AIAA 93-3547

Lessons Learned From A Historical Review of Piloted Aircraft Simulations

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AIAA
Flight Simulation and Technologies Conference
August 9-11, 1993 / Monterey, CA

LESSONS LEARNED FROM A HISTORICAL REVIEW OF PILOTED AIRCRAFT SIMULATORS AT NASA AMES RESEARCH CENTER

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ABSTRACT

This paper traces the conception and development of piloted aircraft simulators at NASA Ames Research Center, starting with the first fixed based simulator in 1955 and continuing to the early 1990's. Problems with their development and operation and how limitations were handled are recounted. Advances needed in simulator equipment to improve performance and fidelity to gain pilot acceptance are discussed. The uses of these simulators in various aircraft research and development programs and their importance to aircraft design and flight testing are reviewed. Lessons learned include a better understanding of the tradeoff between motion cues and visual cues, the importance of simulation sophistication when examining aircraft with marginal handling qualities characteristics, and the continuing need for upgrading simulation technology as more complex problems are encountered.

INTRODUCTION

Piloted flight simulators have developed dramatically since the early Link Blue Box Procedures Trainer. Currently, simulators are used by industry worldwide for conceptual design studies and development of a wide variety of complex aircraft. Key elements in development of the simulator for research use include the visual display, the computation in "real time" of a math model of the vehicle being studied, the cockpit hardware including the mechanical characteristics of the control system, the instrument panel equipped for the specific study, and the mechanization of the motion system including motion wash out logic.

At the NASA Ames Research Center, piloted flight simulator development started in the mid 1950s with rudimentary fixed base types. Early on, the need for improved realism both in terms of cockpit motion cues and visual displays was recognized as more definitive answers were required for more complex problems. As a result, simulators were designed and developed to provide two, three, five, and finally six degrees of motion freedom, and visual displays increased in sophistication to provide out-the-window, wide field of view scenes approaching real life quality.

One may ask what the future holds for simulators by the turn of the century. A partial answer may be found by examining the past for the lessons learned which motivated continued advancement in simulator technology. It is convenient to review the history of piloted simulator development at NASA Ames where simulation has developed into a major national research facility. In particular, the purpose of this paper is to review the history of piloted flight simulation development to show what was needed to gain pilot acceptance for various research applications, and thereby focus attention on what needs to be done for continued improvement.

The scope includes a brief description and photo of each of several select multipurpose research simulators used in aeronautical studies at NASA Ames Research Center (excludes human-factors type simulators), examples of the types of research results obtained, and a review of the problems (and solutions) encountered along the way.

DISCUSSION

Rudimentary Fixed Base Simulator

Description and Research Projects

One of the early applications of piloted simulators for aeronautical research originated in the NACA time period, 1955, as part of a study to develop criteria for selecting carrier landing approach speeds (ref. 1). This

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simulator (figure 1) was very rudimentary, consisting of a control stick geared linearly to aircraft lift coefficient (no stick force gradient) through a first-order time constant, a throttle geared linearly to thrust, a stall-warning audible buzzer, a visual presentation of an airspeed indicator and a CRT showing altitude (horizontal line) above a ground reference with a shorter horizontal line to indicate vertical acceleration. These visual references were selected to give information on control of altitude, the primary reason given by pilots for selecting the minimum airspeed in most carrier approach landings. An analog computer was used to model basic flight characteristics for each of three carrier type aircraft.

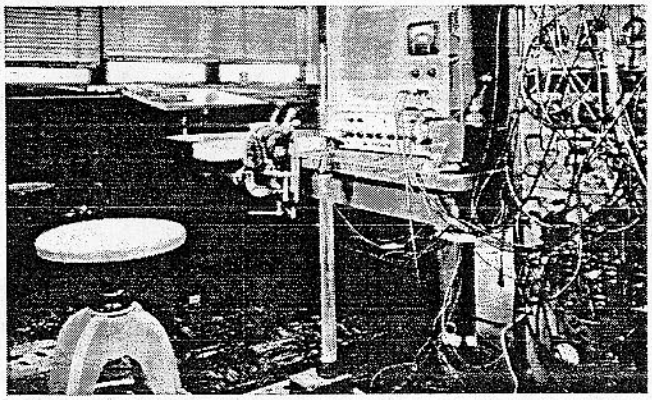

Figure 1. Rudimentary Fixed Base Simulator

Initially, the pilots were skeptical that the crude simulator environment would provide any degree of correlation with flight. However, after suitable adjustments were made to such items as stick gain (C_L per δ_e), throttle response, and thrust margin, reasonable correlation with flight was achieved for approach speeds (within 3 knots) for several Navy carrier aircraft.

Lessons Learned

- Because of the use of a "generalized" math model, lack of cockpit realism and lack of associated motion response, the pilot could not "identify" flying a particular aircraft, thereby restricting correlation to only those conditions where altitude control was the primary factor for selecting minimum approach speed.
- The simulator lacked the sophistication needed to determine minimum approach speed when other factors such as adverse stability and control characteristics were dominant reasons for choosing approach speed.
- In part because of the lack of motion cues, a form of atmospheric disturbance was needed to provide flight path excursions similar to those encountered in actual approaches since this factor directly impacts ability to control altitude and therefore the selection of approach speed.
- Although the pilots were less than enthusiastic about the credibility of their answers, this early study showed the potential for using piloted simulators to study important aircraft operational problems.

F-86A/D Cockpit Simulator

Description and Research Projects

Recognizing the need to improve cockpit realism, a fixed base simulator (figure 2) was made operational in 1958 using of the forward half of an F-86A/D airplane with the cockpit interior and controls closely resembling those of the actual airplane. The cockpit could be covered with an opaque canopy to isolate the test pilot from outside distractions or left open to provide a real-world view.

