PAST APPLICATIONS AND FUTURE POTENTIAL OF VARIABLE STABILITY RESEARCH HELICOPTERS

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Summary

Variable-stability research helicopters began to be used more than 25 years ago to investigate flying qualities criteria for helicopters. However, their application was soon diverted to investigate mainly the problems of V/STOL aircraft. This emphasis prevailed until the past decade when the greatly increased use of helicopters for a wide variety of more demanding applications resulted in renewed use of these facilities for rotary-wing research. The historical development of variable-stability research helicopters and some of their previous applications are presented as a guide for assessing their future potential. The features of three general-purpose rotary-wing flight research aircraft that provide complementary capabilities are described briefly, and a number of future applications are proposed.

Introduction

In the past 25 years, variable-stability aircraft have made major contributions to the formulation of flying qualities criteria, guidance, control, and display systems requirements. They have also been used as development tools for particular designs, and as training vehicles to demonstrate a wide range of generic control characteristics or to provide pilot familiarization prior to flying a new aircraft. In the early days, use of these airborne simulation facilities was fairly extensive, since ground-based simulation equipment, if it existed, had extremely limited capabilities. Until recently, this was particularly true for helicopters and V/STOL aircraft, for which the motion and visual requirements in hover and in low-speed maneuvering flight placed severe demands on simulation fidelity. Today, however, major advances in the capabilities of ground-based simulators, exemplified by the Vertical Motion Simulator at NASA-Ames and by multi-window computer-generated imagery systems, have tended to cause much greater confidence to be placed in this means of aircraft and systems design, and criteria development. Nevertheless, variable-stability research aircraft have continued to be used throughout this period, during which their capabilities have improved and their applications have diversified.

It is the purpose of this presentation to review briefly the evolution of variable-stability research helicopters, with a view to emphasizing that these facilities are general-purpose in nature and represent major long-term investments similar to a large wind-tunnel or a sophisticated ground-based simulator installation. Some past and recent applications of several variable-stability research helicopters are reviewed as a means towards understanding the role that these facilities may have in the future. The features of three different variable-stability helicopters having complementary capabilities, and some of the considerations involved in airborne simulation technology are summarized to provide a basis for determining their future potential. To conclude, a number of applications to future rotorcraft research are noted.

The three variable-stability research helicopters which are given particular attention in this paper are the NASA/Army CH-47B and the NASA/Army UH-1H helicopters operated at the Ames Research Center, and the Bell model 205A-1 airborne simulator operated by the National Aeronautical Establishment (NAE) in Ottawa, Canada. A BO 105 rigid-rotor variable-stability helicopter operated in Germany(Reference 1), the NASA/Army Rotor Systems Research Aircraft (RSRA) described in Reference 2, and various other rotary-wing aircraft having a variable-stability capability, but which are in the class of technology demonstration or training vehicles, are not discussed.

Evolution and Past Applications

Historically, variable-stability research aircraft have usually evolved with the appearance of new classes of vehicles that have exhibited unsatisfactory or unusual flying qualities in their basic design, or in their subsequent application to more demanding flight tasks. For helicopters, one of the first developments of a variable-stability research vehicle that involved an electromechanical control system and electrical response-feedback techniques was at the NACA Langley Aeronautical Laboratory in 1955 (Reference 3). With this helicopter, various levels of control power, control sensitivity, and rate damping augmentation were evaluated in an effort to provide a data base for handling qualities criteria during instrument approach. For this control task, the military helicopter flying qualities criteria, MIL H 8501A (Nov 52), developed for visual flight, were found to be inadequate (Reference 4). However, it seems that the profusion of V/STOL configurations that also began to appear at this time re-oriented the application of variable-stability helicopters largely toward this field of research, an emphasis that persisted until about 1970.

