RESULTS OF NASA/FAA GROUND- AND FLIGHT-SIMULATION EXPERIMENTS CONCERNING HELICOPTER IFR AIRWORTHINESS CRITERIA

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Abstract

A sequence of ground- and flight-simulation experiments was conducted at the Ames Research Center as part of a joint NASA/FAA program to investigate helicopter instrument-flight-rules (IFR) airworthiness criteria. This paper describes the first six of these experiments and summarizes major results. Five of the experiments were conducted on large-amplitude motion base simulators at Ames Research Center; the NASA-Army V/STOLAND UH-1H variable-stability helicopter was used in the flight experiment. Taken together, the results of the experiments indicate, among other things, that 1) some level of artificial stability and control augmentation is generally required for adequate flying qualities during precision instrument flight; 2) neutral longitudinal or lateral control position gradients do not result in inadequate flying qualities, given good directional characteristics, but an unstable longitudinal gradient can prove to be inadequate for instrument operations in turbulence; 3) pitch and roll attitude augmentation in the stability and control augmentation system (SCAS) plus directional augmentation including at least yaw damping is required to achieve satisfactory precision instrument flying qualities irrespective of the type of rotor or level of display assistance; 4) flight directors provide some compensation for poor flying qualities in dual-pilot situations but are of minimal assistance in this regard for single-pilot operations; and 5) the SCAS level required for ratings of satisfactory is the same (pitch and roll attitude augmentation) for the range of approach types considered (nonprecision versus precision, constant speed versus deceleration to a low speed).

Introduction

Current and projected expansion of civil helicopter operations has led to increasing efforts to assess problem areas in civil helicopter design, certification, and operation. Of concern are the influences of the helicopter's inherent flight dynamics, flight-control system, and display complement on flying qualities for instrument flight rules (IFR) flight, both in terms of design parameters to 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:

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

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.

With respect to the first goal, the sections of the Ref. 1 criteria that deal with static and dynamic stability attempt to prescribe quantitative values of several helicopter flight characteristics that would be required for IFR certification. To the extent that these values are a carryover from fixed-wing practice or an amalgam of previous handling-qualities requirements for military aircraft (e.g., Ref. 4), it is necessary to ascertain their validity for civil helicopter certification. One aspect of interest has to do with the requirements for stable force or position control gradients longitudinally, laterally, or directionally. Another aspect of interest is the difference in criteria for normal category rotorcraft depending on whether the aircraft is to be certificated single or dual pilot, particularly since most of existing substantiating data pertain only to dual-pilot operation. Yet another area of concern is the influence of displays on the instrument meteorological conditions (IMC) flying qualities, which is not considered in Ref. 1 but has been shown in some cases to compensate for less-than-satisfactory inherent flying qualities (e.g., Ref. 5).

With respect to the second general goal, most helicopters currently certificated for single-pilot IFR operations use advanced stability and control augmentation systems (SCAS) or displays or both.[6] Of concern is the level of complexity of the SCAS required to achieve a good IMC capability because of the cost, control authority, and reliability factors the SCAS introduces. Of interest also is the expansion of helicopter IMC operations to exploit the helicopter's unique capability to fly at very low airspeeds; this expansion requires additional definition of the required flight dynamics, flight controls, and displays.

The various experiments discussed in this paper were designed to investigate elements of interest in achieving both goals in a consistent fashion. Specifically, the objectives of each experiment, listed in chronological order, may be summarized as follows. 1) First experiment (ground simulation, 1978):[7] develop generic models of current helicopters having three different rotor types; explore SCAS concepts and influence of longitudinal static stability; and determine relative influence of IFR compared to VFR approaches. 2) Second experiment (ground simulation, 1979):[8,9] determine suitability of requirements on cockpit control position; examine efficacy of several SCAS concepts; and explore influence of turbulence. 3) Third experiment (ground simulation, 1980):[10] determine influence of crew-loading (single pilot versus dual pilot); determine influence of three-cue flight director displays; and examine suitability of additional SCAS concepts. 4) Fourth experiment (flight, 1980):[11] validate selected results of ground-simulation experiments in flight concerning static longitudinal stability, level of SCAS, and flight director displays. 5) Fifth experiment (ground simulation, 1980):[12] examine influences of unstable static control gradients, angle-of-attack stability, and pitch-speed coupling; and examine influence of failed SCAS. 6) Sixth experiment (ground simulation, 1981):[13] investigate SCAS requirements for decelerating instrument approach; explore influence of electronic display format; and examine influence of approach geometry and deceleration profile.

The remainder of this paper is organized as follows. The following section summarizes the designs of the experiments with an emphasis on variations that were carried across all of them, and the next section provides a review of their conduct, again emphasizing the similarities. Following these summaries, the results of all the experiments are compared with each other, followed by some general conclusions.

Experimental Design

Mathematical Models

In the ground-simulation experiments, the basic mathematical model used to simulate the flight dynamics of the helicopters was a nine-degree-of-freedom model developed for use in nap-of-the-earth (NOE) simulations.[14] The model explicitly includes the three-degree-of-freedom tip-path-plane dynamic equations for the main rotor[15] and the six-degree-of-freedom rigid-body equations. The main-rotor model includes 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) was accomplished by appropriate combinations of those design parameters.

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

In the first experiment, the rotor design and helicopter geometric parameters of the mathematical model were selected and tuned to simulate stability and control characteristics similar to those of the UH-1H, OH-6A, and BO-105 aircraft, which use teetering-, articulated-, and hingeless-rotor systems, respectively.[7] These same three generic helicopters were used as the baseline configurations for the second experiment; only the teetering model was used in the successive experiments. Reference 9 lists several of the geometric and rotor design parameters for them. It is emphasized that the resulting static and dynamic characteristics are intended to be representative of the three types of rotor systems investigated for the three weight classes of helicopters that were simulated; they are not, in all respects, identical to the characteristics of the UH-1H, OH-6A, or BO-105.[7]

Static Stability

One type of configuration variation carried across most of these experiments was changes in longitudinal, lateral, or directional static stability as measured through cockpit control positions with speed or sideslip. For the purposes of this paper, the variations in longitudinal control position with velocity will be emphasized. Of the three baseline helicopter models developed in the first experiment, the models with articulated and hingeless rotors had stable control position gradients at 60 knots; the position gradient for the teetering rotor was unstable. One of the SCAS concepts considered (rate damping with input decoupling, longitudinal cyclic to collective gearing scheduled with speed) turned out to destabilize this gradient, yielding an almost neutral gradient for the hingeless rotor, an unstable gradient for the articulated rotor, and a more unstable gradient for the teetering rotor.[7] In addition, a preliminary investigation of the influences of this gradient was made in a controlled fashion for the hingeless-rotor model by using the variable-stability aspect of the model structure, with feedback of longitudinal velocity to longitudinal cyclic being used to vary the effective M_u. Table 1 summarizes the gradients and the times to either half or double amplitude of the prevalent low-frequency roots.

This variable-stability capability was used in succeeding experiments to control the longitudinal control position gradient with speed, including the influences of the SCAS gearings. In the second experiment, two levels of gradients were considered for the hingeless rotor (stable and neutral), and neutral values were designed for the teetering and articulated rotor models also.[8,9] In the third experiment, only the teetering-rotor model was used, with the gradient held at neutral (to highlight influences of SCAS and displays, as will be described below).[10] The flight experiment considered three levels of gradient (basic airframe, increased value to roughly that of the ground experiments, decreased value to neutral), with the variable-stability capability of the aircraft being used in a fashion analogous to the ground simulation model to vary M_u, and the resulting control gradient being measured in flight.[11] In the fifth experiment, this gradient was systematically varied for the teetering-rotor model from quite stable to unstable values, yielding times-to-double-amplitude down to about 6 sec.[12] The values considered across all the experiments are summarized in Table 1 for SCAS implementations incorporating only rate feedbacks.

