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Use of Ground Based Simulators in Aircraft Design

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The growth in flight simulation technology in the flight training context and the extension of this technology to engineering oriented flight simulation is discussed briefly. Basic differences between simulation used for training and engineering design are identified. The use of ground based flight simulation in support of aircraft design is demonstrated by presenting three diverse but typical examples. The specific engineering oriented simulations discussed are an air combat simulation used to evaluate the effect of changes in gross aircraft characteristics on air combat effectiveness, the approach and landing on board an aircraft carrier at night to evaluate aircraft handling qualities in this critical tracking task, and a V/STOL assault transport simulation used to tailor aircraft dynamics, control feel system characteristics and flying qualities over the complete aircraft flight envelope.

Introduction

SOPHISTICATED ground based flight simulation has been in general use since the advent of real time electronic analog computers. Over the past decade great strides have been made in improving the fidelity of flight simulators associated with training, through the rapid development of hybrid/digital computers and the associated environmental devices—principally cockpit motion and real world visual display systems. Application of this technology to the engineering design task has added a new dimension to the analysis and synthesis of flight systems.

The flight training simulator is used to promote a change in behavior through practice in the simulated flight environment. The simulator, normally restricted to the representation of a single aircraft over a well-defined flight regime, becomes available only after the design of the aircraft is completed.

The engineering simulator, on the other hand, is used in the very early stages of the design cycle to establish aircraft and aircraft systems design requirements and the evaluation of alternative approaches to the solution of engineering design problems. Typical engineering tasks include the assessment of flying qualities, evaluation of flight control feel systems, study of stabilization and automatic flight control systems, determination of the significance of gross aircraft design parameters, appraisal of crew station configurations, development of cockpit displays, exploration of head-up display symbology, evaluation of system failure modes and emergency conditions, etc. The simulator, normally configured on a very short time scale by the use of flexible hardware and software "building blocks," has a brief life span in any particular configuration. An individual program is nearly always devoted to the study of a single design problem. The fidelity of the mathematical model of the aircraft and its systems and the environmental devices employed are largely dictated by the status of the particular design. Early in the design, the mathematical models are generally first order approximations. As the design progresses, the fidelity of the mathematical models are improved appropriately—ultimately including all major nonlinearities which might affect design decisions. In a similar manner, the environmental devices employed extend over the full range of fidelity. Therefore, throughout the research and development phase of an aircraft or aircraft system one is likely to see a wide range of simulation fidelity—ranging from very simple single degree of airframe freedom, restricted maneuvering range, fixed base, instrument flight studies to full 6° of airframe freedom, maneuvering over the complete flight envelope, realistic cockpit mounted on a motion system, and employing a real world visual display.

Numerous examples of the use of ground based flight simulation in support of aircraft design are evident throughout the aircraft industry, Department of Defense laboratories, and the NASA. Several typical examples of engineering oriented flight simulation studies, recently conducted at the Vought Aeronautics Company, LTV Aerospace Corp., are presented below.

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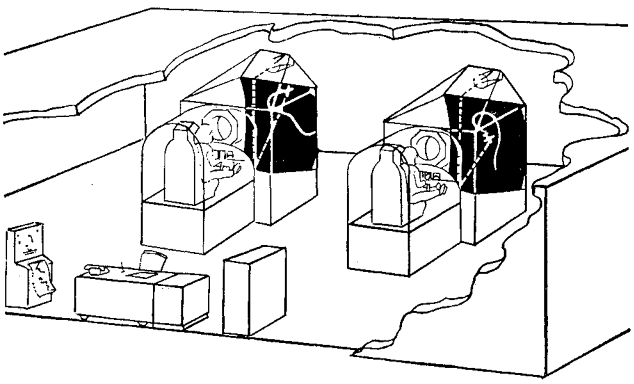

Fig. 1 Air combat simulator.

