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By the Ad Hoc Study Group for Aeronautics Panel of the Aeronautics and Astronautics Coordinating Board

November 1979

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TABLE OF CONTENTS

I. INTRODUCTION

V/STOL aircraft are subject to a larger penalty in operational performance than conventional aircraft when nonoptimum flight control characteristics are used, because control must be extracted from the propulsion system for low-speed operation. Traditionally, variable stability aircraft have played a key role in determining control system requirements as well as flight testing to establish proper levels of stability and control, control feel, and guidance, and display systems -- and to establish credibility of proposed handling qualities requirements.

For V/STOL aircraft some in-flight simulation capability is currently provided by two fixed-wing aircraft, the Bell X-22A and the X-14B, and a few helicopters. In general, these aircraft are limited in their ability to conduct future research on advanced control system and display concepts in terms of a real life operational envelope and environment. The X-22A has fulfilled many in-flight simulator requirements, but its airframe is nearing the end of its design life, and will not likely remain operational beyond 1981 within current plans. Unless action is taken to identify and pursue a course of action for a replacement or extension, the U.S. will not have a fixed-wing V/STOL flight research capability during the 1980's, a period of intensive research and technology development for advanced V/STOL aircraft concepts.

Ground-based simulation capability has improved over the years and is recognized as a valuable research tool for advanced aircraft designs. However, a critical need continues to exist for V/STOL in-flight simulation to guide and validate ground-based simulation results, as well as to investigate conclusively problems beyond the capabilities of even the most sophisticated ground-based simulators. Nevertheless, despite backing by DOD and NASA, several joint and continuing independent attempts in recent years to acquire a research vehicle for in-flight simulation have been unsuccessful.

Accordingly, the Aeronautics Panel of the Aeronautics and Astronautics Coordinating Board (AACB) established in mid-1978 an Ad Hoc Study Group on V/STOL Flight Simulation to review requirements and potential approaches for meeting them, and to identify possible areas of joint DOD/NASA activity. A copy of the Study Group charter is attached as Appendix A. The membership was constituted as:

Mr. Ralph W. May	NASA Hqs. - NASA Co-Chairman
Mr. Raymond F. Siewert	NAVAIR/OUSDRE DOD Co-Chairman
Mr. Seth B. Anderson	NASA Ames Research Center
Mr. John Clark	Naval Air Development Center
Dr. Irving C. Statler	Army Aeromechanics Lab. (AVRADCOM)
Lt. Col. Ronald Traudt	Air Force Systems Command

The Study Group met November 13 and 14, 1978, at the Ames Research Center and on February 7, 1979, at NAVAIR, Washington, D.C. Many NASA, Navy, and Calspan individuals beyond the membership contributed to the Study Group activities. Special recognition is given to the Ames Research Center for several key sections of this written report and for publishing it.

The remaining body of this report is organized in sections which (1) describe the necessary and complementary roles of ground-based and in-flight simulation, (2) specify capabilities desired and required in V/STOL in-flight simulation, (3) describe and relate the experience gained with recent/current V/STOL in-flight simulation vehicles (including more detailed description in Appendix B), (4) discuss future V/STOL in-flight simulation candidate options, and (5) relate the primary conclusions and recommendations.

II. IN-FLIGHT VIS-A-VIS GROUND-BASED SIMULATION

To provide a perspective on the contribution of and need for in-flight V/STOL simulation, it is expedient to review the capabilities and short-comings of ground-based simulation facilities. In the following sections a review is made of ground-based simulator characteristics, the need for in-flight operational environment, and experience with conventional aircraft simulators.

Ground-based simulator characteristics. These simulators are intended to replicate, to varying degrees of fidelity, the aircraft and its operational environment. Either fixed-base or moving-base simulators are useful for (1) an initial assessment of flying qualities of a new design, (2) preliminary design and evaluation of control system concepts including hardware, and (3) the initial evaluation of hypotheses concerning flying qualities criteria to permit screening of experimental configurations and operating conditions for a thorough and expensive experimental program.

A ground-based simulation usually contains two basic elements: (1) a mathematical model representing a particular vehicle and its operating environment, and (2) a system to supply sensory information to the pilot. Both of these elements are in many cases imperfect and incomplete. In particular, for the V/STOL operating regime from 60 kts to touch-down, the aerodynamic parameters are nonlinear and not accurately defined in the math model, and the simulator visual scenes are limited in field-of-view such that the simulation results are of low confidence level and suspect. To improve confidence in this area a number of evaluations of V/STOL aircraft flying qualities, flight control system and display concepts, and operational procedures concerned with land-based and shipboard missions needs to be performed using the full range of Ames simulators. These evaluations can provide parametric data concerning flying qualities design criteria for attitude and velocity control systems and displays, and indications of IFR operational capability during shipboard landing in heavy seas. Need for this research will continue using these simulators over the next few years to develop a more complete data base.

In spite of the improved sophistication of these simulation facilities, numerous uncertainties remain about their ability to satisfactorily represent the flight characteristics and operational environment of V/STOL aircraft. These uncertainties involve the effect of limitations of motion and visual systems and an insufficient understanding of the importance of the operational environment including atmospheric turbulence, ground effect upsets, and tasks appropriate to V/STOL flight operations.

Limitations of simulator visual and motion systems have been the basis for extensive discussion. For the most part, current NASA-Ames simulation facilities are considered inadequate for V/STOL operational research in several respects. These include restricted vertical and longitudinal motion and a narrow visual field-of-view. Such deficiencies have, for example, led to erroneous conclusions regarding flare and landing capability for STOL operation. Moving-base simulation results indicated that performing the flare through control of thrust or a combined control technique using pitch rotation and thrust modulation would be unacceptable. Flight experience with the Augmentor Wing Aircraft reversed this result by demonstrating that these controls could perform quite satisfactorily for this task. In 1980, the Vertical Motion Simulator at Ames will become operational with a four window, computer graphics visual scene. This simulator will partially overcome past deficiencies and will give NASA a reasonable V/STOL ground-based simulation capability. However, uncertainties remain concerning the adequacy of the longitudinal motion authority when simulating a decoupled velocity control system relying on thrust deflection for control. Current computer generated imagery is still rudimentary and severe restrictions exist on placement of the four windows for use in shipboard operations.

Need for representative operational environment. In the absence of actual flight experience with a new V/STOL aircraft, it is difficult to fully appreciate the aircraft's operational capability by means of ground-based simulation; in other words, it is difficult to appreciate that simulation is not reality. Until the aircraft is flown in a real-life mission demanding precise vertical and ground tracking flight trajectories, an understanding of all the possible and useful operational techniques does not exist and the pertinent flight tasks cannot be accurately identified. In flight, the pilot may be aggressive or cautious as the situation demands and the aircraft capability warrants. In particular, the ability to anticipate and simulate the operational environment is deficient regarding the ability both to describe it accurately and to represent all the cues normally available to the pilot. This deficiency is particularly true for operation aboard ships and small pads or platforms in constrained spaces. Meaningful results can be obtained only by flight operation aboard ships since wind environments cannot be well modelled for these circumstances, nor can the visual cues attainable from fine detail on structures or terrain. Hence, it is essential to have the contact with reality that an actual V/STOL flight operation provides not only to substantiate simulation results, but also to permit anything but the most rudimentary simulation to be conducted at all. Further, in ground-based simulation testing, the pilot operates in a relatively relaxed setting and consequently may not be motivated to adjust his gain high enough to identify critical flight control system problems. This point is discussed in the following section.

Experience with conventional in-flight simulation aircraft. Lest it be inferred that the justification for in-flight simulation is only peculiar to V/STOL aircraft, it should be noted that discrepancies between ground-based simulation results and actual flight continue to occur with regularity also for conventional aircraft and operational regimes. The value of in-flight simulation has been demonstrated by the Calspan T-33 aircraft which has been used to troubleshoot potential control problems on the latest series of Air Force and Navy fighter aircraft, the F-15 through F-18. In the case of the F-16, a serious anomaly in the lateral control system which was not evident in piloted ground-based simulation, was identified on the in-flight simulator and confirmed with nearly disasterous consequences on the initial liftoff of the No. 1 aircraft. The YF-17 landing characteristics as influenced by a pitch control model pre-filter were found in the T-33 evaluations to be deficient. In this case, given the previous experience with the YF-16, a new pitch control mechanization for landing was designed and checked in the T-33 prior to first flight of the YF-17. The landing approach characteristics of the F-18 were also evaluated in the T-33 prior to first flight. A lateral sensitivity problem not demonstrated in the ground simulations was disclosed, although not as severe as in the F-16, and the control system was modified prior to first flight. In all of these cases, ground simulation had inadequately predicted the effect of critical airplane flying qualities in "high gain" situations for the pilot. The in-flight simulator was able to replicate correctly the appropriate environment of motion/visual cues and task loading needed to expose the problem.

The Space Shuttle vehicle proved to have longitudinal and lateral control system deficiencies when required to perform a precise landing maneuver, which were only vaguely evident at best in the more sophisticated ground-based simulators. Subsequent investigations of the Shuttle's control system with the Calspan TIFS aircraft reproduced the problems and provided information used in design modifications to correct the deficiencies.

In light of this experience with aircraft which have a longer history of development, design refinements, and operational use, and considering the much greater uncertainties of V/STOL aircraft modelling, motion, and visual system requirements, and the more demanding V/STOL operational environment, it becomes clear that a V/STOL flight research capability is required both for its own sake and for the credibility it can ultimately provide for V/STOL simulation in ground-based facilities.

III. REQUIRED CAPABILITIES OF IN-FLIGHT SIMULATORS

There are several capabilities which need to be provided by an in-flight simulator to fulfill research needs for V/STOL aircraft design. These include:

a. Provide features for obtaining realistic tradeoffs between control system complexity and display sophistication for various task-oriented situations.

b. Provide the capability to define handling qualities requirements of a broad range of V/STOL concepts.

c. Provide the capability to allow solutions of specific handling qualities problems of existing or proposed V/STOL aircraft.

d. Provide for sufficient performance capability and suitable cockpit environment compatible with mission requirements such that realistic evaluations of handling qualities can be made under real-life operational conditions.

e. Provide adequate compatibility with ground-based simulators so that in-flight validation of ground-based results can be made to establish more meaningful flight envelope boundaries.

f. Provide for adequate representation of the performance parameters which influence handling qualities during RTOL and STOL operation in ground effect.

g. Provide sufficient flexibility to adequately represent airframe/propulsion system interaction effects representative of a broad class of V/STOL aircraft.

Details of the requirements to meet the foregoing capabilities are discussed in the following paragraphs. Some overlap in the requirements for the in-flight simulator in providing these capabilities is expected because of the interrelationship of the many factors involved. In addition, it may not be possible to provide all the aforementioned capabilities with only one type of in-flight simulator.

Control system/display characteristics. One of the key contributions to be made by an in-flight simulator to aid the design of V/STOL aircraft is a determination of the tradeoff between control system complexity and cockpit display sophistication. Several studies have shown that pilots will accept a less complex control system for IFR operation if adequate information is provided in a heads-up display (HUD). Ground-based simulators can effectively establish a broad data base on various control/display concepts and map out the range of variables of interest. Because control system/display complexity affects not only the operational utility of the aircraft but also has a great influence on the cost, maintenance, and reliability, a judicious selection of a concept is very important. The in-flight simulator is required to provide this more definitive selection using the real world environment of turbulence, accurate acceleration cues, noncompromised motion travel, and realistic pilot workload.

For this research activity, the in-flight simulator must have the capability to vary the control system characteristics and a programmable HUD.

Although considerable flight experience has been obtained on control characteristics for less sophisticated systems such as the rate-damped feedback used on AV-8A Harrier, systematic flight research is needed on more advanced systems, particularly on attitude/velocity decoupled systems and for a range of display formats with individual control concepts.

Requirements for examining V/STOL aircraft handling qualities. In order to adequately simulate the static and dynamic response of a broad range of V/STOL aircraft, it is desirable that the in-flight simulator have the following characteristics:

a. High control power about all axes

b. Low-control time lags, including thrust lag

c. Vertical (height) control

d. Disc loading close to the mean of the class

e. Wing loading close to the mean of the class

f. Variable feel control system

These requirements are quantified at two levels in Table 1, namely, a desired level and a minimum acceptable level. Included also are the current capabilities of several candidate in-flight simulator aircraft.

Higher control power is needed when simulating aircraft with a lower order augmentation system. With low augmentation (i.e., using only rate damping feedback), a wide variation in the static and dynamic characteristics of various V/STOL concepts exists and high control power is needed to duplicate this range of characteristics. As the level of augmentation increases, all the V/STOL concepts tend to have similar response characteristics, and the research aircraft requires less control power to duplicate these common characteristics. It follows that an in-flight simulator meeting the minimum acceptable requirements may have difficulty in duplicating the characteristics of some V/STOL concepts which have low levels of augmentation, and this detracts somewhat from its versatility. However, it is doubtful that any of the V/STOL concepts will be fully operational without high augmentation, and the lack of versatility may only impact on the ability to study fully the effects of augmentation failure for some V/STOL concepts.

Low-control lags are needed to insure that control actuator dynamics do not compromise overall aircraft response and also so that high gain following SCAS modes can be studied. It is difficult to simulate the characteristics of a concept with short-control lags using an in-flight simulator which has high-control lags. In fact, if the control lags are too high, a meaningful simulation may not be possible.

