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ROTORCRAFT HANDLING-QUALITIES DESIGN CRITERIA DEVELOPMENT

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SUMMARY

Handling qualities are those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform those flight tasks required in support of an aircraft mission. These qualities include not only the basic vehicle stability and control characteristics but also the displays and controllers that comprise the pilot-vehicle interface. Joint NASA/Army efforts at Ames Research Center to develop rotorcraft handling-qualities design criteria began in earnest in 1975. At that time, primarily because of the need to simulate Army missions embodying the new doctrine of nap-of-the-Earth (NOE) operations and the emergence of Ames as the lead rotorcraft research center for NASA, the development of both ground-based and flight research facilities was intiated. Notable results of this effort were the UH-1H VSTOLAND variable stability helicopter, the VFA-2 camera-and-terrain-board simulator visual system, and the generic helicopter real-time mathematical model, ARMCOP. Using these facilities, an initial series of handling-qualities studies was conducted to assess the effects of rotor design parameters, interaxis coupling, and various levels of stability and control augmentation. In addition, the effects of the format and dynamics of electronic display symbols were investigated for NOE tasks conducted during night and adverse weather conditions.

Further improvements in the capability for rotorcraft handling-qualities research occurred in 1979, when the Vertical Motion Simulator became operational, and in 1982, with the addition of a multiwindow, computer-generated-imagery visual system. Using these new facilities, many noteworthy research efforts were, and are continuing to be, conducted. Included among these are investigations of the effects of side-stick controllers, roll-control requirements, directional-control requirements, and requirements for helicopter air combat agility and maneuverability. The capability of the current research facility to conduct moving-base simulations of near-terrain helicopter air combat is unmatched and is critical for this newly defined mission.

The ability to conduct in-flight handling-qualities research has been enhanced by the development of the NASA/Army CH-47 variable-stability helicopter. This

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facility allows the investigation of a wide range of control response and electronic display characteristics in the actual flight environment. Research programs conducted using this vehicle include vertical-response investigations, hover augmentation systems, and the effects of control-force characteristics.

The handling-qualities data base created by these and other experimental programs was judged to be sufficient to allow an update of the military helicopter handling-qualities specification, MIL-H-8501. That effort was intiated in 1982 and, by December 1985, a version was ready to be included as part of the request for proposals for the new Army Family of Light Helicopters, LHX.

This report summarizes these efforts, including not only the in-house experimental work but also contracted research and collaborative programs performed under the auspices of various international agreements. The report concludes by reviewing the topics that are currently most in need of work and the plans for addressing these topics.

INTRODUCTION

Handling qualities are "those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of the aircraft role" (ref. 1).

Handling qualities may, therefore, be thought of as being a measure of the degree to which the pilot is able to exploit the aircraft's inherent performance potential, with acceptable workload and training. The effect of inadequate handling qualities is less obvious than is an error in structural limit and weight or drag estimation. This situation occurs because handling-qualities involve the ability of the pilot to perform certain mission tasks, and pilots are very adaptable; moreover, the performance requirements for mission tasks are usually ill-defined. Thus, the tasks may still be performed even though the pilot is overworked and, perhaps, only marginally in control. Such shortcomings manifest themselves as high accident rates (pilot error is the most common cause of accidents), pilot fatigue, and excessive training required to develop and maintain proficiency.

A more obvious example in which better handling-qualities design capabilities may have avoided a problem is the redesign of the AH-64 Apache empennage from a T-tail to a low-mounted, horizontal stabilizer late in the development program. Similarly, better criteria and simulation capabilities may have avoided potential problems with the UH-60 Black Hawk stabilator, which even now is undergoing design changes. High-performance fixed-wing aircraft are replete with handling-qualities problems discovered at or after first flight, even though the data supporting fixed-wing handling-qualities criteria and specifications are better defined than they are for rotorcraft.

Many modern rotorcraft missions involve flight close to the ground or near obstacles such as ships. These missions demand a continual precision of control that is necessary in other aircraft only during takeoff and landing or in formation flight. To perform these missions, the outside world has to be visible at all times, and yet the user wants to operate in poor weather and at night. As a result, vision aids have to be used, and, since it will be many years before vision aids provide anything close to the fidelity of looking out the window in visual meteorological conditions (VMC), the visual cues can be expected to be degraded and therefore to have a major effect on handling qualities.

Many of these low-altitude, low-speed mission tasks are performed relative to some ground-fixed reference, so even a constant wind is a complicating handling-qualities factor. Local objects, such as buildings, trees, or hills can disturb the airflow to make the task even more difficult. Another unique mission capability of rotorcraft is their ability to carry slung loads. This introduces many complications to the overall handling-qualities task. These mission characteristics not only make helicopter handling qualities very demanding and critical to mission accomplishment, but also very difficult to reproduce in a simulator for research, development, or training.

In addition to the missions performed by rotorcraft, the vehicles themselves have many unique characteristics with implications for handling-qualities needs and criteria development. Because of their complex aerodynamics, they are exceedingly difficult to represent mathematically for accurate analysis and simulation. For example, there are complex interactions between the main and tail rotors. When flying at low speed, the low dynamic pressure means that small perturbations in flight direction or wind can have large effects on the rotorcraft forces and moments. The kinematics are more predictable but still highly complex. The overall result is that considerable cross-coupling exists between longitudinal and lateral directional axes (pitch-to-roll, collective control to yaw, etc.); responses to control and disturbances are nonlinear, so that response to control is different to the left than to the right; and the responses change nonlinearly with the size of the disturbance. In addition, many of these effects are frequency-dependent.

Another ramification of these complexities that is important for handling qualities is the multiplicity of limits that the pilot has to observe. These limits tend not to be unique. For example, normal load-factor limit depends on the mix of longitudinal cyclic and collective control used to induce the load-factor excursion. Many limiting parameters are difficult to sense, and few limits are indicated to the pilot. As a result, pilots tend to give dangerous limiting conditions a wide berth so they stay well within the available performance envelope instead of exploiting the rotorcraft's full potential.

Finally, the critical factor in handling qualities, the pilot, is subjected to a unique environment of high noise, high vibration, and extreme temperatures. As a result, most old helicopter pilots are hard of hearing and have bad backs.

Methods of achieving good handling qualities are indicated in figure 1. Clearly, the cost of making any changes to correct deficiencies increases as the aircraft moves into the later development stages, so handling-qualities criteria and specifications significantly affect development cost. Handling-qualities criteria and specifications can provide the following capabilities:

1. The ability for the Department of Defense (DOD) and the manufacturers to make intelligent, informed design trade-offs during aircraft design and development.

2. A central source of design guidance when the data are documented and compiled in a handling-qualities specification. This will help avoid repeating past mistakes each time a new aircraft is developed or an existing aircraft modified.

3. A method for DOD agencies to effectively monitor, guide, or evaluate the manufacturer's research and designs.

The current helicopter handling-qualities specification, MIL-H-8501, was written in 1952 with a minor revision in 1961. It has long been recognized as obsolete (refs. 1, 2). Table 1 indicates the primary deficiencies of MIL-H-8501 and also summarizes the characteristics of other proposed specifications. Despite these shortcomings, MIL-H-8501 is still being used for testing by the flight-test community; yet, it is ignored for mission-suitability assessment. A new specification is essential.

In 1975 the Army recognized these specification deficiencies and, in collaboration with NASA, started a major effort to develop a data base and design criteria that could eventually be integrated into a new specification. By 1982, sufficient progress had been made to justify initiating the development of a new specification. Army responsibility for helicopter specifications rests with the Aviation Systems Command (AVSCOM) Directorate of Engineering, but the effort to generate the new specification is being led by the Aeroflightdynamics Directorate of ARTA, with help from Ames Research Center. The work is monitored by a Technical Review Committee having representation from Army user organizations; Army test organizations; the Navy, through the Naval Air Development Center and the Naval Test Pilot School; the Air Force Wright Aeronautical laboratories; and the Federal Aviation Administration (FAA). Manufacturers have been involved at every step. A version oriented at LHX was developed and adopted by AVSCOM as an Airworthiness Design Standard (ADS-33) in December 1985. This standard was distributed with the LHX draft request for proposals in 1986. Since that time, efforts have been made to expand its coverage to other types of helicopters so that it can become a credible generic specification.

The purpose of this report is to review these Army/NASA efforts in rotorcraft handling qualities. First, the development of major ground and flight-research facilities is described; then ground-based and flight-based research are reviewed. The ground and flight research sections are divided into two parts: tasks conducted in VMC and tasks conducted in instrument meteorological conditions (IMC) or in night conditions for which displays and vision aids play a large role. Finally, the status of these efforts in providing a data base for the specification is assessed, and recommendations for future rotorcraft handling-qualities research are provided.

GROUND-BASED AND IN-FLIGHT SIMULATION FACILITIES

Ground-Based Simulation Facilities

In order to conduct handling-qualities research in an efficient and safe manner, a necessary element in the approach to that research is the use of ground-simulation facilities. These facilities can be very productive sources of handling-qualities data, and their use is mandatory for investigations of handling qualities under hazardous conditions such as exist at night, during adverse weather, or with equipment failures. However, the validity of these data is heavily dependent on the fidelity of the various components of the simulation environment, including the vehicle mathematical model, the system used to provide the visual cues from the outside world, and the cockpit motion simulation.

Over the past decade, a significant number of rotorcraft handling-qualities investigations, many of which are summarized herein, have been conducted using the Ames ground-simulation facilities. The requirements for these and other research programs have provided the impetus for continuing improvements in the piloted simulation capabilities at Ames. This capability to perform rotorcraft simulation has progressed from the use of fixed-base facilities with limited field-of-view, low-resolution, camera-and-terrain board visual systems to simulators with limited cockpit motion capabilities and later to large-amplitude, moving-base simulators with wide field-of-view, high-resolution, computer-generated visual displays. This progression is illustrated by the following summary of the attributes of three of the major Ames moving-base simulator facilities which have been heavily utilized in rotorcraft handling-qualities experimental research programs. A more detailed discussion of rotorcraft simulation technology at Ames is contained in reference 3.

The Six-Degree-of-Freedom Motion Simulator (fig. 2) became operational in 1964. Although the translational motion of this facility is limited to an 18-ft cube, it is an extremely useful tool for the investigation of precision hover handling qualities. In the cab configuration illustrated in figure 2, the pilot is provided with real-world visual cues, and the motion system is set up to reproduce the actual motions of the simulated aircraft within the physical limits of the motion system. Investigations of handling-qualities requirements for hover translational rate command systems have been conducted in this configuration. Alternatively, the cab may be covered, the motion system software altered, and visual cues provided by a single, black-and-white, TV monitor (fig. 3). This cab configuration was used in an investigation of control and display requirements for a night and adverse weather attack helicopter mission. In this experiment, the source of the visual cues was a camera-and-terrain board visual system suitable for NOE flight simulation. Superimposed on the terrain board imagery were selectable sets of symbols generated by a computer graphics system.

In 1969, the Flight Simulator for Advanced Aircraft (FSAA) became operational (fig. 4). This facility was orginally designed for fixed-wing aircraft research and includes a capability for high-fidelity lateral motion cueing -- a total of 80 ft -- for the simulation of sideslip during landing approach or engine failure during takeoff. Much of the initial work on NOE handling qualities and FAA rotorcraft certification requirements for IFR flight was conducted on this facility. Fundamental limitations of the FSAA for rotorcraft research simulations were the restricted field of view associated with the simulator visual system -- approximately 34° by 48° -- and the limited fidelity of the vertical motion cueing caused by the 8 ft of available vertical travel.

As a direct result of the burgeoning requirements for improved-fidelity rotorcraft simulations, the Vertical Motion Simulator (VMS) was designed and developed (fig. 5). Its 60 ft of available vertical travel allows an extremely high level of fidelity in vertical motion cueing. By rotating the cab about its vertical axis, the experimenter may tailor the motion system capabilities in the longitudinal and lateral axes to his own requirements; the available 40 ft of travel has been used in the lateral axis for experiments that evaluate the use of sideslip in air combat, for example, or in the longitudinal axis for investigations in areas such as the potential benefits of thrust-vector control for NOE flight. In addition, a wide-field-of-view, four-window, high-resolution, computer-generated-imagery system provides a significant improvement in the ability to supply the pilot with a compelling visual environment. One of the four visual channels may be used to represent the view from an independent eye point, thus allowing the simulation of an opponent aircraft in air combat or the representation of the image from a remote sensor. Since it became operational in 1979, the VMS has supported simulations of rotorcraft such as the UH-60 Black Hawk, the Rotor Systems Research Aircraft, the XV-15 and V-22 tilt-rotor aircraft, and the X-Wing. Simulated mission tasks include NOE flight, touchdown autorotations, shipboard landings, landing approaches to oil rigs, terrain-following/terrain-avoidance, and helicopter air combat.

Although marked improvements have been made in the ability to simulate rotorcraft flight in the near-Earth environment, it will likely never be economically feasible to duplicate that flight environment. Significant simulation deficiencies for handling-qualities research still exist. These shortcomings, which include items such as visual system computational-time delays and dynamic mismatches between simulated and real-world motion cues, cast some doubt on the absolute validity of handling-qualities data generated solely in piloted simulations and make mandatory the use of in-flight simulation using variable-stability rotorcraft to verify the simulation results. In addition, these research aircraft may be used as tools to assist in the efforts to improve the fidelity of rotorcraft simulation. Ground- and in-flight simulation, therefore, must be considered as integral elements of experimental handling-qualities research.

In-Flight Simulation Facilities

For experimental handling-qualities research, the validation of results from ground-based facilities in the actual flight environment is considered to be of fundamental importance. This requirement implies, for generic research not tied to a specific vehicle, that a flight facility with variable stability, control, and display capabilities be developed and used as an integral research tool. This need has been filled for the NASA/Army handling-qualities research primarily by two vehicles: the modified UH-1H and the modified CH-47B helicopters.

The UH-1H helicopter was modified to provide an in-flight simulation capability by adding an avionics system called VSTOLAND (fig. 6). 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. A block diagram of the system components is shown in figure 7; a more complete description of the system capabilities is given in references 4 and 5.

The flight-control portion of the VSTOLAND 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, retains the standard UH-1H cyclic and cockpit instruments. Handling-qualities experiments are conducted in the research mode, with the software providing a set of flight-control laws with variable gains. A schematic diagram of one such control-law channel is shown in figure 8 to illustrate the operation of the system.

Although suitable for generic investigations of configurations not too dissimilar to that of a UH-1H, the VSTOLAND UH-1H implementation using limited-authority series servos, in combination with flight envelope restrictions imposed by the teetering rotor system and control authority of the basic machine, resulted in insufficient research flexibility to examine a broad range of rotorcraft flight-control and handling-qualities issues. Accordingly, the CH-47B, orginally modified for the TAGS program (ref. 6) and subsequently used by NASA Langley for terminal-area investigations (ref. 7), was further modified and extended for NASA/Army handling-qualities and flight-control research at Ames

The CH-47B (fig. 9) is equipped with full-authority, electrohydraulic actuators in each of the four control axes: differential collective (pitch), lateral cyclic (roll), differential lateral cyclic (yaw), and collective (heave). These actuators receive position commands generated by control laws that are programmed in on-board digital and analog computers. Their output motion is transmitted to the flight-control system of the basic CH-47B through electrohydraulic rotary clutches, thereby causing the safety pilot's controls to move in parallel. Downstream from these clutches and their associated mechanical linkages, there are essentially no modifications to the basic flight-control system of the standard production CH-47B. Figure 10 shows the implementation of the electronic control system (ECS) for a typical axis. Electric control inputs from the evaluation pilot's controls (center-line or side-stick) are combined in the flight computers with data from the motion sensors to generate commands to the parallel ECS actuators that drive the basic CH-47B flight-control system.

The various controls, displays, sensors, and computers that make up the research system are shown schematically in figure 11. The CH-47B is equipped with a Sperry 1819A minicomputer; a Digital Equipment Corporation PDP 11/73 microcomputer;

and an Electronic Associates, Inc. TR-48 analog computer. To support instrument-flight tasks with the aircraft, a Sperry Flight Systems color electronic attitude director indicator (EADI) is also installed. Finally, unlike the UH-1H, the evaluation pilot's center stick has been modified to incorporate a programmable artificial feel and trim system manufactured by the Calspan Corporation; a right-hand, four-axis, small-displacement side-stick controller is also available for use in selectable combinations with the existing conventional collective and pedal controllers. A complete description of the facility is given in reference 8.