During the period 1955-1970, more than 25 different VTOL and V/STOL non-rotary-wing configurations were test-flown by NATO countries. Although this number of V/STOL concepts was probably significantly smaller than the number of new helicopters introduced in the same period, attention was focussed on them because of their novel operational capabilities and the diversity in the design of their propulsive-lift and flight control systems, not to mention their often notorious safety record. In response to the need for criteria which could more efficiently lead to a successful and capable V/STOL design, a succession of efforts was undertaken by NASA (Reference 5), AGARD (References 6-9), and the U.S. military (Reference 10). To create an additional source of data for these efforts, the U.S. Army provided helicopters to NASA Langley and to NAE for modification as V/STOL research vehicles. These flight research aircraft, described in References 11 and 12, were the first to use the model-controlled method of airborne simulation which was originally proposed in Reference 13. As shown in Fig. 1, this method is virtually identical to a ground-simulation implementation except, in this case, the moving "cab" can follow the model-generated motion commands without restriction, and with fidelity determined by the bandwidth of response and the degree of pure (uncoupled) control achievable in that axis. Because only four relatively uncoupled controls are normally available in a helicopter, the motion can be accurately controlled only in four degrees-of-freedom, hence creating some limitations for the simulation of V/STOL and STOL aircraft. Nevertheless, significant contributions to the V/STOL criteria were made by these helicopters, and by other variable-stability research vehicles such as the Ryan X-14A operated at NASA-Ames, the Bell X-22A operated by Calspan, and the Short SC-1 at RAE Bedford.

In addition to the use of these facilities for the development of general V/STOL criteria, some of them were also used as development tools for specific designs. The use of the NAE airborne simulator in separate development programs for the Canadair CL-84, the Hawker-Siddeley P-1127 (Kestrel), the Vereinigte Flugtechnische Werke VAK 191B, and the DeHavilland DHC-7 is summarized in Reference 14.

Although some of these research efforts were also applicable to helicopters, such as in the areas of lateral-directional flying qualities and steep low-speed instrument approaches, it was not until the early to mid-seventies that rotary-wing applications began to be emphasized by the NASA and NAE variable-stability helicopters. By then, these facilities consisted of second and third generation research vehicles equipped with much higher capacity hybrid computing equipment (References 15-17). In response to an emphasis on all-weather capability, and in recognition of the potential for trading-off vehicle control system complexity for sophistication in cockpit displays, these aircraft also began to acquire the capability for flight-systems research involving advanced navigation equipment and programmable CRT displays. This change in emphasis away from V/STOL applications was perhaps partly due to the failure of any V/STOL aircraft (with the notable exception of the Harrier) to achieve operational application, from which would have emerged the much needed experience with which to validate, revise, or extend the V/STOL criteria. However, it was precisely this stage of development that was taking place for the helicopter. New and more demanding mission requirements were creating the need for improved flying qualities beyond those which had been adequate in the past. The nature of these requirements, and some recent applications of variable-stability aircraft in addressing them, are discussed briefly in the following section.

Recent Applications

Perhaps the most significant factor influencing the recent use of variable-stability research helicopters has been the strong civil demand for dual or single pilot instrument flight capability to support natural resource operations, or to allow effective commercial use of helicopters in weather conditions at least equivalent to CTOL operations under Instrument Flight Rules (IFR). Although the first instrument flight certification of a civil helicopter occurred in 1960, the strong demand of the seventies suddenly emerged at a time when the National Airspace System was ill-equipped to allow the unique capabilities of the helicopter to be used efficiently. This led the Federal Aviation Administration (FAA) to institute a broad program in cooperation with industry and NASA (Reference 18), parts of which were to better define the minimum requirements for helicopter IFR certification, and to investigate systems for improving the operational efficiency of rotary-wing aircraft in instrument flight conditions. Among research facilities that have been used in this program are the extensive ground-based simulation facilities at the Ames Research Center, and the UH-1H and B205A-1 variable-stability helicopters operated by Ames and NAE respectively. Three flight programs that were carried out in support of this requirement are described in References 19-21. As indicated, this requirement for flying qualities criteria arose differently than had been the earlier case for V/STOL aircraft, since in general, the helicopter manufacturers and the avionics companies were able to provide a satisfactory capability,without the need for detailed guidelines. Rather, the motivation for this effort was more to assess the validity and, where necessary, extend the scope of a set of "interim standards" which previously had been employed in the certification process.