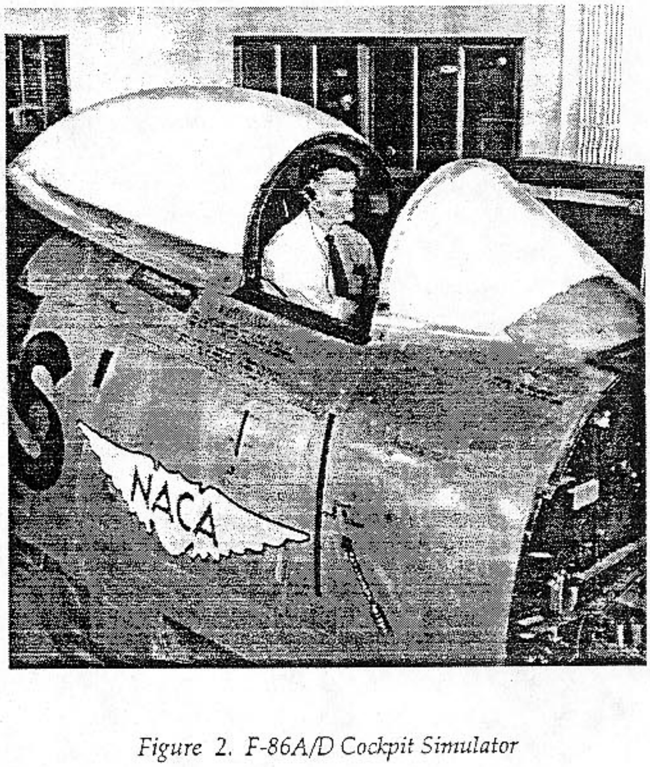

Figure 2. F-86A/D Cockpit Simulator

The only cockpit instrument was a 5" oscilloscope, which was used to display attitude and a target for a tracking task in a study of the effects of longitudinal control-system dynamics (ref. 2), and bank angle for a study of lateral control requirements for fighter-type aircraft (ref. 3). The drive signals to the oscilloscope were provided by an analog computer which solved the equations of motion for the airplane.

Lessons Learned

- These early studies showed that good correlation with flight test results was restricted to areas where handling qualities were satisfactory.
- Correlation with flight results was poor when exploring areas of low damping and poor stability or when investigating control characteristics conducive to pilot induced oscillations (PIO).
- Although the F-86 cockpit added realism, the lack of motion cues and good visual scene tended to produce results which were too conservative.

NE 2 Simulator

Description and Research Projects

The need to improve acuracy in establishing control system requirements by using motion cues resulted in the first motion research simulator (figure 3) introduced in 1959. It was called the NE-2 ("any two") because its gimbal arrangement provided mounting for roll and pitch, pitch and yaw, or yaw and roll motion. Approximately ± 45 deg angular motion was provided by an electric motor. An analog computer provided outputs for angular position, rate, and acceleration. The cockpit controls were similar to those of an actual airplane. Control requirements for a VTOL hover task were studied (ref. 4) with an open cockpit view of the outside world. In studies of lateral control requirements for fighter-type aircraft (ref. 3), the cockpit was covered, and a CRT and a limited number of panel instruments provided aircraft state information.

Figure 3. NE-2 Simulator

Although use of this first motion simulator was short lived, several historical points of interest indicated the importance of motion feedback. For example, the effect of an engine failure for the YF-12 aircraft in cruise (Mach 3) showed the importance of motion cues to provide an operationally acceptable control to avoid catastrophic directional divergence. In another case, a test pilot from the U.K. was given an opportunity to sample the hover control characteristics of the X-14 VTOL aircraft, which he was scheduled to fly at Ames before starting flight tests of the British Harrier VTOL aircraft. Apparently, the information provided in the practice runs in the simulator was inadequate since he did not eliminate lateral drift before touchdown, severely damaging the X-14 aircraft.

Lesson Learned

- The motion cues resulted in more accurate pilot opinion of control power and damping requirements for VTOL hover operation using the open cockpit visual scene.
- The pilots were able to use the roll angular acceleration cues to define satisfactory levels of lateral control power; however, large amplitude roll angles were not helpful for simulations of aircraft maneuvering because of unrealistic (disorienting) side forces imposed on the pilot.
- Multi-axes motion feedback was necessary to obtain good correlation with flight particularly for simulation of VTOL hovering when poor stability and low damping aircraft characteristics prevailed.
- The single place cab was adequate for studies of fighter aircraft control requirements, but the motion characteristics restricted studies to simple one axis tracking tasks where control cross coupling was essentially non-existent.

Five Degree of Freedom Simulator

Description and Research Projects

The Five Degree of Freedom Simulator (5DOFS) (figure 4) introduced in 1960 was designed for use as a piloted centrifuge test facility. It had a three-gimbaled cab mounted on a vertical track which, in turn, was mounted on the end of an 30 ft. arm (ref. 5). A circular rail on the floor supported the vertical track assembly. Two interchangeable single place cabs were available: one, representing a conventional aircraft was mounted facing radially outward, whereas the other, representing the pilot seated in a spacecraft, was mounted facing radially inward. In the former case, changes in side acceleration at the cockpit could be simulated by angular acceleration of the centrifuge arm.