Three simulators, and the role they play in aircraft design, discussed in this paper are: a fixed base-VFR (Visual Flight Rules) simulator used to evaluate proposed aircraft designs against various threat aircraft; a moving base-VFR carrier approach simulator used to tailor the aircraft and control system for the precise task of carrier landing; and a fixed base-IFR (Instrument Flight Rules) V/STOL assault transport simulator used to tailor airplane dynamics, feel systems, manual and automatic control systems, and acceptable stability and control characteristics over the entire flight envelope.

Air Combat Simulator

The air combat simulator was developed for the evaluation of aircraft and aircraft armament systems in the close-in visual air combat environment. The simulator consists of two manned fixed base cockpits, interconnected through "out the window" visual displays. Each pilot is free to maneuver his simulated aircraft anywhere within its respective flight envelope, in real time, in response to the dynamic combat situation as he sees it develop. An encounter is terminated with expenditure of munitions by either participant or at a fixed time interval. The "winner" of an engagement is determined by a postflight evaluation of the resultant records on the basis of a selected weapon conversion criteria. Simulator generated parametric results of aircraft or armament system tradeoffs may be used in conjunction with more conventional methods to arrive at the most cost-effective configuration.

An artists' conception of the simulator configuration is depicted in Fig. 1 with a system block diagram representation shown in Fig. 2. Each pilot occupies a fixed base single place fighter aircraft type cockpit. The conventional control arrangement includes stick, rudder pedals, modulated afterburner throttle, speed brakes, trigger, and variable wing sweep. Single gradient mechanical feel systems provide control feel about all three control axes. Parallel beep trim is incorporated in the longitudinal system. An austere array of instruments includes the altimeter, airspeed/Mach number, rate of climb, three axis attitude indicator, normal acceleration, wing sweep position, and fuel quantity. A longitudinal stick shaker simulates penetration into aircraft buffet, increasing in magnitude to an uncontrolled stall departure. Stall recovery is accomplished by relaxing stick pressure. The pilot normally wears a G suit which is inflated to provide suitable normal acceleration cues and increasing pilot work load.

The visual system provides each pilot an instantaneous collimated maximum field of view of 80°, mechanized in a manner, however, to provide relative aircraft position information over 4π sterradians. The visual scene is generated and driven by a digital computer in a light pencil fashion providing a white, stick figure image on a black background. Visual information includes the opponent aircraft, gunsight, horizon, ground plane, and a supplemental "synthetic" (radar indicator) display. The opponent aircraft appears as in real life in the forward 80° cone and as in a large rear view mirror in the rearward 80° cone. Examples of the aircraft images are presented in Fig. 3. The synthetic display, which automatically appears in the lower parts of the visual window when the opponent is in other than the fore or aft 80° cone, provides opponent azimuth, elevation, and range information to the viewer in graphic form. Views of the synthetic image are presented in Fig. 4. The synthetic display is assumed to be in the viewer's X-Y body axis. The cursor clock position defines azimuth, the dot riding off the end of the cursor indicates relative altitude, and the vector sum from the center is an indication of range. An extension of the cursor rides the peripheral circle to avoid azimuth ambiguity at close range.

The Earth-sky is generated by assuming the pilot's eyepoint at the center of an attitude stabilized, open, inverted hexagonal pyramid. The pyramid is assumed to travel with the viewer in the three linear directions providing attitude cues only. In level flight, the pilot sees the horizon and one or two near vertical intersecting lines. A vertical dive is seen as six lines intersecting at the pyramid apex. A gunsight with two fixed reticles, a lead compensation pipper, and a range scale is also presented except when the opponent is in the rear 80° cone. The absence of the gun sight cues the pilot to a rear view scene. A new visual system concept with improved aircraft image resolution, head swiveling requirements and a near 4π sterradian field of view, recently introduced, is shown in the sketch of Fig. 5. As seen from the sketch, each cockpit is surrounded by a spherical projection screen. The aircraft image is beam written by the computer on the face of the fixed CRT projection tube and is then imaged on the surface of the screen through a lens system and gimbal supported mirror. An Earth-sky projector is supported on a second gimbal sys-