Other Baseline Characteristics

As was mentioned above, ground simulation models of helicopters having hingeless-, articulated-, or teetering-rotor systems were used in the first two experiments; in the remaining ground-simulation experiments (and of course in the flight experiment), emphasis was on only the teetering-rotor system. Reference 7 describes the wide range of response characteristics among the three unaugmented baseline models and the resulting flying-qualities deficiencies. For the hingeless and teetering models in particular, however, the addition of SCAS incorporating rate damping and input decoupling effectively minimized these differences, particularly when high-gain feedbacks were used with the teetering model in the second experiment.[9] For this reason, only baseline configuration changes to the teetering-rotor model will be discussed here.

Table 2 lists some of the stability derivatives at 60 knots of the baseline teetering-rotor ground-simulation model. These characteristics were held constant across all the experiments, but in the fifth experiment selected variations were also considered.[12] One of these variations was the steady-state attitude-to-speed gradient. For the baseline model, this gradient was very low (-0.03°/knot at 60 knots), which considerably aggravates the difficulty of controlling speed at low-control gradients; the variation considered was to increase artificially the drag damping (X_u) to produce an attitude-to-speed gradient of -0.33°/knot at 60 knots. Another variation was the angle-of-attack stability, which was nearly zero for the baseline configuration (Table 2). This derivative was made very stable (M_w = -0.025), using the variable-stability system; as is discussed in Ref. 12, this variation had a negligible influence on the longitudinal control position gradient (in contrast to its effect on a fixed-wing vehicle), but did modify short-term response to cyclic. Again, these variations were considered in only the fifth experiment.

Stability and Control Augmentation System (SCAS)

As was discussed in the introduction, one of the major aspects of concern in this sequence of experiments was the type of stability and control augmentation required for a good helicopter IMC capability. Variations in the type of augmentation, and to some extent the level of it, were carried out across all the experiments. In the first experiment, these variations for each of the three baseline aircraft consisted of 1) no augmentation; 2) pitch/roll/yaw rate damping; 3) input decoupling to reduce off-axes accelerations to control inputs added to (2); and 4) pitch and roll attitude augmentation added to (3).[7] The second experiment considered again the last two of these concepts, with the gains for the teetering-rotor configuration increased to provide response characteristic roots similar to the hingeless-rotor configuration; in addition, turn-following augmentation (increased directional stiffness and feedbacks to reduce the Dutch roll excitation) was considered, as was a rate-command-attitude-hold system in pitch and roll that was implemented by adding proportional-plus-integral prefilters to the pitch and roll command channels.[8]

These SCAS types were all considered again in the third experiment, with a selectable wing-leveler (roll-attitude feedback) also added to the rate-damping and rate-damping-input-decoupled SCAS mechanizations to study split-axis augmentation in a preliminary way. For this experiment, reduced levels of rate and attitude feedback were used for these SCAS types, to be more consistent with actual teetering-rotor capabilities. An additional velocity-hold SCAS was designed, which augmented the vertical velocity time-constant to roughly 0.5 sec and used longitudinal velocity feedbacks to increase the effective phugoid frequency and partially eliminate lift-change caused by speed (Z_u).[10]

The fourth (flight) experiment included only the two SCAS types of rate-damping-input-decoupling and pitch/roll attitude augmentation, with the levels designed to be consistent with the third experiment.[11] These same two SCAS types at the same level were also used in the longitudinal axis for the fifth experiment, with the lateral axis held fixed at a high-gain rate-command-attitude-hold type. In addition, a failed longitudinal pitch-rate damper was also simulated by eliminating the pitch-rate feedback in the rate-damping-input-decoupling SCAS.[12] Finally, the sixth experiment also included rate-damping-input-decoupling, rate-command-attitude-hold, and attitude-command SCAS types, with somewhat higher augmentation levels considered because of the decelerating task. Additional designs were a velocity command system and an acceleration-command-velocity-hold system, that incorporated high-gain feedback of longitudinal velocity to longitudinal cyclic (constant term of hovering cubic about 1.7).

Because of the consistency across most of the experiments of rate-damping-input-decoupled, rate-command-attitude-hold, and attitude-command SCAS types, these results will be emphasized in this paper.

Displays

Figure 1 shows the instrument panel layout used in all the ground simulation experiments, except the last. The instruments were arranged in a standard "T," and were conventional, with the exception of the electromechanical attitude indicator (ADI), which was a 5-in. unit incorporating heading (through longitudinal lines on the ball) as well as pitch-roll information. Turn-rate-slip information was presented on a separate instrument, as is frequently done in helicopters, rather than with the attitude indicator. Figure 2 shows the primary flight instruments for the flight experiment. The horizontal situation indicator (HSI) is similar to the one used in the ground experiments, but the ADI incorporated integrated glide-slope and localizer deviation data plus turn-rate-slip information not included in the ground simulator unit. In the last ground simulation experiment, the ADI was replaced with a black-and-white cathode ray tube (CRT) unit to present electronic formats. Figures 3 and 4 illustrate the two electronic formats considered in this experiment. As can be seen, the first is a simplified analog of an electromechanical ADI such as the one used in the flight experiment; the second is one way of integrating a variety of information into one presentation, but will not be discussed in this paper.

Excluding the integrated electronic format, therefore, the primary display variable considered across the experiments was the extent of flight director information provided to the pilot in addition to the raw deviation data. Because the task considered for the first two experiments was a VOR approach, only course-deviation information was presented on the HSI, with the ADI flight director needles biased off scale. In the remaining ground-simulation experiments and in the flight experiment, a precision MLS approach task was considered; for these experiments, azimuth and elevation deviation plus DME (range to go) information was given on the HSI. In the third experiment, one-, two-, or three-cue flight directors were a display variable; in the flight experiment, either no directors or three-cue directors were the variable; in the sixth experiment, all configurations included a three-cue flight director; in the fifth experiment, no flight directors were considered. The general philosophy of the flight director design is discussed in Ref. 10.

Crew-Loading Situation

All but the third experiment were conducted as typical flying-qualities experiments; the pilot's sole task was to perform the desired control task, with no auxiliary tasks of communications or navigation. This scenario of full-attention-available-for-control is consistent with a dual-pilot crew-loading situation. In the third experiment, the configurations were evaluated assuming this situation but they were then also evaluated in as realistic a simulation of a single-pilot situation as possible. For the single-pilot simulations, the pilot always had to communicate with Approach Control and Tower, set a transponder frequency, and switch communication frequencies; for approaches including a missed approach, he also had to switch communication frequencies again, copy a clearance from Departure Control, switch navigation and transponder frequencies, and track a VORTAC. Radio "chatter" from two other helicopters in the area was simulated. To provide a lack of repetition, four different approach plates to four oil rigs were devised, with different frequencies and alternates for each plate; these four possibilities were mixed randomly among the control-display combinations. Finally, on the single-pilot approaches, the pilot did not know whether he would be able to continue the approach or be forced to do a missed approach; the simulated fog was made to start clearing at 100 ft above the decision height and then to either re-fog or continue clearing just below decision height. As a result, the pilot had to make the decision whether to continue.

Wind and Turbulence

An additional variable carried across the experiments was the level of winds and turbulence present. For the ground-simulation experiments, a simple model for atmospheric turbulence[16] was used; it included three independent Gaussian gusts plus a mean wind which could shear in direction or magnitude. In the first experiment, all evaluations were conducted in no turbulence. In the second experiment, the configurations were evaluated in both no turbulence and at a representative level of turbulence ($\sigma_u = \sigma_v = 3.0$ ft/sec, $\sigma_w = 1.5$ ft/sec) with no mean wind. The third experiment added a 10-knot mean wind that sheared rapidly in direction a total of 100° at a range of about 1 mile out; all the configurations were evaluated in this wind and turbulence combination, with no zero-turbulence evaluations. This same wind and turbulence model was again used in the fifth experiment, with evaluations conducted both with it and in no turbulence. The sixth experiment included a vertical shear of the mean wind (from 10 knots at altitude to 2 knots at ground level) in addition to the shear in direction, and considered 1.5 times more turbulence ($\sigma_u = \sigma_v = 4.5$ ft/sec, $\sigma_w = 2.25$ ft/sec); again evaluations were conducted in both calm air and with this turbulence model.