GROUND-BASED EXPERIMENTAL RESEARCH

Visual Meteorological Conditions

The major initial focus of the rotorcraft handling-qualities research performed by NASA and the Army was to ascertain requirements for near-terrain and NOE flight in visual conditions. The need for these new requirements resulted from evolving Army doctrines that emphasize low-level flight to enhance mission survival and effectiveness, and it was recognized that the existing data base was entirely inappropriate for the new tasks that were envisaged. Accordingly, a series of analyses, piloted ground-based simulations, and flight experiments involving terrain-flying tasks and low-altitude tactical missions was initiated.

Studies and experiments designed to examine the effect of aircraft design parameters, interaxis coupling, and levels of stability and control augmentation on the handling qualities and man-machine performance of the low-level flying tasks in VMC were performed initially to provide generic design information (refs. 9-15).

The first visual terrain-flight experiment was conducted on a fixed-based simulator to explore the effects on the handling characteristics of basic single-rotor helicopters of large variations in rotor design parameters, such as flapping-hinge offset, flapping-hinge restraint, blade inertia (or Lock number), and pitch-flap coupling (ref. 9). In the second ground-based simulation experiment, representative configurations from the first experiment were evaluated on a moving-base simulator (the FSAA) to examine the effect of motion cues (ref. 10) and the effects of various levels of stability and control augmentation (ref. 11). A more sophisticated stability and control augmentation system (SCAS) was also synthesized, using linear optimal control theory to meet a set of comprehensive performance criteria (ref. 12). This system, designed expressly for a hingeless-rotor helicopter, was subsequently evaluated in the third piloted ground-simulator experiment on the FSAA. A flight experiment (ref. 13) was conducted on the variable-stability UH-1H/VSTOLAND helicopter to verify some selected configurations from the first two ground experiments, to explore additional configuration variations, and to investigate the effect of field of view on helicopter handling qualities for NOE operations. To relate directly some of the results of these handling qualities experiments to the design parameters of the helicopter, an analytical study was conducted to develop a design rule for the selection of some primary rotor parameters to decouple the longitudinal and lateral motions of the helicopter (refs. 14, 15).

Taken together, these experiments provide a significant design data base concerning the influence of basic helicopter characteristics on pilot acceptance of near-terrain tasks. For example, the influence of coupling from the collective control into pitch and yaw is illustrated for a hingeless rotor helicopter in figure 12; the importance of reducing these couplings can be seen by the improvement of the Cooper-Harper ratings (ref. 17) to "satisfactory" as the couplings are reduced. Similar results were obtained from experiments concerning pitch-roll coupling resulting from aircraft angular rate. In particular, a criterion with respect to the ratio of the roll moment caused by pitch rate to that caused by roll rate and design procedures to minimize this coupling were developed. Recent studies are expanding this information to include limits on the frequency dependency of the coupling (ref. 18).

Following this initial series of experiments that focused on design parameters, more specialized experiments were directed at particular responses of concern. The effects of thrust-response characteristics on rotorcraft handling qualities have been and are being investigated in both ground- and in-flight simulation programs at Ames. Thrust response to the pilot's collective inputs is a complex function of engine-governor dynamics, rotor inertia effects on energy stored in the rotor, excess thrust available, and aircraft vertical damping. A multiphase program is being conducted to study these effects on helicopter handling qualities in hover and during representative low-speed NOE operations. Three moving-base piloted simulations have been conducted on the VMS to provide critera and substantiating data for the updated MIL-H-8501 specification (refs. 19, 20). The results of these investigations are summarized in reference 21.

Based on these experimental results, the proposed vertical-axis requirements include criteria for the time-constant of the altitude rate response to collective input, the shape of that same response, rotor angular speed limits, and vertical control power. The current VMS investigation focuses on three concerns associated with the proposed criteria: (1) conservative vertical damping requirements, (2) conservative control power requirements, and (3) the effects of the shape of the altitude-rate time-response to a collective input. Preliminary results indicate that, when the pilot has sufficient time to perform a bob-up task, satisfactory handling qualities are achieved with very low values of vertical damping (fig. 13); results from a dolphin task also support the need to relax the proposed boundaries. Similarly, the effects of low values of control power are only apparent when the constraints on time required to perform the maneuver are severe. The results from the investigation of the effects of the shape of the alititude-rate response generally support the current requirement but indicate a strong dependence on the details of the task being performed.

Another response-oriented major shortcoming in the current handling-qualities data base is the lack of roll-control effectiveness criteria. This fundamental requirement has a major effect on the basic design of a helicopter. Analyses and two VMS simulations have been conducted to determine a systematic approach to specifying roll-control effectiveness requirements for maneuvering (ref. 22). The results of this program showed that control power requirements can be relaxed for large-amplitude maneuvers such as are required in air combat, and that satisfactory handling qualities are obtained when a sufficiently large margin exists between vehicle performance capability and the requirements of the task. The short-term roll response of the vehicle, determined by rotor stiffness and control-system characteristics and expressed as bandwidth, has a significant effect on handling qualities and performance; this effect is a strong function of task demands (fig. 14).

To compensate for a similar lack of mission-oriented handling-qualities data, a piloted simulation was conducted (ref. 23) to evaluate the effects of the following on the handling-qualities characteristics of various generic rotorcraft configurations including tilt-rotor, coaxial rotor, and no-tail-rotor designs: (1) mission task requirements, (2) basic yaw sensitivity and damping, and (3) directional gust sensitivity. The results of the experiment indicate that rotorcraft configurations with high directional gust sensitivity require more yaw damping to maintain satisfactory handling qualities during NOE tasks. Both yaw damping and control-response characteristics are critical parameters in determining handling qualities for an air-to-air target-acquisition and tracking task. Loss of directional control can occur at low airspeeds under certain wind conditions in which yaw damping is low and gust sensitivity is high.

The characteristics of the controllers to effect these vehicle responses are also important; they are highlighted by the recent trend toward side-stick controllers with multi-axis functions. The first real rotorcraft application of these new controllers was the U.S. Army's Advanced Digital/Optical Control System (ADOCS) program. For this program, a series of piloted simulations was conducted both at the Boeing Vertol facility and on the VMS to assess the interactive effects of side-stick controller (SSC) characteristics and stability and control augmentation on handling qualities (ref. 24). An initial experiment revealed that angular rate stabilization in pitch and roll was sufficient to provide satisfactory handling qualities when a two-axis SSC was used for control of these axes; however, when a rigid three- or four-axis device (which added directional and directional-plus-collective control, respectively to the SSC) was used, attitude stabilization was required to maintain adequate handling qualities (ref. 25). These results were substantiated and expanded upon by the experiment reported in reference 26, which demonstrated that a four-axis, small-deflection SSC yielded satisfactory handling qualities for NOE tasks when it was integrated with a SCAS that incorporated higher levels of augmentation; however, separated controllers were required to maintain satisfactory handling qualities for the more demanding control tasks or when reduced levels of stability and control augmentation were provided (fig. 15).

A summary of the effects of SSC characteristics on terrain flight handling qualities based primarily on the ADOCS results is contained in reference 27. The general approach to these experiments provided the basis for the structure of the proposed updated version of MIL-H-8501 according to control-response types. In addition, the results of this program have had a significant effect on the types of control systems and cockpit controllers currently being developed for the candidate LHX designs in the Advanced Rotorcraft Technology Integration program.

Very recently, the use of rotorcraft in the air-to-air combat environment has become a major new mission requirement for future vehicles. To define handling-qualities capabilities that are necessary for this new role, the Army and NASA initiated modifications to the VMS facility that would permit simulations of air-to-air combat in the near-terrain environment, with good duplication of both visual and motion cues. The initial experiment emphasized the development of this facility capability and included an initial investigation of generic influences of rotor type and stability/control augmentation (ref. 28).

On this basis, the second experiment included a systematic investigation of maneuvering envelope size (normal load factor, sideslip) and directional axis dynamics, using a simplified generic helicopter model (ref. 29). Figure 16 illustrates the aggregate use of sideslip and normal acceleration envelopes in this experiment for three levels: one representative of an AH-1, one of a UH-60, and one expanded for a projected new helicopter LHX. These results indicate that a lower load-factor limit of -0.5 g may be adequate--a value lower than -1.0 g was never achieved. One design implication, of course, is that rotor systems that do not permit any negative g are not suitable for this role. In addition, maximum load factors greater than that achievable with present helicopter designs were often used by the pilots, and the limits presented to the pilot were at times exceeded for all of the configurations. Automatic envelope limiting may be required to use an expanded capability successfully. It was also found that the most successful pilots used aircraft sideslip performance to signficant advantage, with an evelope representative of current utility helicopters being adequate; a potential trade-off of this characteristic with a turreted gun will be examined in an upcoming experiment.

In addition to experiments aimed at defining specific handling-qualities characteristics, such as those described above, more general investigations have been conducted which both exploit and examine the ability of ground simulation to address questions that might be difficult to deal with in flight. One example is the study of autorotation requirements and the simulator capabilities required to investigate this flight phase (ref. 30). Among the variables considered in the experiment was the level of vertical-motion cueing being provided in the simulation; four values ranging from fixed-base up to the full ability of the VMS were investigated.

Figure 17 shows representative plots of collective control use as a function of allowable vertical-axis travel for one pilot. In general, this pilot exercised the proper control technique with the full VMS motion. As the motion performance degraded, the pilot's collective technique changed. Many landing flares with degraded motion performance showed signs of ballooning, stair-stepping, and overcontrol in the collective time-histories. Not all pilots were so affected, and even with full VMS motion, some pilots would show some of the poor control techniques illustrated in figure 17. However, the trend shown did occur for several pilots. It is suggested that, when the control technique used in the simulator is significantly different from that used in flight, confidence in simulator-based research results or in flight-training transfer is reduced.

The issues of transfer of training also become important in the new environment of single-pilot operations in high workload environments. With the exception of research for single-pilot IFR in the civil/FAA context (to be reviewed later in this paper), single-crew concepts had not been considered in helicopter flight-control research. However, the advent of the Army's desire for a single-crew scout/attack helicopter called Light Helicopter Family (LHX) puts more emphasis on single-crew workload. In such a situation, the pilot has to not only control the flight path of the rotorcraft but also perform innumerable other tasks associated with navigation, communications, and threat avoidance or attack. Two experiments, Single Pilot Advanced Cockpit Engineering Simulation (SPACES I and II), were performed on the VMS to investigate these effects (ref. 31). The objective was to determine the SCAS configuration that, when combined with appropriate cockpit displays and controls, would allow adequate mission performance.

The simulation used a highly integrated glass cockpit with helmet-mounted displays, multi-axis side-stick controllers, voice input/output (I/O) systems, moving map displays, programmable switching, sophisticated sensors and detectors, and limited artificial intelligence (expert systems) to improve pilot-vehicle performance.

These tests showed that superimposing the mission management tasks on flight-path management tasks results in degraded handling qualities. Of the configurations investigated, only the SCAS with heading, altitude and airspeed hold, plus turn coordination was rated satisfactory (Level 1) by Army test pilots for single-pilot NOE flight operation at tested conditions. Each axis was augmented sufficiently so that attention to flight-path tasks could be reduced, allowing additional time for accomplishment of mission management tasks.

For two reasons, the pilots considered altitude hold to be the single most important feature in NOE flight: (1) it allowed the pilot to use his left hand for mission management tasks, and (2) it provided terrain avoidance when the pilot could not constantly monitor altitude because of other duties.

Instrument Meteorological Conditions

The requirement that rotorcraft operations be conducted at night and under other conditions of limited visibility has given impetus to research programs designed to investigate the interactive effects of vision aids and displays on handling qualities.

In a program conducted to support the development of the Advanced Attack Helicopter (AAH), various levels of stability and control augmentation together with variations in the format and dynamics of the symbols provided on the Pilot Night Vision System (PNVS) (fig. 18) were investigated in a piloted simulation (ref. 32). It was found that the handling qualities of the baseline control-display system were unsatisfactory and required improvement; recommendations for alterations to the PNVS symbol dynamics and the implementation of a velocity-command system for a hover/bob-up/weapon-delivery task were made to the Army AAH program manager. The velocity-command type of control system was subsequently incorporated into the AH-64 flight-control systems as a selectable hover augmentation system. The approach taken in the design of this experiment heavily influenced the methods used in the ADOCS simulator investigations and the structure of the control laws designed and investigated in those experiments.

An investigation involving the simulation of a less complex night vision aid was conducted to support the Army Helicopter Improvement Program (AHIP) (ref. 33). In that simulation, the effects of presenting the PNVS flight symbols on a panel-mounted display (PMD) versus a head-up display (HUD) were compared for a nighttime scout helicopter mission in which the pilot was provided with night-vision goggles. As a consequence of the experimental results, the OH-58D now includes a pilot's HUD which provides information complementary to that which is available on the instrument panel.

The state-of-the-art night-vision system for combat helicopters includes a visually coupled helmet-mounted display of infrared imagery and superimposed symbols: the Integrated Helmet and Display Sight System (IHADSS) (fig. 19). This system was used in two simulator investigations designed to assess the effects of reduced visibility conditions on the ADOCS visual flight simulation results cited previously (refs. 34, 35). Significant degradations in handling qualities occurred for most tasks flown with the IHADSS relative to the identical tasks flown under visual flight conditions (fig. 20). In general, higher levels of stability augmentation were required to achieve handling qualities comparable to those achieved for the visual flight tasks.

These simulation results have substantiated the highly interactive effects of vision-aid/display characteristics and control-response types on handling qualities requirements under IMC. In recognition of these effects, the proposed update to MIL-H-8501 incorporates a scheme for determining required control-response types based, in part, on the type and quality of the visual cues available to the pilot from vision aids and displays during IMC missions.

Research has also been conducted to ascertain IFR approach requirements for helicopters operating with simpler SCAS and display systems. This work has been aimed at both military and civilian instrument operating conditions and was performed as part of a joint NASA/FAA/CAA program. Six experiments were conducted; they had the following general objectives:

1. First experiment (ground simulation, ref. 36): 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 with VFR approaches.

2. Second experiment (ground simulation, refs. 36, 37): determine suitability of requirements on cockpit control position; examine efficacy of several SCAS concepts; and explore influence of turbulence.

3. Third experiment (ground simulation, ref. 38): 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, ref. 39): 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, ref. 40): 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, ref. 41): investigate SCAS requirements for decelerating instrument approach; explore influence of electronic display format; and examine influence of approach geometry and deceleration profile.

One set of results from these experiments is shown in figure 21, which compares Cooper-Harper ratings for similar stability and control characteristics and displays as a function of the task considered. It should be noted in particular that the difference between the dual-pilot and single-pilot task considered in experiment 3 resulted in a change of almost one pilot rating, justifying, in principle, a division of criteria depending on crew-loading. It may also be seen that a decelerating instrument approach leads to a reduced capability relative to constant-speed approaches; however, the use of appropriate augmentation and flight director displays still permits clearly adequate pilot ratings, with desired performance attainable. The results of this series of experiments have recently formed the basis for an FAA Notice of Proposed Rulemaking (ref. 42) in which the IFR criteria are modified to allow decelerating approaches.

Terminal-area research was also extended to the case of rotorcraft with a thrust-vectoring capability--specifically, tilt-rotors (ref. 43). This class of vehicles introduces a variety of additional operational and handling-qualities concerns to the terminal-area problem, revolving primarily around the change from aerodynamic to thrust-supported lift, or vice versa, and the effect of combinations of speed, descent angle, and thrust-vector angle (conversion corridor) during the conversion. In the experiment, variations in the conversion-corridor, handling-qualities coupling, and levels of SCAS and display assistance given to the pilot, were examined.