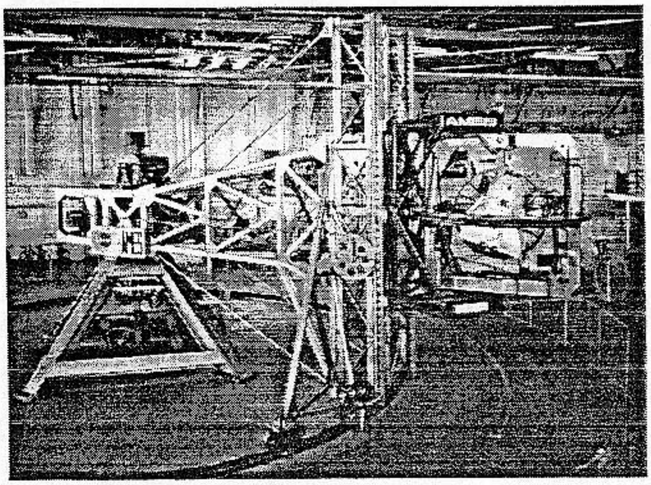

Figure 4. Five Degree-of-Freedom Simulator

Electromechanical servo systems driven by d.c. electrical motors provided rotary degrees of freedom, ±90° in roll, ±40° in pitch, ±70° in yaw. Translational motion was available in two directions, ±1.75 ft. vertically and unlimited sideward movement by rotating the centrifuge arm.

A single-place cockpit was equipped with a stick control, two throttles, and conventional flight instruments. In the three angular degrees of freedom mode, an external view of the real world was used. The cockpit was covered with an opaque canopy for conditions where side acceleration cues were required (ref. 5). In 1969, a televised visual display was installed in the cab.

General purpose analog computers were used to generate the commands for the motion system and instruments (ref. 6).

The 5DOFS was used primarily to study handling qualities requirements for supersonic transports (refs. 5, 7, and 8). Two historical contributions made by this facility are of interest (ref. 9). One was its use in the Gemini spacecraft program to subject potential astronauts to vibrations with the same frequencies and amplitudes as those that had been measured on the Titan launch system. These frequencies were in the critical range (3 to 10 Hz), which might debilitate astronauts during liftoff. The other historical contribution was a non-aerospace use of the simulator (1968) where a bullet fragment in a patient's brain was repositioned by centrifugal forces to a "safe" location.

The 5DOFS was dismantled in 1975.

Lessons Learned

- The 5DOFS centrifuge design did not provide a significant advance in the state-of-the-art for aircraft research studies primarily because of motion deficiencies.
- Providing only a small amount of vertical travel was ineffective since strong (disorienting) washouts were required to avoid hitting stops. In addition, since the cab was not counter balanced, dynamic response was non-linear; downward acceleration was fast and vice versa; therefore this motion was not used in research studies (ref. 7).
- Attempts to accurately reproduce and sustain side accelerations resulted in large velocities of the centrifuge arm which were objectionable to the pilot because of vibration (noise) and centrifugal acceleration effects. The use of washout to minimize the adverse centrifugal effects met with only limited success. In addition, dynamic response was poor due to cable stretch.
- Use of this facility for centrifuge research studies was not undertaken because of large amplitude vibration levels associated with the rail support system and safety concerns when tangential velocities of 60 mph were reached at 5 "g" acceleration.
- The 5DOFS demonstrated the desirability of using interchangeable cabs, where alterations of one cab could occur while the simulator was being used with the other cab.

Basic Simulator with External Horizon

Description and Research Projects

Another fixed base simulator, housed in a 20 ft diameter dome (figure 5), was used briefly in 1961 to investigate the value of extensive peripheral vision cues. The cockpit layout was similar to that of a variable-stability F-86E airplane, with conventional rudder pedals and center stick, a three-axis side-arm controller, and flight instruments.

The simulator had a novel visual system employing a two-axis servo-driven (roll and pitch) motion picture projector, controlled by an analog computer, to project a moving artificial horizon onto a 20-foot-diameter hemispherical screen. To the pilot, the image appeared to be a brightly illuminated layer of clouds several thousand feet below the simulator cockpit. Another projection method used an approach and touchdown scene obtained from a 16mm camera located in the cockpit of a fighter aircraft.

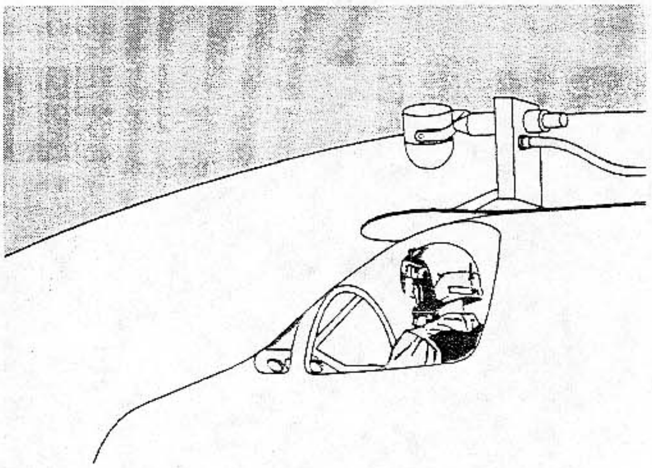

Figure 5. Basic Simulator with External Horizon

The simulator was used in a study of the effect of lateral-directional control coupling in the control-system for supersonic and hypersonic aircraft (ref. 10).

Lessons Learned

- Although the wide field of view provided a much improved bank angle reference, the simulator was not used extensively in part because of the limitations of the visual scene content and lack of motion cues.

- The strong visual cues supplied by the wide field of view horizon projector in the absence of motion cues were disorienting when large amplitude roll excursions were used.

- When the visual system was used for approach and landings with the preprogrammed movie scene, the results were only of subjective interest since no matter how much the pilot pitched and banked the aircraft on approach, a perfect landing always resulted.

- Projecting a useable real world scene over a large area required considerably more light intensity than was available.