For the flight experiment, the level of wind and turbulence was not a controlled variable. As is discussed in Ref. 11, tower estimates of wind magnitude and direction plus the pilots' qualitative estimate of the turbulence level were used to separate the data into two groups: one in which headwinds with little or no turbulence were present, and one in which there was a tailwind component or moderate turbulence or both.

Conduct of the Experiments

Equipment

The first three ground-simulation experiments were conducted using the Flight Simulator for Advanced Aircraft (FSAA) ground-based simulation facility at Ames Research Center; the last two used the Vertical Motion Simulator (VMS) facility at Ames (Figs. 5 and 6). Both facilities include a complex movable structure to provide six-degree-of-freedom motion; in the case of the VMS, a large vertical travel (±30 ft) is available to enhance simulation fidelity of longitudinal motions, and the FSAA is characterized by a large lateral travel (±50 ft). In both facilities, a visual scene from a terrain board is presented through the cab window on a color television monitor with a collimating lens. For the first two experiments, the approaches were conducted to a model of a STOL airport with helipads; the last three ground-simulation experiments considered approaches to a model of an off-shore oil rig.

Instrument conditions were simulated using an electronic fog generator which could obscure all or part of the visual scene as a function of range or altitude. In the first two experiments, the instrument runs were conducted entirely in the fog to a minimum descent altitude of 600 ft, with no breakout simulated. The third and fifth experiments did include a partial clearing of the fog starting at about 100 ft above the decision height, which could then refog at the decision height to force a missed approach; in the sixth experiment, the fog always disappeared at the decision height.

The flight experiment was conducted on a UH-1H helicopter which had been modified as an in-flight simulator by adding an avionics system called V/STOLAND (Fig. 7). The system provides integrated navigation, guidance, display, and control functions through two flight digital computers; it may be operated with or without flight-director commands, in the modes of manual, control-stick steering (CSS), autopilot, or research. The flight-control portion of the V/STOLAND system uses a combination of a full-authority parallel servo and a limited authority (20% to 30%) series servo in each control linkage. In addition, disconnect devices exist in the left cyclic controls to allow for a fly-by-wire mode through this research cyclic stick. The right stick, or safety pilot side, retained the standard UH-1H cyclic and cockpit instruments. This experiment was conducted in the research mode, with the software providing a set of flight-control laws with variable gains and a set of flight-director laws with fixed gains.[11] Instrument flight was simulated with the use of an "IFR Hood."

Evaluation Tasks and Procedures

Although the evaluation tasks differed in detail among the six experiments, they were generically similar for all except the sixth. Each of the first five included a lateral guidance acquisition at constant altitude (about 1200 to 1600 ft AGL, depending on experiment), transition to a vertical descent at a constant speed of 60 knots (1000 ft/min for the VOR approaches of Experiments 1 and 2, acquisition of a 6° glide slope for Experiments 3 through 6), constant speed tracking during the descent (except Experiment 6), and transition to a constant-speed missed-approach maneuver consisting of a standard-rate turn at climb rates varying from 600 to 1000 ft/min, with the transition occurring at the missed-approach point in the first two experiments and at the decision height in Experiments 3 through 5. Experiment 6 included a deceleration while on instruments according to one of three deceleration profiles, and considered two approach geometries (Fig. 8), but a missed approach was not included. Table 3 summarizes the individual details of the evaluation tasks.

Cooper-Harper pilot ratings were assigned to each configuration on the basis of the evaluation task for each experiment, and comments made relative to comment card; task performance and control usage data were also obtained for each. Across all the experiments, the total number of participating pilots by affiliation was as follows: NASA, 3; U.S. Army, 4; Federal Aviation Administration, 4; NAE Canada, 2; and Civil Aviation Authority, UK, 1. Approximate total evaluations for Experiments 1 through 6 were, respectively, 60, 200, 150, 50, 200, 160; taken together, therefore, over 800 evaluations were obtained.

Discussion of Results

Influence of Longitudinal Control Gradient

In Figs. 9a and 9b the average Cooper-Harper pilot ratings from each experiment are plotted as functions of longitudinal static stability without turbulence and in turbulence, respectively. The data are for configurations with a rate-damping-input-decoupling SCAS and a dual-pilot crew-loading situation; they include both hingeless- and teetering-rotor systems in the results for Experiments 1 and 2. To emphasize the important aspects, the pilot ratings are shown versus the gradient level (in./15 knots) for the stable cases but versus the inverse of the time-to-double-amplitude of the divergent root for the unstable cases.

As can be seen, the correlation among all the experiments is quite good. The data show a consistent trend toward a degraded capability as the static stability is reduced to neutral and then unstable, with the trend being more obvious in turbulence. In terms of Cooper-Harper ratings, however, the aircraft systems were still rated as adequate for the tasks considered, irrespective of the static stability. Note that, with this type of SCAS, average ratings in the satisfactory category were not attained, even at the most stable level. In commenting about these configurations, the pilots noted increasing difficulties in maintaining trim and controlling speed precisely as the static stability was decreased, but also noted that the instrument tracking performance was still adequate at least down to neutral stability.

The IFR Appendix requires positive longitudinal control force stability at approach speeds for both transport and normal category helicopters, regardless of crew loading.[1] In these experiments, control force and control position stability were tied together through the use of electrohydraulic control loaders, and so the requirement would prohibit the neutral and unstable gradients that were considered. Considerations for airworthiness acceptance are likely to center on those configurations whose flying qualities are assessed to fall between satisfactory and adequate, but there is no clear correlation between acceptance and the Cooper-Harper pilot rating. All of the ratings fall within the adequate category, and the differences between stable and neutral gradients in individual experiments generally amount to about one pilot rating or less.[8,11,12] Taken together, therefore, the results indicate that the achievement of a clearly adequate (e.g., CHPR < 5) capability probably justifies the requirement for a stable gradient, but a neutral gradient might be marginally acceptable for the dual-pilot situation.

Influence of Other Baseline Characteristics

As was discussed earlier, some modifications to some baseline teetering-rotor model characteristics were considered in the fifth experiment to ascertain any influence of these characteristics on the types of results discussed above. Figure 10 shows the data from this experiment for configurations with a high steady-state attitude-speed relationship (obtained through the introduction of high-drag damping X_u). As can be seen, little change in average rating is evident for the neutral or stable gradients, with a small improvement for the unstable gradient. The pilot comments for these configurations demonstrate mixed reactions and difficulties. One pilot consistently rated the high-drag configurations as better than the low-drag ones because small speed changes resulted in fairly significant rate of climb changes as a result of the increased negative $d\gamma/du$; hence rate of climb could be well controlled using pitch attitude. The other pilots, however, noted that the requirement for large power changes with speed was a detriment, particularly since power was still the primary controller for rate-of-descent; therefore the required changes for speed led to apparent speed-and-rate-of-descent coupling, thereby negating any advantages of more precise speed control. As a result, therefore, in general the average ratings for the equivalent high-drag and low-drag configurations were about the same, both in no turbulence and in light turbulence. As a result, it is unlikely that the low attitude-to-speed gradient of the baseline machine significantly influenced the ratings shown earlier.

Another modification to the baseline characteristics was the introduction of a large increment in angle-of-attack stability. The data for this modification are shown in Fig. 11. As can be seen, the influence on the pilot rating is high in turbulence, with the high angle-of-attack stability configurations being rated as inadequate for the task. As is discussed in Ref. 12, the addition of this stability did not significantly influence the longitudinal control position gradient, but did lead to an "insidious" coupling between rate-of-descent and speed control. Pilot comments indicated that for these configurations the angle-of-attack stability coupled through pitch attitude to large inadvertent speed changes when large changes in rate-of-descent were made with the collective. The important point brought out by these data is that coupling effects have a major influence, and yet the criteria of Ref. 1 do not consider such effects at all. For helicopters, other typical types of coupling are cross-axis inputs (eliminated for most of the configurations investigated in the program) and pitch-roll coupling, particularly for hingeless-rotor machines; such effects should probably be considered quantitatively for airworthiness acceptance.