Some of the results are shown in figure 22, which illustrates the influence of visual conditions, SCAS type, and conversion procedure on Cooper-Harper pilot ratings. On the basis of these results, the general influence of the conversion profile is as follows. Performing all the conversion before glide-slope acquisition (profile A) led to nearly desired performance when an attitude SCAS was implemented and to a clearly adequate capability with a rate SCAS; this method, which allows glide-slope tracking in a fixed configuration, shows results that are generally consistent with those for helicopters. Performing part of the conversion before acquiring the glide-slope and part after acquiring it (profile B) led to degraded pilot ratings for instrument approaches, particularly with the rate SCAS. This degradation was due primarily to conversion-induced pitch and heave coupling. The advantage of performing part of the conversion early in the approach, allowed more time at a fixed configuration to get stabilized before breakout. Finally, performing all conversion while descending on the glide shope (profile C) was considered adequate in visual flight but marginally inadequate on instruments; there was little benefit from the attitude SCAS for instrument approaches. These results indicate the need for additional assistance in augmentation or display sophistication or both for a task in which the aircraft configuration is continually varying during a crucial period.

FLIGHT-BASED EXPERIMENTAL RESEARCH

The use of ground-simulation facilities affords a significant capability to examine efficiently a wide variety of handling-qualities problems, and the improved motion and visual cueing devices used in the NASA simulation facilities, as discussed earlier, provide reasonably high fidelity for several types of rotorcraft missions. Nonetheless, a fundamental requirement exists to validate simulator results in the flight environment, and a basic precept of the NASA/Army handling-qualities research program has been to conduct selected research experiments in flight.

Both of the extensive series of experiments discussed earlier investigating basic handling-qualities parameters in visual flight for near-terrain missions and control and display parameters for instrument operations in the terminal area included one flight-validation experiment using the UH-1H (refs. 44, 45). In the near-terrain experiment, the flight investigation concentrated on validating the influences of roll damping and control sensitivity for a slalom task. Figure 23 compares these flight results (labeled EXP IV) with ground simulation. Because of the limited inherent capability of the VSTOLAND UH-1H, the flight results are limited to one value of control sensivitity and a small range of damping. Nonetheless, the correspondence of flight and simulator data is generally good for this specific task. Similarly, figure 24 compares results from the flight-validation experiment (experiment 4) with ground-simulation data for the helicopter IFR program. Again, the correspondence is good for this task, particularly since one of the simulated configurations had baseline characteristics similar to those of the UH-1H (experiments 3, 5). For both of these relatively benign tasks, therefore, the flight experiments provided the validation necessary to extend the confidence region for the ground-simulation data.

As the demand for more capability from the helicopter/pilot system increases, however, limitations in simulator fidelity become of more concern, and the appropriateness of the UH-1H VSTOLAND as a valid flight research capability becomes limited because of the rotor design and the controls implementation. To address these concerns with flight validation, it has been necessary to use helicopters from other research facilities, as well as the NASA/Army CH-47B.

An initial example of the use of other facilities for flight validation of the NOE research was a collaborative effort with the German Aerospace Research Establishment (DFVLR) Institute for Flight Mechanics, which was conducted under the auspices of a memorandum of understanding between the U.S. Army and the German Ministry of Defense. In this experiment, unmodified UH-1D and BO-105 helicopters were flown over NOE slalom courses to assess the effects on handling qualities of basic rotor characteristics for this task and to provide correlation for the UH-1H VSTOLAND experiment results obtained previously (ref. 44). This flight program, documented in reference 45, demonstrated the superiority of the basic hingeless rotor system of the BO-105 when the task "bandwidth" was increased, thereby indicating the bounds of usefulness of the UH-1H VSTOLAND results. One outgrowth of this collaborative effort has been the development, in Germany, of a variable-stability BO-105 helicopter to provide a practical flight research platform for the more demanding tasks that are representative of current helicopter mission requirements.

Another in-flight simualtion facility is the Bell 205 operated by the National Aeronautical Establishment (NAE) of Canada. This facility is described in reference 46, and a summary of much of the handling-qualities research performed under contract to the Army is contained in reference 47. References 48 and 49 discuss some detailed results. One of the major issues of concern is that, for some tasks, such as precision hover, the ground-simulator results predict more stringent control-system requirements than are observed in flight. Figure 25 (from ref. 46) illustrates some preliminary results concerning this discrepancy. As can be seen, pitch/roll bandwidths of the order of 3.0 rad/sec were predicted to be required to achieve Cooper-Harper pilot ratings in the Level 1 region from VMS results, whereas an equivalent level of acceptability was found in the Bell 205 in-flight simulator for a bandwidth of only 2.0 rad/sec. Similar discrepancies appear to occur for vertical-axis dynamic characteristics (ref. 48). It is emphasized that some of these results are still preliminary; nonetheless, it is of fundamental importance to understanding the underlying reasons, and current research is beginning to address this problem (e.g., ref. 49). Clearly, it is also of fundamental importance to have an in-flight simulation capability as the research facility for use when ground-simulation data are suspect.

To assist in this regard, the NASA/Army CH-47B is currently used to provide flight validation of selected ground-simulation results. This aircraft serves as a complementary facility to the NAE Bell 205 and affords the capability of back-to-back comparisons with ground-simulation experiments conducted at the Ames facilities. Reference 50 describes a recent experiment to extend previous VTOL ground and flight-simulation results to the helicopter bob-up task; in addition, previous simulation helicopter bob-up configurations were implemented for flight evaluation. Figure 26 illustrates the comparison of flight and simulation results for different simulated engine-governor response characteristics. In general, the flight results yielded slightly improved pilot ratings as compared with those of the ground simulator, although the differences are not significant and are within expected rating scatter. The one large difference that occurs with the slow engine-governor indicates a possible unrealistic requirement for rpm monitoring present in the ground simulation.

Both the Bell 205 and the CH-47B flight results have had major effects on draft versions of the revised handling-qualities specification because of the reduced system requirements for a given level of pilot acceptance. Neither of these aircraft, however, has sufficient inherent levels of agility and maneuverability to address properly new tasks consistent with more demanding missions such as air-to-air combat. In addition, although they both incorporate some form of head-down electronic display, neither is currently equipped to examine the interaction of visually coupled (e.g., helmet-mounted) displays with various aircraft stability and control characteristics. For these new in-flight investigations, it will be necessary to develop a new rotorcraft in-flight simulator with increased agility and maneuverability.

RESEARCH CHALLENGES

One measure of the success of the Army/NASA rotorcraft handling-qualities efforts reviewed in the previous sections is the level of completeness of the proposed MIL-H-8501 (ref. 51), because the generation of this specification has been based largely on these results. Although the specification structure follows the philosophy generated for MIL-F-8785B and C, and used in MIL-F-83300, the details of the requirements are considerably different, many of the methods of specifying the requirements are different, and several innovations have been introduced. Most notable of these is the attempt to recognize and accommodate the effects of degraded visual cues resulting from using displays and vision aids at night and in poor weather; the specification requires different response types and different response bandwidths for near-Earth tasks in degraded visual cues.

The heart of the specification, of course, is the adequacy of the quantitative requirements. The specification is based largely on data from Army/NASA rotorcraft program experiments and from several programs of international collaboration at the NAE of Canada, the DFVLR, and the British Royal Aircraft Establishment. Currently, there are still many topics that have not been addressed because of a lack of data. In addition, some of the requirements rely on data that were generated on ground-based simulators with no flight validation. Because the magnitude of the task of generating the needed handling-qualities data is so large (fig. 27), full use must be made of ground-based simulators to do the broad parameter investigations. However, despite considerable investment in simulation facilities by NASA and the Army (refs. 52-54), the fidelity of current ground-based simulation for helicopter research in the region of low speed and hover limits the confidence with which quantitative handling-qualities boundaries can be developed. The predicted trends are usually representative, but because of sensory cue deprivation, the simulator often predicts worse handling qualities than exist in flight.

Figure 28 an example. It is suspected that the visual systems are to blame for deficiencies during small-amplitude maneuvering and that the limited-motion systems are the major contributors in more aggressive tasks. Unfortunately, though several efforts have been made to come to grips with this problem (refs. 49, 55-58), those studies have so far been unsuccessful, and currently there is no focused research effort to determine the basic requirements for an acceptable simulation of the low-speed and hover flight regimes.

Work needs to be performed on both the engineering fidelity, the primary ingredient of which is the mathematical model representing the rotorcraft, and the perceptual fidelity, the primary contributors to which are the visual and motion cues. Methods have to be developed for systematically assessing simulation fidelity and for improving deficient aspects. A major contribution toward improving engineering fidelity could be made by improving the interactional aerodynamic prediction methods which would result in improved simulation mathematical models. Better low-altitude atmospheric disturbance models are also required.

Although much can be achieved with ground-based simulators, for the foreseeable future there will still be a need for flight verification. Although some flight verification can be obtained by comparison with existing aircraft, there is a need for an in-flight simulator, or variable-stability rotorcraft, so that parameters can be varied systematically for a range of tasks and for new configurations as they evolve. Aside from the CH-47 variable-stability research helicopter at Ames Research Center, which is not agile enough and will have to be returned to the Army in 1988, there is no in-flight rotorcraft simulator available for basic research in the United States.

Because advances in ground-based and in-flight simulation tools benefit the designer also, all four major helicopter manufacturers have, or are developing, extensive helicopter simulator facilities as part of their Light Helicopter Family (LHX) pre-design efforts. They will be faced with the same problems of simulation validation that exist in the government. They need improvements in simulator fidelity to be able to use them as credible design tools. Training simulators suffer from similar problems. Both Black Hawk and Apache training simulators are known to have deficiencies that can induce a negative transfer of training.

Some of the topics that need more work are listed in table 2. Some have not been addressed at all; for example, slung loads, response to upsets as distinguished from response to control, multi-mode control blending and nonlinear control characteristics, and digital implementation of high-gain stability and control augmentation systems. Of the topics that have been addressed, and for which data are documented in the Background Information and Users' Guide (BIUG), are side-stick controllers, cross-coupling, and thrust-response dynamics and margins. The topics that need more work are broad-based and pervade the whole specification; for example, the effects of visual-cue degradation and the mission task element definition and performance benefits. Another class of topics needing work has to do with specific missions such as air-to-air combat; these include the uses of thrust-vectoring and maneuver envelope enhancement.

CONCLUSION

The foregoing reflects the dynamic character of rotorcraft technology. As the vehicle capabilities evolve, the mission complexity increases. When MIL-H-8501 was generated (1961 revision), helicopters were underpowered, unstable, and used sedate maneuvering in VMC. When the current Army/NASA research efforts to review this specification started (1975), the doctrine of NOE flying had evolved, with the concurrent need for high agility and maneuverability close to the ground. This requirement later evolved into NOE flight at night and in poor weather, thus bringing in different handling-qualities considerations. The latest evolving rotorcraft mission is that of air-to-air combat (1986). This mission raises agility and maneuverability needs and is clearly dominated by handling-qualities considerations. However, for certain mission requirements that have existed for years, such as shipboard recovery, the criteria are still not adequate; the desired all-weather operational capability has yet to be realized.

Although the work done on rotorcraft handling qualities in the last 12 years is a major contribution, much more remins to be done. The proposed update of MIL-H-8501 is a considerable advance over the existing MIL-H-8501A, but many deficiencies need to be addressed. It is hoped that in another 12 years we will have solved many of these problems, but it is also anticipated that rotorcraft missions and technology will have further evolved, thus providing more challenges to the handling-qualities community.

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TABLE 1.- CURRENT HELICOPTER HANDLING-QUALITIES SPECIFICATIONS

SPECIFICATION	DATE	APPLICATION	COMMENTS
MIL-H-8501	1952	HELICOPTERS	SPECIFICALLY HELICOPTERS SPARSE COVERAGE CRITERIA INADEQUATE FOR ARMY MISSIONS LACKS TREATMENT OF ENVELOPES AND FAILURES BASICALLY FOR VMC
MIL-H-8501A	1961	MINOR REVISION	
AGARD 408	1962	V/STOL	
MIL-F-83300	1970	V/STOL (AND HELICOPTERS USAF ONLY)	BROAD COVERAGE SYSTEMATIC STRUCTURE CRITERIA INADEQUATE FOR ARMY MISSIONS BASED ON V/STOL DATA BASICALLY FOR VMC
UTTAS PIDS	1971	UTTAS	BASED ON 8501A MANEUVERING CRITERIA ADDED
AAH PIDS	1973	AAH	
AGARD 577	1973	V/STOL	
8501B (PROPOSED)	1973	HELICOPTERS	MANY NEW UNSUBSTANTIATED REQUIREMENTS
AHIP SPEC	1981	INTERIM SCOUT	BASICALLY 8501A

TABLE 2.- ROTORCRAFT HANDLING-QUALITIES RESEARCH NEEDS IN THE NEAR TERM

- SLUNG LOADS – INCLUDING TWIN LIFT
- THRUST VECTORING POSSIBILITIES AND POTENTIAL
- VISUAL CUE DEGRADATION EFFECTS AND QUANTIFICATION
- RESPONSE TO COMMAND VERSUS STABILIZATION OF UPSETS
- DIGITAL IMPLEMENTATION OF HIGH GAIN SCAS
- SINGLE PILOT SCAS
- GUIDANCE FOR FAILURE WARNING AND TRANSIENTS
- CROSS COUPLING
- SIDE STICK CONTROLLERS
- MANEUVER ENVELOPE ENHANCEMENT BY LIMITING AND CUEING
- THRUST RESPONSE DYNAMICS AND MARGINS
- CONTROL MODE BLENDING
- NONLINEAR CONTROL BLENDING
- MISSION TASK ELEMENT DEFINITION AND PERFORMANCE BENEFITS
- AIR-AIR COMBAT VEHICLE VERSUS WEAPONS

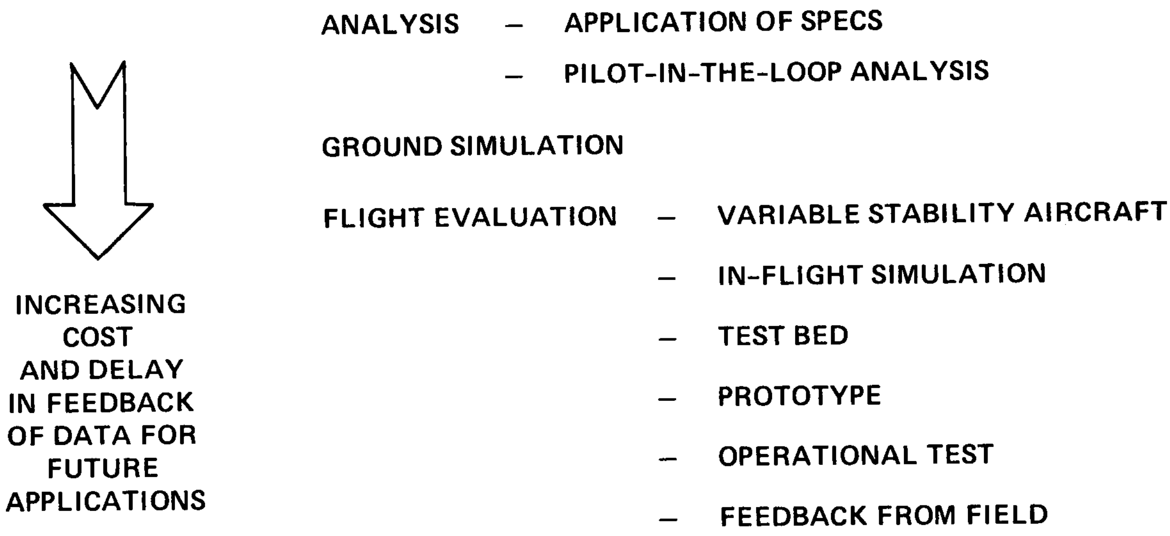


Figure 1.- Methods of achieving good handling qualities.