Transport Landing-Approach Simulator

Description and Research Projects

In part because of the lack of success with the motion system of the 5DOFS, and the immediate need for research results in landing approach for transports, another fixed base system was developed. The Transport Landing-Approach Simulator (figure 6), which became operational in 1961, was a fixed base simulator equipped with a transport-type cockpit, a conventional cockpit instrument display, normal flight controls (with control forces provided by springs and dampers), and a general purpose analog computer programmed with math model equations of six degrees of motion freedom.

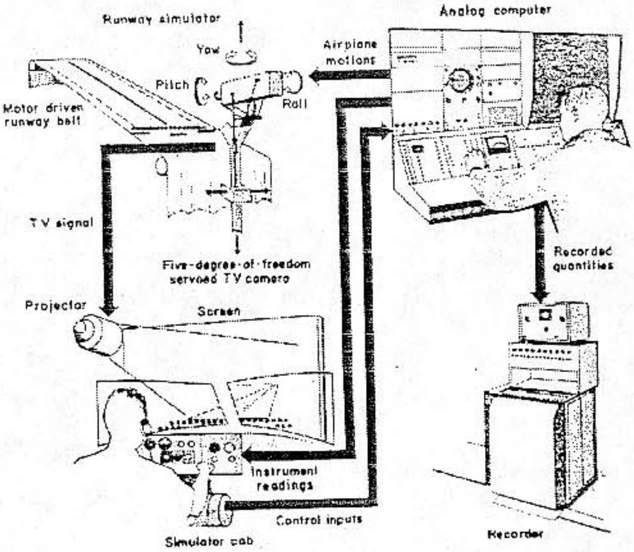

Figure 6. Transport Landing-Approach Simulator

An important addition was an improved out-the-window view of a runway generated by a Dalto Visual System developed for use with training simulators. It consisted of a television camera servo-driven in three angular degrees of freedom, and in altitude and lateral displacement relative to a runway model installed on a continuously moving belt. The resulting television scene, projected onto a screen mounted about 10 feet forward of the simulator cockpit, showed the approach lighting and runway as they would be seen in a landing at dusk with hazy, one-half-mile visibility.

This simulator was used for several handling qualities studies including a supersonic transport configuration in landing approach (refs. 7, 11, and 12) and for lateral-directional evaluations of a large STOL transport airplane (refs. 13 and 14).

Lessons Learned

- Although the addition of the Dalto visual system to a fixed base simulator was found to have a beneficial effect on pilot evaluations of handling qualities, all pilots who flew the visual landing simulation had difficulty performing the landing maneuver, due in part to the lack of motion cues which normally provide lead information.

- To help the pilot "calibrate" the simulator results for the landing task, an opportunity to "fly" a known aircraft proved helpful and was used extensively in following simulator studies.

- Correlation with flight was obtained after the simulator cockpit mechanical control characteristics were modified to provide control centering and low friction so that the pilot could obtain the "feel" of the aircraft in the absence of motion feedback.

- The deficiencies of this visual system (ref. 15) adversely affected precision of landing performance due in part to poor resolution inherent in black and white television projection and other undesirable features including mechanical backlash, noisy drive signals, unsteady video performance, and lags in the camera drives.

- Lateral/directional landing qualities evaluations were compromised particularly for STOL aircraft by the restricted peripheral visual cues inherent in the TV system.

Height Control Test Apparatus (HiConTA)

Description and Research Projects

In the same time period (1961), a somewhat unique (single degree-of-freedom) piloted motion simulator (figure 7) was designed for the primary task of studying height control requirements for VTOL aircraft. Attached to the structural framework of the 40x80-ft Wind Tunnel, it provided a relatively large vertical travel (100 ft) and a true outside world visual scene. A two-place helicopter cab was suitably equipped for several studies: helicopter cockpit controls for a VTOL study (ref. 16), transport type controls for a jet transport control problem study (ref. 17), and a conventional stick for a low level, high speed terrain following program (ref.18). In each case, cockpit panel instruments provided the pilot with essential (but meager) information for each of the test situations. In addition, for a landing performance study (ref. 19), a TV system displayed a night runway scene on a black and white 16 in. TV monitor.

The vertical motion system was driven in response to the analog computed cockpit vertical acceleration modified by high-pass filtering (wash out) to constrain the cab to acceptable excursion limits. A lead network was incorporated to reduce lag in the electric motor drive system. Accelerations of ± 2g and maximum velocities of ± 20 ft/sec were possible. The frequency response was essentially flat out to 1 HZ.

The HiConTA was dismantled about 1984 when the 40x80-ft Wind Tunnel was extensively modified to add an 80x120-ft test section.

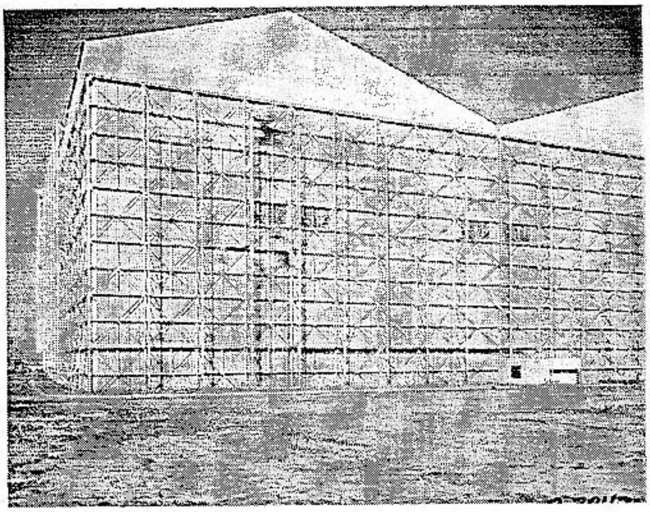

Figure 7. Height Control Test Apparatus

Lessons Learned

- The single degree of freedom (heave) motion was sufficient for the specialized VTOL height control task, and good correlation with flight was achieved.