Influence of the Stability and Control Augmentation System

It was noted in discussing the static gradient results that no ratings in the satisfactory category were achieved for the tasks considered using rate-damping stability augmentation. Figure 12 shows the ratings assigned to the three types of pitch and roll SCAS considered most consistently across all the experiments: rate damping with input decoupling, rate-command-attitude-hold, and attitude command. These cases are primarily for the SCAS incorporated on a machine with neutral basic longitudinal stability; note that a rate-damping SCAS does not alter the control position gradient, a rate-command-attitude-hold SCAS *results* in a neutral gradient, and an attitude SCAS stabilizes the gradient because of the M_θ term. As has been pointed out in the reference for each experiment, attitude augmentation in pitch and roll (implemented either as rate-command-attitude-hold or attitude command) is required to achieve ratings in the satisfactory category.[7,12] The advantages include a reduction in interaxis coupling, reduced turbulence excitation, and improved short-term and long-term dynamics. It is interesting to note that the failed longitudinal damper considered in Experiment 5 still had characteristics that met the criteria of Ref. 2 (with stable gradient) and yet was rated marginal at best in turbulence.[12] Because the criteria do not directly assess short-term dynamics, acceptance of a failed state for this configuration would rest entirely in the hands of the certification pilot and would likely not be granted, even though the criteria are met.

Influence of Flight Director Displays

Figure 13 illustrates some of the data obtained concerning the influence of three-cue flight directors compared with raw-data displays. The Experiment 5 configurations shown were selected because their stability and control characteristics are virtually identical to those of the Experiment 6 configurations; these Experiment 6 data were "calibration" evaluations obtained with no deceleration on instruments. As can be seen, some beneficial influence of the three-cue flight director displays is apparent in the Experiment 3 results, particularly with the higher level of SCAS (attitude augmentation). Considering all the experiments, in general the flight director assistance did improve ratings given to the rate-damping control system sufficiently to provide a clearly adequate capability, but did not improve this SCAS type sufficiently to move it into the satisfactory category. With the attitude-type SCAS, however, the assistance of the flight directors generally pushed the ratings clearly into the satisfactory category. This lack of substantial overall benefit of the flight directors for the rate-damping SCAS type was not expected at the outset of the experiments, and it should be cautioned that the results are likely to be quite sensitive to the design method used.[10,13] Based on these data, relaxed airframe airworthiness requirements, because of "credit" for advanced displays, may be warranted in some cases, and the absence of consideration for displays in the IFR Appendix[1] may require further attention.

Influence of Task

Because the Cooper-Harper pilot rating applies to an airframe-control-system display combination for a specific task, and because the evaluation tasks have varied somewhat across these experiments, it is useful as a final comparison to examine the influence of the task on the ratings. Ratings from several of the experiments are compared in Fig. 14 for similar stability and control characteristics and displays as a function of the task that was considered. It should be noted in particular that the difference between the dual-pilot and single-pilot tasks considered in Experiment 3 resulted in a change of almost one pilot rating, justifying in principle the division in criteria for normal-category helicopters in the IFR Appendix, but leaving in question the lack of distinction for transport-category helicopters.[1] It may also be seen that a decelerating instrument approach leads to worse ratings than even the single-pilot task with a constant-speed approach. Decelerating approaches are not explicitly considered by the IFR Appendix,[1] and these data intimate that more stringent criteria may be required for these more demanding tasks.

Concluding Remarks

A sequence of ground- and flight-simulation experiments concerning helicopter IFR airworthiness has been described in this paper. A total of over 800 piloted evaluations of several aspects of concern for helicopter instrument flight was obtained in these experiments. Although there are variations in detail among the experiments, the general results with respect to IFR airworthiness can be compared. On the basis of these results, as presented here and in previous documentation of the experiments, the following conclusions may be drawn, particularly concerning the proposed IFR Appendix:

1) The criterion requiring a stable longitudinal force gradient with speed is probably justifiable for rate-damping types of SCAS, although little significant degradation has been shown with neutral or slightly unstable gradients; hence the neutral gradient, at least, could be considered marginally acceptable. It should be emphasized that a rate-command-attitude-hold-type of SCAS, as considered in these experiments, results in a neutral longitudinal gradient; this type of configuration was generally rated in the satisfactory category. Hence, this type of criterion needs to be linked to the type of SCAS employed, which it currently is not.

2) Inherent characteristics of the helicopter lead to a variety of types of interaxis coupling. One type explicitly considered in these experiments led to a considerable degradation in pilot ratings. The current IFR Appendix does not address off-axis coupling; perhaps future versions should.

3) In all the experiments, attitude augmentation in pitch and roll has been required to achieve pilot ratings in the satisfactory category. Rate damping augmentation, even at a fairly high level and with input decoupling, generally has received ratings ranging from marginally adequate to just worse than satisfactory, depending on other factors. A failed rate damper was considered marginally inadequate, even though the aircraft characteristics were still within the IFR Appendix criteria.

4) The addition of three-cue flight directors did not improve the IFR capability for rate-damping control systems to the satisfactory category, if all the experiments are considered; some beneficial effect in achieving ratings in the satisfactory category with an attitude-augmented SCAS was apparent. Inadequate flying qualities could not be improved to satisfactory with the use of flight directors, but the improvement might take a marginal configuration into the clearly adequate category. This possible improvement is not considered in the current criteria.

5) Increasing the difficulty of the task (e.g., single-pilot or inclusion of an instrument deceleration) did result in degraded ratings for equivalent configurations. A difference in requirements for single- and dual-pilot operations was therefore shown to be warranted. Similarly, a difference in requirements of future versions which consider decelerating instrument operations may be projected.

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Table 1. Summary of longitudinal control position gradients.

Experiment	Rotor	Configuration	Gradient, in./15 knots	Time-to-double amplitude, sec
1	Teetering		+0.06	5.8
	Hingeless		-0.05	
2	Hingeless	Neutral	~0	
	Hingeless	Stable	-0.63	
	Teetering	Neutral	-0.02	
3	Teetering		-0.02	
4	Teetering	More stable	~-0.50	
		Base UH-1H	~-0.25	
		Neutral	~0	
5	Teetering	Most stable	-1.03	
		Stable	-0.53	
		Neutral	-0.03	
		Unstable	+0.03	11.0
		Most unstable	+0.125	6.3
6	Teetering		-0.41	

Table 2. Longitudinal derivatives of baseline teetering-rotor helicopter at 60 knots.

Derivative	Units	Value
M_u	rad/sec²/ft/sec	-0.00022[a]
M_w	rad/sec²/ft/sec	-0.00278
M_q	1/sec	-0.847[b]
M_p	1/sec	+0.143[b]
$M\delta_e$	rad/sec²/in.	0.17[b]
$M\delta_c$	rad/sec²/in.	0.0223[b]
X_u	1/sec	-0.005[a]
X_w	1/sec	0.026
Z_u	1/sec	-0.013[a]
Z_w	1/sec	-1.28
$Z\delta_e$	ft/sec²/in.	-2.58[b]
$Z\delta_c$	ft/sec²/in.	-10.00

[a]Baseline, unmodified for gradient changes.

[b]No SCAS.

Table 3. Task details.