It follows that the foregoing desired requirements apply also to the use of the in-flight simulator to aid in the solution of specific handling qualities problems of existing or proposed V/STOL aircraft. For most cases, it would be necessary to degrade the characteristics of the in-flight simulator to initially match the specific problem from which a solution would be sought.

Vertical height control is also an important consideration for a satisfactory research tool. Table I lists the T/W available for several V/STOL aircraft. Implicit in this area is the point that long hover time available implies a greater excess T/W for height (flight path) control experiments since fuel weight can be traded for Δ T/W. An absolute (minimum) requirement for T/W is difficult to specify since many interrelated factors must be considered.

The last two items, disc loading and wing loading, although less important, nevertheless influence the ability of the flight simulator to adequately represent transition characteristics and behavior in ground effect of a particular concept being investigated. For example, simulation of a low-wing loading configuration with a high-wing loading research aircraft would be difficult because the magnitude of the forces and moments available may be too small to represent the effects of aerodynamic lift and drag through transition. Finally, disc loading effects would also be difficult (or impossible) to simulate with a given research configuration. Since both aerodynamic interference (suckdown) and recirculation and reingestion characteristics are functions not only of disc loading but also engine configuration (placement), the forces and moments generation capability of the in-flight simulator must be versatile enough to represent a broad range of characteristics.

<u>Solution of handling qualities problems</u>. Past experience with conventional variable stability aircraft such as the Calspan T-33 has indicated that successful use of in-flight simulation to solve problems of existing aircraft requires at least two essential ingredients: (1) a certain amount of flexibility in the variable stability control system, including variable control system mechanical (feel) characteristics, and (2) the ability to divorce the in-flight simulator's known aerodynamic characteristics from entering into the problem area.

For example, if control system problems were to develop on the AV-8B aircraft, the in-flight simulator must have the flexibility to cover all essential elements which relate to the problem. These could include adjusting the mechanical control characteristics by a variable feel feature to match the friction breakout, damping, and force gradient of the problem aircraft. In addition, a sufficient range of control power, control sensitivities, and response characteristics must be available.

The second requirement, the ability to isolate unwanted aircraft responses, requires the application of current model-following techniques with sufficient program computer capacity to store and recall the essential ingredients of the problem. The ability to uncouple axes, which is an inherent part of the requirement, may be difficult to achieve in all cases. For example, if side translation is needed without bank angle, a suitable side force mechanization must exist on the in-flight simulator.

Evaluation of handling qualities under "Operational" conditions. In order to provide meaningful handling qualities criteria for design of advanced V/STOL aircraft, the in-flight simulator must have sufficient performance capability and a suitable cockpit environment such that a close match can be made to real-life operational conditions. In regard to performance considerations, an important item is hover endurance. There must be sufficient fuel capacity to perform the complete terminal area task whether it involves a vertical or short landing. How much hover time is required for a successful in-flight simulator is difficult to specify; however, as a guideline, figure 1 shows the amounts available from several current and proposed aircraft. It would appear necessary to specify that at least 10 minutes of hover time be available to allow sufficient powered flight time for several circuits in the terminal area.

In-flight validation of ground-based simulation results. The major contribution to be made by the in-flight simulator is to improve on the points where the ground-based simulator results may be weak or suspect. Of concern are pilot cues including visual, aural, acceleration inputs, and a more realistic exposure to environmental effects of turbulence, unsteadiness in ground effect, etc.

Requirements for the in-flight simulator to provide satisfactory pilot cues include adequate cockpit visibility, proper sensors, and displays which give indications of the performance boundaries.

It is necessary for valid results to assure that the in-flight simulator represents the same aircraft model as the ground-based simulator. This requires that the inherent aerodynamic characteristics of the in-flight simulator are properly marked. In addition, if the task requires IFR operation, the in-flight cockpit must be reasonably similar to that of the ground-based simulator, including the "break out" features.

Provide performance and handling qualities characteristics peculiar to RTOL and STOL operation. The ability to simulate handling qualities during RTOL and STOL operation in ground effect is obviously difficult because strong configuration-dependent effects may predominate and overpower the force and moment producers of the in-flight simulator. The aerodynamic lift and drag characteristics in ground effect, which influence aircraft behavior, are usually nonlinear and depend on the number and type of lift units used as well as the placement and alignment of the thrust gases or slipstream. A key design requirement for the simulator is control of the thrust vector to allow adjustment of magnitude and direction, including decoupling of attitude/speed effects. There obviously are limitations in the ability of one type of in-flight simulator to adequately represent handling characteristics in ground effect for all types of V/STOL concepts. For example, the vectored thrust principle used on the Harrier could not be expected to adequately represent a 3 lift fan arrangement because of the difficulty in simulating the correct directional effects of the exhaust gases.

Representation of airframe/propulsion system interaction. Propulsion-induced effects are configuration dependent and relate to several interacting technology disciplines. The forces and moment producing capabilities of the in-flight simulator must be adequate to respond to the factors discussed in the following paragraphs.

Aerodynamic lift loss and asymmetric lift due to exhaust/inlet flow upon the aircraft surfaces in ground effect are critical issues for which analytical prediction techniques are weak and need validation. The exhaust flow can induce either lifting or suckdown forces near the ground. To study these ground effect problems the in-flight simulator must have programmable height control (variable T/W) and both positive and negative vertical height damping.

At low speeds the flow field of the propulsion system can dominate the flight behavior of the aircraft. In particular, adverse influence on the roll and pitch trim requirements has plagued the development of the majority of V/STOL aircraft. The requirements for researching this area with the in-flight simulator include appropriate means to accurately establish side velocity, fore and aft velocity, including the ability to decouple velocity and aircraft attitude.

IV. PAST/CURRENT EXPERIENCE WITH V/STOL IN-FLIGHT SIMULATORS

Previous sections of this report have discussed the need for in-flight simulators to validate the results of ground-based simulation in the flight environment and in some cases to uncover problem areas not identified because of shortcomings in the ground-based simulation. A detailed listing of the capabilities required of in-flight simulators compared with the characteristics of existing and proposed V/STOL aircraft are given in Tables I and II. With that in mind, this section will discuss the experience gained with current and past in-flight simulators and give an assessment of the positive and negative factors influencing their capabilities for conducting future in-flight simulation programs. The aircraft features restricting the in-flight simulation capability of these aircraft are listed in Table III along with those of some other possible in-flight simulation aircraft. These other aircraft will be discussed in later sections of this report. The aircraft discussed in this section are the variable stability X-22A, the tilt wing CL-84, the Bell X-14B, the CH-47B helicopter, the UH-1H VSTOLAND helicopter, and the Rotor Systems Research Aircraft (RSRA). Detailed descriptions of these aircraft and the associated flight programs are given in Appendix B.

IV-1 X-22A

The X-22A is a variable stability aircraft developed by the Bell Aerosystems Company which has four engines and four ducted propellers. The engines are connected to a common system of rotating shafts which distribute propulsive power to the propellers.

The X-22A has been used extensively over the past 13 years in three major areas of research: (1) obtaining flying qualities data for both visual and instrument STOL landing approach (refs. 1,2), (2) investigating control display and guidance requirements for VTOL instrument transitions (refs. 3-6), and (3) investigating V/STOL flying qualities requirements in hover and transition. The results of the STOL landing approach work were used in the establishment of flying qualities specifications and provided valuable data to aid in the design of STOL aircraft. Results have already been used in the AMST program which developed the YC-14 and YC-15 STOL aircraft for the Air Force. The investigations of control display and guidance requirements for V/STOL instrument transitions made a valuable initial contribution to understanding the problems of interaction of aircraft control system complexity, guidance requirements, display sophistication, and aircraft flying qualities. Acceptable and satisfactory control display combinations were defined and resulting HUD formats are being considered for the AV-8B. Investigations of V/STOL flying qualities requirements in hover and transition are currently underway and will continue through 1980.

The X-22A V/STOL Flight Research Facility has a number of unique positive attributes regarding its capabilities as an in-flight simulator. The following list summarizes the more important ones.

- Dual pilot cockpit (safety and evaluation pilot) both with full ejection capability for both pilots enhances safe operation.

- Variable control power is quite large and the feel system allows for wide variation of control force break-out and viscous damping characteristics.

- Extensive variable display capability (both headup and headdown), combined with in-flight control of display formats, allows for wide range of display investigations both for IFR and VFR operations.

- Vertical T/W of 1.35 allows for a single-engine-out hover capability.

- The aircraft transition envelope is reasonably wide allowing for in-flight simulation from hover through the transition flight regime.

The utility of the X-22A as a V/STOL simulator is somewhat limited by a number of factors as outlined below.

- The engine/fan systems are hover limited operationally to air temperatures below 80°F by gearbox temperature limits. This precludes significant amounts of hover flight during the summer months. Allowance for engine-out hover may further limit operations as a function of atmospheric conditions.

• The X-22A has only limited capabilities of producing uncoupled direct force in the longitudinal and vertical directions. There is no side force capability.

• Duct tilt rate is limited to 5 deg/sec controlled by an off/on switch which may impose limits on rapid transition characteristics.

• Maximum VSS flight speed is limited to approximately 125 knots. This precludes in-flight simulation at the "upper end" of the transition flight regime.

• The X-22A is nearing the end of its established service life of 500 flight hours. Upon completion of the current research program at the end of 1980 only 80 flight hours will remain.

IV-2 CL-84

The CL-84 is twin-turboprop V/STOL aircraft utilizing the tilt wing deflected slipstream concept. This two-engine airplane has a cross shaft connecting the propeller gearboxes to ensure symmetrical thrust. The cross shaft is also connected to two horizontally oriented, contrarotating tail propellers which are stopped and longitudinally aligned for conventional flight.

The CL-84 was used in two research programs: (1) an evaluation of various head-up display formats (ref. 7) and (2) an evaluation of the tilt wing concept in the shipboard environment (ref. 8). The CL-84 proved to be inadequate for the HUD evaluation. The most significant result of the shipboard trials was determination of the minimum acceptable thrust-to-weight ratio for this type of aircraft under relatively favorable weather and sea conditions.

The CL-84 does not appear to be a viable candidate for a V/STOL in-flight simulator and is no longer available as a research aircraft.

IV-3 X-14B

The Bell X-14B is a single-place twin jet VTOL aircraft which can serve as a VFR in-flight simulator for studies of rate and attitude stabilization requirements in hover and very low speed maneuvering flight.

The X-14A was used for VTOL research for over 15 years (refs. 9-12). Basic information has been obtained regarding control sensitivity, damping, and control power required for hover, the effect of size on hover control requirements, the use of direct side force control for lateral translation, and the effect of various trajectories and piloting techniques for VTOL operations in general. The X-14B, with its model following system, is currently being used to obtain more accurate and more extensive information on:

1. control force-feel characteristics

2. control sensitivity requirements

3. rate and attitude stabilization requirements

4. response lag tolerances

5. translational rate feedback systems

The positive attributes of the X-14B are its relatively high flexibility and fidelity in the reproduction of rotational characteristics, its simplicity, and its low cost of operation. Principal limitations of the system are its constraint to VFR hover and low speed maneuvering flight, and its inability to translate in this regime by means other than rotation of the entire aircraft. These limitations are brought about by several factors, the most important of which is the lack of servo controls on the thrust vector. With the addition of that feature, the aircraft's usefulness could be extended appreciably. Its constraint to VFR investigations is permanent, however, since any kind of guidance/display capability would require, at the least, more thrust to carry the equipment and the addition of an ejection seat for safety.

Life status of the X-14B is sufficient to pursue all foreseeable research objectives of the vehicle, even if it were upgraded to include servo control of the thrust vector. The engines are essentially new and the airframe has no specific limitation at the present.

IV-4 CH-47B

The NASA/Army CH-47B is a twin engine tandem rotor helicopter with capability for variable stability and variable display research.

Research uses of the VALT CH-47B (and earlier CH-46) have emphasized terminal area control-display research, automatic decelerating approaches to touchdown and digital control system research (e.g., refs. 13-19). The full-authority variable stability system coupled with fairly high control authorities in pitch and roll implies the capability of simulating the moment and thrust characteristics of a wide range of helicopters for a variety of tasks. It is important to note, for example, that the use of differential blade collective pitch for pitch moment control results in no rotor "lag" of control inputs such as is typical of single, articulated rotors; hence, good simulation of pitch responses for hingeless rotors can be obtained. Likewise, the on-board computational capability, coupled with a programmable display capability, results in essentially unlimited flexibility for helicopter control-display research; the large speed range (up to 160 kt) is also attractive for VTOL terminal area research, and it is possible that gross deceleration characteristics of some V/STOL aircraft (e.g., AV-8A) can be simulated; the lack of independent fore-aft force effectors precludes, however, the capability to examine thrust vectoring control concepts. For helicopters, therefore, the CH-47B has few limitations for general terminal area research, but VTOL flight simulation would require the addition of independent fore-aft effectors to make the aircraft useful in this context.

The CH-47B is currently being operated by Ames Research Center as a research aircraft.