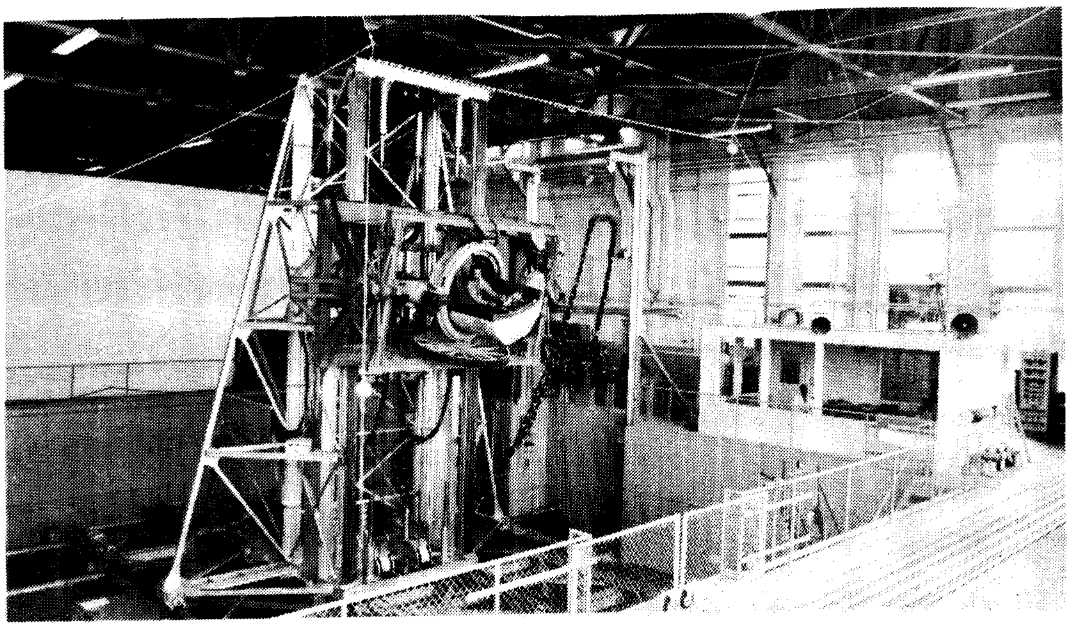


Figure 2.- Six-degree-of-freedom motion simulator.

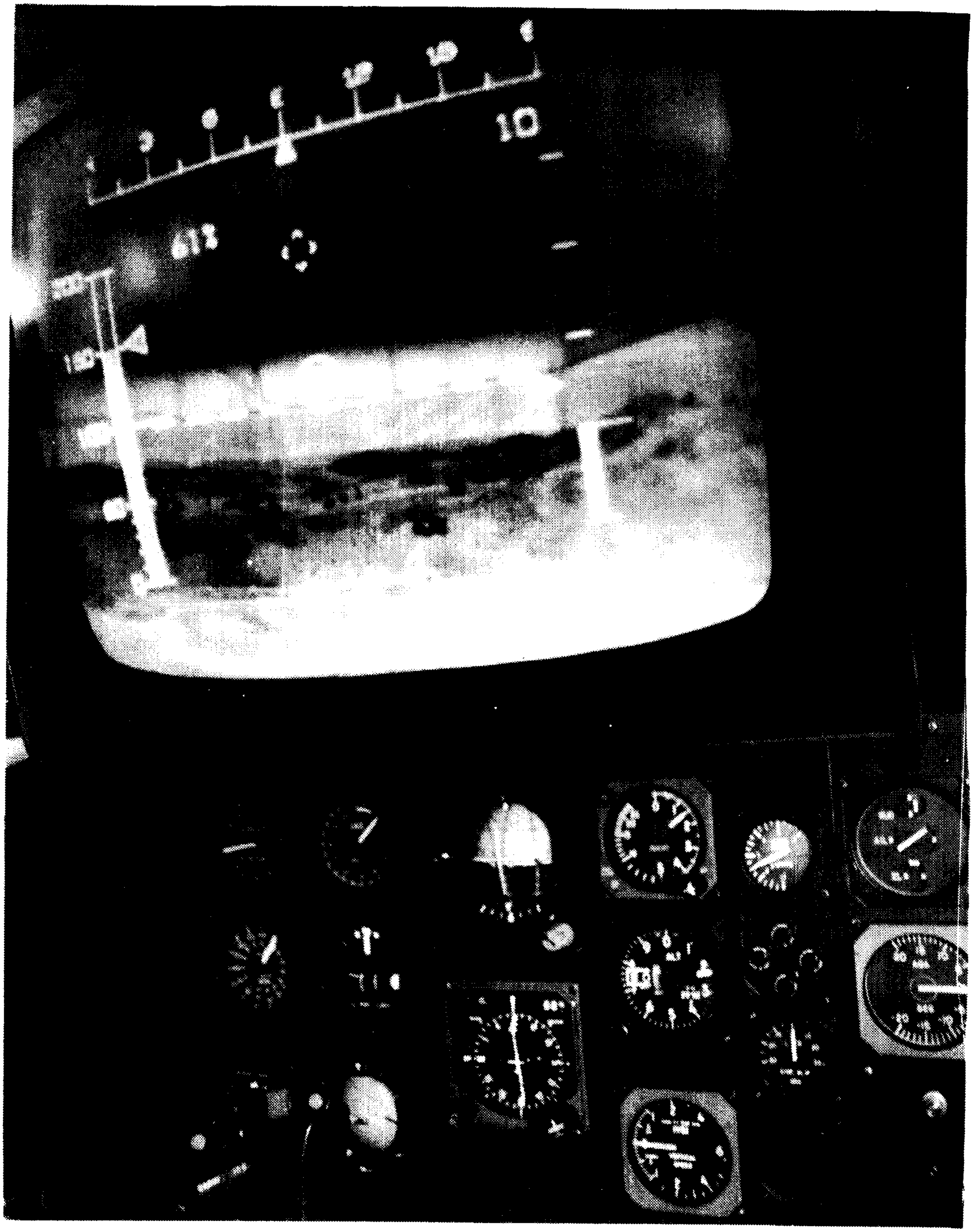


Figure 3.- Cab configuration for control-display investigation.

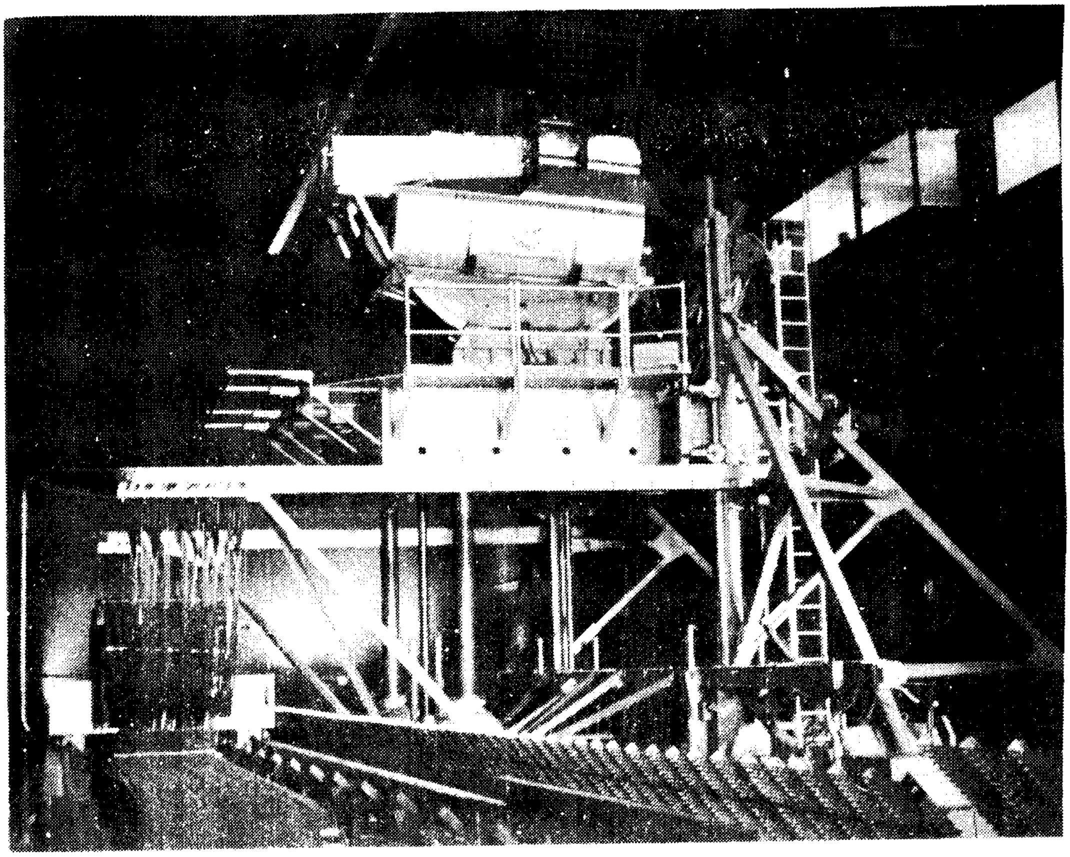
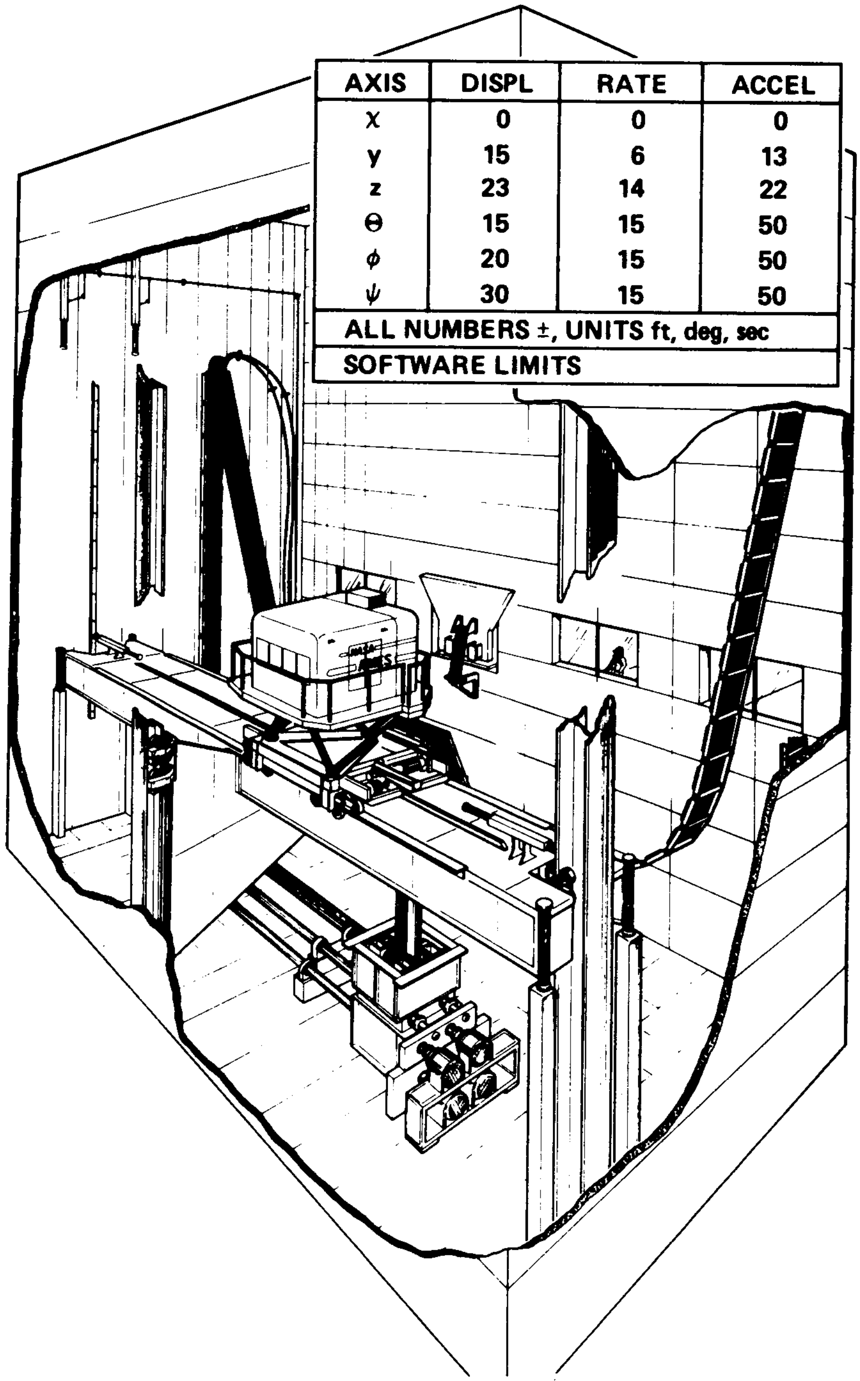


Figure 4.- Flight simulator for advanced aircraft.



AXIS	DISPL	RATE	ACCEL
x	0	0	0
y	15	6	13
z	23	14	22
Θ	15	15	50
φ	20	15	50
ψ	30	15	50
ALL NUMBERS ±, UNITS ft, deg, sec			
SOFTWARE LIMITS			

Figure 5.- Vertical motion simulator.

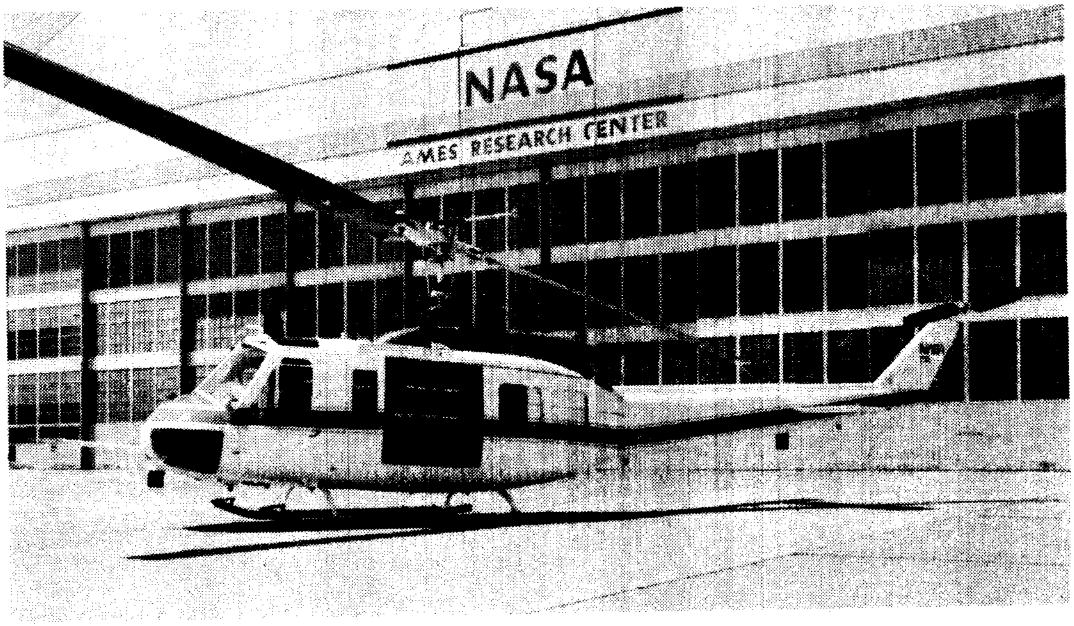


Figure 6.- UH-1H VSTOLAND aircraft.

