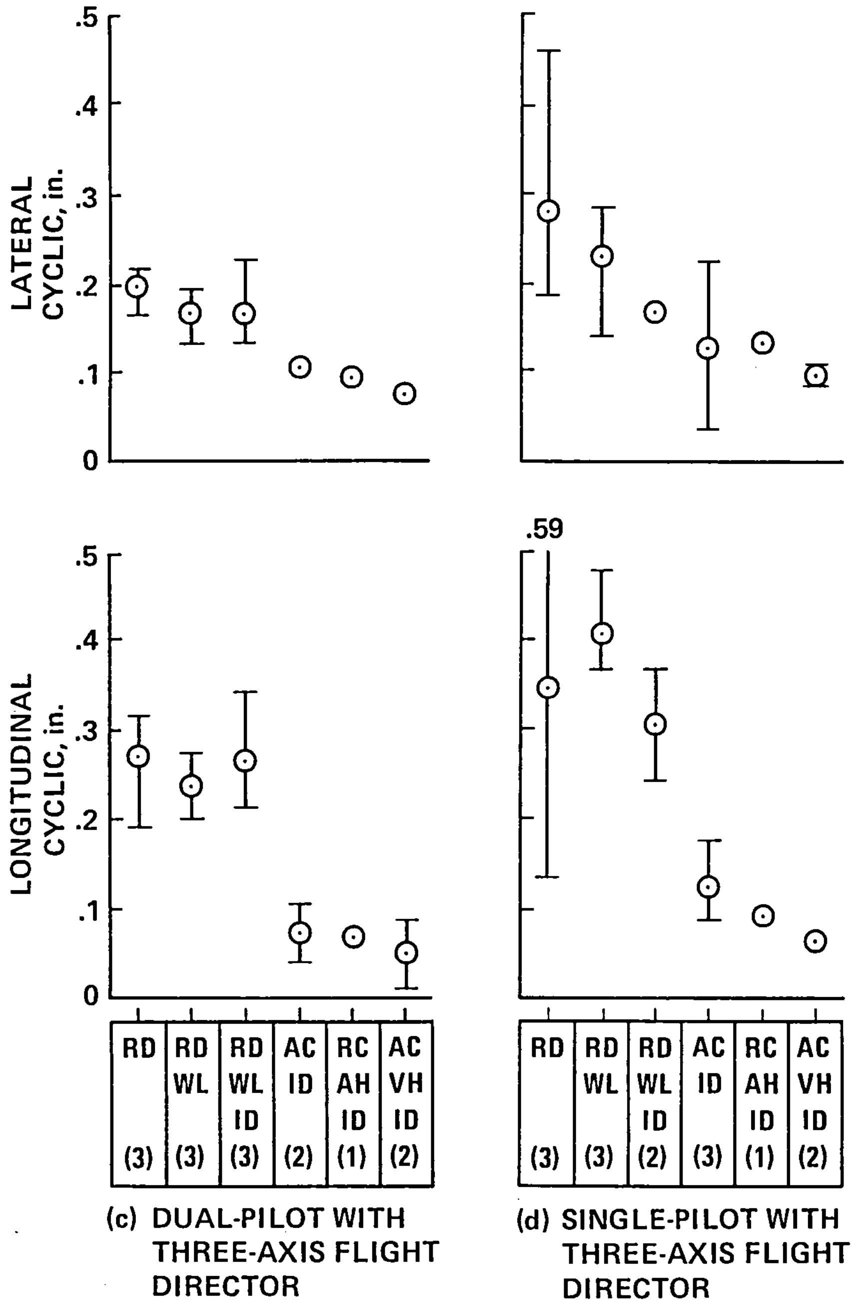
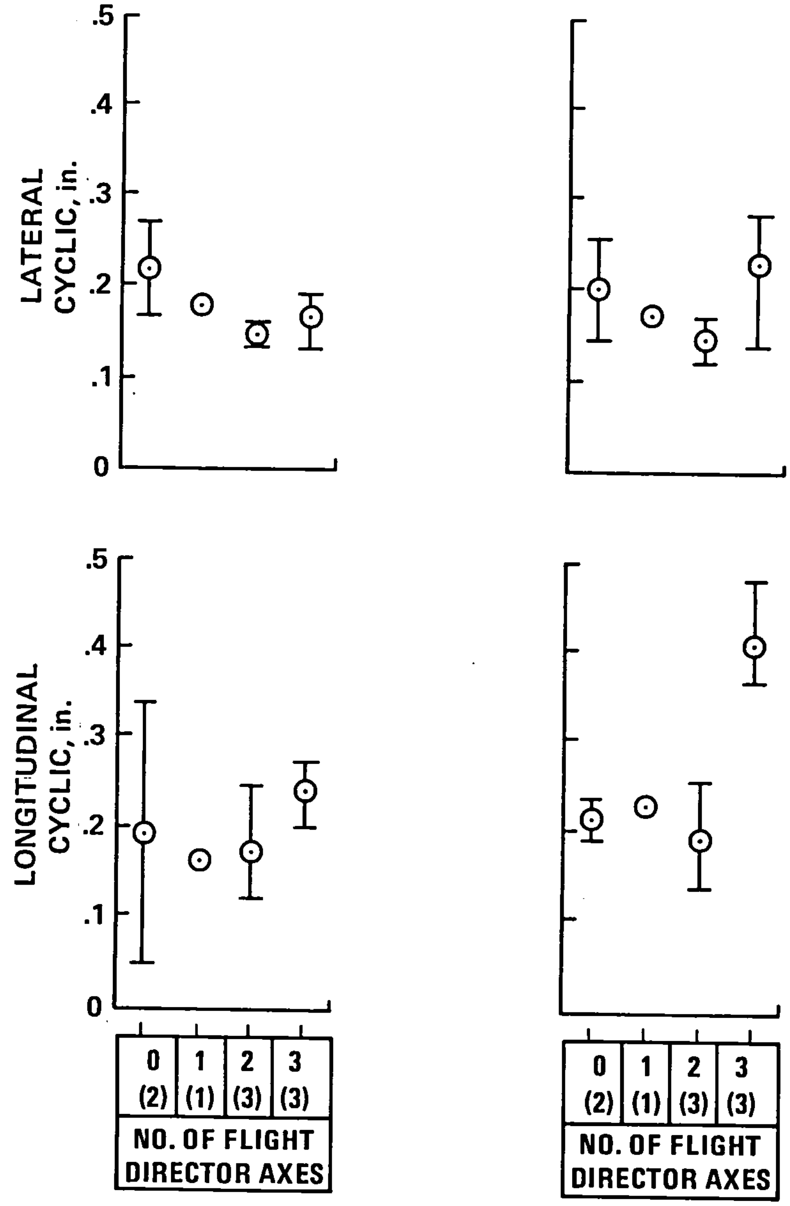