Although there do not appear to be any major flying quality problems in current helicopters for the relatively conventional instrument approach task, there has been general agreement that their very low-speed capabilities have not yet been exploited for all-weather operations. As reviewed in Reference 22, a considerable amount of research in this area has already been carried out, much of it at the NASA Langley Research Center using the CH-46C and CH-47B variable-stability helicopters. Control and display requirements for carrying out decelerating approaches to hover in instrument conditions were investigated for both manual and automatic control as described, for example, in References 17 and 23. A more recent investigation in this area using the NASA/Army UH-1H helicopter, combined an automatic decelerating approach with a helical let-down trajectory designed to perhaps permit helicopter instrument approaches to a busy airport without impacting existing CTOL operations (Reference 24). The investigation of means to improve the operational efficiency of rotary-wing aircraft in the National Airspace System is well-suited to these variable-stability helicopters. Their broad sensor complement and programmable navigation, control and display systems allow for fairly rapid implementation of system conepts, followed by comprehensive evaluation in the real environment.

Unlike the need for helicopter all-weather capability that has persisted to varying degrees for the past 20 years, the military requirement for Nap-of-the-Earth (NOE) operations has more recently created genuinely new needs for flying qualities and agility criteria, and cockpit engineering advances to include both displays and controllers. This mission requirement is so severe that it can only be partially addressed in even the most advanced moving-base ground simulator, or in airborne simulators, where well-designed task elements perhaps could be separately developed towards a satisfactory solution. One research effort using the NASA/Army UH-1H variable-stability helicopter to evaluate different flying qualities during a simulated NOE mission is described in Reference 25. Another investigation, carried out in the NAE B205A-1, evaluated various multi-axis, isometric, side-arm controller configurations as alternatives to the conventional helicopter cyclic stick, pedals and collective controls (Reference 26).

Variable-stability helicopters have not been widely used by the rotorcraft industry as development tools for particular designs. However, some recent examples where specific flight programs have been conducted are described in Reference 27, pertaining to the RSRA, and in Reference 28, which describes the role of airborne simulation during part of the development program for the Sikorsky S-76.

The broad capabilities of these general-purpose research facilities have been characterized by referring to their past and recent applications. In the following sections, the principal features of three current variable-stability research helicopters having complementary capabilities are summarized, along with a short discussion of some of the considerations involved in implementing the technology of airborne simulation.

Principal Capabilities of Three Variable-Stability Research Helicopters

General Features

The NASA/Army CH-47B is a twin-engine tandem-rotor cargo helicopter capable of lifting an internal or external payload of approximately 10,000 pounds. The aircraft is specially equipped with high bandwidth parallel electrohydraulic actuators that are able to drive the basic helicopter control system over its full range through electrohydraulically-operated clutches. During variable-stability operation, the evaluation pilot's electrical control inputs drive these actuators through the flight computer and the engaged clutches, thereby operating the basic CH-47B controls. The parallel control mechanization permits the safety pilot's controls to follow the basic helicopter controls at all times, although in general, the action of the safety pilot's controls will be quite different than that of the evaluation pilot's. Several mechanical safety features are incorporated to insure that the safety pilot can control the aircraft in the event that a clutch fails to disengage following a system disconnect. This helicopter had originally been used in the technology demonstration program described in Reference 29. After its completion, the aircraft was acquired by NASA-Langley where it was modified for use as their third-generation variable-stability research helicopter (Reference 17). The aircraft was transferred to the Ames Research Center in 1979.

The NASA/Army UH-1H is equipped with the V/STOLAND avionics systems described in Reference 30. Its variable-stability control system consists of high bandwidth limited authority electrohydraulic series servos as well as lower bandwidth limited rate but full authority parallel electromechanical servos. The parallel actuators are used to off-load or to assist the series servos during sustained or aggressive maneuvers commanded by the evaluation pilot, or for following the lower frequency components of automatic control laws implemented in the flight computer. Although the action of the parallel servos can be isolated from the evaluation pilot's longitudinal and lateral cyclic controls, any action of the parallel servos in the main or tail rotor collective channels is reflected to the collective and pedal controls of both pilots. (The evaluation pilot can momentarily disable these parallel servos if their action interferes with his own control inputs; however, the series actuators may saturate during this time.) Despite these limitations, this aircraft can be an extremely effective research tool since it is supported by a dedicated fixed-base simulation facility that permits efficient development of flight software. The aircraft has been in operation at the Ames Research Center since 1977.