Experiment	Guidance	Speed profile	Decision height, ft AGL	Missed approach
1	VOR	60 knots, constant	600	Yes
2	VOR	Decelerate 80-60 knots before let-down, 60 knots constant thereafter	600	Yes
3	6° MLS	Decelerate 80-60 knots before vertical intercept, 60 knots constant thereafter	300	Yes
4	6° MLS	Constant 60 knots	200	Yes
5	6° MLS	Decelerate 80-60 knots before vertical intercept, 60 knots constant thereafter	300	Yes
6	6° MLS	Constant 60 knots until ~0.5 n.mi. to go, decelerate to ~15 knots on instruments	130	No

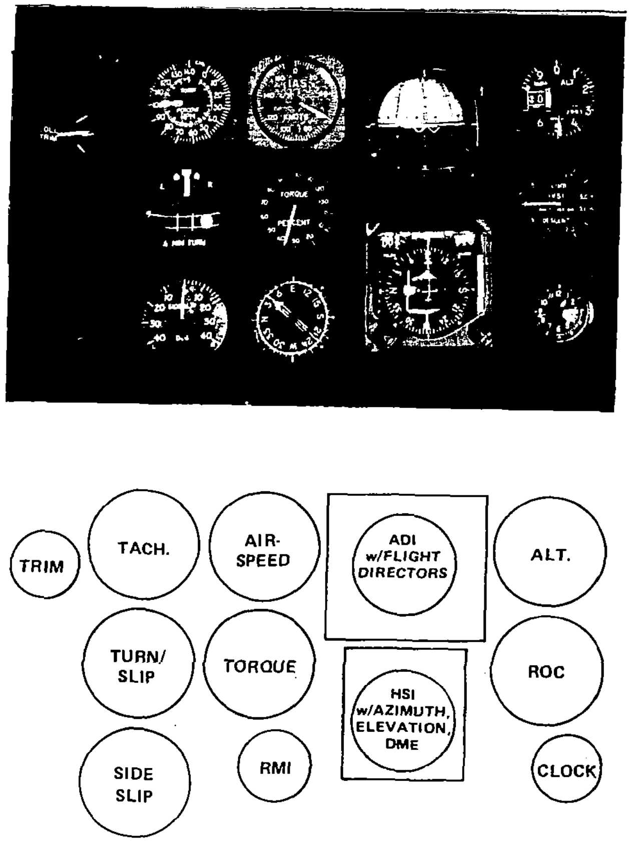
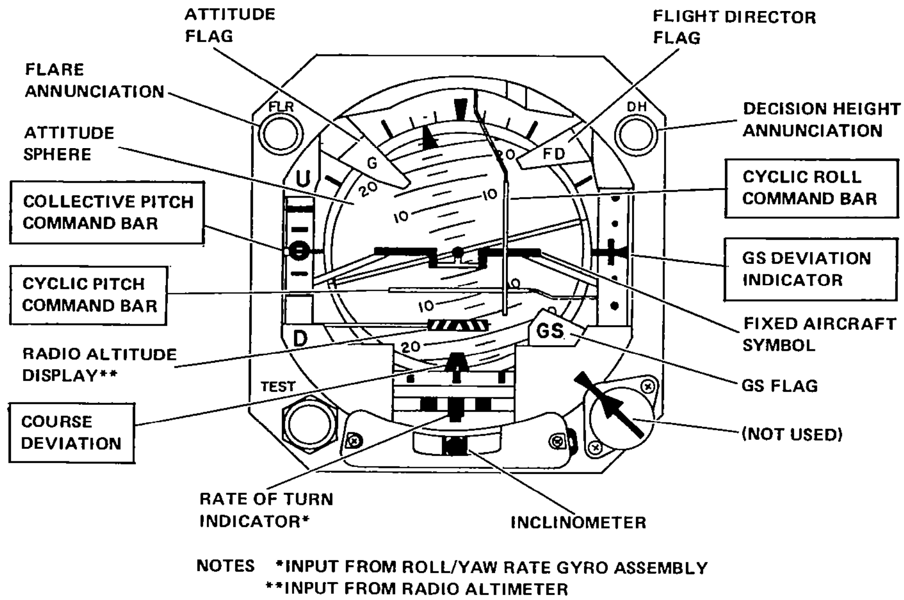
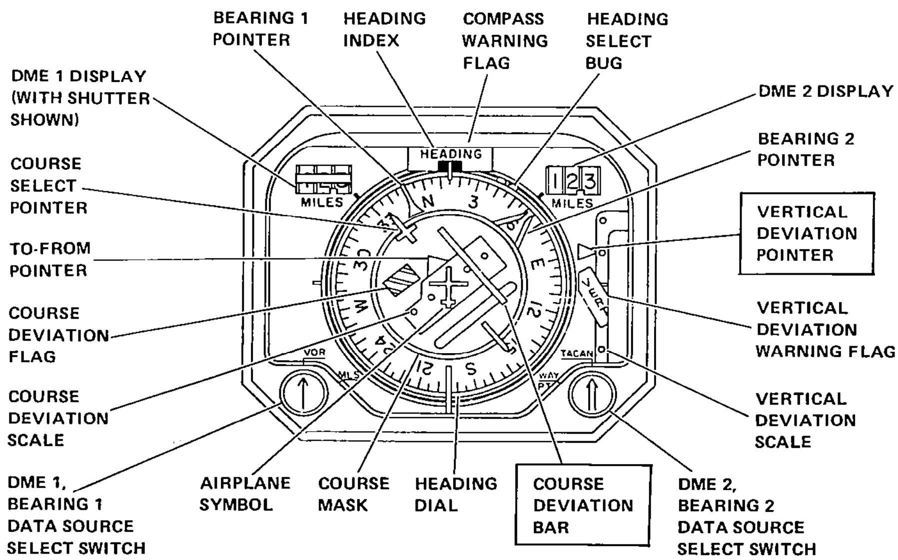


Fig. 1 Instrument panel layout.



(a) Attitude director indicator.



(b) Horizontal situation indicator.

Fig. 2 Flight director displays.

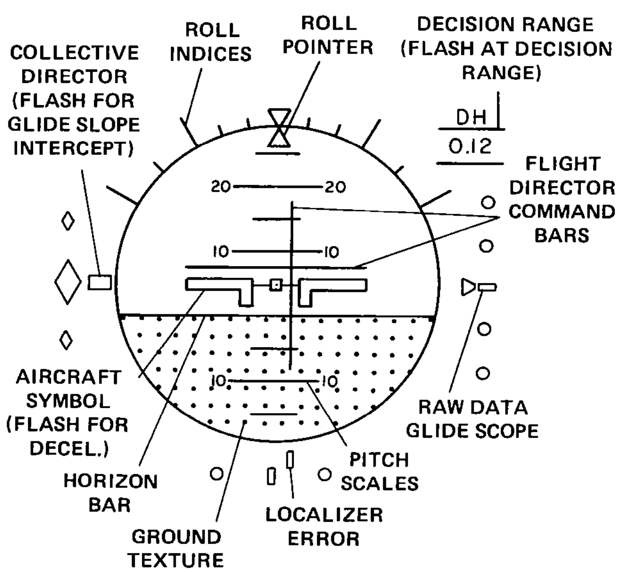
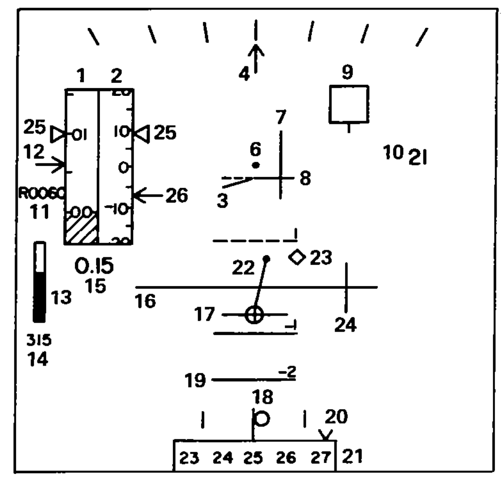


Fig. 3 C format for Experiment 6.



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

Fig. 4 X format for Experiment 6.