- For landing performance studies, only 40 ft (± 20 ft) of vertical travel was needed to obtain desired fidelity for acceptable "wash out" frequencies, and ± 20 ft/sec vertical velocity capability was adequate. (This specification for vertical travel was later used in designing the motion system of the VMS.)

- Motion system noises (track rumble detracted from simulation fidelity, giving false cues to washed out velocities.

- Landing performance measurements (touchdown velocities) on the simulator correlated well with flight; however, considerable pilot adaptation (landing practices) was required, in part due to lack of other motion cues and limited visual cues from the TV display. Again, flying a "known" aircraft was helpful.

- The vertical dynamics inherent in the cable/drive system realistically simulated cockpit motion for transport jet aircraft when used in studies to determine reasons for loss of flight path control when flying in large scale atmospheric turbulence.

- Only a few experiments were conducted on this equipment for several reasons:

  (1) The amount of vertical travel was larger than necessary, with adverse implications on safety, dynamic response (cable stretch), and maintenance.

  (2) Improved sophistication in terms of visual displays or additional degrees of freedom were not possible with the cab because of the adverse effect of added weight on dynamic response.

  (3) The location (remoteness) of the simulator from the centralized computational equipment used with other simulators made it difficult to improve the HiConTA system.

Moving Base Transport Simulator

Description and Research Projects

Motivated by the need for improved accuracy in developing handling qualities criteria for STOL aircraft, the Moving Base Transport Simulator (MBTS) (figure 8) became operational in 1963. The motion system used three linear hydraulic servo actuators, which operated differentially or in synchronization to provide roll angles in the range of ±9°, pitch angles from -6° to +14°, and a small amount of vertical travel (2 ft.)

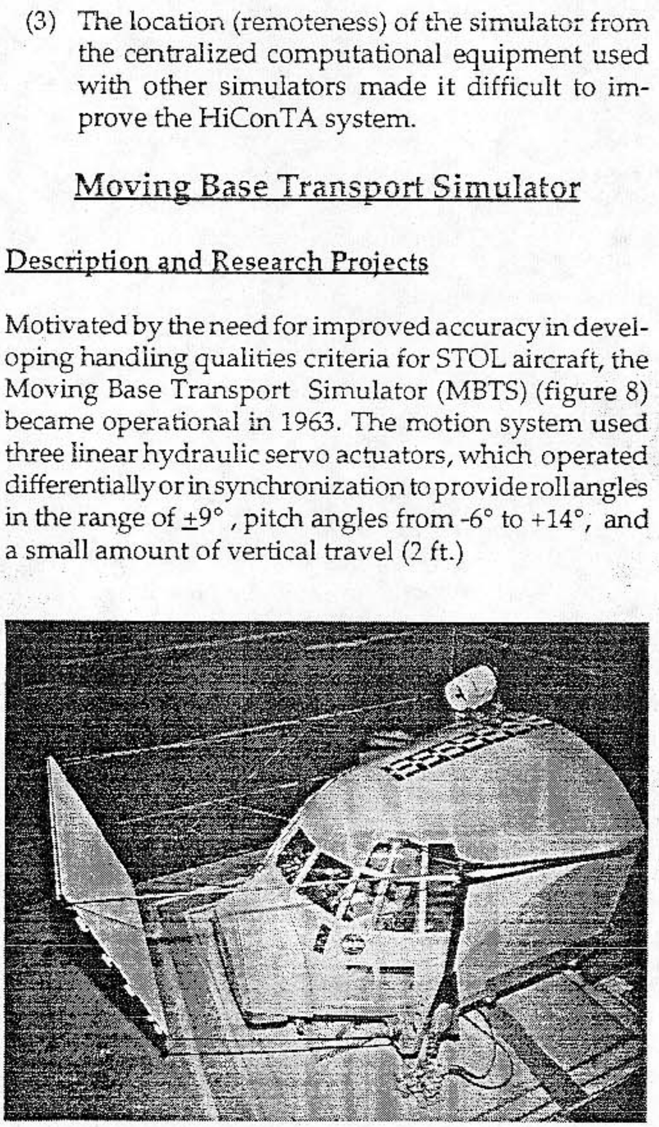

Figure 8. Moving Base Transport Simulator

A transport cab was used with conventional seating for two pilots, instrumentation, and controls which were hydraulically powered for variation of the control system parameters. Initially a scene of the approach lighting and runway was projected onto a screen outside the cab by the Dalto visual system. Later, the Redifon color TV system was implemented.

The drive signals for the motion system, instruments, and visual system were generated by an analog computer.

The MBTS was used for a variety of studies, including several carrier landing aircraft, handling qualities requirements of a STOL seaplane (ref. 20), STOL aircraft (ref. 21 and 22), and a special purpose counterinsurgency (COIN) aircraft.

The MBTS had a long history of successful use and was finally dismantled circa 1984.

Lessons Learned

- The very limited amount of vertical motion (2 ft.), was not usable in STOL landing approach studies because of adverse dynamics response characteristics associated with large wash out requirements.

- The lack of versatility of the Dalto visual system (moving belt scene) restricted the simulated landings for a STOL seaplane study to a runway because the system could not simulate water sea state conditions.

- When the roll motion was programmed to provide a 1-to-1 ratio of input bank angle to cab motion, large bank angles typical of STOL operations could not be used because the pilot felt an unrealistic side force and the cab reached the stops too soon. Also, the motion system had no yaw capability which was needed to study roll / yaw crosscoupling problems.

- The addition of the Redifon color system was a strong factor in improving pilot acceptance of handling qualities results and compensated to some degree for the lack of yaw and heave motion.