The NAE B205A-1 (Reference 16), essentially the civilian equivalent of the UH-1H, has been extensively modified to maximize its capabilities as an airborne simulator. It is equipped with full authority dual-mode actuators that were specially designed to replace the boost actuators of the basic production helicopter. The actuator servo valves are mechanically signalled when the safety pilot has control; in the variable-stability mode they are commanded electrically from the evaluation pilot's control via the flight computers. Other modifications include removal of the stabilizer bar to improve rotor responsiveness to cyclic inputs, and installation of a separate electrohydraulic actuator to drive the horizontal stabilizer which was disconnected from the longitudinal cyclic. The latter feature is generally not used except to trim fuselage attitudes in forward flight. This airborne simulator is the third such general-purpose research facility that has been developed by NAE. It has been carrying out various research programs since 1974.

Simulation Envelopes

The capability of a variable-stability helicopter to simulate the flight regime and dynamic response characteristics of other aircraft is limited in part by its own flight envelope, the control power available in each axis, and the bandwidth and authority limits of the electromechanical or electrohydraulic actuators used in the variable-stability system. As mentioned in a previous section, when only the four conventional helicopter controls are available, then motion can be controlled accurately in only four degrees-of-freedom. This has greater implications than just precluding accurate simulation of V/STOL or compound helicopter designs with their special longitudinal force-generating features, since sideforce and turbulence responce characteristics are also compromised. Although several airborne simulators for conventional aircraft have been operating for several years now with additional control devices installed to provide control over all six degrees-of-freedom, only NAE has undertaken serious study of possible configurations that could provide this capability in a helicopter.

An important consideration that can also strongly influence the available simulation envelope is the method used to monitor the acceptability of maneuvers generated during the in-flight simulation. Automatic monitoring of control rate and position is usually incorporated, particularly in the case where series servos are used in the variable-stability system. If only parallel or dual-mode actuators, such as those in the NAE B205A-1, are employed, then the safety pilot can be relied upon to a much greater extent for monitoring the remaining control margins. This usually permits simulations of more aggressive maneuvers such as may be encountered following simulated engine or stability augmentation system (SAS) failures. Flight programs where these considerations influenced the simulated evaluation task in contrasting ways are described in References 25 and 31.

A summary of factors influencing the available simulation envelopes of the three aircraft described here is provided in Table 1.

Modeling Techniques

A central issue in the use of variable-stability aircraft, and one which also influences the simulation envelope, is the fidelity of motion response that can be achieved during the in-flight simulation. For some investigations, such as those involving only generic flying qualities, the importance of accurately representing specific dynamic response characteristics may not be of great concern. However, the accurate simulation of a specific design, the investigation of higher frequency modes of motion, or the representation of turbulence response characteristics may require a level of performance from the variable-stability control system that is very difficult to achieve.

In general, control of the dynamic response characteristics is accomplished either using response-feedback and control-feedforward techniques, effectively equivalent to most conventional stability and control augmentation system implementations, or with model-following systems such as that shown in Fig. 1. Some of the considerations involved with each method are summarized in Table 2, which identifies that there are major advantages, at least theoretically, in using model-following techniques. Although model-following autopilots with quite good performance (i.e. moderate bandwidth) were relatively easy to develop for some of the earlier light single-rotor variable-stability helicopters (Reference 12), the larger facilities presently in use have presented difficulties that tend to be associated with control crosscoupling and higher frequency structural modes, which are in addition to the usual difficult aerodynamic and vibrational environments. The use of modern multivariable control system design techniques (e.g. References 32,33), or methods involving the inverse solution of the equations of motion of the basic platform (Reference 34), are possible means for improving the motion fidelity of variable-stability helicopters which could benefit the three facilities described here.