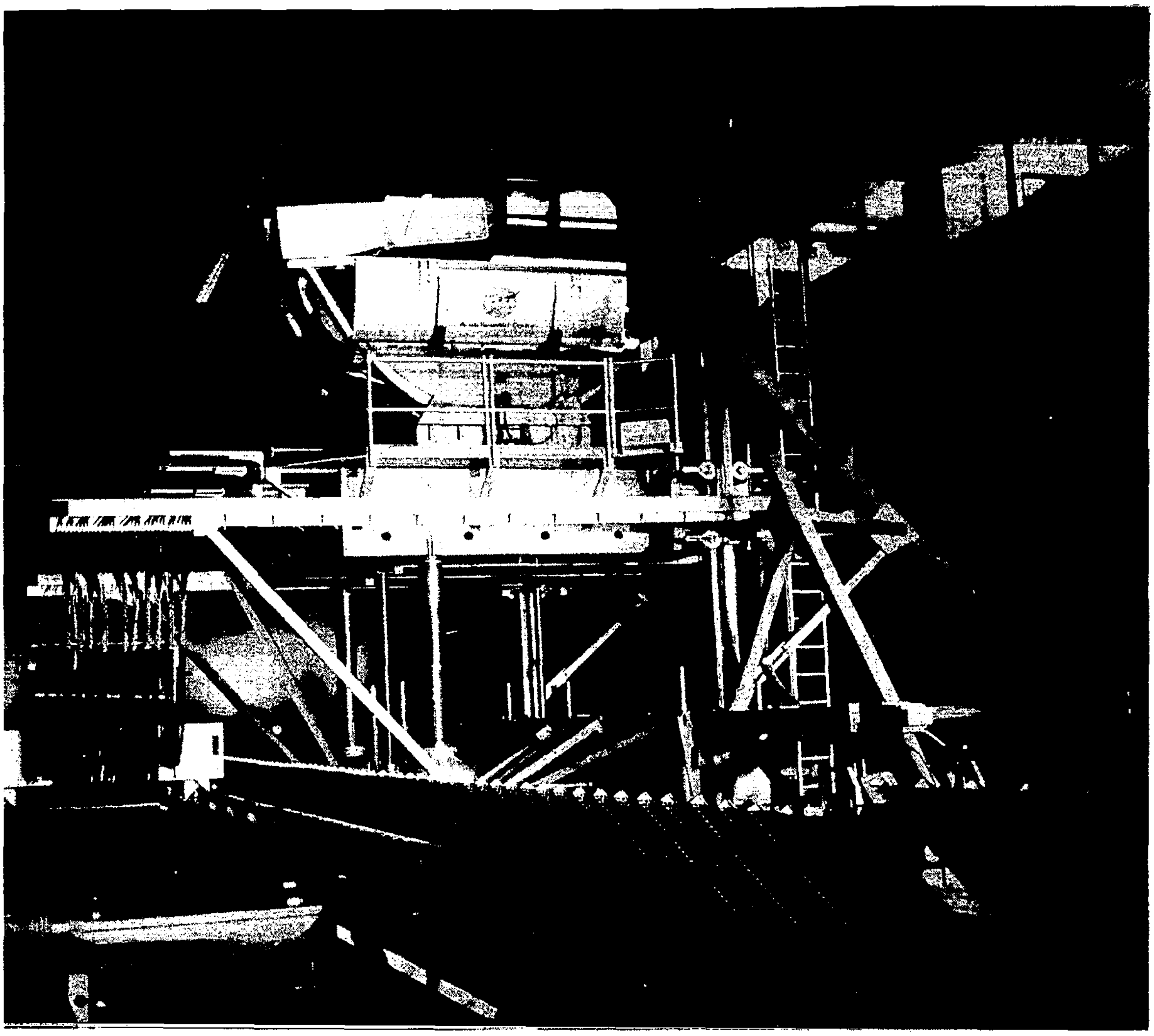
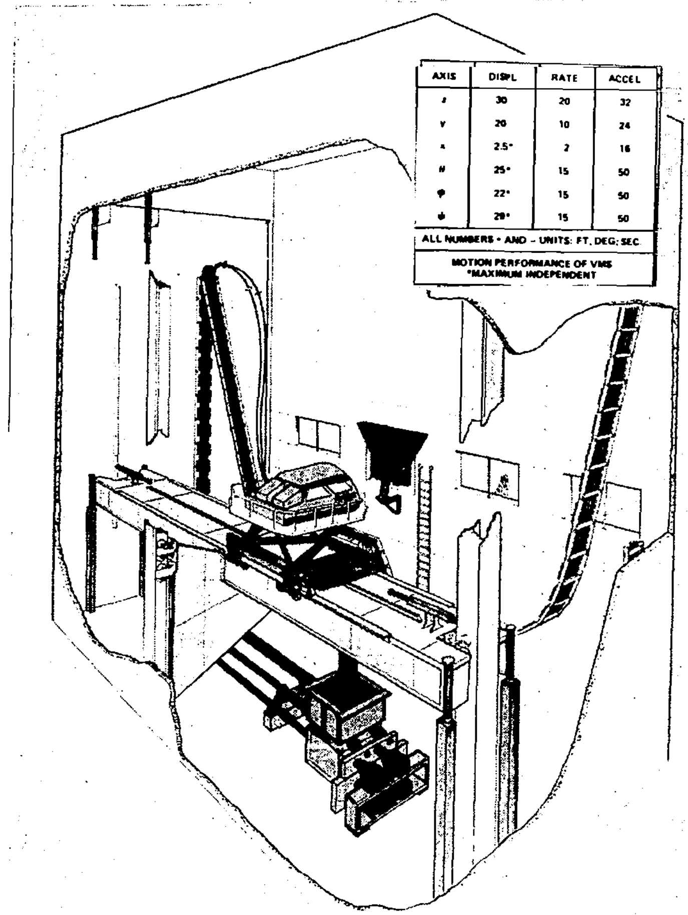


Fig. 5 Flight Simulator for Advanced Aircraft.



AXIS	DISPL	RATE	ACCEL
z	30	20	32
y	20	10	24
x	2.5*	2	16
θ	25*	15	50
ϕ	22*	15	50
ψ	29*	15	50

ALL NUMBERS + AND – UNITS: FT, DEG; SEC

MOTION PERFORMANCE OF VMS
*MAXIMUM INDEPENDENT

Fig. 6 Vertical Motion Simulator.

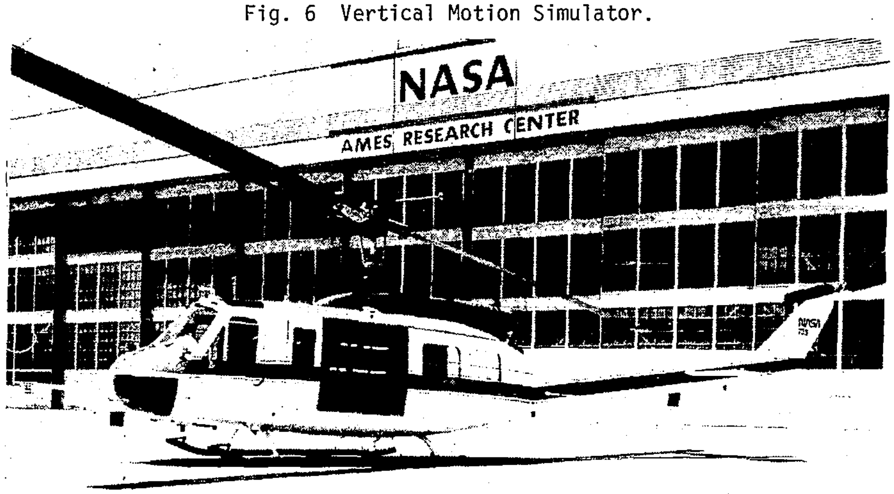


Fig. 7 UH-1H V/STOLAND helicopter.