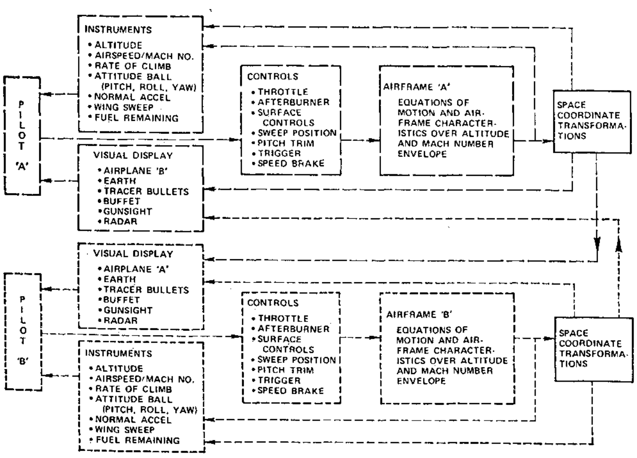

Fig. 2 Air combat simulator block diagram.

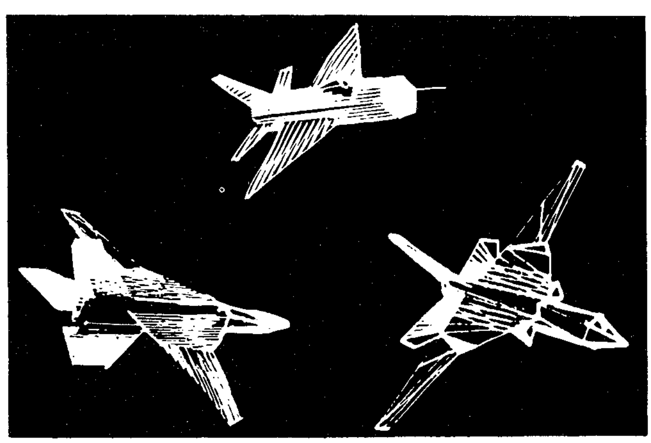

Fig. 3 Aircraft images.

tem to provide attitude information, while gunsight imagery is mechanized through two additional projectors.

While the original visual concept has been used extensively and has provided results comparable to the real world situation, extensive pilot training is required for instinctive use of the synthetic display. It is anticipated that minimum transition will be required and pilot acceptance improved with the new visual concept.

Prime use of the simulator to date as an aircraft performance evaluation tool has led to a simplified airframe representation of five degrees of freedom (neglects sideslip). Flying qualities representative of desirable or known flight characteristics throughout the flight envelope are achieved through adjustment of stability parameters and applying appropriate slopes and limits to generated functions, without the need for detailed inner control loop mechanization. A single Scientific Data Systems SDS-930 digital computer with a computations cycle time of 20 times/sec coupled to a 1×10^6 character fixed head magnetic storage disk and approximately 80 analog amplifiers is required to conduct the simulation with the original visual system concept. An SDS-930 coupled to a shared Sigma 5 is required with the improved visual system.

Since most of the experience to date has been with the original visual system concept, further remarks will be limited to the simulator use in that configuration.

The general reaction to the simulator by experienced fighter pilots has been enthusiastic. They are generally pleased with the perspective view of the opponent aircraft and the maneuvering freedom throughout the flight envelope. While the interpretation of the synthetic display requires significant training for instinctive use—approximately twelve hours—subsequent ability to execute conventional aerial combat maneuvers while pursuing or evading the opponent is consistently demonstrated. The objective of the air combat simulator operation to date has been to determine, through systematic studies, the relative importance of various airplane design parameters and performance characteristics in close-in air-to-air combat. These parameters and characteristics can then be combined to obtain a quantitative measure of combat effectiveness in the form of a measure of performance (MOP) factor to be used in preliminary design studies. The principal aircraft parameters investigated included thrust-to-weight ratio, wing loading, aspect ratio, zero lift drag, airplane efficiency factor, lift coefficient for buffet onset, maximum usable lift coefficient, and combat fuel allowance. Parametric aircraft were systematically synthesized and evaluated against specific threat aircraft. Experienced jet fighter pilots manned the cockpits and alternately flew the threat and parametric aircraft.