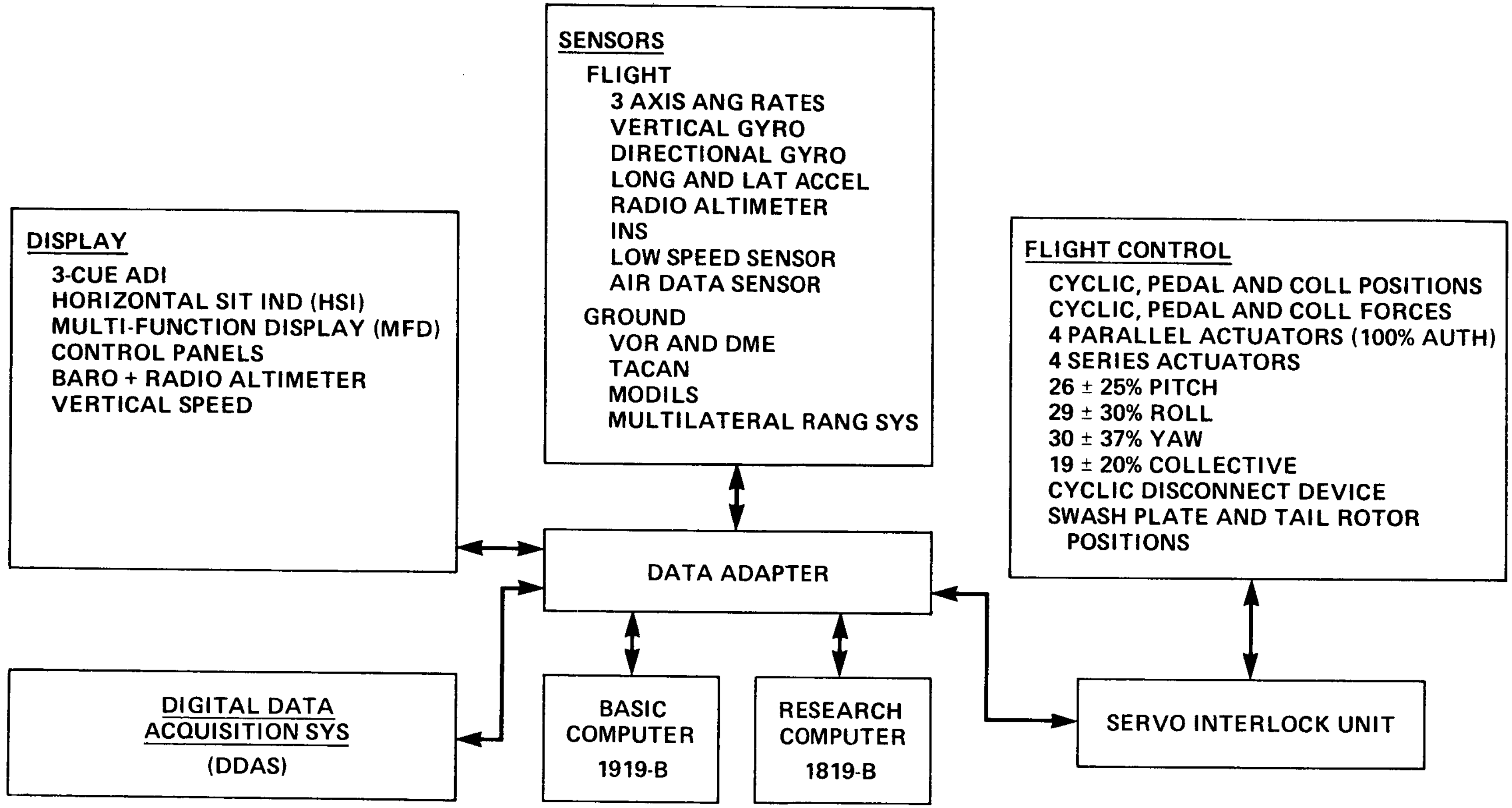
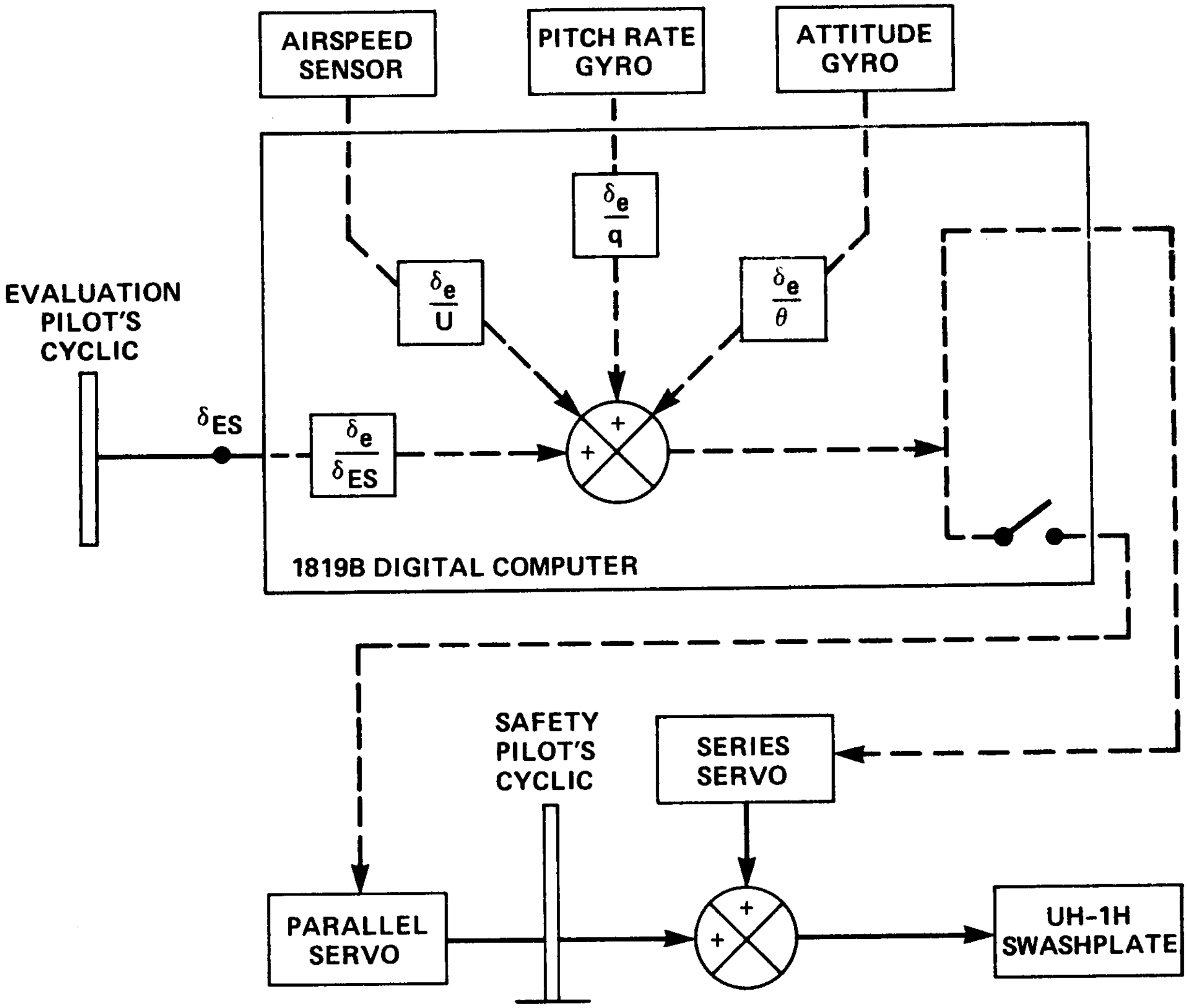


Figure 7.- UH-1H VSTOLAND system components.



– – – ELECTRICAL
——— MECHANICAL

$$M_{\delta_{ES}}|_{SIMULATED} = M_{\delta_e}|_{UH1H} \cdot \frac{\delta_e}{\delta_{ES}}$$

$$M_q|_{SIMULATED} = M_q|_{UH1H} + M_{\delta_e}|_{UH1H} \cdot \frac{\delta_e}{q}$$

$$M_\theta|_{SIMULATED} = M_{\delta_e}|_{UH1H} \cdot \frac{\delta_e}{\theta}$$

$$M_U \text{ SIMULATED} = M_U|_{UH1H} + M_{\delta_e}|_{UH1H} \cdot \frac{\delta_e}{U}$$

Figure 8.- VSTOLAND control-law channel.

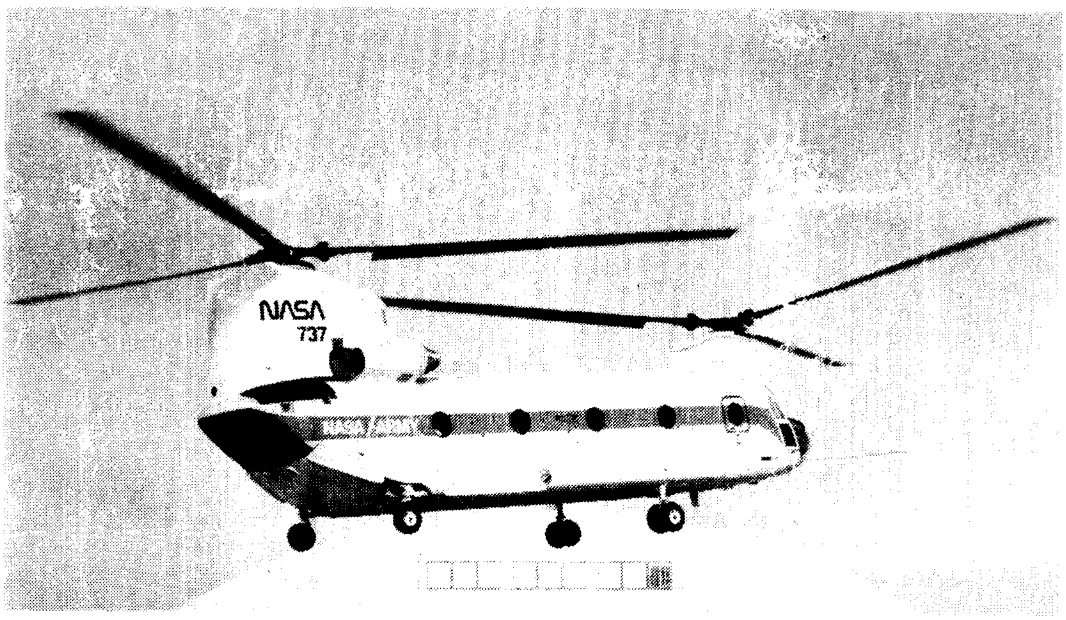


Figure 9.- CH-47B variable stability helicopter.

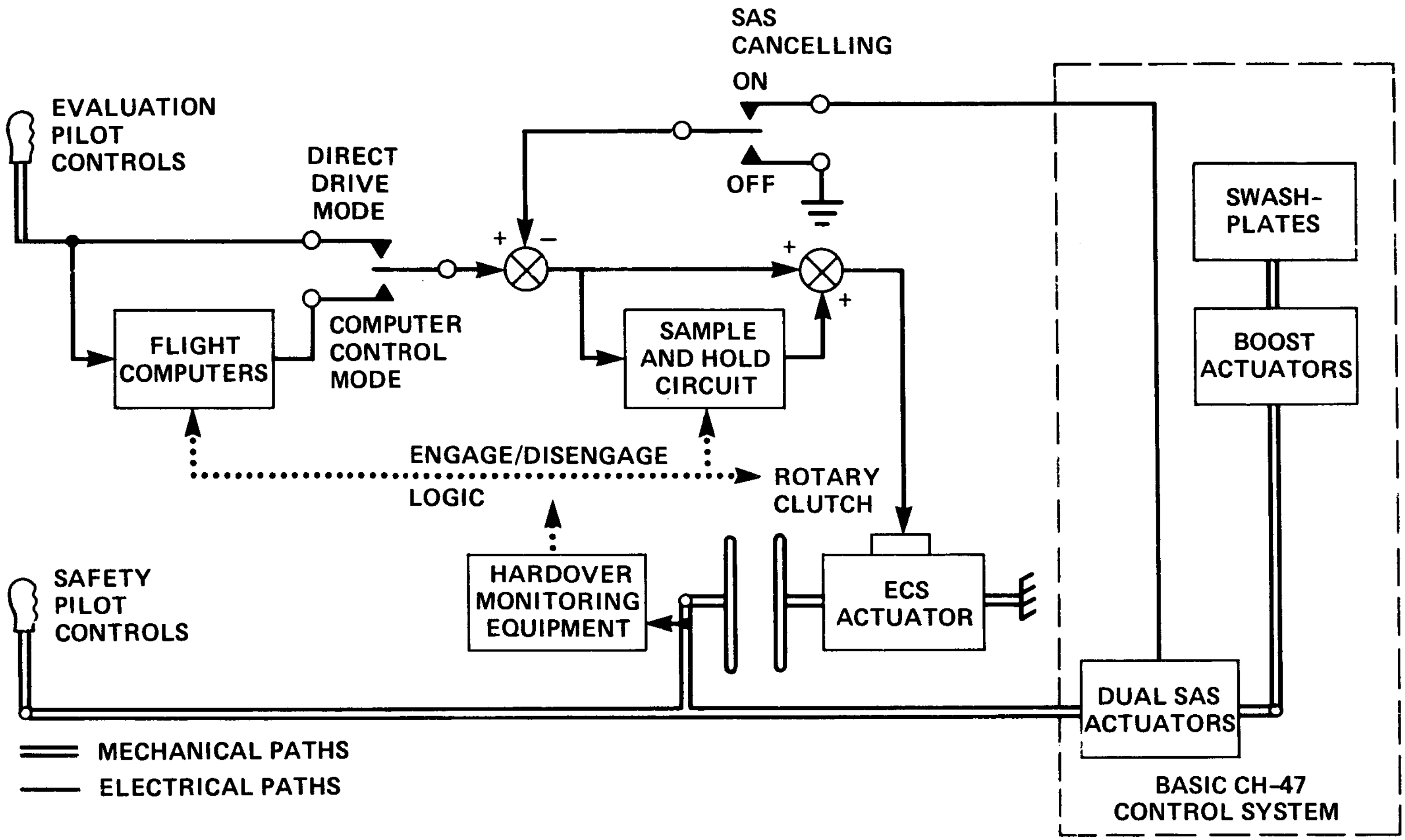


Figure 10.- CH-47B electronic control system.

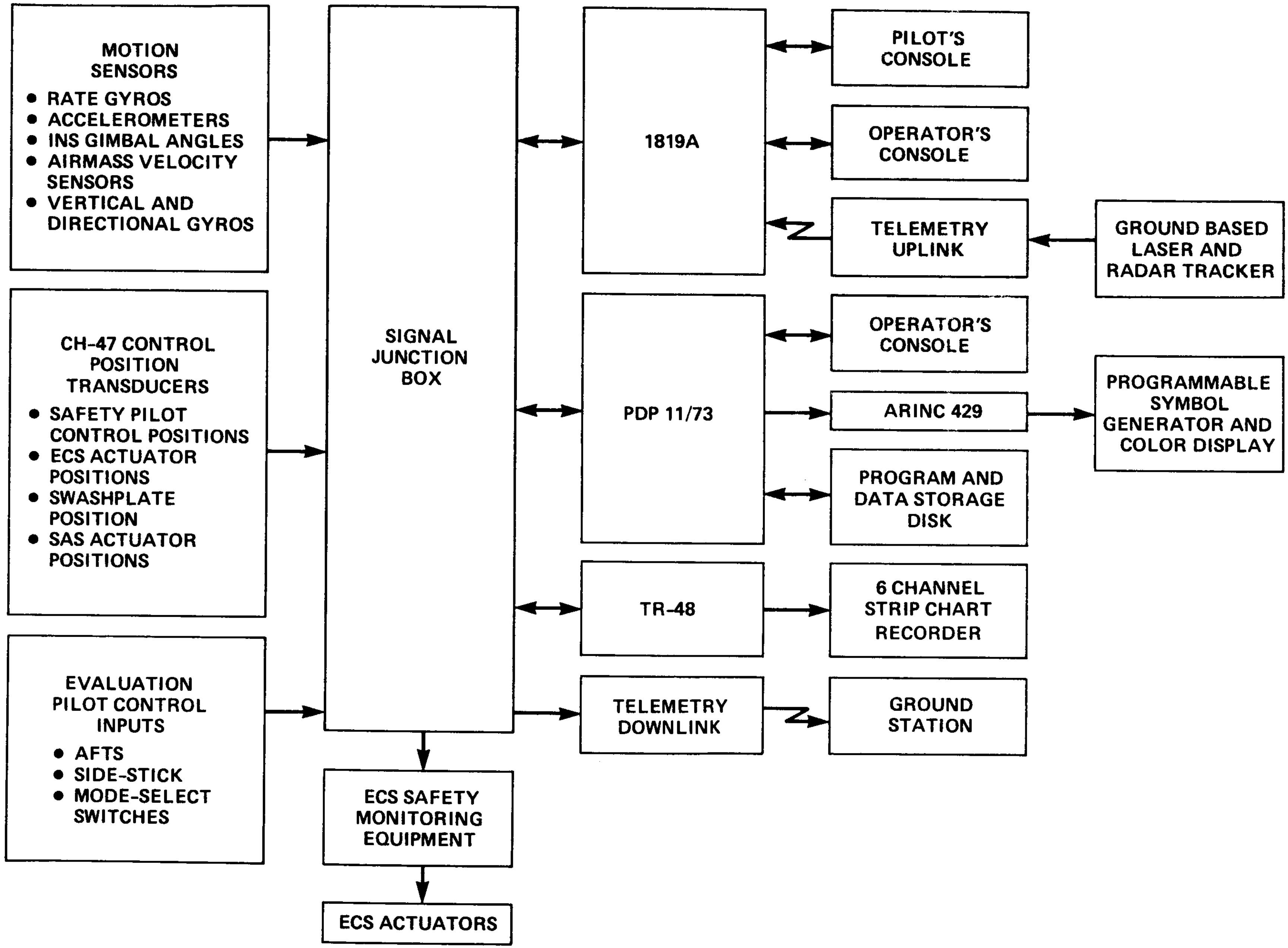


Figure 11.- CH-47B research system.