IV-5 UH-1H VSTOLAND

The NASA/Army UH-1H VSTOLAND helicopter is a single engine, teetering rotor aircraft used for variable flight control and display research. The UH-1H VSTOLAND helicopter is entering its flight research phase for investigation of flying qualities for low altitude agility maneuvering. It has not been used previously as a variable stability research aircraft. Its primary limitations for V/STOL flight research concern its inability to conduct transitions representative of fixed wing V/STOL aircraft, its lack of thrust vectoring capability, and the limited control authorities available in its variable stability series actuators.

IV-6 RSRA

The two NASA/Army RSRA aircraft were designed and constructed by Sikorsky. These flight research vehicles are intended for comprehensive in-flight testing and verification of promising new rotor concepts and supporting technology. The RSRA is designed to fly as a pure helicopter, a compound helicopter, or a fixed wing aircraft.

A primary feature of the RSRA design is a rotor vibration isolation system to separate the rotor and aircraft dynamics and load cell sensing devices to measure separately the forces and moments produced by the rotor, wing, propulsive engines, and tail rotor.

The principal areas of rotor research at which the RSRA is aimed are:

- Evaluation of rotor performance and vibration for a wide variety of rotors and rotor control systems on a wide range of operating conditions between hover and 300 kt.

- Determination of those rotor aerodynamic characteristics not attainable from ground test facilities, e.g., rotary derivatives.

- Measurement of rotor noise characteristics.

The primary limitations of the RSRA as an in-flight simulator are its lack of longitudinal or lateral thrust deflection, limited pitch and yaw control powers, and the absence of electronic displays. In addition, the aircraft is designed for safe hover only in the helicopter configuration. The RSRA is just beginning its service as a research aircraft.

V. CANDIDATE OPTIONS

There are some options available beyond resumed/continued use of past/current in-flight simulators in their existing or modified form as described in Section IV and Appendix B. Three such options addressed by the Study Group are the V/STOLAND XV-15 Tilt Rotor Research Aircraft, a TAV-8A two-place Harrier modified as an in-flight simulator, and the YAV-8B advanced Harrier prototype aircraft with some modifications to enhance its flight research and simulation capability. These three aircraft options are described in Appendix C. Some of their attributes and restrictions as in-flight simulator options are summarized in figure 1 and Tables I and II, together with the other vehicles addressed in Section IV.

When comparing the required capabilities of V/STOL in-flight simulators as discussed in Section III with the various aircraft attributes and restrictions summarized in Tables I and III, it becomes readily apparent that none of the options using existing vehicles will meet all of the requirements. The full solution to achieving an adequate in-flight simulation capability for future V/STOL aircraft lies in the development of an entirely new research aircraft. However, to develop a new aircraft solely as an in-flight simulator would be prohibitively expensive. A viable solution would be to develop an in-flight simulator for a basic technology demonstration aircraft, such as in the now defunct NASA/Navy Lift-fan Research and Technology Aircraft (RTA) program. For the research aircraft to be capable of being a good in-flight simulator, the necessary characteristics (control, power, thrust to weight, etc.) must be embodied in the aircraft from the start. Such was the aim of the RTA program.

The probability of developing a new V/STOL research aircraft that would be available for in-flight simulation purposes is remote for the next several years. Accordingly, the best course of action appears to be to develop an interim capability, utilizing an existing aircraft. Of those aircraft listed in Tables I and II, those appearing to offer the most potential are the X-22A, CH-47B VALT, TAV-8A, and the YAV-8B. The issues concerning the use of each of these aircraft are briefly discussed in the following paragraphs.

<u>X-22A</u> - Of the four aircraft listed, the X-22A offers the greatest capability as an in-flight simulator. With the exception of duct rotation rate, the X-22A characteristics exceed all of the minimum requirements of Table I. The major problem with the X-22A is that during the aircraft development the service life was established at 500 hours. The aircraft design life is 1000 hours, but the reduced limit was imposed as a result of cutbacks in the qualification testing. At this writing the nature of the critical components and criteria used to establish the service life are not known. It is conceivable that the service life of the aircraft could be extended either through proper structural beef-up, shorter inspection intervals and/or more rigorous inspections, and re-evaluation of the criteria.

NASA CH-47B VALT - The CH-47B possesses considerable capability as an in-flight simulator. The problem is that it is a helicopter, and as such, the thrust vector cannot be deflected independent of body attitude. This characteristic precludes evaluation of decoupled attitude -- translational velocity control and transition from forward flight to hover, which is representative of fixed-wing V/STOL aircraft. It is possible to fit the CH-47B with some form of auxiliary thrust device and, to some extent, decouple the rotation from the translation. The degree to which this decoupling can be accomplished and the extent of the implementation problems with this concept are unknown and must be investigated before serious consideration can be given to the CH-47B as an in-flight simulator for V/STOL aircraft other than helicopters.

TAV-8A - The TAV-8A two-place Harrier has not previously been utilized as an in-flight simulator. However, in-depth studies conducted by the NASA have shown that with proper modification, the TAV-8A could possess substantial in-flight simulator capability. The limitations of marginal roll control capability and short hover time cannot be overcome in a short term modification program. Cost estimates to convert the TAV-8A to an in-flight simulator range from $25M to $40M. These relatively high costs, coupled with a lack of available aircraft, make the use of the TAV-8A in the simulator role very remote.

However, the United Kingdom is in the process of developing a limited in-flight simulation capability in an existing two-place Harrier aircraft. This aircraft will be used in extensive evaluation of various flight control systems and displays for instrument approaches both land based and at sea. The U.S. can, and should, seek in-depth information regarding these experiments through existing exchange agreements, such as IEP-B53, and through other less formal exchanges as may be arranged.

YAV-8B - Two YAV-8B aircraft were developed as prototypes for an advanced Harrier aircraft. These modified AV-8A aircraft were never intended to be used as in-flight research simulators. The aircraft flight simulation limitations are a consequence of restricted servo authority for attitude and thrust controls and thrust deflection are imposed to insure safe, single pilot operation. Furthermore, simulated IFR transitions down to realistic minimum altitudes cannot be made due to the lack of a safety pilot. Velocity command systems cannot be investigated during transition due to the limited servo authority available for thrust control and thrust deflection. Nevertheless, the YAV-8B does possess increased control power and greater hover lift capability than the TAV-8A. With suitable modifications, the aircraft could be made to have a significant in-flight simulator capability, especially in regard to displays and controls for its class of vehicle, and for simulation research at altitudes deemed safe for such single pilot operations. It should be noted also that the research value of the YAV-8B in its present form, though limited, is appreciable. To this end, consideration should be given to operating at least one YAV-8B in a flight research program after the completion of the Navy/Marine Corps flight test program. An extended flight research program can be defined that takes into account cost/benefit issues for the aircraft in its current form and with different degrees of modification to provide simulation capability.

VI. CONCLUSIONS/RECOMMENDATIONS

Based on the discussion and analysis contained herein, the following conclusions can be drawn:

A. V/STOL in-flight simulation capability is required if the United States intends to pursue the development of high performance V/STOL aircraft.

B. The only viable solution to developing the simulation with totally acceptable characteristics is to develop an entirely new research aircraft. Since there are currently no planned developments of this nature, the cost of developing a dedicated simulator is considered to be prohibitive.

C. An interim solution to providing at least a part of the required capability is the use of existing aircraft. Those showing the most potential as in-flight simulator facilities are the X-22A, CH-47B, and the YAV-8B aircraft which has good potential for control/display flight research for its vehicle class.

The following recommendations are made in light of the above conclusions:

A. The Navy initiate a study into all the factors that have been considered in the service life of the X-22A to determine the potential for extension of the service life beyond the present 500 hour limit.

B. The NASA initiate a study to investigate the capabilities, limitations, and cost of equipping the CH-47B with auxiliary thrust devices to enhance its capability as a V/STOL in-flight simulator.

C. The United Kingdom experiments using the RAE modified two-seat Harrier be closely monitored under the auspices of existing data exchange agreements and less formal arrangements.

D. A YAV-8B aircraft be made available to NASA, upon completion of the current Navy test program, for extended research flight testing including controls, displays, and flight simulation to the extent reasonably feasible for its class of aircraft in a one-place configuration. NASA should initiate definition of a flight research program including proposed aircraft modifications to enhance its research and simulation capability.

TABLE I.- AIRCRAFT CHARACTERISTICS REQUIRED FOR V/STOL IN-FLIGHT SIMULATION COMPARED WITH EXISTING/PROPOSED VEHICLES

AIRCRAFT	Wing Loading (Max VTOL) lb/ft^2	Disc Loading (Max VTOL) lb/ft^2	Control Power (Hover)				Control Time Constants				Max Thrust Vector Angle Rate °/sec
			Roll	Pitch	Yaw	T/W	Roll	Pitch	Yaw	Thrust	
Desired Requirements	50-100	500-1500	2.5	1.5	1.0	1.2 with 20 min hover	0.05	0.05	0.05	0.05	90
Minimum Requirements	50-100	100-2000	1.5	0.5	0.3	1.15 with 10 min hover	0.1	0.1	0.1	0.25	20
Proposed NASA/Navy RTA (Variable pitch fans)	80	700	2.28	1.98	0.92	See Figure 1	0.05	0.05	0.05	0.05	50
X22A	64	110	3.4	3.2	0.76	See Figure 1	0.015	0.015	0.015	0.015	5
X14	23	2500	1.4	0.75	0.4	See Figure 1	0.015	0.015	0.015	0.15	20
CH-47B VALT	—	5	1.9	1.9	0.9	Exceeds desired requirements	0.015	0.015	0.015	0.015	---
V/STOLAND UH-1H	—	5.5	2.5	1.0	1.8	Exceeds desired requirements	0.04	0.04	0.04	0.04	---
RSRA with propulsive engines	—	8.5	2.0	0.55	0.41	Exceeds desired requirements	0.015	0.015	0.015	0.015	---
V/STOLAND XV-15	88	15	2.0	1.2	0.34	Exceeds desired requirements	0.04	0.04	0.04	0.015	12
TAV8-A (G-VTOL)	90	2000	1.7	0.55	0.35	See Figure 1	0.04	0.08	0.04	0.25	90
YAV8-B	78	2000	2.34	0.55	0.3	See Figure 1	0.04	0.08	0.04	0.25	90

TABLE II.- V/STOL RESEARCH AIRCRAFT
(BASIC SYSTEM FEATURES)

	Requirements		Existing V/STOL Research Aircraft								Operationally Configured Aircraft	Aircraft Modified for Research		New Research Aircraft
			Fixed Wing		Rotorcraft									
	Desired	Minimum	X22A	X14	CH-47B	V/STOLAND UH 1H	RSRA	V/STOLAND XV-15	TAV8-A and TAV8-B	TAV8-A (C-VTOL)	TAV8-B	NASA/Navy RTA
No of pilots / Ejection seats	2 / Yes	1 / Yes	2 / Yes	1 / No	2 / No	2 / No	2 / Yes	2 / Yes	See following two columns	2 / Yes	1 / Yes	2 / Yes
Control Type	Two Independent FBW Digital Triplex	FBW Digital Simplex Att. Duplex Trans. with Manual Over-ride	FBW Analog Simplex with Manual Over-ride	FBW Digital Simplex Att. with Manual Over-ride Manual Thrust & Vector Angle	FBW Simplex Digital/Analog (Triplex Monitors) with Manual Over-ride	FBW Simplex Digital with Manual Over-ride	FBW Simplex Digital with Manual Over-ride	Manual with Att. SCAS	Manual with Att. SAS	FBW Digital Simplex, Duplex or Triplex With Manual Over-ride	Digital Simplex Augmentation With Manual Over-ride	FBW Independent Digital and Analog Triplex
Control Servo Authority	100%	40% Att. 100% Trans.	100%	100% Att.	100% Parallel 4 Axes	20%-40% Series 100% Parallel 4 Axes	100% Parallel 4 Axes	10%-15% Series SCAS	22%-50% Series SAS	100%	<40%	100%
Research Control System Computer	Programmable With HOL	Programmable With HOL	Programmable (Analog)	Programmable Without HOL	Programmable Digital/Analog Without HOL	Programmable Without HOL	Programmable Digital Without HOL	Fixed Analog SCAS	Fixed Analog SAS	Programmable With HOL	Programmable With HOL	Programmable With HOL
Research Pilot's Manipulators	All Easily Changeable	Flight Path Controllers Easily Changeable	Not Easily Changeable	Not Easily Changeable	Not Easily Changeable	Not Easily Changeable	Not Easily Changeable	Not Easily Changeable	Not Easily Changeable	All Easily Changeable	Flight Path Controllers Easily Changeable	All Easily Changeable
Electronic Display	HUD and HDD	HUD	HUD and HDD	None	HUD and HDD	HDD (Symbology Limited)	None	HDD (Symbology Limited)	HUD Fixed Symbology	HUD and HDD	HUD and HDD	HUD and HDD
Display Computer	Digital Programmable With HOL	Digital Programmable Without HOL	Digital Programmable Without HOL	—	Digital Programmable With HOL	Digital Programmable Without HOL	—	Digital Programmable Without HOL	Digital Non-Programmable	Digital Programmable Without HOL	Digital Programmable Without HOL	Digital Programmable With HOL
On-Board Inertial Sensors	Full Set	Full Set	Attitude Only	Attitude Only	Full Set	Full Set	Linear Accel. Attitude Accel, Rate & Position	Full Set	Att. Rates & Positions	Full Set	Full Set	Full Set
Low Airspeed Sensor	Yes	Yes	Yes (Loras)	No	Yes	Yes (Loras)	No	No	No	Yes	Yes	Yes
Long Thrust Deflect. / Lat. Thrust Deflect.	Yes / Yes	Yes / No	Yes / No	Yes / No	±5° only / No	No / No	Above 40 kt / No	Yes / No	Yes / No	Yes / No	Yes / No	Yes / Yes
Data Acquisition	Telemetry and On-Board Recorder 230 Measurands	On-Board Recorder 100 Measurands	Telemetry 200 Measurands	On-Board Recorder	Telemetry and On-Board Recorder 144 Measurands	Telemetry and On-Board Recorder 200 Measurands	Telemetry and On-Board Recorder 288 Measurands	Telemetry and On-Board Recorder 200 Measurands	None	Telemetry and On-Board Recorder 100 Measurands	Telemetry and On-Board Recorder 100 Measurands	Telemetry and On-Board Recorder 200 Measurands