All-Axes Motion Generator

Description and Research Projects

Based primarily on the need to provide more definitive control system design values for VTOL aircraft, the first six-degree-of-freedom motion simulator at Ames (figure 9) was put into operation in 1964. The single place cab could move ± 45° about the pitch, roll, and yaw axes and translate ± 9 feet in three orthogonal directions. This simulator was one of the first to use equilibrators, instead of a counterweight, to help offset gravitational effects and thereby improve vertical dynamic performance. A conventional center stick, rudder pedals, and a fighter-type throttle quadrant were provided for the pilot's controls. An analog computer system generated the drive signals for the motion system and instruments.

The system was designed primarily to investigate the VTOL hover regime. Hangar doors were opened to provide the pilot with a natural outdoor scene, and the VTOL hover task could be conducted without the need for motion washout.

Operational safety was a primary concern. A shock absorber system was developed to avoid excessive loads at the extremities of travel. Several large orange colored balls were appropriately located in space to warn the pilot of impending travel limits. In addition, the electric drive system would automatically shut off if the pilot commanded too large translational velocities when approaching limits of travel. On a few occasions, the cockpit restraint system (pilot safety belts) proved valuable when the cab was inadvertently driven hard-over to the extremities of all six degrees of freedom.

Figure 9. All-Axes Motion Generator Simulator

The simulator validated its intended design features by providing the real-life important sensations of VTOL hover operation (ref. 23). The results showed that motion provided good correlation with flight, providing the opportunity to evaluate advanced control systems such as rate command, attitude hold. This proved valuable in preparing for a cooperative flight test program of the German DO-31 VTOL jet transport aircraft. Also, in one of the first studies made of the translational control requirements for lateral positioning in hover, the simulator results (ref. 24) defined the magnitude of side acceleration needed to translate without banking. These values were incorporated in a thrust vectoring system that was flight tested in the X-14B VTOL aircraft. In addition to the above two studies, it is of historical interest to note that this simulator was used by the Apollo Lunar Lander pilots, starting with Neil Armstrong, to simulate lunar landing dynamics (ref. 9).

Only a limited amount of testing was conducted with a hooded cab. A 16" CRT with a TV terrain-model system made by Redifon Limited was used in a study to examine transition flight to touchdown on a moving ship model. Later, in preparation for testing hover control requirements for vertical attitude take off and landing (VATOL) concepts, the simulator was upgraded to permit repositioning the cab to a nominal 90° pitch-up angle (pilot was lying on the back) for hover operation. No research results were obtained for the VATOL configuration, in part because of lack of priority and interest for the type vehicle.

The All-Axes Motion Generator was mothballed circa 1986.

Lessons Learned

- The travel limited within an 18 ft cube VTOL control evaluations to a hover maneuver task. More extensive translation motion than available was desired when evaluating more sophisticated systems such as velocity command control.
- Although the outside view provided flight-like realism, the pilots still felt the confining effect of the inner walls of the building.
- Providing six degrees of motion freedom did not in itself guarantee high utilization of this simulator. The single place cab and low quality cockpit visual display available at that time discouraged more extensive use. In addition, for large lateral maneuvers the required wash out accellerations were larger than the input values, and therefore disorienting.
- Safety requirements to limit translational velocities caused frequent shut down of the drive system and inconvenient reset procedures for start up.
- The suspended heavy utility cable introduced undesirable (spurious) cab motion.
- The use of equilibrators successfully improved ver-

tical dynamic response and were used on subsequent motion simulators.

- Excessive maintenance associated with the electromechanical system and the costs of upgrading an electronics interface system that was approaching obsolescence further discouraged utilization.

Flight Simulator for Advanced Aircraft (FSAA)

Description and Research Projects

Past experience in simulation of large aircraft had pointed out a strong need for multi crew cabs with more extensive translational motion capabilities. Accordingly, the FSAA (figure 10) became operational in 1969 (refs. 25, 26, and 27). Its six degrees of freedom motion system, having all DC velocity servo drives, included an extended lateral travel (± 40 ft), vertical travel (± 4 ft) and fore and aft (± 3-1/2 ft) motion. Two tractors moved the simulator laterally, with supporting wheels taking the principal vertical loads. The lateral carriage carried a vertical platform raised and lowered by three continuous ball screws. To unburden the screw drive, equilibrators were used to float the vertical platform. On top of the vertical platform was the longitudinal motion system which used a single ball screw to drive the cockpit and gimbal systems fore and aft. Relatively conventional chain-drive gimbals provided three angular motions. For operational safety, the position, velocity, and acceleration of each motion system axis were constrained by an array of electrical limiters and ultimately by mechanical buffers.

The FSAA had ~~interchangable~~ reconfigurable cabs configured to represent a transport aircraft, an advanced bomber, or hypersonic-cruise aircraft. For transport simulation studies, the cab was outfitted with a typical transport-type instrument display panel, glare shield, and controls with force-feel cues produced by a control force-feel system which consisted of basic electrohydraulic servos controlled by an analog computer.

Initially, the visual system consisted of a Schmidt color projector mounted on top of the cab to project the visual scene onto a large screen 7 ft in front of the cab. The pilot viewed this screen through a collimating lens located in place of the windshield (ref. 26). Later, this system was replaced with collimated television monitor displays with the image generated by a Redifon TV terrain-model system with a variety of landing scenes.