Platform Instrumentation

The in-flight simulation objective imposes severe accuracy requirements on the motion measurements of the helicopter which, in the final analysis, are used to validate the dynamic response characteristics. Particular attention must usually be devoted to in-flight steady-state and dynamic calibrations, especially for airspeed measurements, to obtain the degree of precision required of a general-purpose research facility. For example, the inertial and air mass velocity measurements in the NAE airborne simulator were developed to sufficient accuracy to warrant its use for several atmospheric wind and turbulence measurement programs (Reference 35). Of additional benefit, the frequent availability of redundant measurements from a variety of sensors, combined with the recent remarkable advances in digital computing equipment, now make it possible to implement modern state estimation and filtering algorithms to achieve improved accuracy and noise suppression.

While navigation equipment usually plays a supporting role for pilot in-the-loop flying qualities investigations, it can assume a more central role for investigations of a systems nature, such as curved decelerating approaches. These may be carried out using either manual or automatic control.

The motion and navigation sensor complements of the NASA and NAE research helicopters are summarized in Table 3.

Evaluation Pilot Controls and Displays

An important requirement in any piloted simulation is the representation of control force characteristics. Similar to sophisticated ground-based research simulators, nearly all variable-stability aircraft today have the capability to model a wide range of force-deflection characteristics, including breakout, hysteresis, viscous and coulomb friction, and nonlinear spring gradients. These characteristics may also be influenced by the motion of the simulated aircraft being "flown" by the evaluation pilot. The flexibility that the three variable-stability research helicopters have for varying the evaluation pilot's control characteristics is summarized in Table 4.

Rapid advances have also taken place in cockpit display system hardware that now make it possible to consider more difficult control tasks such as curved or decelerating approaches. The programmable display equipment available in the NASA and NAE helicopters is also noted in Table 4.

Computational Capacity

It is usually not possible for variable-stability aircraft today to employ the full potential of current computer technology. To take advantage of increasingly compact and more powerful computing equipment would compromise the availability of the aircraft for conducting research programs. As a notable exception to this statement, the NAE B205A-1 has recently been equipped with a locally-designed multi-microprocessor digital computing system that replaced the original minicomputer installation. This development has provided the ability to carry full laboratory operating-system software,and to implement on-line data handling programs in addition to the necessary flight programs.

While the NAE capability is exceptional, the computational capacity of the CH-47B and the UH-1H(V/STOLAND) research helicopters, listed in Table 5, is adequate to meet requirements at their current stages of development.

The objectives of presenting these brief descriptions have been to illustrate the differing yet complementary capabilities of these research helicopters, to identify areas where further development could be warranted, and to provide a basis for assessing the potential of these facilities to carry out future rotorcraft research. These considerations are discussed briefly in the following section.

Future Potential of Variable Stability Research Helicopters

There is little doubt that the application of variable-stability helicopters to various general or specific research and development problems would be broadened significantly if their capabilities were improved. Such indeed turned out to be the case when several of the conventional variable-stability aircraft developed five or six degree-of-freedom simulation capabilities in the past decade. Some of their applications to new classes of aircraft and to basic research in the field of human response studies, for example, are noted in Reference 36. However, achieving full six degree-of-freedom controlled motion capability in a helicopter is admittedly more complex. (The additional longitudinal and lateral force-generating capability in hover needs to be provided by an auxiliary reactive propulsion system.) Increased application to V/STOL vehicles is the usual justification given for proposing this capability, but may also be one reason why it has not yet been realized. A fairly large amount of longitudinal-force control power is usually considered necessary for this application; whereas, a considerably smaller amount could still permit investigation of important rotorcraft problems such as instrument flying qualities criteria with external loads (where oscillatory longitudinal motions can be a source of difficulty). In addition, simulations of large heavy-lift helicopters and airships might be possible.