NOTE: HOL - Higher Order Language; Att - Attitude; Trans - Translational; HUD - Head-up Display; HDD - Head-down Display

TABLE III.- AIRCRAFT FEATURES RESTRICTING IN-FLIGHT SIMULATION CAPABILITY

Aircraft	Major Features Restricting Research Capability
Proposed NASA/Navy RTA	None
X22A	Low thrust vector deflection rate No lateral thrust deflection Lack of some inertial sensors
X14	Single pilot, no ejection system Thrust and thrust vector angle not servoed No lateral thrust deflection No electronic displays Lack of some inertial sensors Limited control power No low airspeed measuring system Limited data acquisition
CH-47B	Very restricted longitudinal thrust deflection No lateral thrust deflection No pilot ejection system
V/STOLAND UH-1H	No longitudinal or lateral thrust deflection Limited electronic displays Limited large amplitude control bandwidth No pilot ejection system
RSRA	No longitudinal or lateral thrust deflection No electronic displays Limited pitch and yaw control powers Lack of some inertial sensors No low airspeed measuring system
V/STOLAND XV-15	Limited control system flexibility Limited electronic displays No lateral thrust deflection No low airspeed measuring system
Basic TAV8-A and YAV8-B	No control system flexibility Limited electronic display flexibility Limited control power No lateral thrust deflection Lack of some inertial sensors No low airspeed measuring system YAV8-B has single pilot
Modified TAV8-A	Limited control power No lateral thrust deflection Marginal hover duration
Modified YAV8-B	Single Pilot No lateral thrust deflection Limited control power

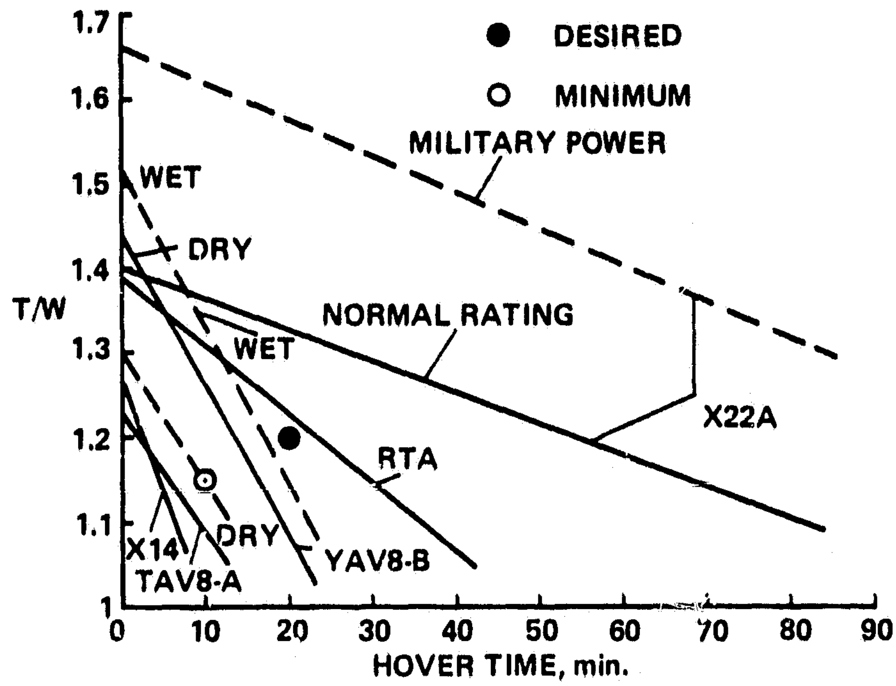

Figure 1.- Variation of maximum available thrust-to-weight ratio (T/W) with hover duration.

APPENDIX A

CHARTER FOR AERONAUTICS PANEL AD HOC STUDY GROUP ON V/STOL FLIGHT SIMULATION

Background:

The Navy is investing heavily in a joint endeavor to upgrade the ground-based simulation facilities at the NASA Ames Research Center for greatly improved capability to investigate V/STOL flight characteristics and systems. (The Army likewise is anticipated to participate in the ground-based simulator upgrade for helicopter needs.) However, both the Navy's X-22 and NASA's X-14 V/STOL flight simulation experimental aircraft are nearing the end of their service life. A continuing need exists for V/STOL in-flight simulation facilities to guide and validate the ground-based simulation, as well as to conclusively investigate those problems beyond the capability of even the best ground-based simulation. Both agencies have been unsuccessful to date in several joint and continuing independent attempts to acquire a modern V/STOL aircraft for in-flight simulation. A top down review under AACB auspices would be helpful in determining future actions.

Objective:

A. Review DOD/NASA requirements for flight test investigation of simulated V/STOL flight characteristics and systems.

B. Identify and broadly assess the technical adequacy of potential approaches for providing the identified flight test requirements.

C. Identify possible areas for joint DOD/NASA activity.

Scope:

For the purpose of this study group, the V/STOL flight simulation to be considered shall be that related to high speed non-rotorcraft type V/STOL aircraft. The DOD and NASA V/STOL flight test simulation requirements shall be identified as clearly and specifically as is feasible in relation to potential V/STOL aircraft and flight system development needs, and in relation to anticipated ground-based flight simulation programs.

Membership:

The primary non-rotorcraft V/STOL activities reside with the Navy and NASA, and they should co-chair the Study Group. However, there is some interplay with helicopter and CTOL military aircraft flight simulation of concern to the Army and Air Force, and they should be represented on the Study Group.

DOD Co-Chairman	NASA Co-Chairman
Mr. Raymond Siewert Naval Air Systems Command	Mr. Ralph W. May, Jr. NASA Headquarters

APPENDIX B

PAST/CURRENT IN-FLIGHT SIMULATORS AND ASSOCIATED RESEARCH PROGRAMS

Detailed descriptions of the six (6) in-flight simulator aircraft discussed in Section IV of this report are presented in this Appendix. In addition, past and current research programs utilizing the various aircraft are also discussed. The aircraft are the X-22A, the CL-84, the X-14B, the CH-47B, the UH-1H VSTOLAND, and the RSRA.

B.1 X-22A

The X-22A (fig. B-1) is a variable stability aircraft developed by the Bell Aerosystems Company with four ducted propellers and four engines. The engines are connected to a common system of rotating shafts which distribute propulsive power to the four propellers. Changes in the direction of the thrust vector are accomplished by rotating the ducts which are interconnected to rotate through the same angle between 0 and 95 degrees. Thrust magnitude is determined by a collective pitch lever, very similar to a helicopter. Conventional pitch, roll, and yaw controls in the cockpit provide the desired control moments by differentially positioning the appropriate control elements (propeller pitch or elevon deflection) in each duct.

In hovering flight the X-22A employs fore and aft differential blade pitch for pitching moments, left and right differential blade pitch for rolling moments, left and right differential blade pitch for yawing moments. A mechanical mixer directs and proportions the pilot's commands to the appropriate propellers and elevons as a function of the duct angle. Maximum speed in the present configurations is 150 knots and the aircraft is capable of full transitions from this speed to a hover.

The following are nominal X-22A control power levels available for variable stability at hover:

Roll (p) - 3.45 rad/sec^2

Pitch (q) - 3.20 rad/sec^2

Yaw (r) - 0.75 rad/sec^2

The available evaluation pilot's control force gradients range from 1.5 lbs/in to a "stiff" stick for pitch and roll and from 7 lbs/in to no displacement (stiff) pedals for yaw control. Frequency response data for the feel system indicates that it is approximately second order with a 2 Hz frequency and a damping of 0.6 which is considered to be sufficiently fast so as not to be a limiting factor for low speed simulation work.

Collective deflection of the elevons allows for a very limited amount of uncoupled longitudinal and vertical direct force implementation. The aircraft does not have the capability of producing direct side force.

The X-22A has primarily an analog Variable Stability System (VSS) which is augmented by an on-board digital computer. The VSS nominally operates in a response feedback mode to alter the aircraft characteristics in vertical, pitch, roll, and yaw degrees of freedom. The system has limited VSS capability in the longitudinal direction and no VSS capability in the lateral (side force) direction.

There are four VSS controllers - thrust, pitch, roll, and yaw - and three artificial feel servos for the evaluation pilot cockpit controls, each employing electrohydraulic servos. When rigged for VSS flight, the left hand flight controls are mechanically disconnected from the right hand flight controls and connected to the set of VSS pitch, roll, and yaw feel servos. The VSS thrust servo operates the boost servo for the collective pitch system. VSS pitch, roll, and yaw servos operate the right hand flight controls, moving the same linkages which are moved manually by the right hand pilot in normal non-VSS flight. (In fact, these same actuators serve a dual role by providing artificial feel for the primary flight control system when the VSS is not engaged.) Phasing of these control motions to the blades and elevons is accomplished by the mechanical mixer as for normal flight.

During VSS operation, the evaluation pilot occupies the left hand seat in the cockpit. The system operator, who also serves as the safety pilot, occupies the right hand seat. The evaluation pilot's inputs, in the form of electrical signals, operate the appropriate right hand flight controls through the electrohydraulic servos. In addition to the evaluation pilot's inputs, signals proportional to aircraft motion and relative wind variables (for example, angle of attack or pitch rate) are fed back to move the right hand controls in the required manner and thus modify the aircraft's response characteristics as desired. The response-feedback and input gain controls are located beside the safety pilot and are used to set up the simulation configurations in flight. Note that the evaluation pilot cannot feel the basic X-22A control motions caused by the variable stability system. An electronic control limiter can be inserted in any channel to systematically change the control power available to the evaluation pilot.

A unique feature of the X-22A VSS is that the response feedback gains are programmable with velocity throughout the full range of airspeeds, from -30 knots rearward through zero to 150 knots forward airspeed. This is accomplished by a multi-channel function generator which receives its airspeed input from the LORAS (Linear Omnidirectional Resolving Airspeed System). A second LORAS is located on the nose boom to measure the vertical component of airspeed, specifically for VSS work in hover.

Another unique feature of the X-22A is the Feedforward Flight Control System (FFCS). This is a limited authority, precision control system which acts like a vernier on the basic X-22A flight control system during VSS operation. The FFCS makes it possible to achieve extremely high precision in positioning the actuators for the X-22A aerodynamic controls - propeller pitch and elevon angle. Such control system precision is required for the satisfactory operation of the "closed-loop" VSS airplane.

In addition to the variable stability and control capability afforded by the VSS, the X-22A aircraft systems include guidance and display equipment to permit variable guidance and variable display investigations. These systems consist of several computational units plus both a Head-Up Display (HUD) unit and a Head-Down Display (HDD) cathode ray tube. Other features of the X-22A include a Microwave landing system capability and an extensive data acquisition and processing system.

The first three X-22A research programs were supported by the X-22A Interagency Steering Group, composed of Navy, Air Force, NASA-Langley, and FAA personnel. Starting with the fourth program, sponsorship has been totally Navy generated. The first two X-22A experiments involved STOL flying qualities research for the landing approach (refs. 1 and 2). The third and fourth programs concentrated on control system, display and guidance requirements for VTOL aircraft instrument approach and landing with the fourth program specifically addressing requirements for the AV-8B advanced Harrier (refs. 3-6). The current research program is investigating V/STOL flying qualities requirements in hover and transition. Each program is described in somewhat more detail in the following.

The first program on the X-22A investigated the effects of longitudinal short-term dynamics on flying qualities for both instrument and visual STOL landing approach. Fifty evaluations were made by two pilots of eighteen combinations of short period frequency and damping at two approach velocities (65 kt, 80 kt) for several representative steep STOL approach paths (6-10 degrees) in both noticeable and negligible turbulence. It is worth noting that essentially no flying qualities data of this type for STOL landing approach existed prior to the Task I program. A major purpose of the program was, therefore, to supply these data in support of flying qualities specifications (e.g., MIL-F-83300). The results of the flight experiment demonstrated clearly that steep STOL approaches under instrument conditions could be performed satisfactorily, given good short-term dynamics as defined by the data, with only ILS information displayed. Results of these studies were applied in the YC-14/15 STOL aircraft development.