At the beginning of the air encounter, each pilot is aware of the presence, type, and location of the other aircraft. Pilots attack and evade each other, maneuvering and firing as the combat situation dictates. The problem is terminated on the firing out of either pilot's guns or with the elapse of a fixed combat time. Data are recorded during each run on both magnetic tape and analog strip recorders. Continuous traces of altitude, throttle setting, speed brake position,

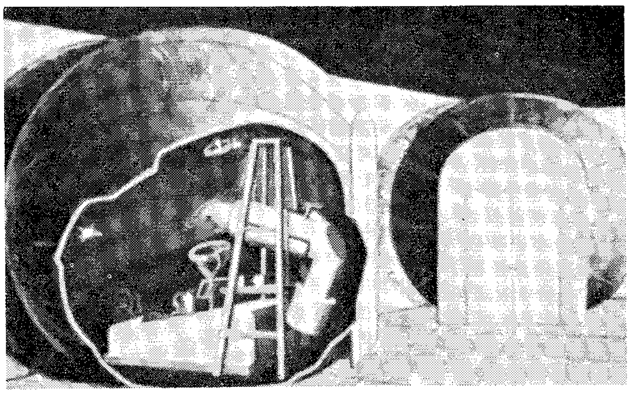

Fig. 5 Improved configuration air combat simulator.

trigger pulls, wing sweep, heading, and bank angle are recorded for each aircraft. Sufficient data are stored on the magnetic tape for a complete off line analysis of each encounter and a statistical analysis of all like aircraft combinations and encounters.

The method of aircraft evaluation currently employed is to compare the probability of conversion of the two aircraft with respect to each other. A conversion or win is scored to the first aircraft firing a round within a specified criterion of range, aspect angle, and miss distance.

Figure 6 presents the probability of conversion P_{CA} (percent wins) of the superior aircraft plotted against the probability of conversion P_{CB} of the opponent and against the probability of a draw P_D. It is seen that the data spreads over a significant band.

Correlation of data for various configurations has been attempted by use of a quantitative measure of combat performance capability in the form of an MOP factor. Assuming that there is such a correlation factor, the relative merits of two aircraft can then be predicted on the basis of their relative MOP values. The MOP is believed to be primarily dependent upon sustained maneuvering capability below the drag divergence Mach number, instantaneous maneuvering capability at low speed, and axial acceleration capability.

Any valid measure of combat performance must include all parameters which govern this capability. A number of variations of the MOP factor have been investigated and a single factor has been isolated which appears the most promising. Figure 7 presents a curve of conversion probability vs the measure of performance ratio for parametric aircraft against a threat. Except for an MOP ratio of one, two points are generated for each parametric aircraft and a single threat; i.e., one is the reciprocal of the other (MOP ratio 1.5 also becomes 0.667). The right side of the curve shows the

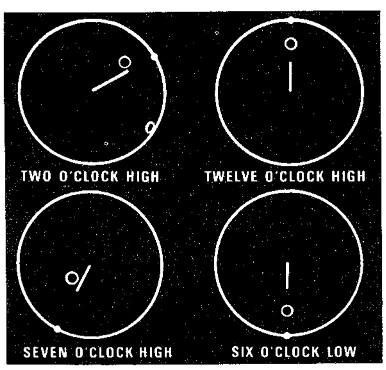

Fig. 4 Synthetic display.

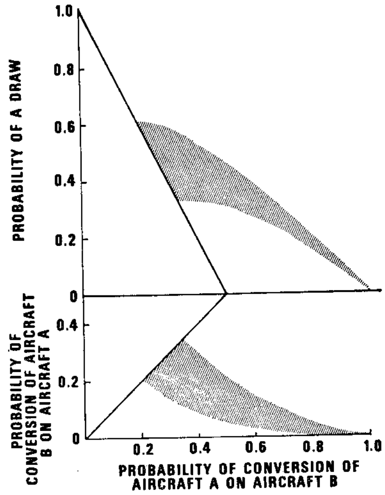

Fig. 6 Correlation—probability of conversion.