Associated with an expanded simulation envelope is the continuous need for improved simulation fidelity. Greatly enhanced computational capacity combined with modern multivariable control system design methods should ultimately result in improved variable-stability system performance. If model-following methods are employed, an associated area to benefit is the simulation of wind and turbulence, including windshear. Also requiring improvement is the simulation of instrument flight conditions, particularly the transition to visual flight at instrument approach minimums. Technology to permit more realistic representation of this critial area would be of major benefit to all in-flight simulators, and possibly ground-based simulators as well.

The three variable-stability helicopters that are described briefly in this presentation could indeed benefit from these and other improvements. However. each has distinctly different and complementary capabilities that tend to focus its applications. The UH-1H (V/STOLAND) helicopter's navigation sensors make it ideally suited to investigations of a systems nature, such as terminal-area approach procedures, or the implementation and testing of new automatic guidance and control concepts. In this regard, a full-flight-envelope autopilot designed using the inverse model techniques described in Reference 34, is under development and is nearing flight test. Although the capability of this aircraft to simulate a wide range of flying qualities or to perform aggressive NOE-type maneuvers even with low levels of stability augmentation is severely limited by its variable-stability system actuators, the facility is considered adequate for representing the generic flying qualities of most current SAS-equipped helicopters during conventional instrument approach tasks.

Alternatively, the NAE B205A-1 is undoubtedly the superior vehicle for general flying qualities research, including the simulation of specific designs. Limited only by the inherent control power available from its teetering rotor, and its four controlled degrees-of-freedom, it is able, among other attributes, to accommodate aggressive maneuvers such as might arise from simulated systems failures, even when close to the ground. However, it has a limited cockpit display and navigation system capability with which to conduct advanced integrated systems investigations.

The CH-47B, also intended primarily for pilot in-the-loop flying qualities investigations, is distinctive for its ability to address problem areas associated with external load control. In addition, its greater amount of control power in pitch, which arises from the use of differential collective for this purpose, permits simulation of the response characteristics that may be associated with different rotor system designs. The aircraft is also equipped with a programmable symbol generator and associated electronic CRT cockpit displays, giving it the greatest capability in this area of the research helicopters discussed in this paper. However, the CH-47B is presently at a considerably lower level of development than the other facilities.

These aircraft are capable of making significant contributions to the development of flying qualities criteria and systems requirements for a variety of mission requirements applications, such as the FAA certification and military NOE programs mentioned earlier. In addition to the research programs that have already been undertaken, a number of other applications also within these general areas are as proposed:

1) The development of sensors and control laws for automatic hover control, including precision control of an external load and hover relative to a moving platform; and the development of stability augmentation systems and displays to support the manual execution of these tasks.

2) The investigation of stabilization systems for external loads in hover and in forward flight, along with associated flying qualities in instrument flight conditions.

3) The development of navigation, guidance, control and display system requirements necessary to exploit the very low-speed capabilities of the helicopter in instrument flight conditions in both remote and congested areas.

4) The evaluation of new man-machine interface technology, such as voice actuation, tactile controllers, and multi-axis side-arm controllers, that requires development to exploit new electronic flight control systems.

5) The investigation of energy management techniques and associated control and display requirements applied to engine-failure situations in single or twin-engine helicopters.

6) The evaluation of advanced theoretical control system concepts for which modeling errors and sensor noise and accuracy may represent major limitations.

An important aspect of these criteria and system development efforts that is sometimes overlooked is the determination of boundaries defining minimum acceptable standards for FAA criteria, or to meet Level II and Level III military flying qualities and performance specifications. This usually involves the systematic variation of configurations in realistic mission simulations for which general-purpose ground-based or airborne simulators are well-suited. Rarely, however, can a single facility provide all of the required data with the level of confidence necessary to establish criteria. Instead, a number of carefully planned investigations using facilities with complementary capabilities are usually conducted. The unique features of variable-stability research helicopters, such as those described in this presentation, offer important capabilities with which to address these issues.