The second program was considerably more ambitious and complex than the first. Two experiments were run concurrently. The primary experiment again was concerned with flying qualities for visual and instrument STOL landing approach, but this time the investigation centered on lateral-directional dynamics and roll control power requirements. Dynamic variables investigated in the experiment were roll mode time constant, Dutch roll frequency, roll caused by sideslip and yaw caused by aileron. To investigate roll control power requirements, the control power available was electrically limited in the variable stability system for selected sets of dynamic characteristics. Three pilots flew 109 evaluations of 17 sets of dynamic characteristics with several values of limited roll authority for four of these sets. Both visual and instrument STOL approaches were performed at a glide slope angle of 7.5 degrees and velocity of 65 knots. A large number of results was obtained from this experiment. Among the most salient were that approximately twice as much roll damping is necessary for satisfactory flying qualities than specified in MIL F-83300; a definite linearly degrading pilot opinion results from reducing roll control authority past a prescribed minimum amount, and the roll control power necessary to obtain satisfactory flying qualities is approximately half that prescribed by the MIL SPEC flying qualities specifications.

The other experiment explored and expanded the hover and transition capabilities of the X-22A variable stability system for use in follow-on flight experiments. The results of this experiment revealed no fundamental limitations of the variable stability system that might compromise future transition research, and, in fact, the first vertical landings on the VSS ever performed were made to demonstrate the capabilities.

The third flight research program using the variable stability X-22A aircraft was undertaken to investigate control, display, and guidance requirements for VTOL instrument transitions. The primary purpose of the experiment was to provide meaningful data related to the interaction of the aircraft control system and displayed information characteristics on pilot rating and performance during a steep decelerating descending transition from a representative forward velocity (100 kt) to the hover completely under instrument conditions. Extensive theoretical analyses and ground simulator verifications were used in the design of the 45-hour flight experiment to ensure maximum efficiency.

Thirty-seven in-flight evaluations were performed of combinations of five generic display presentations, ranging from position-information-only to four-axis control directors, and five levels of control augmentation systems, ranging from rate-augmentation-only to decoupled longitudinal and vertical velocity responses and automatic configuration changes. In addition, new guidance developments of fundamental importance to V/STOL instrument terminal area operations, including an Independent Thrust Vector Inclination Command (ITVIC) and a procedure for automatically switching between airspeed and groundspeed tracking to account for headwinds and crosswinds, were conceived, designed, and demonstrated during the experiment.

The task flown consisted of a localizer capture followed by a constant-speed acquisition of a 7.5° glide slope. At a point on the glide slope, the deceleration level of approximately .05 g was used. The final portion of the task consisted of the flare, continued deceleration to a hover at 100 feet, and touchdown.

Primary results of the program included the demonstration of an inverse relationship between control complexity and display sophistication, as was hypothesized in the experiment design, and the definition of acceptable and satisfactory control-display combinations. In particular, it was found that the explicit display of translational velocities is required for a satisfactory system, regardless of control system complexity or automation, and the rate-augmentation-only may be acceptable (though still unsatisfactory) only if full control director commands are provided in addition to velocity status information. Analysis of the results in terms of simple pilot-in-the-loop considerations and measured performance and workload were also conducted to provide initial guidelines for the design of future VTOL control-display characteristics.

The interaction of aircraft control system complexity, guidance requirements, display sophistication, and aircraft flying qualities presents a multi-dimensional research problem whose solution is not yet well understood. The program just discussed made a valuable initial contribution to understanding this problem for V/STOL instrument landing, and provided the background for the design of the next flight experiment.

The fourth flight research program using the variable stability/variable display X-22A VTOL research aircraft was undertaken with the objective of expanding the operational capability of VTOL aircraft under adverse weather conditions. The experiment investigated a matrix of control, display and task variables for the landing approach task in a ground simulation phase followed by an in-flight simulation phase. Aerodynamic characteristics of the McDonnell-Douglas AV-8B Advanced Harrier were simulated for a prescribed decelerating approach profile using the X-22A's variable stability system. Around this simulation an analog of the AV-8 control system was implemented to investigate a range of realizable control system designs. Combinations of these control concepts and a variety of head-up display formats and information levels were evaluated in flight for simulated instrument approaches. A total of 43 in-flight evaluations were obtained for 22 different configurations selected from a matrix of six flight control schemes and seven head-up-display formats. The flight control schemes included simple rate-SAS, rate-command-attitude-hold and attitude-command-attitude-hold systems. The display presentations were comprised of two basic formats, each of which provided orientation, airspeed, altitude, and range to touchdown. Variations on the basic formats involved display of velocity, velocity commands, control-directors and horizontal-situation information. Although the previously demonstrated trend of improved pilot rating with increased display information was not evident, one result of the experiment was that none of the display formats produced consistently satisfactory pilot ratings for the landing approach task when used in combination with the proposed AV-8B rate SAS. However, with more complex flight-control schemes, i.e., rate-command-attitude-hold or attitude-command-attitude-hold, satisfactory pilot ratings were obtained with a variety of display formats. Results of this program, particularly the resulting HUD formats, are being considered for implementation (at least in part) in the AV-8B.

The current X-22A flight research program began in April, 1978, and is scheduled to continue through the end of 1980. The objective of the program encompasses the development, modification, and validation of existing and proposed V/STOL flying qualities design guidelines and criteria. Three tasks are planned (each lasting 8 to 10 months):

Task (a) - Hover/low-speed static and dynamic criteria for VFR operations; emphasis will be placed on translational rate control system requirements.

Task (b) - Hover/low-speed static and dynamic criteria as affected by IFR operations.

Task (c) - Transition/conversion dynamic criteria. Task (a) is currently underway. The second and third tasks are to be planned in detail at a later time so that full use of evolving analytical and ground-based simulation flying qualities data may be made.

B.2 CL-84 TILT WING

The 13,000 lb. CL-84 (fig. B-2) is a twin-turboprop V/STOL aircraft utilizing the tilt wing deflected slipstream concept. Two 1,500 SHP T-53 engines drive two 14-foot diameter four-bladed propellers. A cross shaft connects the propeller gear boxes to ensure that symmetrical thrust is retained in the event of an engine failure. The cross shaft is also connected to a pair of 7-foot diameter, horizontally oriented, contrarotating, two-bladed tail propellers which are stopped and aligned with the longitudinal axes for conventional flight.

The low aspect ratio, constant chord wing can be pivoted about the 45 percent chord point, to a maximum tilt angle of 100 degrees by a ball screw actuator driven by hydraulic motors. The wing is almost entirely immersed in slipstream and has full-span leading and trailing edge flaps. These, together with the variable incidence tail plane are programmed with wing tilt to minimize trim changes automatically during conversion from hover and low speed flight to conventional flight.

Hover longitudinal control is achieved by varying tail propeller pitch; yaw control is accomplished by deflection of the slipstream-immersed flaps/ailerons; roll control is provided by differential variation of main propeller pitch; and height control is achieved by simultaneous variation of main propeller collective pitch and engine power. Available control powers in hover are:

Pitch	0.62 rad/sec^2
Roll	1.35 rad/sec^2
Yaw	0.11 rad/sec^2

As the wing is tilted downward during conversion, automatic mixing and scheduling programs smoothly convert the hover control functions to those of a conventional turboprop aircraft.

Stability augmentation is provided in the hover and transition flight phases. The stability augmentation system provides rate damping about roll, yaw, and pitch axes and attitude stabilization in pitch. There is no stability augmentation in the conventional flight mode.

The CL-84-1 Tilt Wing aircraft is not a variable stability in-flight simulator. However, it was used in a three phase Tripartite V/STOL instrumentation program among the U.S. Navy, the United Kingdom Ministry of Defense, and the Canadian Department of Industry, Trade, and Commerce, principally to evaluate various head-up display concepts and formats (ref. 7). The aircraft was also used in shipboard trials to evaluate the tilt wing concept in that environment (ref. 8). In the head-up display evaluation, each of the participating nations was responsible for a given phase wherein their particular display concept was evaluated. This included responsibility for analysis and documenting the results. Therefore, only the U.S. effort will be discussed here. It is felt that the results obtained during the U.S. phase are representative of the CL-84 capabilities as a V/STOL research vehicle.

The U.S. phase of the Tripartite program involved the evaluation of a head-up display with a real-world overlay for instrument approach and landing of V/STOL aircraft. The shortcomings of using a particular aircraft for generalized research is illustrated by the fact that all of the evaluation pilots considered height control of the aircraft during the conversion from approach to hover configuration, to be the most demanding task throughout the landing profile. Although the pilots reported that they could effectively use the runway symbol to assess the situational aspects of the conversion, it is apparent from both the measured height control performance and pilot comments that both the display and stability augmentation system characteristics were insufficient to meet the requirements of conversion for instrument flight conditions. No effort was made to improve the level of stability augmentation during these tests.

The shipboard trials of the CL-84 aboard the USS GUADALCANAL (LPH-7) were conducted to evaluate the characteristics of the CL-84 in that environment. While several interesting and enlightening conclusions resulted from that exercise, the most significant was that the minimum acceptable thrust to weight for this type of aircraft was 1.07. It should be noted that this value was derived under relatively favorable weather and sea conditions.

B.3 X-14B

The Bell X-14B (fig. B-3) is a single place 4300 lb. twin jet VTOL with a 24 PSF wing loading. In its current configuration it can serve as a VFR in-flight simulator for studies of rotational stability and control in hover and very low speed maneuvering flight. The system is a model-follower type consisting of adjustable force-feel stick and rudder pedals, an airborne digital computer, and a (model-following) autopilot operating with 100% authority over reaction-jet moment generators at the wing tips and tail. Roll, pitch, and yaw motions can be duplicated with less than 40° phase lag at a bandwidth of about 6 rad/sec. Control powers are approximately:

Pitch - 0.7 rad/sec^2

Roll - 1.4 rad/sec^2

Yaw - 0.4 rad/sec^2

Maximum standard-day thrust-to-weight varies from about 1.1 to 1.25 throughout a hover duration of 8 minutes.

The X-14A was used for VTOL research for over 15 years (refs. 9-12). Basic information has been obtained regarding control sensitivity, damping, and control power required for hover, the effect of size on hover control requirements, the use of direct side force control for lateral translation, and the effect of various trajectories and piloting techniques for VTOL operations in general. The X-14B, with its model-following system, will be used to obtain more accurate and more extensive information on:

1. control force-feel characteristics
2. control sensitivity requirements
3. rate and attitude stabilization requirements
4. response lag tolerances
5. translational rate feedback systems

B.4 CH-47B

The NASA-Army CH-47B helicopter (Fig. B-4) is a variable stability, variable display research aircraft. Briefly, the CH-47B is a twin-engine tandem rotor helicopter with a speed range of -30 to +160 kt and a payload of approximately 9000 lb. The basic aircraft control system, operated by the safety pilot, includes hydraulic boost actuators both near the pilot's station and below the swashplates, and incorporates dual series actuators for the basic Stability Augmentation System (SAS). Normal aircraft-type pitch, roll, and yaw controls in the cockpit provide the desired control moments through differential collective blade pitch (pitch), lateral cyclic (roll), and differential lateral cyclic (yaw); thrust magnitude is determined by a collective pitch lever which commands collective blade pitch on both rotors. Available control powers at hover are approximately:

Pitch - 1.9 rad/sec^2

Roll - 1.9 rad/sec^2

Yaw - 0.9 rad/sec^2

Thrust-Weight - 1.5

As part of the TAGS program (refs. 13 and 14), the CH-47B control system was modified to incorporate a full-authority four-axis (pitch, roll, yaw, thrust) fly-by-wire variable stability system, currently capable of functioning in either response-feedback or model-following modes. The evaluation pilot's control inputs (from the right-hand seat in this aircraft), in the form of electrical signals, are processed in both analog and digital computers, along with aircraft response measurements, and summed to operate the left-hand controls through electrohydraulic servos and a clutching system. A time constant of roughly 0.015 seconds for these servos permits high bandwidths in the variable stability system. The system operator, who also serves as the safety pilot, occupies the left-hand seat, and operates the aircraft through the primary flight control system when the variable-stability system is disengaged. A triplex digital monitoring system (HOME) monitors the fly-by-wire actuators during VSS operation and automatically disengages the system in the event of a failure. Current computational units are one Sperry (1819A) and one ROLM digital computers and an EAI TR-48 analog computer.

The sensor complement of the aircraft includes linear accelerometers for three axes, rate and attitude gyros for all three axes, airspeed (down to 40 kt), sideslip, and angle of attack. As presently configured, ground-referenced positions and velocities are available via a tracking radar and complementary filters; for future work, interface equipment appropriate for operations against MLS guidance will be required. The research capability of the aircraft is also somewhat constrained by the lack of low airspeed sensors for any of the three air velocity components, but this deficiency is expected to be corrected.

A variable display capability is currently achieved through either one or two CRT displays plus an electromechanical ADI. The CRT displays are driven by telemetered video signals generated by a ground-based computer facility, which is in turn linked to aircraft motions via telemetered states and commands from the airborne Sperry computer. An advantage of this system is a considerable degree of programming flexibility plus the capability to evaluate several formats during a given flight, but a significant disadvantage is the reliance on a ground station and an inability to generate stroke-written formats (e.g., HUD). It is planned to replace this display system with an on-board programmable symbol generator capable of driving two CRT's, one raster/stroke and the other stroke-only (e.g., two head-down displays or one head-down and one head-up).