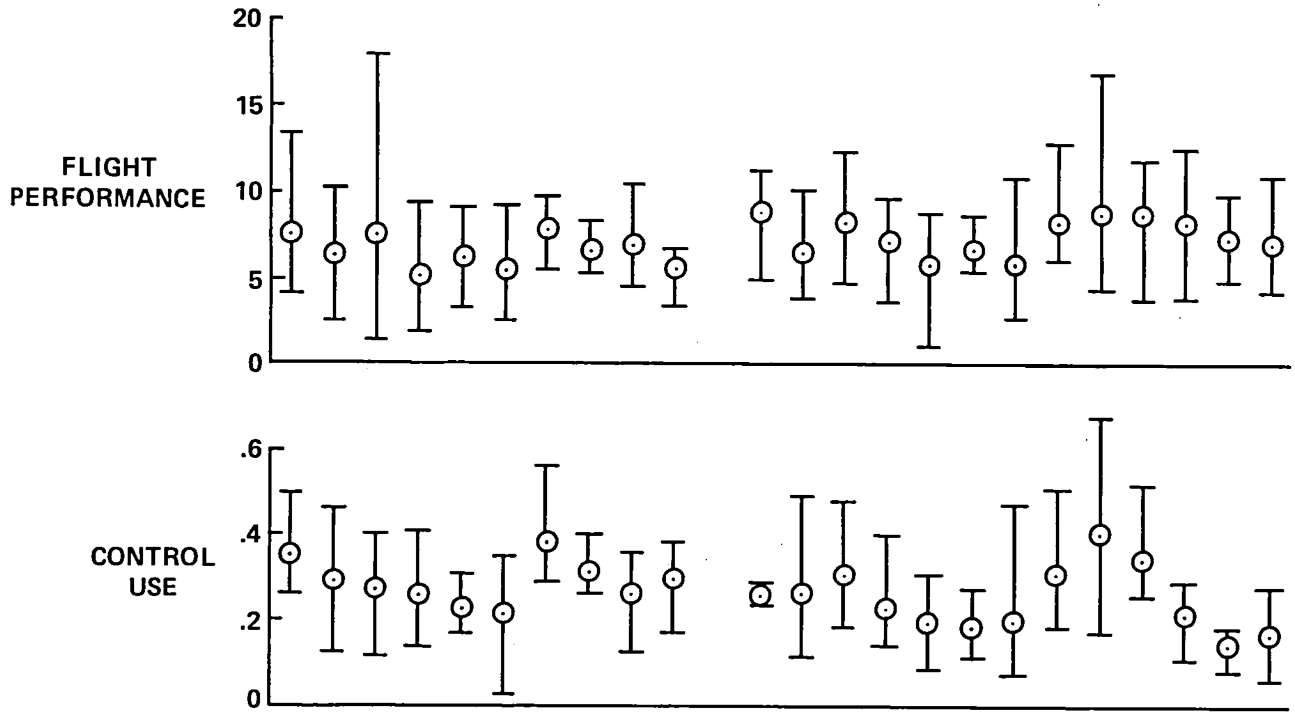
Figure 17.- Continued.