Concluding Remarks

The application of variable-stability research helicopters to support new developments in the rotorcraft industry has increased significantly in the past several years. This has been associated mainly with developing criteria to support the recent widespread use of helicopters in more demanding missions, and to a lesser extent, with the development of new designs. Still, recognition of the potential of these facilities has been overshadowed by the confidence, much of it yet to be substantiated, that has been growing in the new capabilities of modern ground-simulation technology. This presentation has called attention to the historical development of these aircraft that places them in the class of long-term general-purpose flight research facilities. The review of their previous applications, and the summary of their current and potential capabilities that have been presented, suggest the nature of the applications that could emerge for these vehicles in the future. At a time when rotorcraft and flight control system technologies are making rapid advances, and the use of helicopters for a variety of new tasks is becoming more widespread, it is probable that variable-stability reseach helicopters will continue to serve an increasingly useful role.

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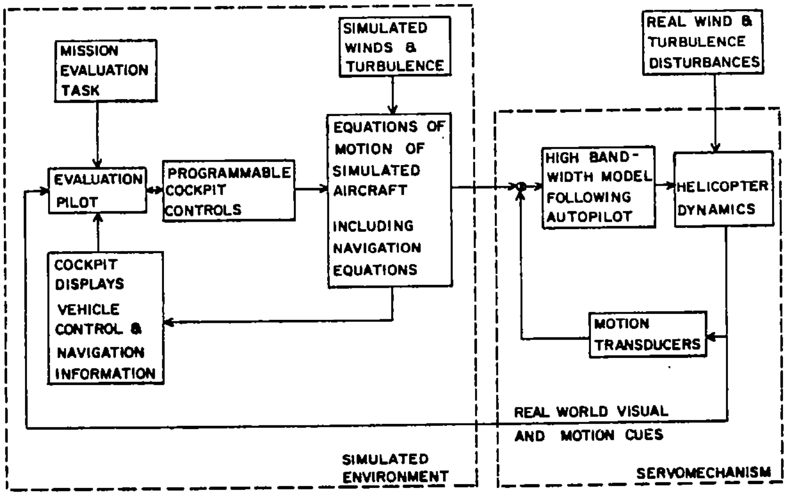

Figure 1. Model-Following Method for Airborne Simulation

Table 1. Comparison of Variable Stability Helicopter Simulation Envelopes

		NASA CH-47B	NASA UH-1H (V/STOLAND)	NAE B 205A-1
Flight envelope of basic production aircraft.		-30 to 160 kts longitudinally 35 kts in lateral flight. Maximum bank angle 40 deg below 145 kts, 20 deg at 160 kts.	-30 to 120 kts longitudinally 35 kts in lateral flight.	-30 to 120 kts longitudinally 35 kts in lateral flight.
Rotor system.		Fully articulated tandem counter-rotating rotors.	Single teetering rotor.	Single teetering rotor, stabilizer bar removed.
Basic controls available	. pitch . roll . yaw . heave . longitudinal pitch trim	Differential collective Lateral cyclic Differential lateral cyclic Main rotor collectives Independent longitudinal cyclic trim	Longitudinal cyclic Lateral cyclic Tail rotor collective Main rotor collective Mechanical elevator interconnect	Longitudinal cyclic Lateral cyclic Tail rotor collective Main rotor collective Independent elevator trim
Approximate control power in hover	. pitch . roll . yaw . heave^1	1.9 r/sec^2 1.9 r/sec^2 0.9 r/sec^2 1.4 g	1.0 r/sec^2 2.5 r/sec^2 1.8 r/sec^2 1.15 g	1.0 r/sec^2 2.5 r/sec^2 1.8 r/sec^2 1.2 g
Variable stability system actuator characteristics. Notes 2 vicinity 50hz 3 vicinity 40hz		Parallel ectrohydraulic actuatorsin 4-axes with 100% authority high bandwidth^2. Stop-to-stop travels achieved in approximately 1.5 sec.	Parallel electromechanical actuators in 4-axes with nearly 100% authority, lower bandwidth^3, and rate limits giving stop-to-stop control travels between 5.4 sec (collective) to 9.3 sec (tail rotor). Series electrohydraulic actuators in 4-axes with high bandwidth^2 and authority limited between 19% (collective) and 30% (tail rotor) of full travel. Rate limits 7 times faster than parallel servos.	Dual mode electrohydraulic actuators 4-axes 100% authority high bandwidth^2. Stop-to-stop travels achieved within 0.75 sec.
Control system monitoring		Basic helicopter control rates monitored by hardware system with adjustable trip thresholds.	Hardware and software monitors with trip thresholds based on persisting servo command-response errors.	Safety pilot monitors control rate and position except for trips near max swash plate angles sensed by flapping angle transducers.
Remarks		Longitudinal cyclic trim gives very limited 5 degree-of-freedom control.		Extension to 5 or 6 degrees of freedom with auxiliary thrusting engines under investigation.