Research uses of the VALT CH-47B (an earlier CH-46) have emphasized terminal area control-display research, automatic decelerating approaches to touchdown and digital control system research (e.g., refs. 15-19).

B.5 UH-1H

The NASA-Army UH-1H VSTOLAND helicopter (fig. B-5) is a variable flight control and display research aircraft currently operated at NASA-Ames Research Center. It is a single engine, teetering rotor aircraft with a speed range from hover to 100 knots.

The basic control includes hydraulic boost actuators which drive the main rotor collective pitch, longitudinal and lateral cyclic pitch, and the tail rotor collective pitch. Available control power in each axis at hover is:

Pitch	-	1.0 rad/sec^2
Roll	-	2.5 rad/sec^2
Yaw	-	1.8 rad/sec^2
Thrust/Wt	-	1.13

Control and display research capability is provided by the VSTOLAND avionics system. The left-hand seat is designated as the research or evaluation side while the right-hand seat is the safety pilot side and its controls will remain essentially as a basic UH-1H.

The flight control portion of the VSTOLAND system is one which utilizes a combination of a parallel and a series actuator in the linkage of each control. Both actuators are driven by the control laws as programmed in the on-board 1819B digital computer. Functionally, the series actuators, which are limited in authority (approximately 20-40%), are the faster responding actuators and thus act primarily on the transient behavior. The parallel actuators are full authority rate servos which act to off-load the series servos and thus provide a trimming function. One additional hardware element of the VSTOLAND control system is a disconnect device on the research stick which allows the pitch and roll cyclic to operate in a fly-by-wire mode. As indicated above, all flight control experiments will be flown from the left seat and thus in the event of a system malfunction or failure, control will revert to the right-hand seat.

Series servo authorities for each axis as a percentage of full throttle are:

Pitch	-	26%
Roll	-	29%
Yaw	-	30%
Collective	-	19%

All servos have rate limits of 20 deg/sec of blade pitch and bandwidths of 75 rad/sec. Parallel actuators have rate limits of 2.8 deg/sec and bandwidths of 40 rad/sec.

Displays which are installed in the left seat for the evaluation pilot are a standard electromechanical attitude director indicator and horizontal situation indicator and a cathode ray tube multifunction display presentation.

The evaluation pilot can select information to be displayed ranging from raw data to a three axis flight director and moving map presentation.

All VSTOLAND functions are implemented by software in the large VSTOLAND general-purpose digital computer. Software is highly modular, which provides flexibility for research and for interfacing with widely different aircraft. Selected parameters, such as control-stick steering mode gains, can be changed within safe limits in flight by the research pilot. Navigation is performed within the VSTOLAND computer by using dead-reckoning updated by NAVAID data in three dimensions and time. Software is provided for accepting data from inertial navigation systems and from navigation systems being developed by other government agencies which include a data link.

The UH-1H VSTOLAND helicopter is entering its flight research phase for investigation of flying qualities for low altitude agility maneuvering. It has not been used previously as a variable stability research aircraft.

B.6 RSRA

The U.S. Army and NASA have jointly contracted with Sikorsky Aircraft for the design and construction of two RSRA aircraft (fig. B-6). These flight research vehicles are being developed as a national facility to provide an efficient means for comprehensive in-flight testing and verification of promising new rotor concepts and supporting technology.

The RSRA is designed to fly as a pure helicopter, a compound helicopter, or a fixed wing aircraft. The basic configuration uses the dynamic components of the Sikorsky H-3 series helicopter with the rotor powered by two General Electric T-58-GE-5 engines. For the compound helicopter configuration, two General Electric TF-34-GE-400A turbofan propulsion engines are provided in addition to a variable incidence wing and horizontal stabilizer.

A primary feature of the RSRA design is a rotor vibration isolation system to separate the rotor and aircraft dynamics and load cell sensing devices to measure separately the forces and moments produced by the rotor, wing, propulsive engines, and tail rotor to an accuracy of 1 to 2%.

The principal areas of rotor research at which the RSRA is aimed are:

- Evaluation of rotor performance and vibration for a wide variety of rotors and rotor control systems on a wide range of operating conditions between hover and 300 kt.

- Determination of those rotor aerodynamic characteristics not attainable from ground test facilities, e.g., rotary derivaties.

- Measurement of rotor noise characteristics.

The aircraft is equipped with an advanced fly-by-wire digital control system to provide various rotor control systems and adequate vehicle handling qualities on a wide range of operating conditions with rotors of uncertain characteristics. This system has full authority, fast acting, (100% per second) control of the rotor and fixed wing surfaces, but is subject to override by a hardover monitoring system and by the co-pilot. The digital computer can be programmed to provide a wide variety of both manual and automatic flight control laws. In addition, the aircraft has an additional margin of safety by being equipped with a crew escape system.

The aircraft's control power in hover, with the basic rotor and in the helicopter configuration (no propulsive engines or wing) are:

Roll	4.0 rad/sec^2
Pitch	0.56 rad/sec^2
Yaw	0.46 rad/sec^2

The large roll control power is required because of the large moment of inertia in roll of the aircraft in the compound configuration (approx. 2.5 times that of the helicopter configuration).

The maximum practical hover weight of the RSRA is limited by the rotor power train to that equivalent to a rotor shaft thrust of about 22,500 lb. It is important to note here that the aircraft is designed for safe hover only in the helicopter configuration.

The minimum control speed of the aircraft in the compound configuration is limited, by control power, to about 40 kt.

The RSRA is just beginning its service as a research aircraft.

Figure B-1.- X-22A variable stability V/STOL aircraft.

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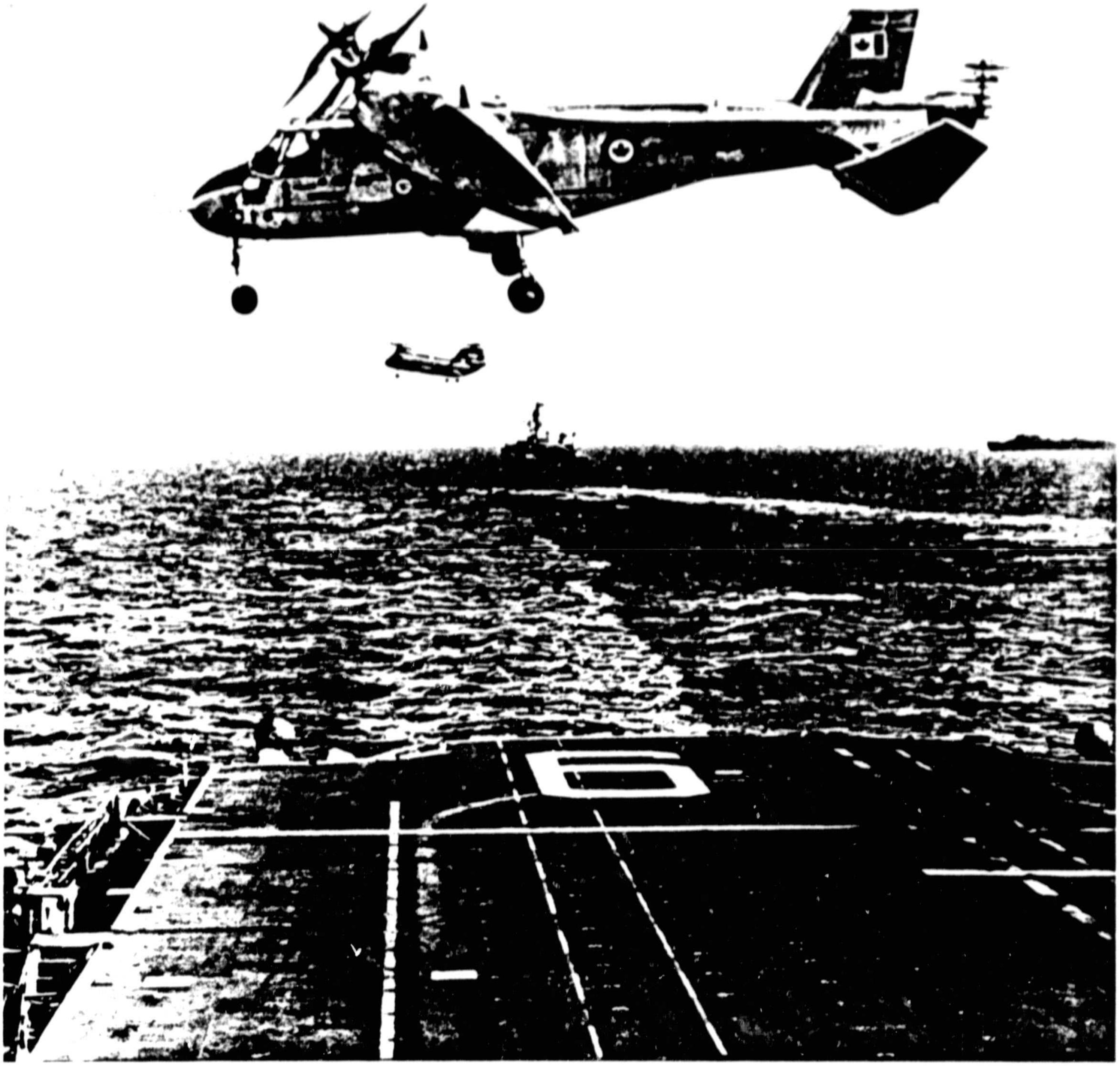

Figure B-2.- CL-84 tilt wing V/STOL aircraft.

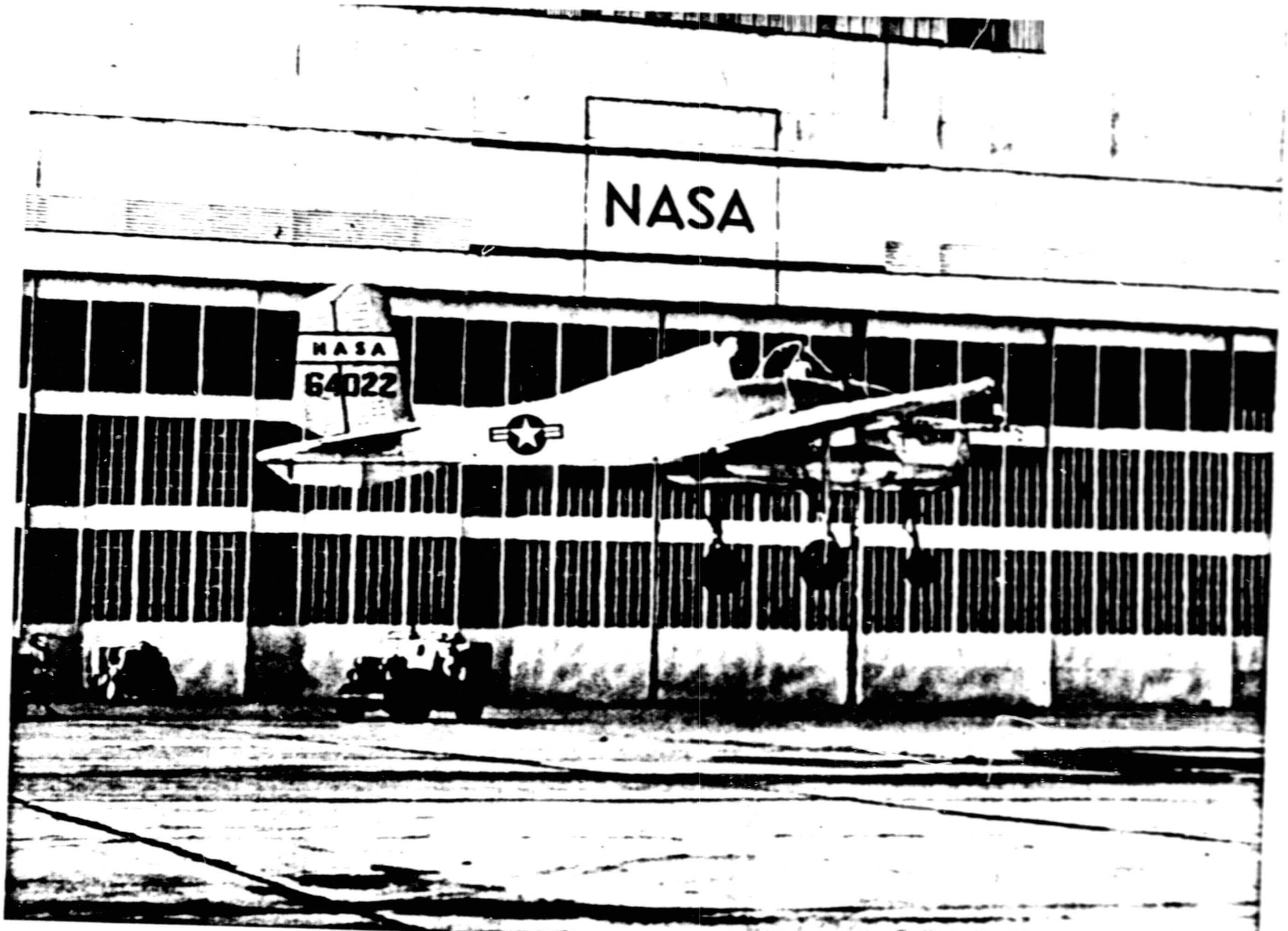

Figure B-3.- X-14B V/STOL aircraft.