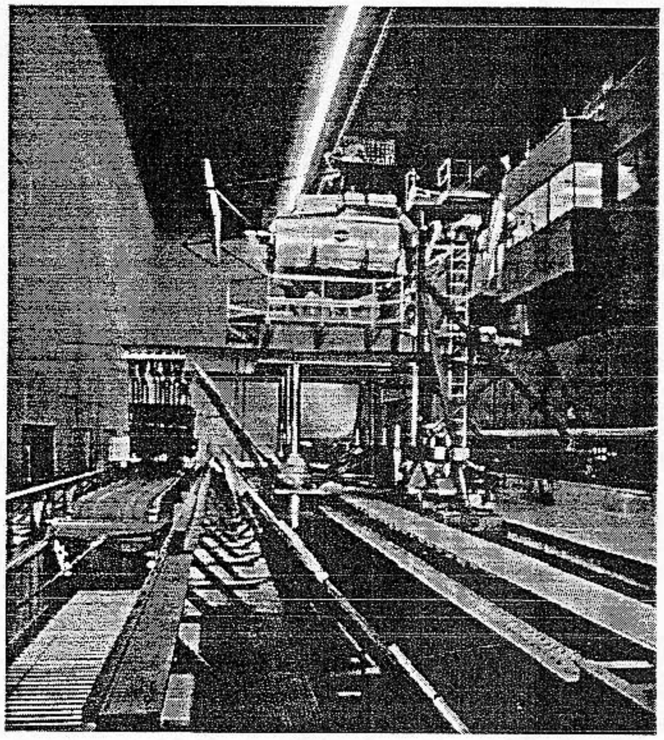

Figure 10. Flight Simulator for Advanced Aircraft

The FSAA was a major step up in simulator sophistication offering for the first time a 3 place cab with full motion including a uniquely large lateral travel range which provided more realistic side force cues associated with engine failure for transports where the pilot's position is far forward of the C.G. and for turn entry maneuvers peculiar to STOL aircraft. A wide range of notable aircraft research and development programs used the FSAA including the Supersonic Transport Concorde Aircraft, many V/STOL and VTOL aircraft, and the Space Shuttle Orbiter. (ref. 28).

The FSAA was dismantled circa 1985.

Lessons Learned

- Although the FSAA proved quite useful in several important research programs, it had some basic limitations which would eventually limit the service life of this research tool.

- The need to provide motion (travel) harmony was not fully appreciated in the design of the FSAA. Less lateral travel would have been acceptable, but considerably more vertical travel was needed. The extensive lateral travel was a constant source of maintenance.

- Investigations found that the FSAA had limitations in matching flight performance in control of flight path near touchdown (ref. 29), indicating that vertical motion cues were inadequate to provide high-fidelity simulation of flare and touchdown.
- The fore and aft travel (± 3.5 ft.) was adequate for conventional aircraft simulation; however more travel was needed for simulation of low speed maneuvers with VTOL aircraft and rotorcraft.
- The analog computer initially used (ref. 30) had so many elements that the program could not be quickly and thoroughly checked.
- A compensation circuit (ref. 26) was required to reduce the "turn-around-bump", a disturbance which could occur every time a motion drive reversed direction in the lateral and vertical drives.
- The realism of the simulation was compromised by a velocity-related audible noise in the lateral drive of the motion system (refs. 26 and 27) and required amplification of aural cues for the engine to mask this disturbance.
- The Redifon TV visual system, although providing real life color cues and a well appreciated go-around capability was limited in diversity for multi task operation and by the narrow field of view.

Vertical Motion Simulator

Description and Research Projects

Building on the lessons learned from the FSAA operation, an improved Vertical Motion Simulator (VMS) (figure 11), began operation in 1980 with a better match in motion harmony (ref.9). Compared to the FSAA, it had extended vertical travel and less than half the amount of lateral motion. In 1987, a major upgrade to the VMS (refs. 31 and 32) was completed under the Rotorcraft Systems Integration Simulator (RSIS) project to provide enhanced motion capabilities and visual cues.

The VMS (ref. 33) utilizes a large aluminum platform supported from below by two pneumatic equilibrators, each of which is driven vertically (± 22 ft) by four dc servo motors. The lateral travel (± 15 ft) is provided by a carriage moved across the platform by four d.c. servo motors. Originally, a synergistic hydraulic motion system (hexapod), was mounted on the carriage to provide the longitudinal and rotational degrees of freedom. As part of the RSIS upgrade, the hexapod was replaced with the hydraulically driven four degrees-of-freedom Rotorcraft System Motion Generator (RSMG), which has increased angular-rate and acceleration capabilities and increased longitudinal displacement (± 3 ft). A programmable vibration generator system provides high frequency, low amplitude accelerationss characteristic of helicopter vibrations.