Note 1 $T/W \doteq$ max wt for hover o.g.e. at s.l. with max cont. power/normal operating weight.

Table 2. Comparison of In-Flight Simulation Methods

Consideration	Response-Feedback	Model-Following
Implementation of simulated dynamics.	Desired dynamic response of each simulated configuration must be separately constructed from basic vehicle characteristics plus some combination of feedforwards/feedbacks.	Standard equations-of-motion model structure with aerodynamics of simulated vehicle incorporated directly for each program.
Requirement for precision on-line motion estimation.	Not necessarily required on-line.	Required for the degrees of freedom in which motion is controlled.
Requirement for in-flight dynamic calibrations for each simulated configuration.	Typically necessary to confirm characteristics.	Desirable but not generally required.
Knowledge required of basic vehicle response characteristics.	High precision.	Low precision except as needed for basic autopilot design.
Capability to control and simulate turbulence response.	Real turbulence effects not suppressed. Simulated turbulence response difficult to effect without influencing maneuver response.	Real turbulence effects suppressed. Simulated turbulence easily introduced, including windshears in the degrees of freedom that are controlled.

Table 3. Summary of Principal Instrumentation

	NASA CH-47B	NASA UH-IH(V/STOLand)	NAE B 205A-1
Motion Sensors in addition to 3-axis linear accelerometers 3-axis rate gyros Vertical and directional gyros	• INS linear velocities • INS gimbal angles • Laser doppler velocimeter low airspeed (3-axis) sensor planned • Instrumented boom with α, β vanes and static ports	• INS linear velocities • INS gimbal angles • 3-axis body-fixed Doppler radar • Loras and J-TEC low airspeed sensors • Laser doppler velocimeter low airspeed (3-axis) sensor planned (removable) • Instrumented boom with α, β vanes and static ports	• 3-axis body-fixed Doppler radar • Instrumented boom with α, β vanes and swivelling static port
Navigation and related sensors input to flight computers	• MLS • INS • Radar altimeter	• VOR/LOC, ILS • TACAN, DME • INS • MLS Cubic DME-based triangulation system • Radar altimeter	• MLS • Radar altimeter

Table 4. Summary of Evaluation Pilot Control and Display Hardware

	NASA CH-47B	NASA UH-IH(V/STOLAND)	NAE B 205A-1
Evaluation Pilot Controls	2-axis (pitch-roll) programmable force-feel system in procurement. Magnetic brake on collective lever and pedals. Adjustable spring cartridges on pedals.	Spring cartridge bungees with magnetic brake release and fixed gradients.	3-axis programmable force-feel system. Electric power lever or a collective can be installed. Side-arm controllers can be installed.
Cockpit Displays	Programmable electromechanical flight director (AD-350). Black and white CRT Displays-Electronic Attitude Director Indicator (EADI) and Multifunction Display with Programmable Symbol Generator.	Programmable electromechanical flight director (HZ-6F) and HSI. Programmable multifunction CRT display for situation and systems data.	Programmable electromechanical flight director (FD-109).

Table 5. Summary of Computational Capacity

	NASA CH-47B	NASA UH-IH(V/STOLAND)	NAE B 205A-1
Digital Computers	1 Sperry 1919A minicomputer 32K 18 bit words of RAM 50hz frame rate.	2 Sperry 1819B minicomputers each with 16K 18 bit words of RAM 50hz and 25hz frame rates.	3 PDP 11/23 microprocessors 48K RAM 64hz frame rate.
Analog Computers	EAI TR-48		120 operational amplifiers 60 integrators 120 manual pots 30 servo-set pots.