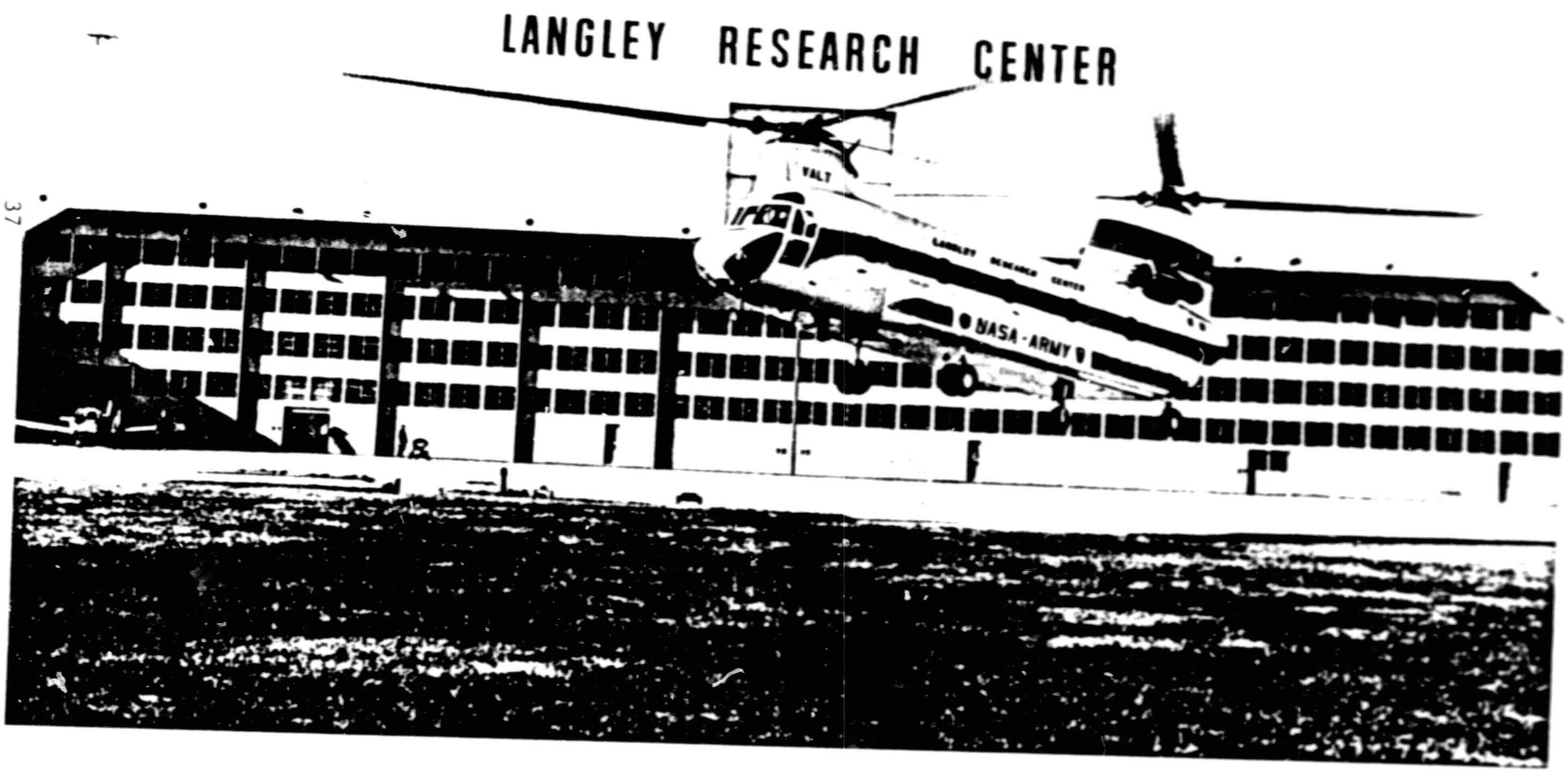

Figure B-4.- CH-47B variable stability helicopter.

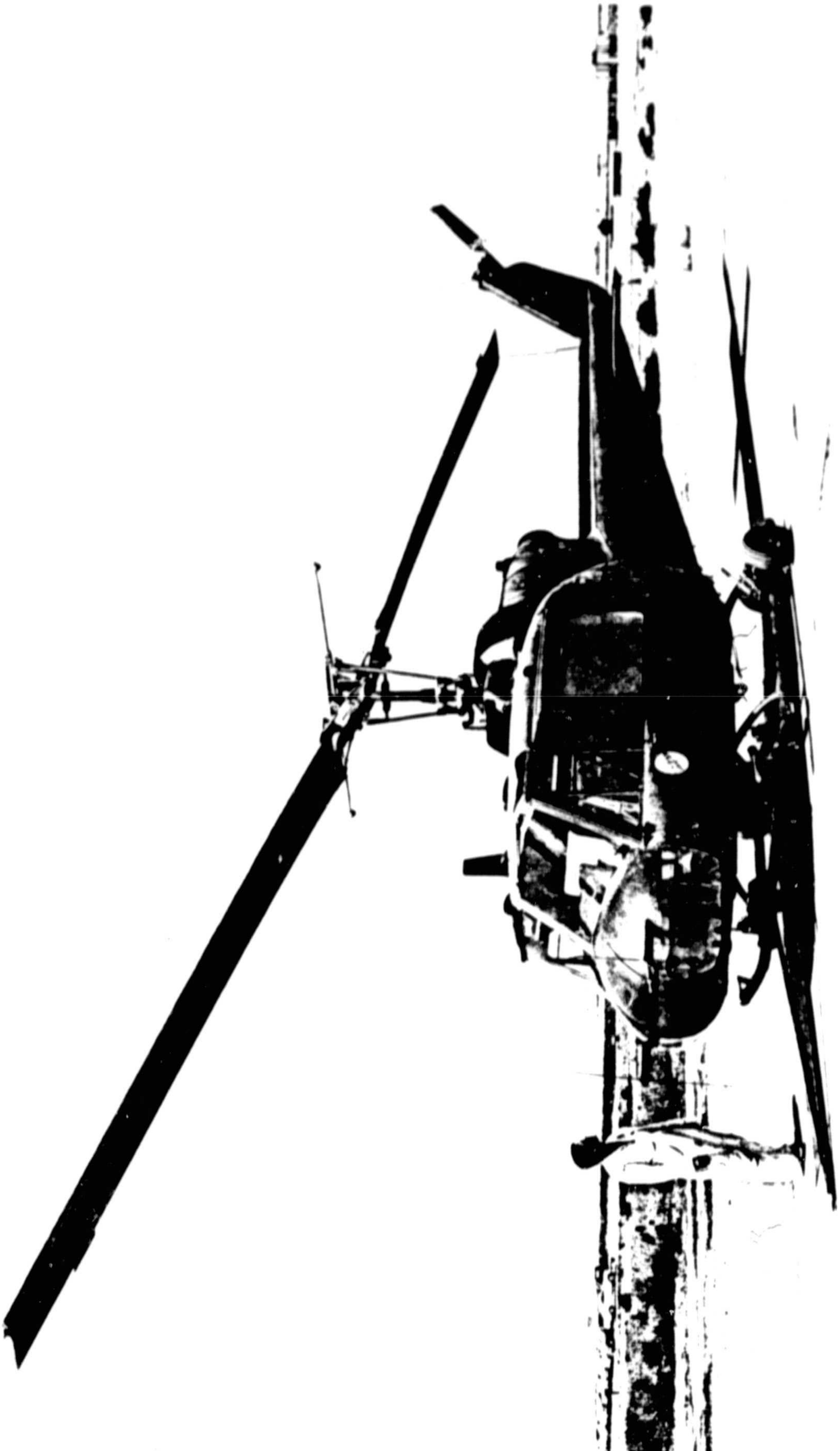

Figure B-5.- UH-1H helicopter.

Figure B-6.- RSRA (Rotor Systems Research Aircraft).

APPENDIX C

DESCRIPTION OF CANDIDATE OPTIONS OTHER THAN CURRENT SIMULATOR AIRCRAFT

C.1 XV-15 TILT ROTOR RESEARCH AIRCRAFT

The XV-15 is the product of several years of technology development carried out by the Army and NASA-Ames. The feasibility of the tilt rotor concept was initially examined using the Bell XV-3 aircraft. Subsequent investigation to provide solutions to the basic rotor/pylon/wing dynamic stability problems evidenced in the flight tests of the XV-3 have provided a technology base to develop a tilt rotor concept with a potential speed range from zero to 300 knots.

The primary objective of the XV-15 research aircraft program is to demonstrate the viability of the tilt rotor concept by verifying rotor/pylon/wing dynamic stability over a large speed range.

The XV-15 Tilt Rotor Research Aircraft (fig. C-1) has a design gross weight of 13,000 lb and a wing loading of 75 lb/ft^2.

The hover lift and cruise propulsive force is provided by low disc loading rotors located at each wing tip. The rotor axes rotate from the vertical (or near vertical), the normal position for hover and helicopter flight, to the horizontal for airplane mode flight. Hover control is provided by rotor generated forces and moments while airplane mode flight control is obtained primarily by the use of conventional aerodynamic control surfaces.

A cross-shafting system connecting the rotors provides several benefits. This system precludes the complete loss of power to either rotor due to a single engine failure, permits power transfer for transient conditions, and provides rotational speed synchronization. Rotor axis tilt synchronization is achieved by a separate interconnect shaft.

The aircraft is capable of high duration hover (approximately one hour at design gross weight), helicopter mode flight, versatility in performing conversion (steady-state flight is possible at any point in the broad transition corridor), and airplane mode level flight at speeds greater than 300 knots. The low disc loading rotors can be operated in the autorotation state to reduce descent rate in the event of total power loss. Research operation at the design gross weight allows for a total useful load of over 2900 pounds.

At intermediate rotor axis tilt angles (between 60° and 75°) the aircraft can perform STOL operations at weights above the maximum VTOL gross weight.

The Lycoming LTCIK-4K engines (a modification of the T53-L-13B) and main transmissions are located in wing-tip nacelles to minimize the operational loads on the cross-shaft system and, with the rotors, tilt as a single unit. The use of the free turbine engines permits the reduction of rotor rotational speed for airplane mode flight to improve rotor performance and reduce cruise noise.

The Tilt Rotor Research Aircraft utilizes 25-ft-diameter gimbal-mounted, stiff-inplane, three-bladed rotors, with elastomeric flapping restraints for increasing helicopter mode control power and damping. The forward-swept wings provide clearance for the 12° of flapping which will accommodate gusts and maneuver excursions while operating in the airplane mode. Wing/rotor/pylog stability is accomplished by selecting a stiff wing and pylon-to-wing attachment and minimizing the distance of the rotor hub from the wing. Airplane mode wing/rotor/pylon stability is retained up to airspeeds of 370 knots even with a 20-percent reduction in wing and pylon stiffness.

For hover flight, the wing flaps and flaperons are deflected downward to reduce the wing download and increase hovering efficiency. Hover roll control is provided by differential rotor collective pitch, pitch control by cyclic pitch, and yaw control by differential cyclic pitch. Pilot controls in the helicopter mode are similar to that of a conventional helicopter. A collective stick provides power and collective pitch for height control and a control stick provides longitudinal and lateral control.

In the airplane mode, conventional airplane stick and rudder pedals are employed while the collective stick/power lever continues to be used for power management. An H-tail configuration (two vertical stabilizers) has been selected to provide improved airplane directional stability around a zero yaw angle. Control authority for the power lever, blade pitch governor, cyclic, differential cyclic, differential collective, and flap/flaperon relationship are phased with mast angle of mechanical mixing linkages.

Safety is of paramount importance in the design of the Tilt Rotor Research Aircraft. The size of the Tilt Rotor Research Aircraft itself contributes to its safety. While the aircraft is large enough to accomplish the objective of the project, i.e., demonstrate proof-of-concept, it is also small enough for full-scale testing in the Ames 40- by 80-Foot Wind Tunnel prior to first flight. This feature can also be profitably exploited in later advanced research programs. Additional safety provisions include pilot and copilot zero-zero injection seats and redundant, fail operational critical aircraft systems and components. No single subsystem failure will result in a critical unsafe condition and, with automatic indication of the failure on the crew advisory light panel, normal flight operations may be continued. No double failure will precent the crew from exercising the option of ejection from the aircraft.

At this time the low speed envelope has been explored in hover and through transition (rotors full forward) up to a speed of 207 knots in conventional flight. Use of this concept for in-flight simulation would require modifications to the control system to a fly-by-wire type and a more thorough understanding of its flight dynamics and performance characteristics than is currently available.

C.2 MODIFIED TWO-PLACE HARRIER VTOL RESEARCH AIRCRAFT

One of the least expensive concepts for a VTOL research that has been studied recently by NASA is a modified two-place Harrier. A study was completed in 1978 to define the modification and to determine cost estimates for modifying the two-place Harrier No. G-VTOL (similar to TAV-8A) to provide a research capability to investigate criteria for VTOL flight controls, handling qualities, displays, and terminal area guidance. The basic concept considered for the research was to configure the aircraft in such a manner that the evaluation pilot (aft cockpit) can fly the aircraft through an advanced control system with advanced displays and guidance systems. The controls in the front cockpit would be standard Harrier controls and the front cockpit pilot would act as safety pilot. The evaluation pilot would control the aircraft through an independent fly-by-wire control system that includes digital computer and parallel servos to the five basic controls of the aircraft (pitch, roll, yaw, engine thrust, and thrust deflection angle).