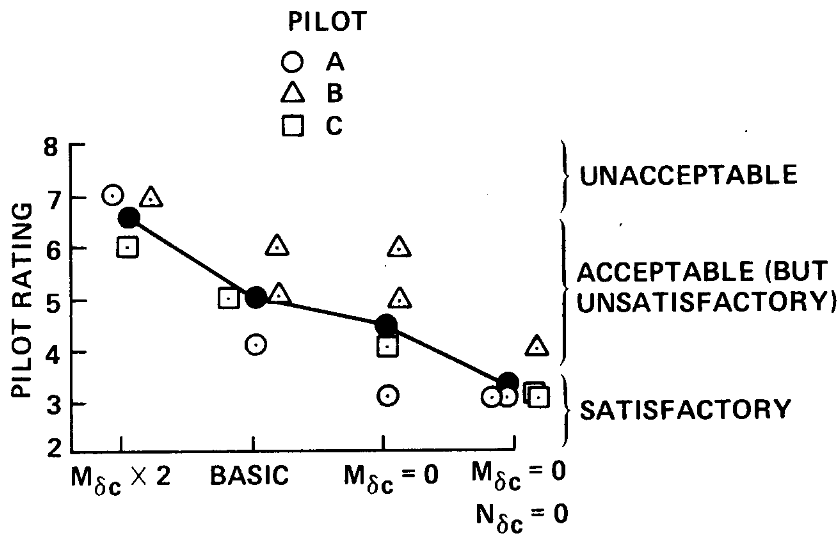


Figure 12.- Effect of pitch and yaw response to collective input.

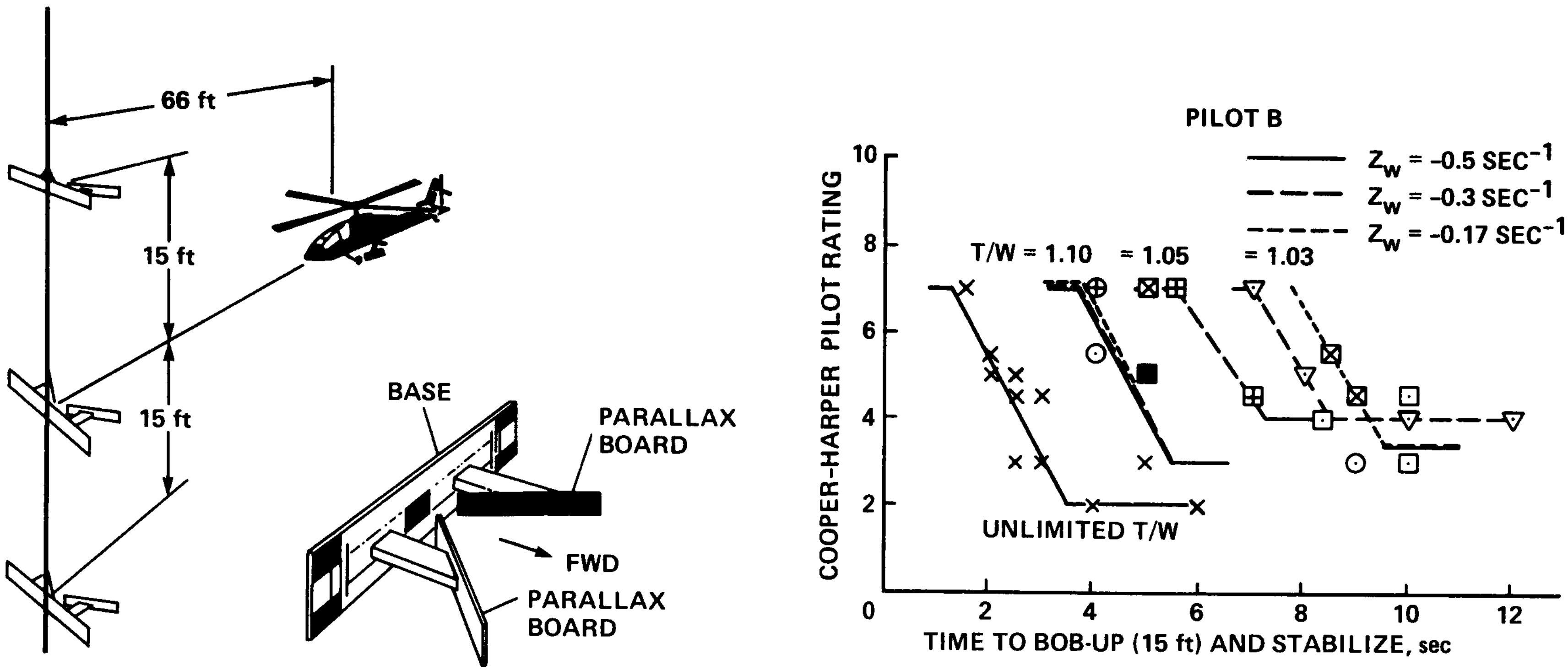


Figure 13.- Effects of time-constraints and vertical damping on bob-up handling qualities.

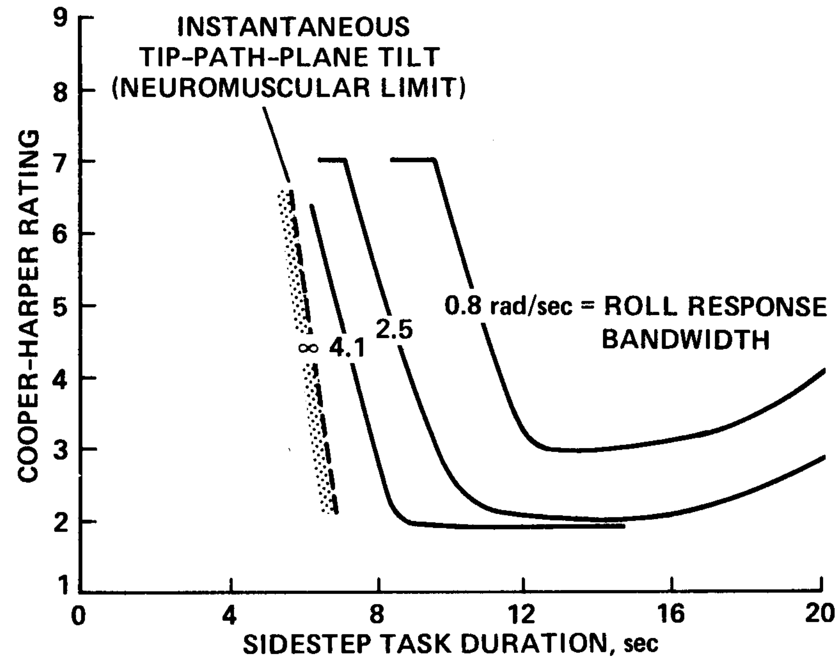


Figure 14.- Effects of short-term roll response as a function of time-constraints.

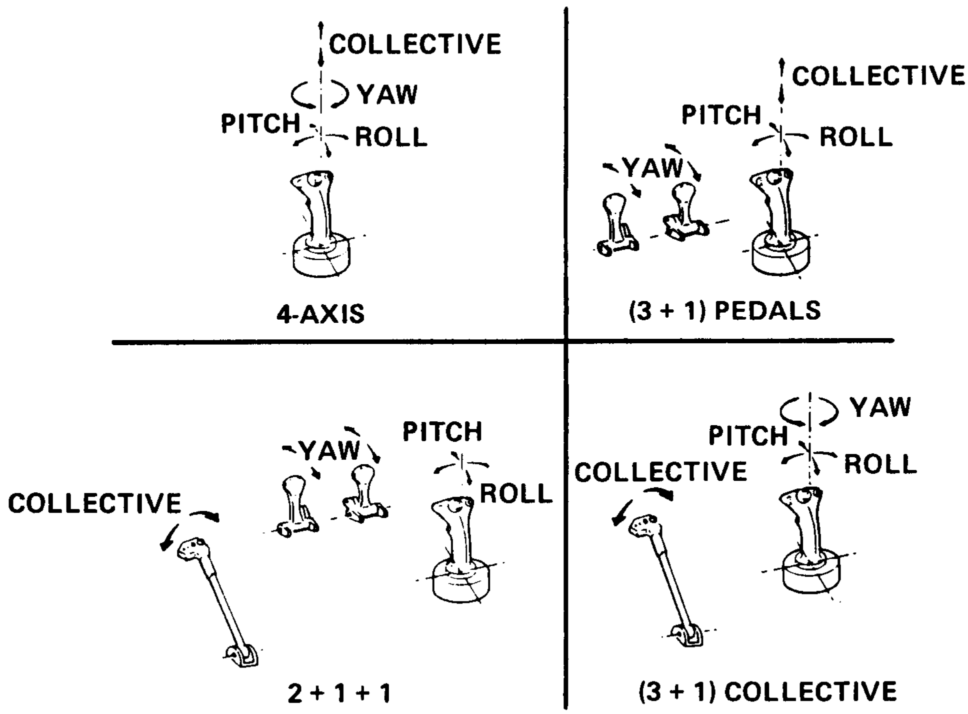


Figure 15.- ADOCS controller configurations.

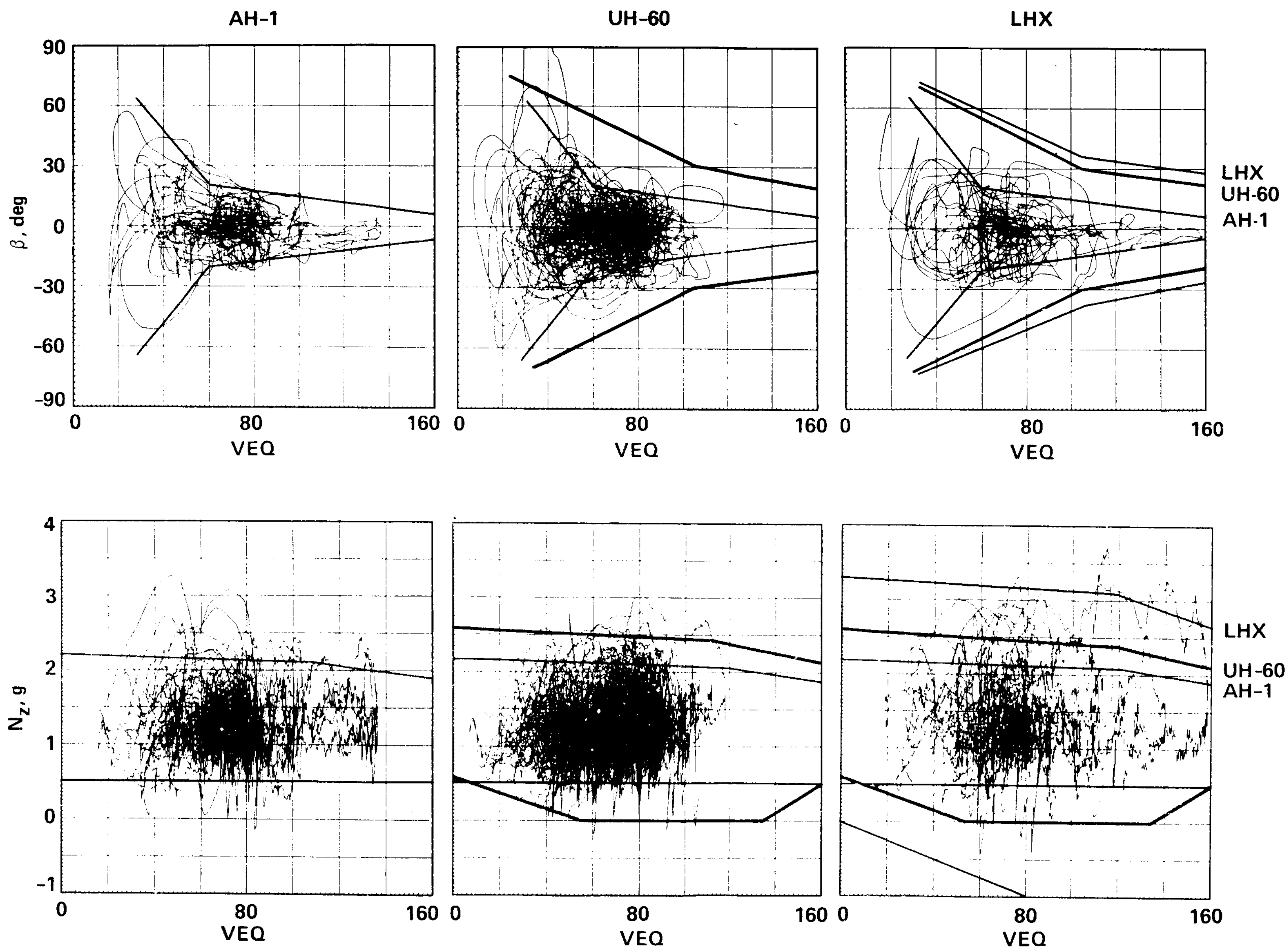


Figure 16.- Use of sideslip and normal acceleration in helicopter air combat simulation.

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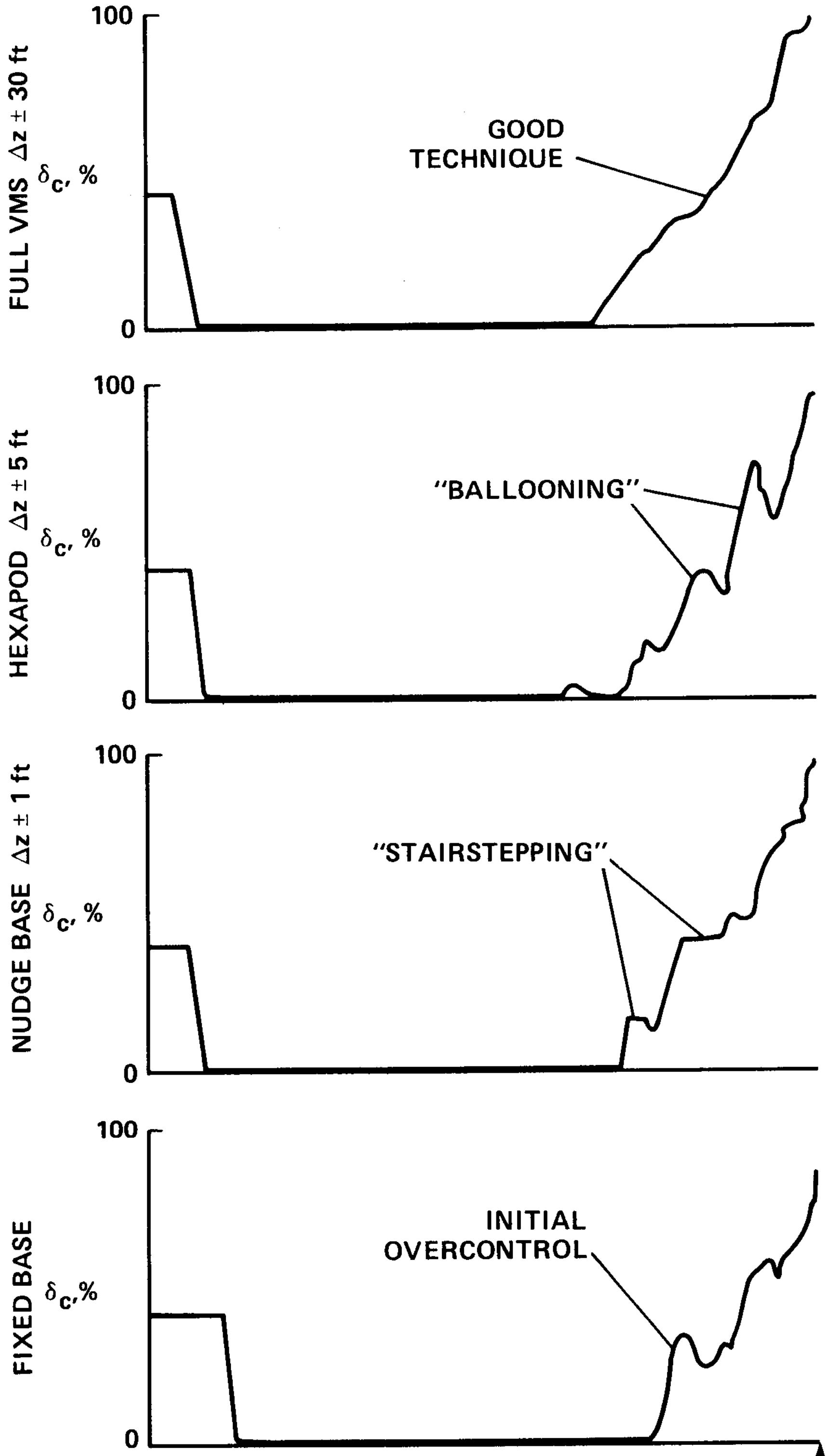

Figure 17.- Effect of motion system characteristics on collective use during simulated autorotations.