(e) DUAL-PILOT WITH RDWL CONTROL SYSTEM

(f) SINGLE-PILOT WITH RDWL CONTROL SYSTEM

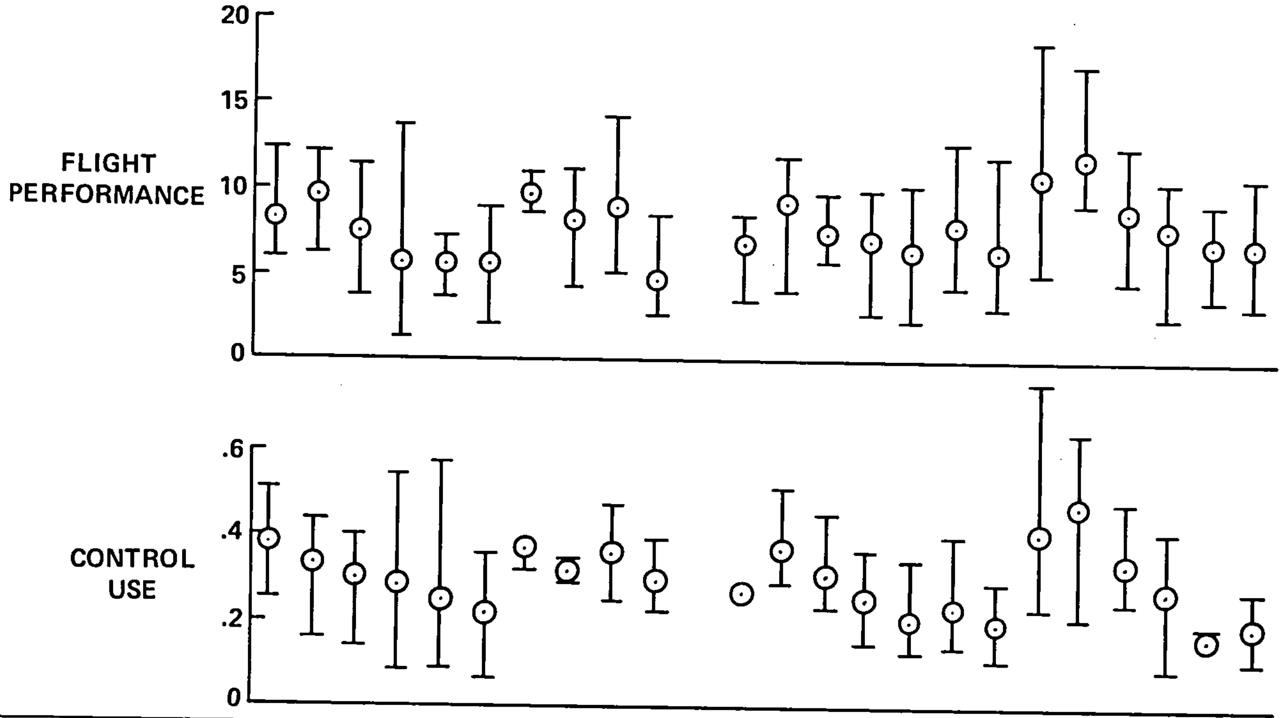
Figure 17.- Concluded.



CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	3	2	3	3	2	4	1	1	2	1	0	1	3	3	3	3	3	2	3	3	3	2	1	2
AVERAGE CHPR	5.5	4	5	4	2.8	3.9	7	5	4	4		3	5	4.5	3.8	3.3	2.7	3.5	5.2	4.8	3.7	2.5	3	2.5
FLIGHT DIRECTOR	NONE						1-AXIS						2-AXIS						3-AXIS					

(a) DUAL-PILOT

Figure 18.- Effect of control system, display, and crew loading on flight performance and control use.



FLIGHT DIRECTOR	NONE					
CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	3	2	3	3	2	4
AVERAGE CHPR	6.8	5.8	6.2	4.8	3.3	4.1

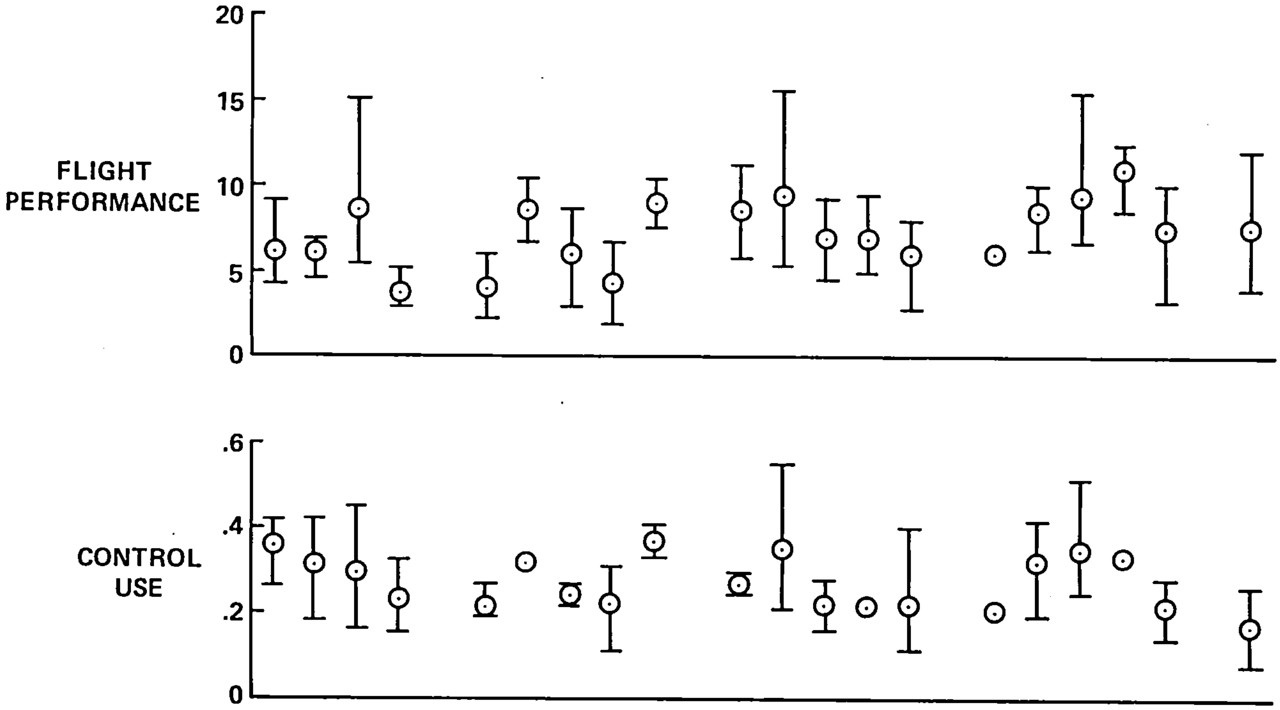
FLIGHT DIRECTOR	1-AXIS					
CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	1	1	3	1	0	1
AVERAGE CHPR	8	6	5	5.5		3.5

FLIGHT DIRECTOR	2-AXIS					
CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	3	3	3	3	3	2
AVERAGE CHPR	6.7	6.3	6.5	3.7	3.5	3.5

FLIGHT DIRECTOR	3-AXIS					
CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	3	3	3	3	1	2
AVERAGE CHPR	7	6.7	4.7	3.3	3.5	3.3

(b) SINGLE-PILOT

Figure 18.- Continued.