The additions and modifications to the aircraft to provide the desired research capability are shown schematically in figure C-2 and discussed in the following paragraphs.

The major modification to the aircraft would be to mechanically disconnect the stick, pedals, throttle, and nozzle position lever from their respective systems and to install full authority parallel servos to drive the control systems. The disconnected cockpit control, the parallel servo, and necessary sensors would be interfaced to an on-board digital computer to provide a fully fly-by-wire capability from the aft cockpit. The controls in the front cockpit would be essentially unchanged and any motion of control elements due to the computer inputs would be reflected in the forward cockpit for the safety pilot. The control modification would enable various types of advanced control systems to be investigated by proper programming of the computer, including rate command, acceleration command, attitude command, velocity command, or combinations of the above.

The modification to the head-up display (HUD) to provide the desired research capability would include replacing the Current HUD Display Symbol Generator with a Programmable Display Processor (PDP). The pilot display units in the front and aft cockpits would be unchanged.

The direct replacement PDP is an all-digital-calligraphics generator under the control of a microprocessor. It can communicate with both analog and digital equipment and can simultaneously drive the two Pilot Display Units (PDUs) with an almost unlimited variety of symbology. The PDP has a Programmable Read Only Memory (PROM) enabling it to perform the HUD display function independently of the aircraft digital computer. This feature reserves the computer time for the flight control functions and provides the pilot with head-up primary flight data in case of computer failure.

To provide the guidance and navigation system research capability, an inertial navigation system, microwave landing system equipment, along with other sensors will be installed and interfaced with existing avionics equipment and the on-board digital computer and HUD. These system elements would provide for a wide variety of research in terminal area guidance and navigation applicable to simulated and actual small ship landing tasks.

A data acquisition system would be installed to provide for the measurement of the various parameters needed for the research. A low-speed airspeed system with high accuracy near zero airspeed would be installed. Many of the data acquisition components would be mounted in an external pod on the fuselage.

The study has shown that the modification and addition of the research equipment will increase the weight of the aircraft about 600 pounds. There will be sufficient fuel for two VTOL research mission circuits, five STOL circuits, or approximately 19 minutes of hover. Since the increase in weight will decrease the operational flight time, a weight reduction program would be a part of the modification to increase the fuel that could be carried for a VTOL liftoff.

Since most of the weight increase will be near the aircraft center of gravity, the available control power will not be significantly changed. The following table tabulates the maximum control power available in hover at maximum VTOL liftoff weight.

Axis	$\frac{\text{Maximum Control Moment}}{\text{Inertia}}$
Roll	1.58 rad/sec^2
Pitch - nose up	0.44 rad/sec^2
Pitch - nose down	0.62 rad/sec^2
Yaw	0.35 rad/sec^2

The above control powers provide for maximum control in one axis with at least 30-percent available in the other two axes.

An option to improve the roll control power is to install the wing tip puffers developed by the British for the Sea Harrier. The improved nozzle would provide a 10-percent increase in roll control power.

C.3 MODIFIED YAV-8B AIRCRAFT

The McDonnell-Douglas YAV-8B is a prototype modification of the Hawker-Siddley AV-8A "Harrier" single-place, single-engine, vectored-jet V/STOL aircraft. It has a wing loading of 78 lb/ft^2 and a hover thrust disc loading of about 2000 lb/ft^2. Principal improvements relating to terminal area flight are an increase in VTO lift near the ground (reduced negative ground effect), an increase in roll control power, and greatly improved STOL performance. With an operating VTO weight of 12,400 lb plus fuel, the YAV-8B should be able to hover at least 15 minutes with a dry thrust-to-weight ranging from 1.2 to 1.4 as fuel burns off. Control powers are about 2.3 rad/sec^2 for roll, 0.5 rad/sec^2 for pitch, and 0.3 rad/sec^2 for yaw. Roll and pitch stability can be augmented by rate and attitude feedback to series servos having 50-percent authority over the control moment generators. Yaw stability can be augmented by rate feedback having 22-percent authority.

The research value of the YAV-8B in its present form is limited but nevertheless appreciable. Although it cannot be used to simulate other aircraft, much can be learned about the flight characteristics peculiar to its own configuration, which is and probably will remain, an important one. At the same time, valuable flight experience can be accumulated in the framework of realistic terminal area tasks using the vectored-jet VTOL concept. This kind of first-hand exposure is essential to the development and execution of a rational research program. And the relatively ample values of hover endurance, thrust-to-weight, and control power are reasonable assurance that a useful range of terminal area flight tasks can be performed. Proposed modifications to increase its in-flight simulation capability are shown in figure C-2.

Initial work with the YAV-8B will focus on the definition of its flight envelope in the terminal area. Boundaries will be distinguished on the basis of performance limitations or handling deficiencies. Within the narrow range of variables afforded by the YAV-8B system, the effect of stabilization levels will be determined. In parallel with the flight work, a moving-base six-degrees-of-freedom simulation of the YAV-8B will be incorporated and maintained in the framework of a ground-based simulation being developed for both generic and specific VSTOL studies. The resulting capability for point-design comparisons will provide a necessary and continuing means for validating the transfer of simulator results to flight. Also, the YAV-8B simulation will be used to design modifications to that aircraft, especially if it is selected as the base vehicle for the development of an in-flight VSTOL simulator.

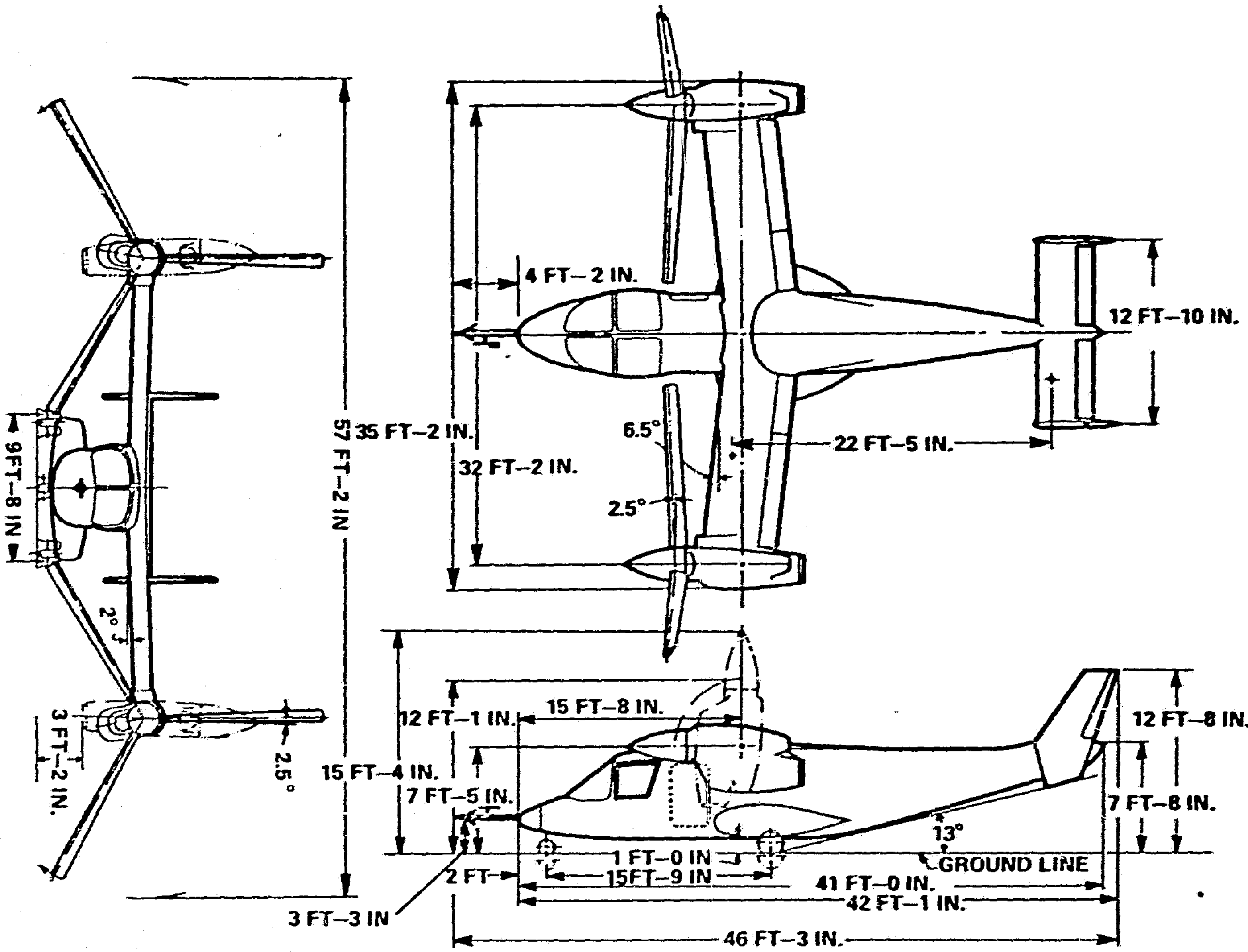

Figure C-1.- XV-15 Tilt Rotor Research Aircraft.

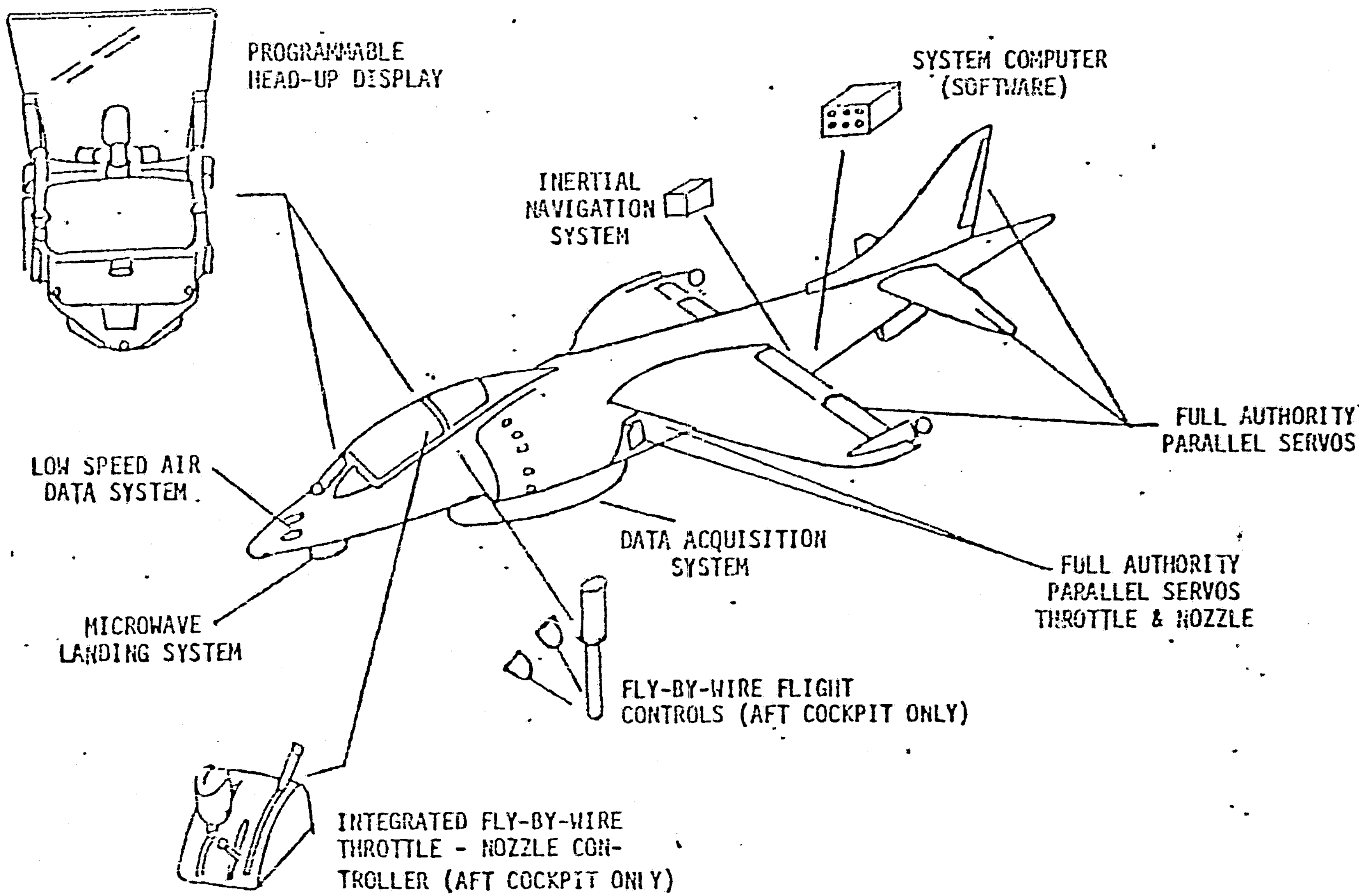

Figure C-2.- Modifications for Harrier VTOL Research Aircraft.

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