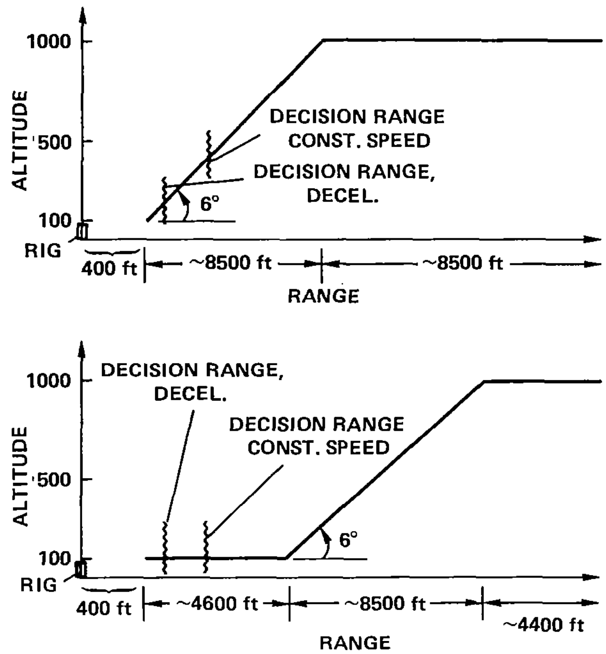
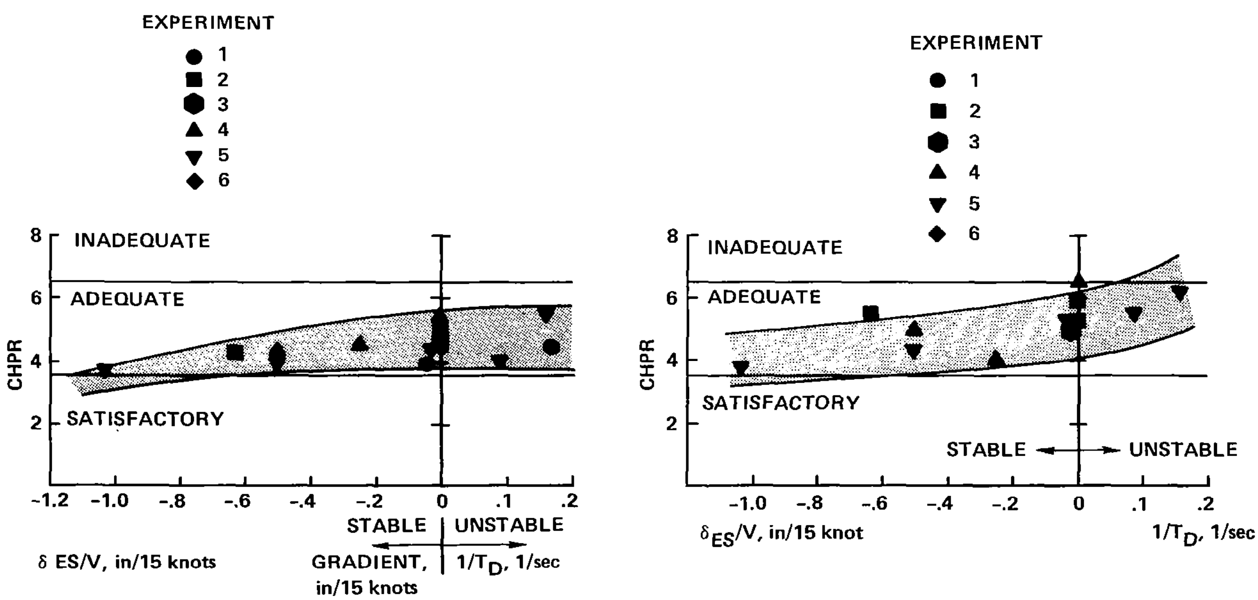


Fig. 8 Approach profile geometries.



(a) No turbulence, no flight directors.

(b) In turbulence, no flight directors.

Fig. 9 Pilot rating data as function of longitudinal stick gradient.

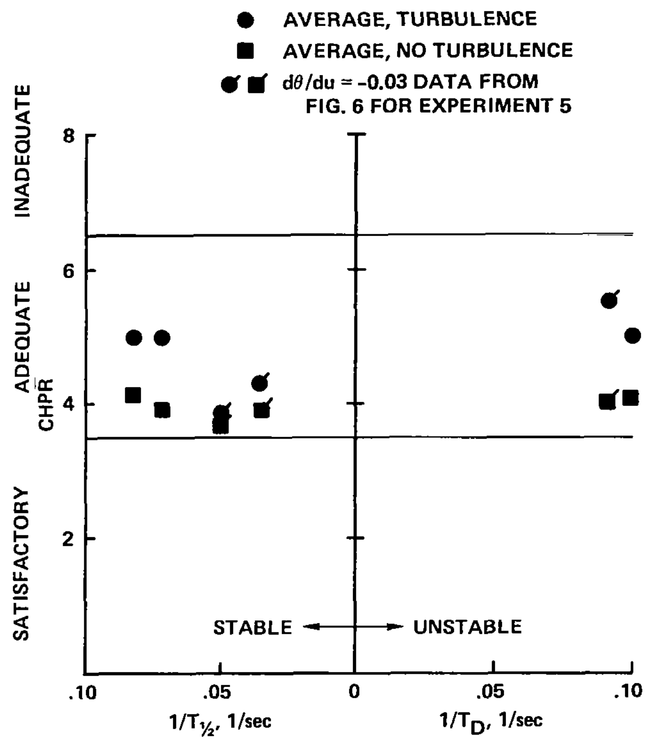


Fig. 10 Influence of dθ/du = -0.33°/knot (from Experiment 5).

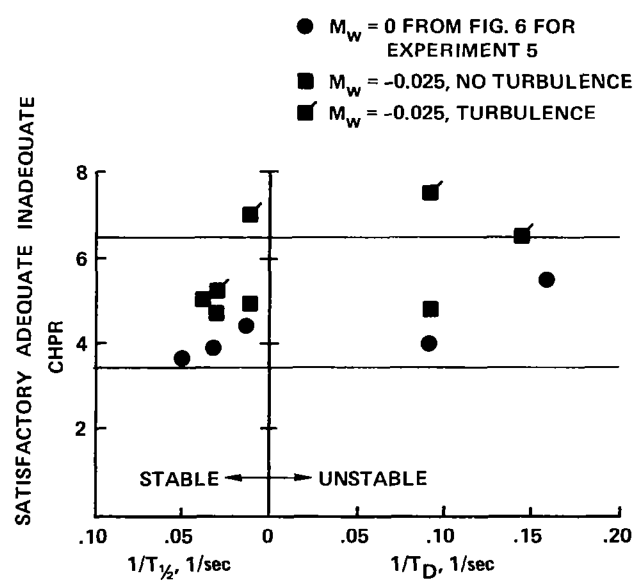
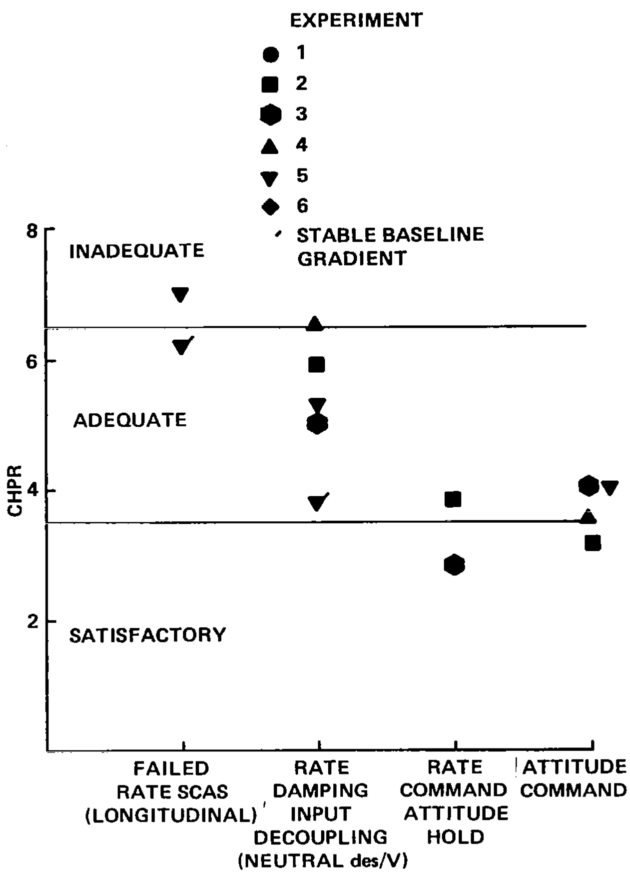
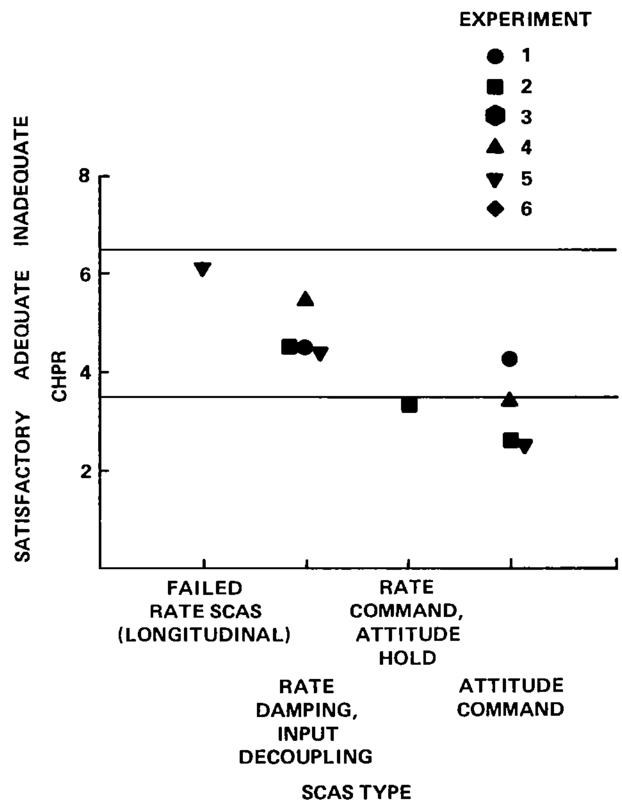