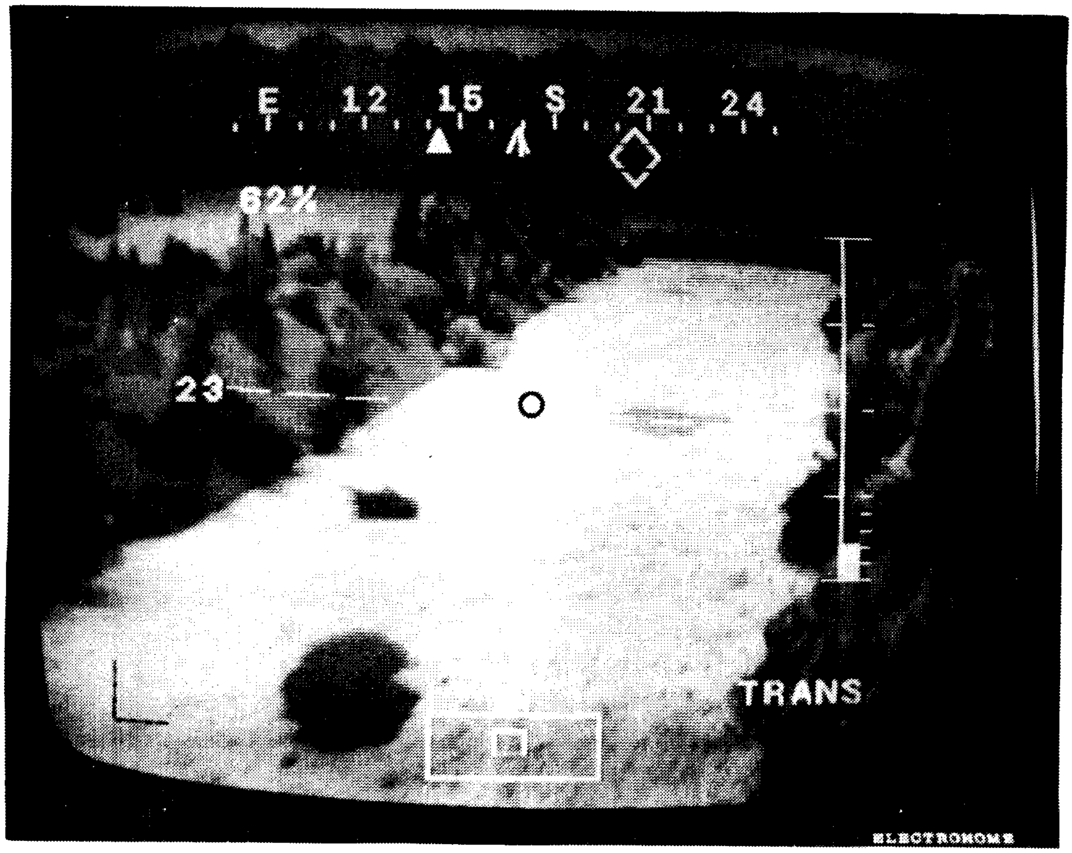

Figure 18.- Pilot night vision system symbols.

Figure 19.- Integrated helmet and display sight system.

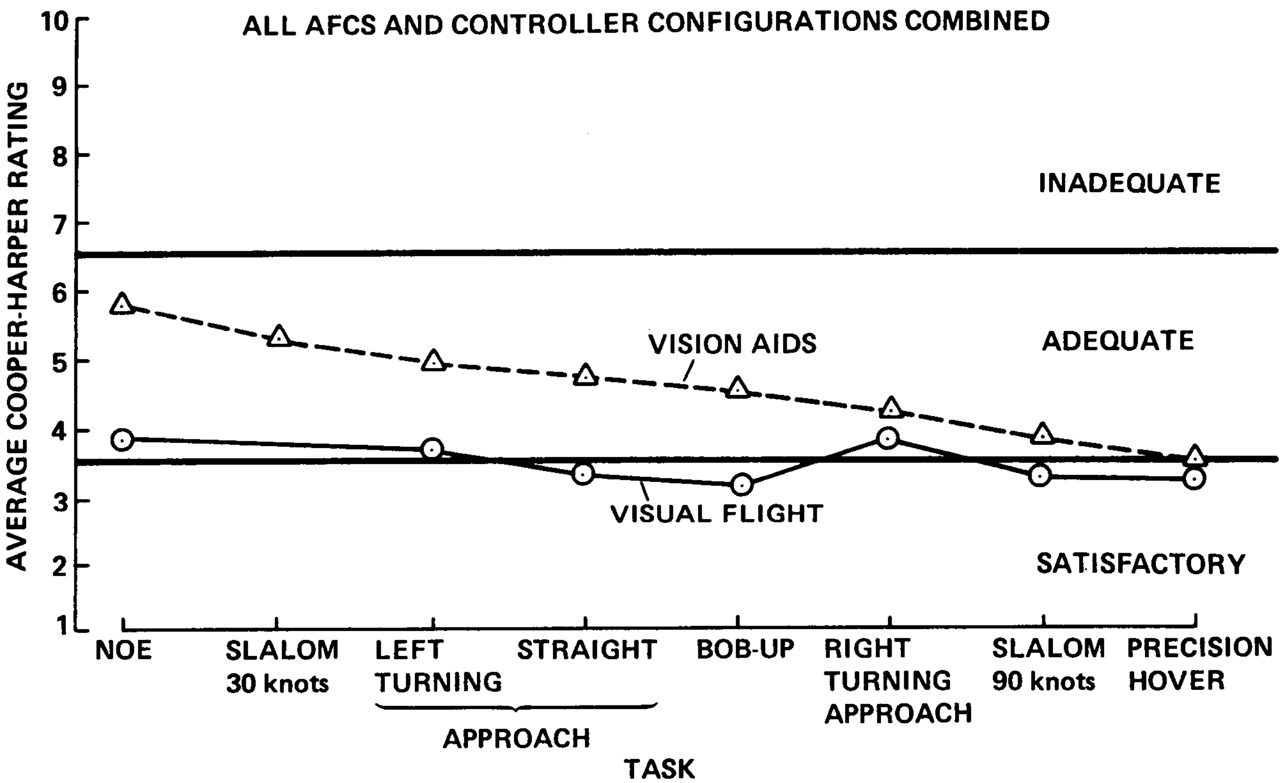

Figure 20.- Effect of reduced visibility conditions on handling qualities.

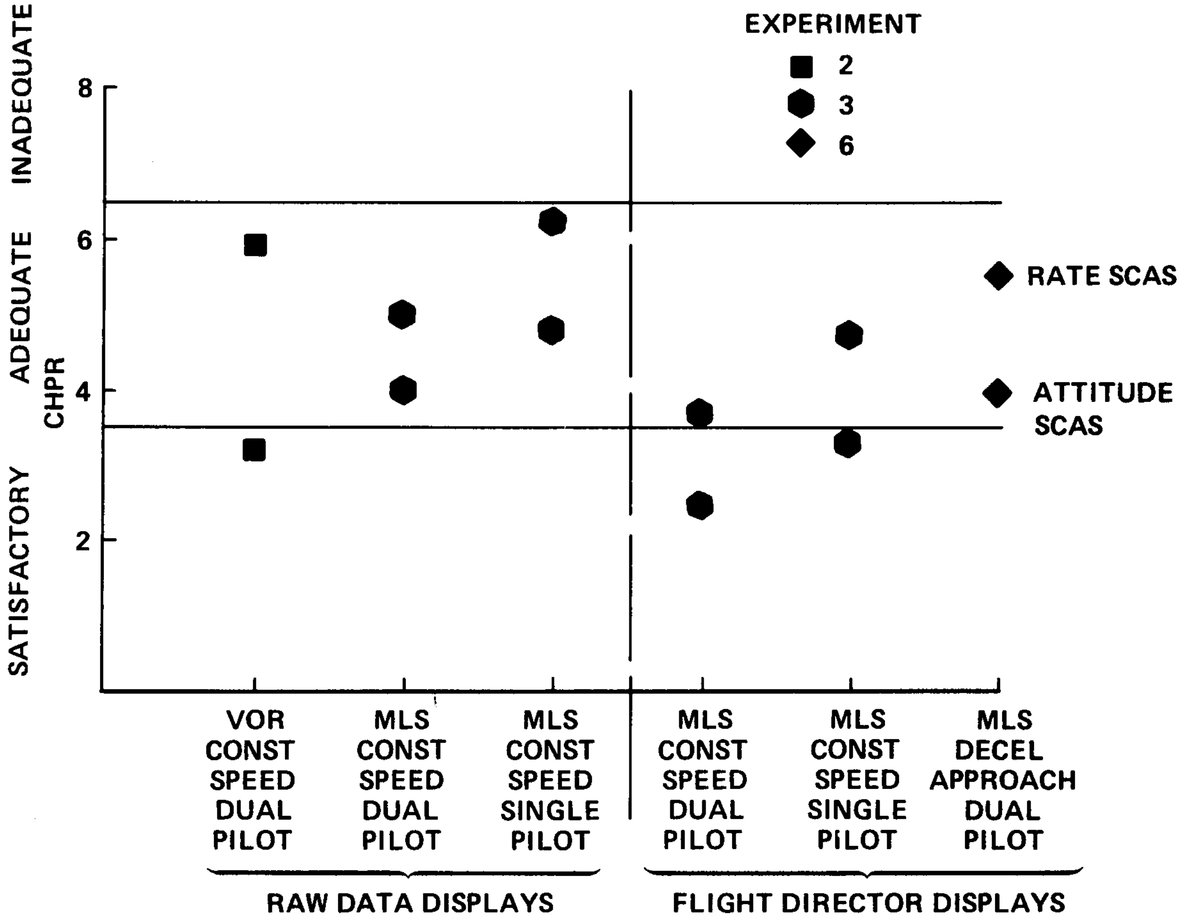

Figure 21.- Influence of task on IFR handling qualities.

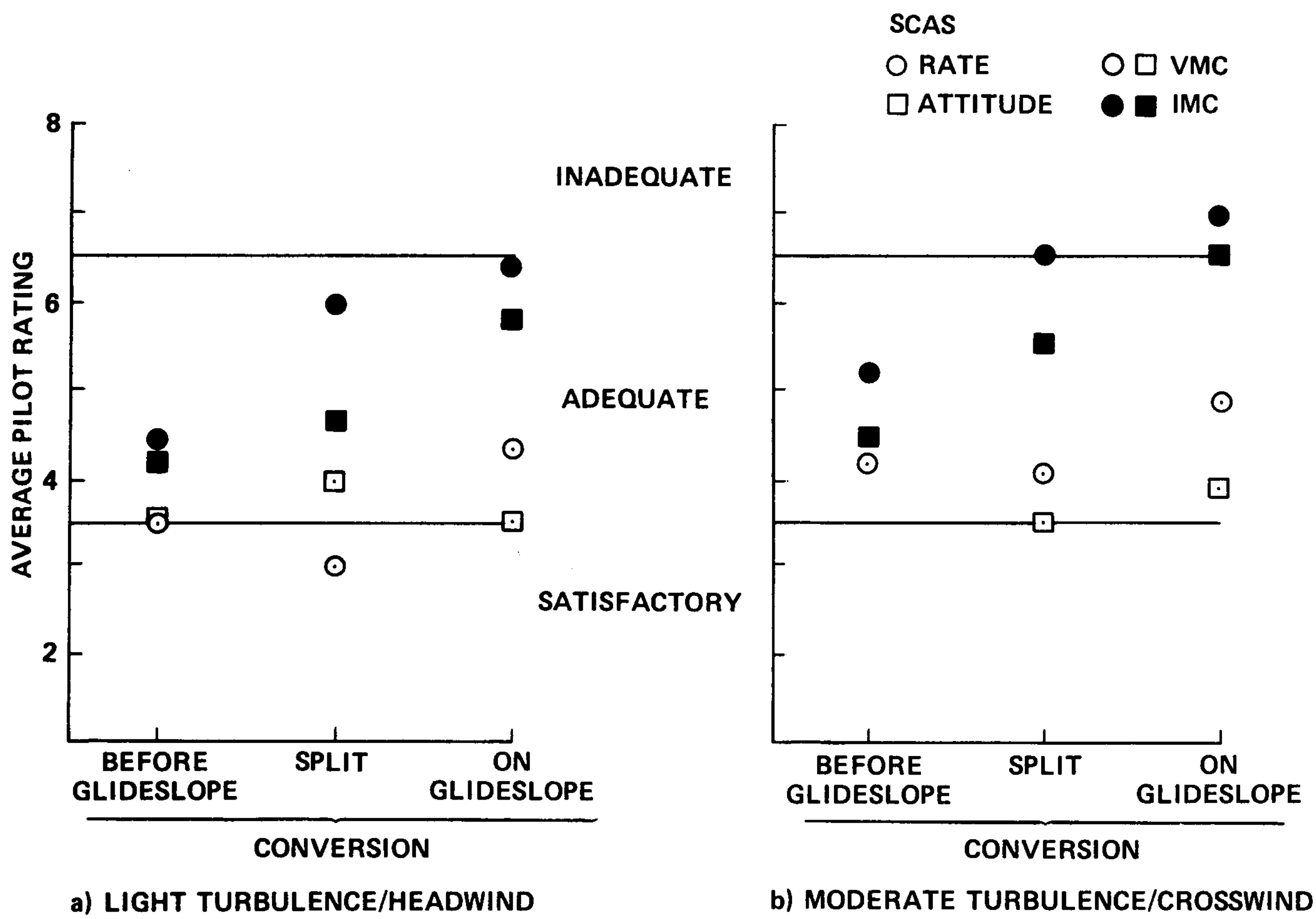

Figure 22.- Influence of conversion procedure, SCAS, and visual conditions on tilt-rotor handling qualities.

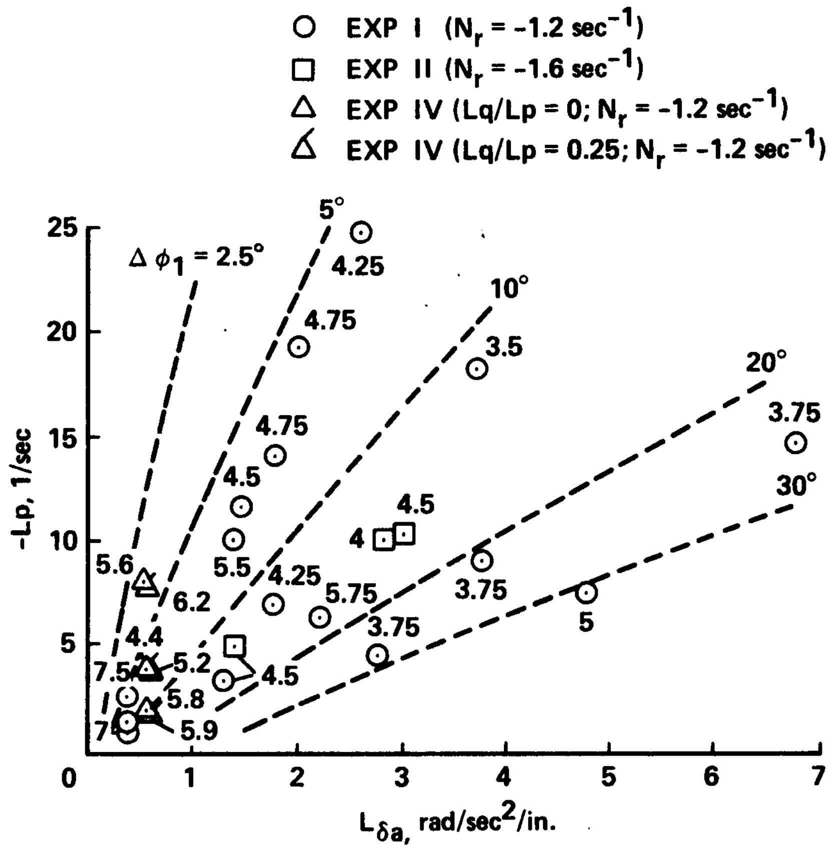

Figure 23.- Ground and in-flight simulation results: roll control requirements for a slalom task.