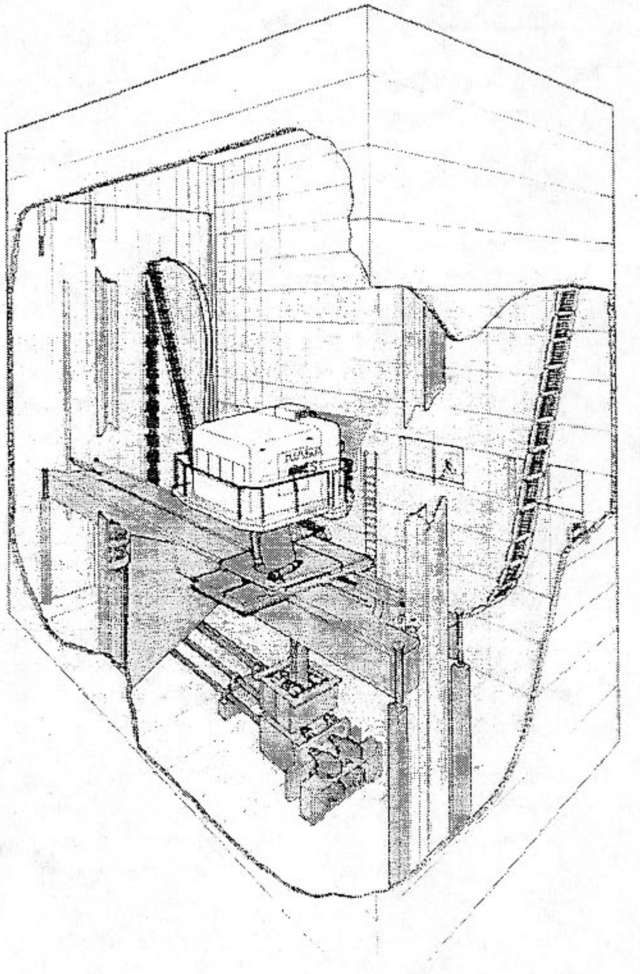

Figure 11. Vertical Motion Simulator

Four interchangeable cabs (ICABs) are available, each of which can be mounted on the RSMG and easily reoriented 90° to gain additional longitudinal travel. The four ICABs can simulate the cockpit/crew for a variety of aerospace vehicles: a three-window two-seat side-by-side configuration for simulating transport aircraft or the Space Shuttle, two four-window configurations used primarily for simulating helicopters and

V/STOL aircraft, and a three-window continuous wraparound configuration for simulating a single seat fighter aircraft. Cockpit controls for different aircraft configurations with realistic force-feel cues are provided by a programmable McFadden control loader system.

The windows each use a collimating mirror/beamsplitter system to present a color display of the visual scene. Originally, the Redifon TV terrain model system and a Singer-Link DIG1 Computer Image Generator (CIG) system were used, but during the RSIS upgrade, an Evans and Sutherland (E&S) CT5A CIG was added.

Four speakers mounted in the cab reproduce a wide variety of sounds associated with different types of aircraft and helicopters.

A succession of digital host computers have been used on the VMS: Xerox Data Systems Sigma 7, 8, and 9 computers, CDC 7600 and 875 computers, and now DEC VAX9000, VAX6000, and VAX4000 computers.

The first simulation run on the VMS was a Space Shuttle approach and landing (ref. 9). The VMS has continued to be used by Astronauts to examine important operational characteristics. Another major program, the XV-15 tilt rotor aircraft has been invaluable in supporting important aspects of the vehicle's design, flight experiments, and research (ref. 34). Other major research and development programs include the UH-60 Blackhawk Helicopter, LHX Helicopter, RASCAL, YAV88 Harrier, STOVL Fighter Attack Aircraft, Oblique Wing, Automated Nap-Of-The-Earth Rotorcraft Guidance, Helicopter Terrain-Following Terrain-Avoidance System, VTOL Flight Controls and Display Concepts for Shipboard Operations, Computer Aided Guidance for Low-Altitude Helicopter Flight.

Lessons Learned

- The ICAB feature has greatly increased utility and efficiency in conducting research on a wide variety of vehicle concepts. The ability to reconfigure, check out, and use a cab for fixed-base simulation in a separate development area has proved invaluable.

- The advent of digital computers and in-house development of remote input/output interfaces have reduced greatly the number of electrical and data leads connected to the cab thus improving reliability and reducing maintenance.

- There was a continuing need for increasing computational capacity to model more advanced vehicle/rotor configurations, advanced rotorcraft on-board systems, and integrated flight/propulsion control.

- The replacement of the TV terrain model visual system with CIGs resulted in a much improved field of view, clarity, and scene content and detail; however, lead compensation (ref. 35) was required to remove inherent transport lags.

- The VMS with existing motion capabilities and improved visual system has received a high degree of pilot acceptance.

- Pilot criticism of motion roughness and noise, occasional occurrences of "simulator sickness," and reference to lack of depth perception remain important challenges.

The Future Of Research Simulators

Based on past experience, future development of the piloted research simulator will hinge for the most part on improvements in its subsystems. It is not expected that any major changes in motion travel will be made, however reducing time delays of the motion system response will be needed for solving more complex problems with visual/motion/model mismatches. Improvements in the cab environment will require acoustic engineering and better lighting realism. Also expected is the greater use of the "glass cockpit", with all-digital displays and voice interactive systems as the technology becomes more mature. The greatest advance in technology will come from the use of later generation CIGs to improve realism of flight. In this regard, a new E&S ESIG3000 state-of-the-art CIG, having six channels, is scheduled to be delivered in October 1993 (ref. 9) for use on the VMS. In addition, advances in computer technology will allow an increase in sophistication and complexity of simulation models. Other future developments will reflect the need to simulate advances made in the cockpits of future transport aircraft. According to a National Research Council study (ref. 36), such advances will take the form of the pilot's view being augmented by a combination of sensor data, previously stored data, and real-time data received through aircraft data links to create what the study calls "virtual reality", meaning that the pilot's view need not be tied to the pilot's eye location.

CONCLUDING REMARKS

A brief historical review of the development and use of piloted research simulators at NASA Ames has shown that the specific task and related maneuvering requirements dictated the level of motion system sophistication required. When conducting tests to determine selection of carrier approach speeds with an aircraft that had satisfactory stability and control charactertistics, a fixed base simulator was adequate. When evaluating flight path control for a vehicle with stability and control limitations such as the space shuttle, a very sophisticated all axes motion system is required to achieve meaningful results. The type and amount of motion needed to evaluate aircraft control also depends on the task. For example, in a VTOL hover task, initial angular control response is sufficient. For tasks where translational positioning is critical such as engine failure during take off, a large amount of lateral translation is required. Experience has indicated that in a trade off with all six degrees of freedom, vertical motion should not be compromized. The degree of motion system sophistication is also influenced by the type of visual display. In general, TV displays were adequate only when limited maneuvering was required. CIG displays with a wide field of view are required to define control requirements for translational tasks.

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