Fig. 11 Influence of M_w = -0.025 (from Experiment 5).



(a) No turbulence, no flight directors.



(b) In turbulence, no flight directors.

Fig. 12 Influence of SCAS.

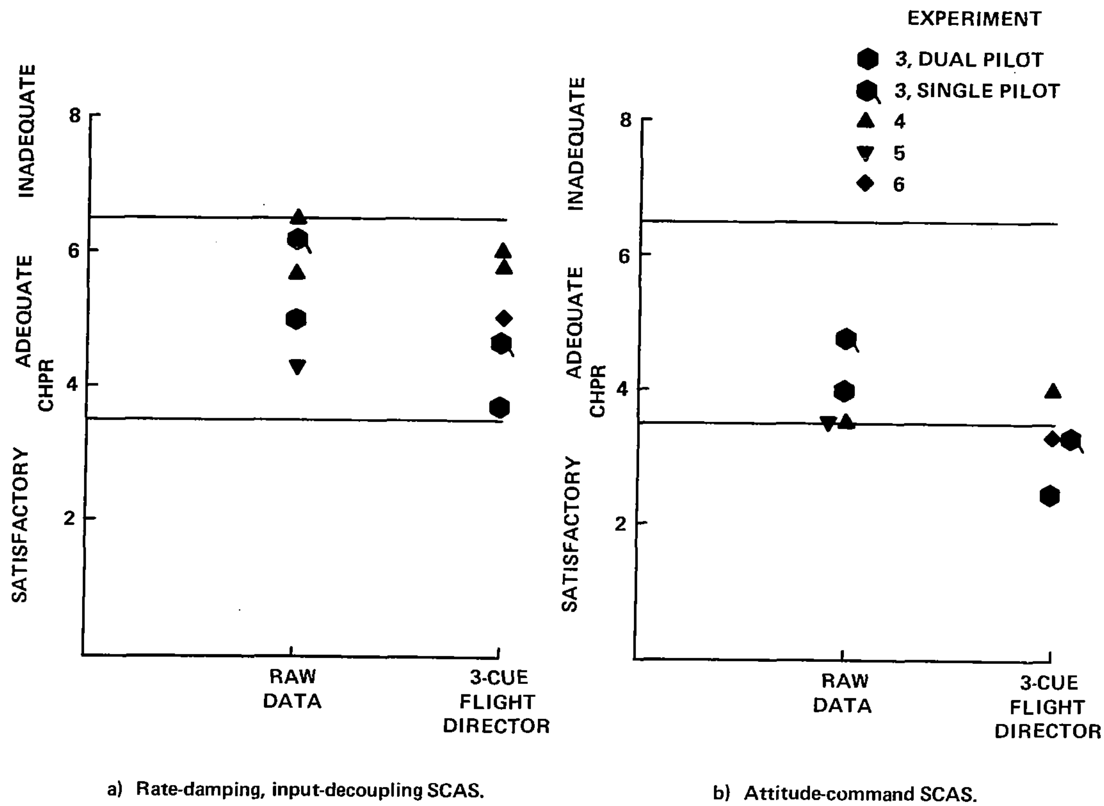


Fig. 13 Influence of three-cue flight director: in turbulence, dual pilot.

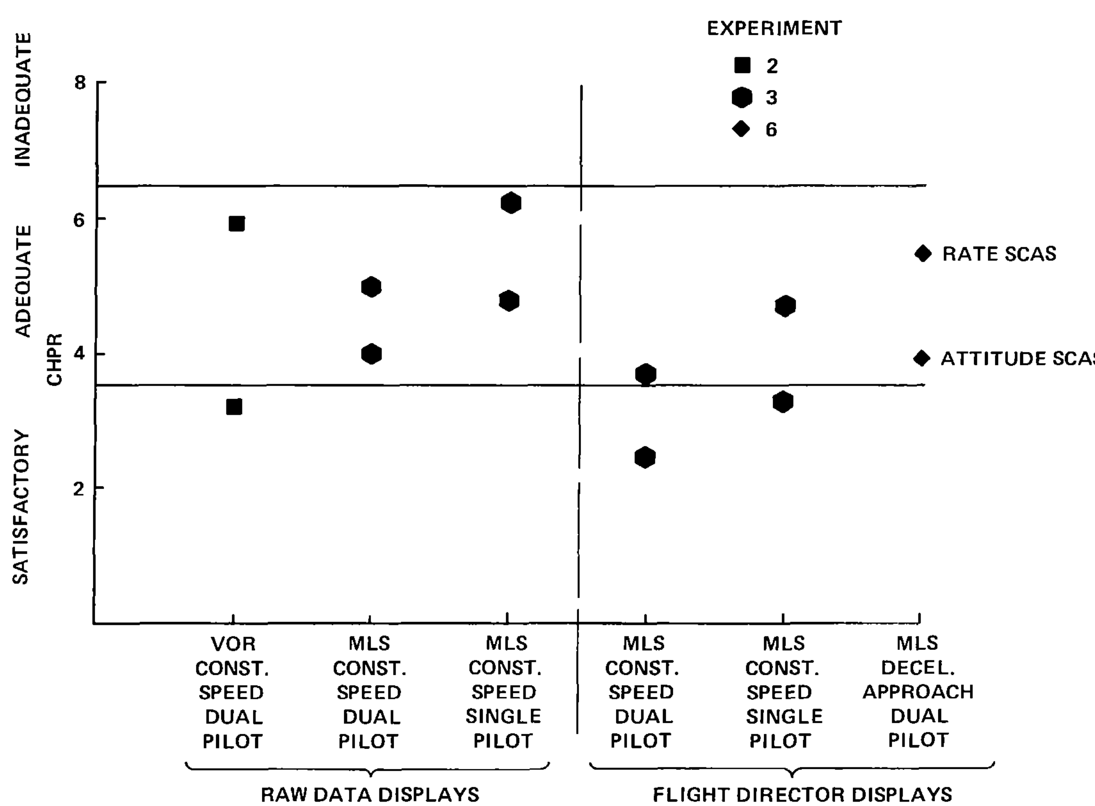


Fig. 14 Influence of task: in turbulence.