CONTROL SYSTEM	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID	RD	RD WL	RD WL ID	AC ID	RC AH ID	AC VH ID
NUMBER OF RUNS	3	2	3	2	0	3	1	1	2	1	0	1	3	1	2	3	0	1	2	3	2	3	0	2
AVERAGE CHPR	5.5	5.3	5.8	4.5		3.5	7	6	4.8	5.5		3.5	6	6	4.5	3.5		3	6.5	5.5	5	3.5		3.3
FLIGHT DIRECTOR	NONE						1-AXIS						2-AXIS						3-AXIS					

(c) SINGLE-PILOT WITHOUT MISSED APPROACH

Figure 18.- Concluded.

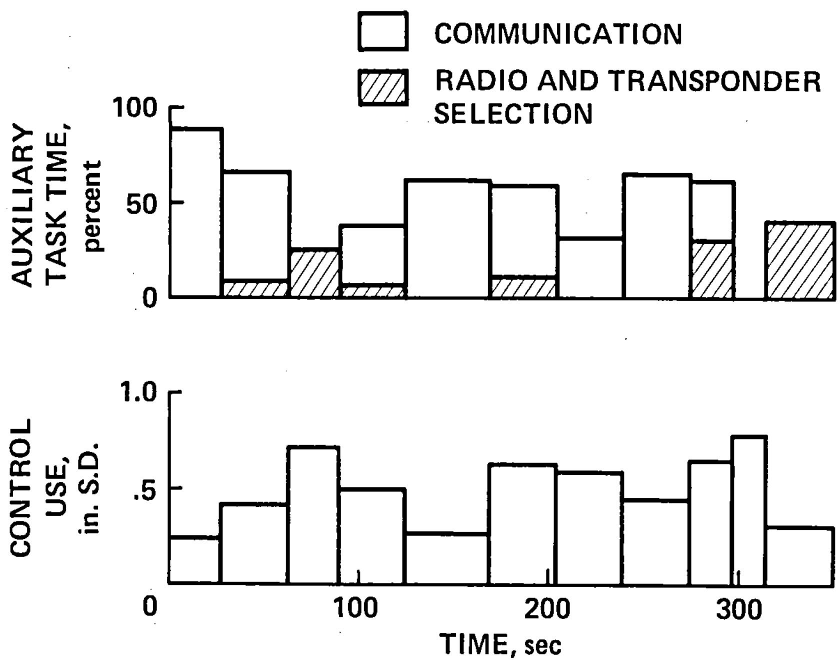


Figure 19.- Auxiliary task time and control-use indicators of pilot workload, configuration T13, single-pilot approach.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM 84258		

4. Title and Subtitle	5. Report Date
A Piloted Simulator Investigation of Stability and Control, Display, and Crew-Loading Requirements for Helicopter Instrument Approaches. Part I - Technical Discussion and Results	September 1982
	6. Performing Organization Code: A-9056
7. Author(s): J. V. Lebacqz, R. D. Forest,* and R. M. Gerdes	8. Performing Organization Report No.
	10. Work Unit No.: 505-42-21
9. Performing Organization Name and Address: Ames Research Center, Moffett Field, CA 94035 *Federal Aviation Administration, Ames Research Center, Moffett Field, CA 94035	11. Contract or Grant No.
	13. Type of Report and Period Covered: Technical Memorandum
12. Sponsoring Agency Name and Address: National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

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16. Abstract A ground-simulation experiment was conducted to investigate the influence and interaction of flight-control system, fight-director display, and crew-loading situation on helicopter flying qualities during terminal-area operations in instrument conditions. The experiment was conducted on the Flight Simulator for Advanced Aircraft at Ames Research Center. 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 (representative auxiliary tasks of navigation, communications, and decision-making). 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 single-pilot operation than that for the dual pilot situation.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Helicopter Airworthiness Instrument flight	Unlimited Subject Dategory - 08

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	83	A05

*For sale by the National Technical Information Service, Springfield, Virginia 22161