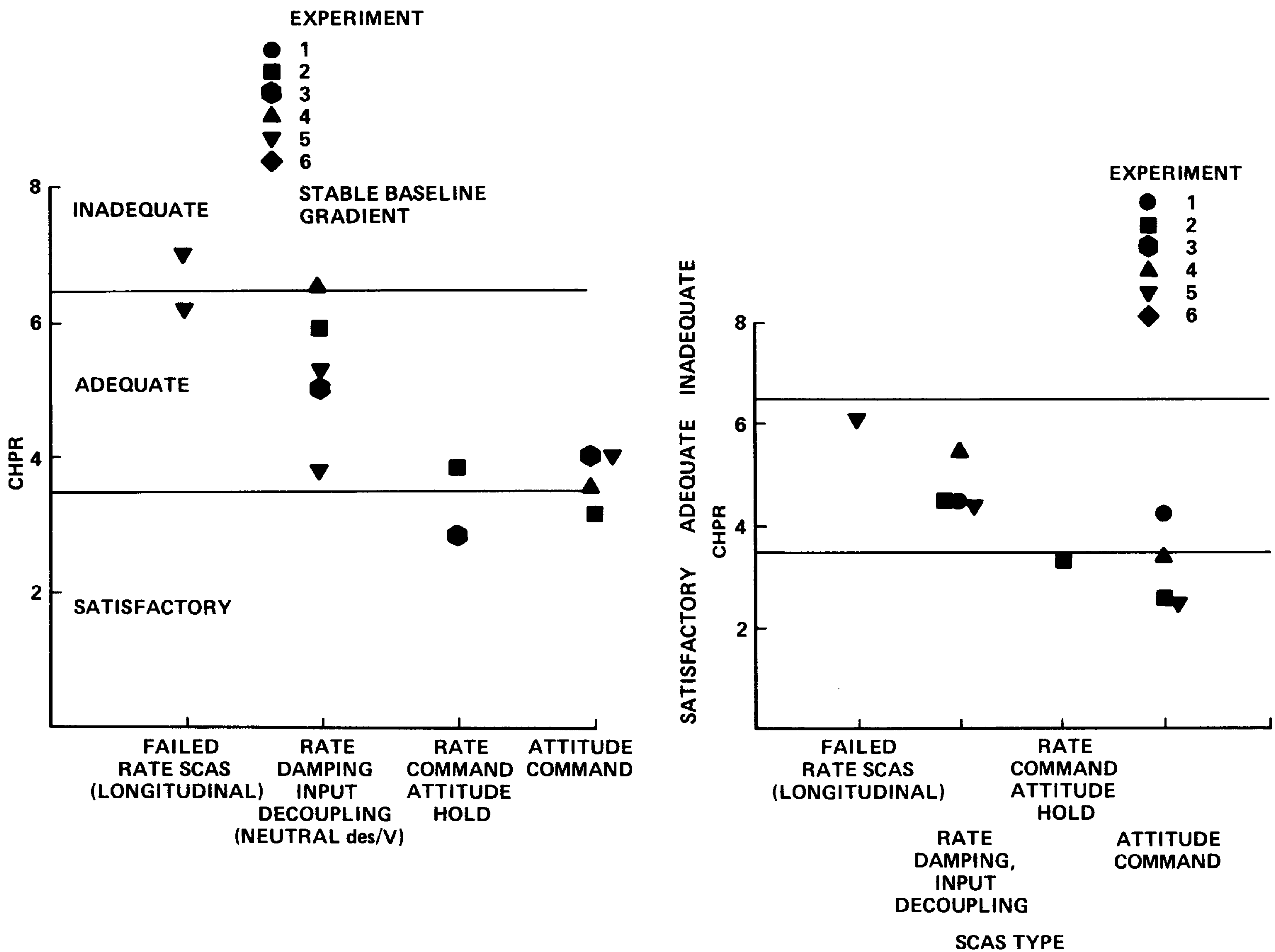

Figure 24.- Ground and in-flight simulation results: helicopter IFR program.

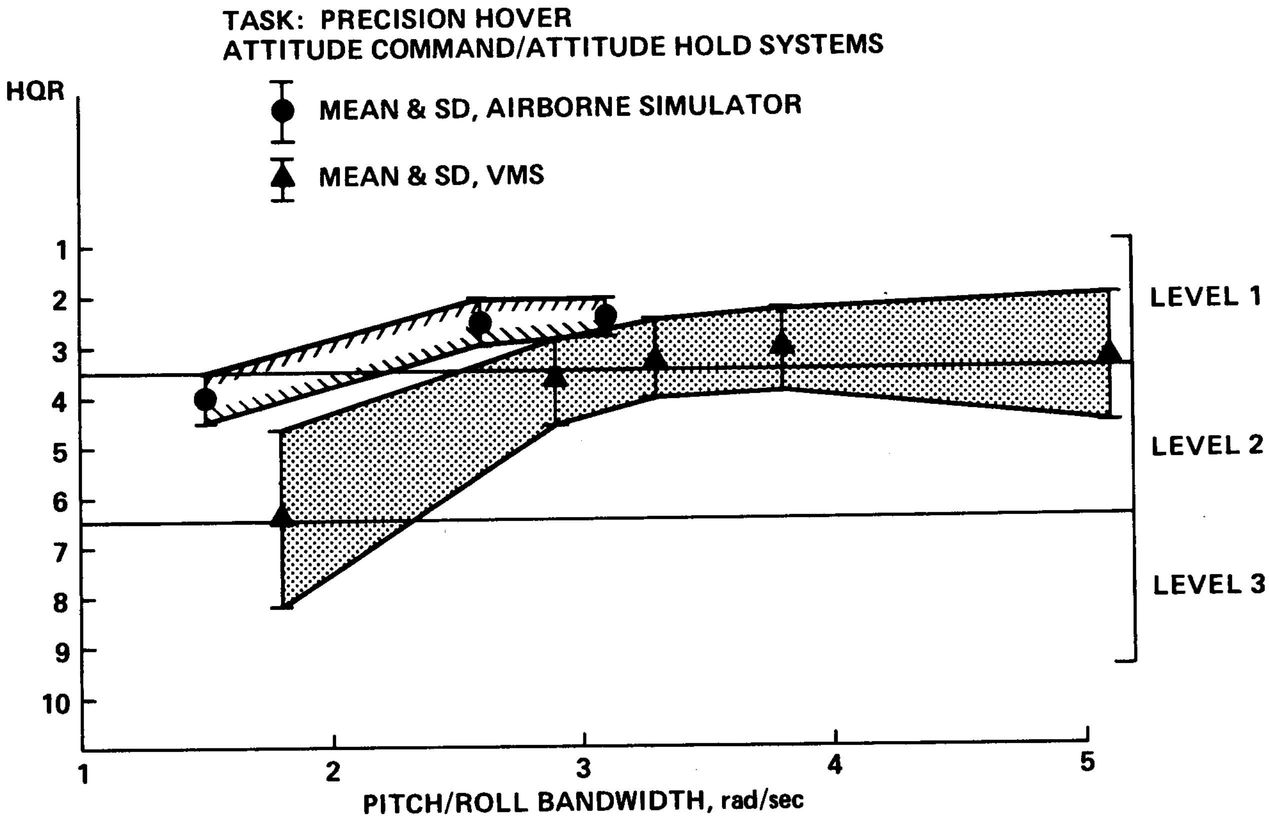

Figure 25.- Ground and in-flight simulation results: precision hover tasks.

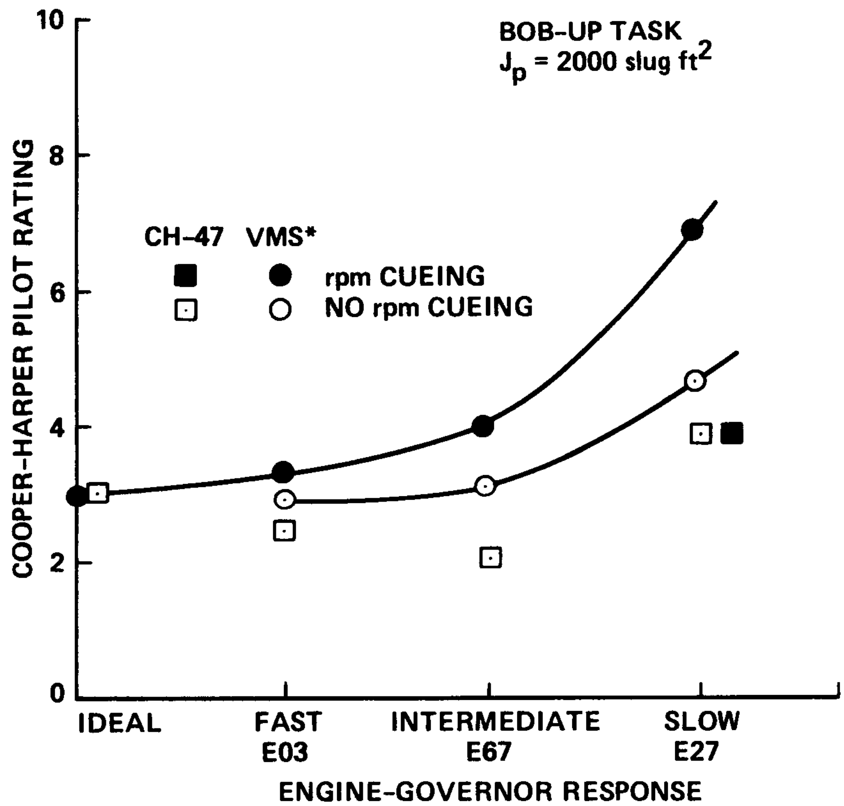

Figure 26.- Ground and in-flight simulation results: engine-governor response.

CHARACTERIZE HELICOPTER:

	u v w p q r	δ_e δ_a δ_r δ_c
X		
Y		
Z		
L		
M		
N		

LINEAR 10 × 6	60
ENGINE	4
CONTROLLERS δ&F	6
PARAMETERS	70

TASKS

HOVER — VERTICAL
HORIZONTAL; LONG, LAT, DIR
COMBINED
SHIPBOARD, SLUNG LOADS

FORWARD FLIGHT — (V ⩾ 45 kt)
MANEUVERING – LONG, LAT, DIR, AIR-AIR
APPROACH AND LANDING

12

ENVIRONMENT

VMC/IMC/NIGHT DISPLAYS/VISION AIDS
WIND, SHEAR, TURBULENCE

10

EXPERIMENT

5 PARA × 4 VALUES = 5×5×5×5 = 625
2 TASKS, 2 ENVIR × 2 PILOTS (50% REPEAT) = 12

7600 EVALS

SIMULATION TIME

15 MIN/EVAL × 20 HOURS/WEEK × 5 WEEKS =

400/SIMULATIONS

Figure 27.- Scope of rotorcraft handling-qualities problem.

SYM	REF	RESPONSE TYPE	AIRCRAFT (FLIGHT/SIM)	TASK(S)	ω_{BW_θ}	TURB
○	5	RATE	UH-60A (VMS)	SIDESTEP	2.3	LIGHT
●	5	RATE	UH-60A (FLIGHT)	SIDESTEP	2.1	LIGHT
○	13	RATE	V/STOL (FSAA)	SHIPBOARD LDG	2.3	LIGHT
◇	14	RCAH	ADOCS (VERTOL SIM)	NOE	2.6	NONE
△	14	RCAH	ADOCS (VMS)	NOE	2.8	NONE
△	14	RCAH	ADOCS (VMS)	PRECISION HOVER	2.8	MOD
◆	45	RCAH	XV-15 (FLIGHT)	HOVER TRANSL	2.9	LIGHT
◆	45	RATE (SAS OFF)	XV-15 (FLIGHT)	HOVER TRANSL	0.4	LIGHT
■	46	RATE	AV-8A (FLIGHT)	HOVER (DAY)	2.3 (EST)	LIGHT
⌂	48	RATE	V/STOL (VMS)	SHIPBOARD LDG	1.8	LIGHT
◣	NCR	RCAH AND RATE ($\tau_p \leq 0.14$ sec)	UH-1H (FLIGHT)	LANDING	1.5-2.8	LIGHT

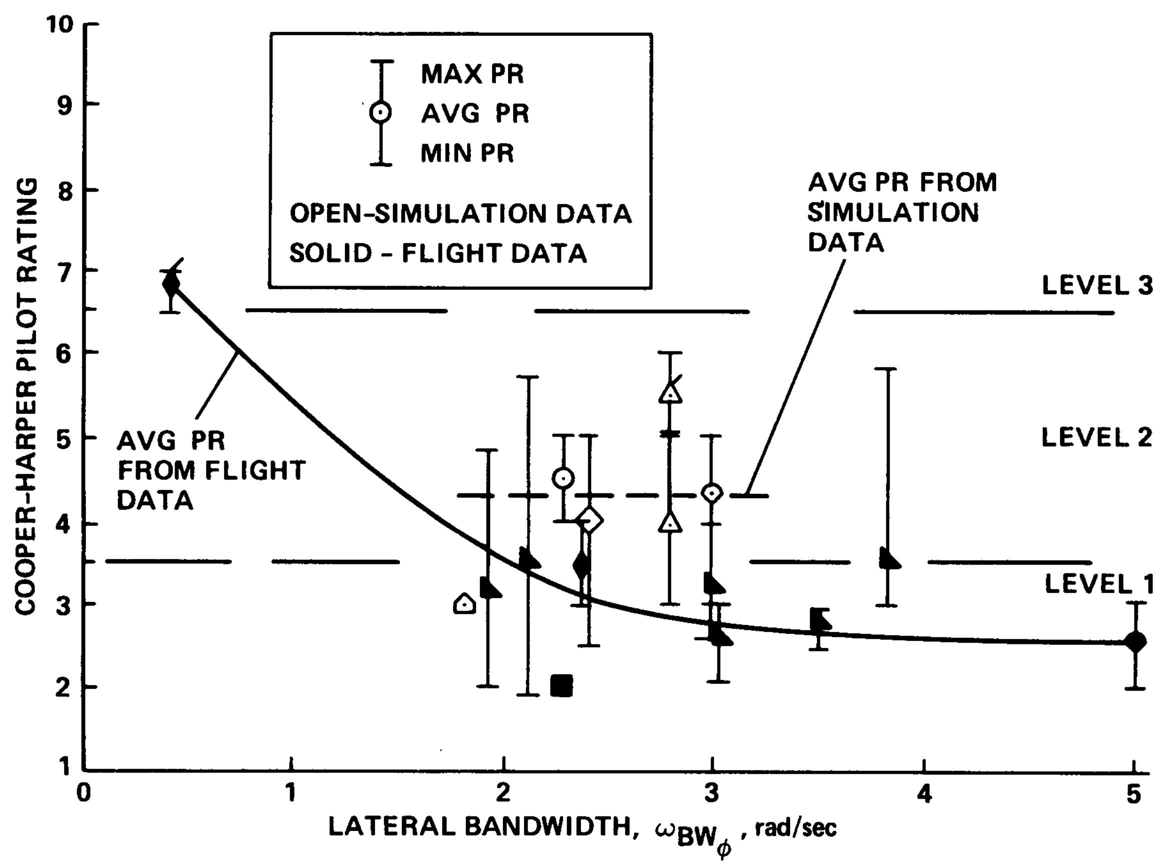

Figure 28.- Comparison of flight and simulation results for rate-response types.