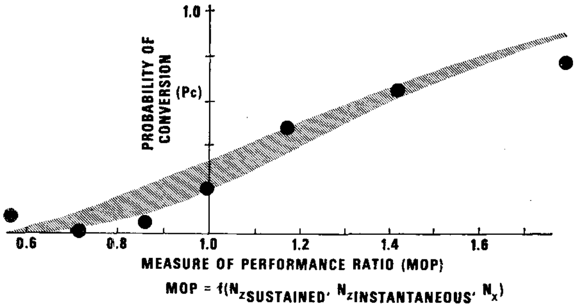

Fig. 7 Comparison measure of performance ratio to probability of conversion.

probability of conversion of the superior aircraft while the left side shows the probability of conversion of the inferior aircraft. The remainder of the battles are draws. The fact that a band exists suggests that an alternative MOP might correlate better or that a family of curves exists which are related to the absolute performance level of the combatants. In any event, it appears that the conversion probability of a given parametric aircraft against a given threat may be predicted with a reasonable degree of accuracy. Based on observations to date it appears that as higher performance aircraft are employed against each other, pilot proficiency becomes more significant. Another conclusion is that as the performance level of both aircraft is increased, a higher performance differential is required to provide a substantial advantage in combat effectiveness.

Although only limited real life data are available for comparison, some typical results are superimposed in Fig. 7. While the correlation with parametric simulator results is not exact, the similarity of trends between simulation and flight appears quite promising.

Carrier Approach Simulator

The Carrier Approach Simulator consists of a 6 degree-of-freedom representation of the airplane, a 3 degree-of-freedom representation of the aircraft carrier (pitch, translation, and heave), a visual display of the night carrier landing situation, and a single-place cockpit with instruments and appropriate control functions. The cockpit is mounted on a moving base providing onset acceleration cues due to pilot control inputs and atmospheric turbulence. The objective of the simulation is to investigate the handling qualities of an aircraft on the carrier approach glide slope from glide slope intercept to touchdown. A means is thereby provided for the flight test pilot to participate in and influence the aircraft design to ensure carrier suitability.

The simulated cockpit is a typical single-place aircraft configuration with conventional stick and rudder primary flight controls, throttle, and speed brake control. Longitudinal parallel beep trim and proportional spring loaded to center direct lift control are provided on a conventional control stick grip. Variable control feel forces are provided about all three axes. Mechanically adjustable breakout and single force gradients are provided in the lateral and directional channels while a programmable electro-hydraulic force servo system provides feel forces in the longitudinal channel. Computer-driven cockpit instruments include attitude direction indicator, airspeed, altitude, rate of climb, angle of attack, angle-of-attack indexer, pitch trim, speed brake position, and engine RPM. A simulation of engine noise, modulated by throttle movements through a suitable lag, is provided through a headset or loudspeaker system. The visual display, consisting of a collimating lens system and a 19-in. shadow mask color cathode ray tube mounted above the instrument panel, provides a 20° × 30° view of a carrier at night. The visual image generated in the digital computer is a realistic reproduction in true color of the carrier deck edge lights, the runway center line and edge lights, the runway end lights, the vertical drop line at the ramp, and the Fresnel Lens Optical Landing System (FLOLS). The FLOLS provides the pilot with a visual glide slope during the carrier approach. A large red light designated the "meat-ball," rides in a vertical path with respect to a set of horizontal green datum lights. The movement of the ball from the centered position is directly proportional to glide path change from the nominal. Ship's motion in heave is reflected in the "line stabilized" ball as a sinusoidal motion while maintaining a fixed glide slope. The visible glide slope variation is $\pm\frac{3}{4}°$ about the nominal. A simulated real world horizon is also provided in the visual display. The visual scene responds to the pilot's control inputs, FLOLS stabilization inputs, and to carrier pitch and heave motion so as to continuously display a correct perspective view of the carrier light system down to wire engagement, waveoff, bolter, or ramp impact. The cockpit and visual display are mounted on a 3 degree-of-freedom moving base which provides coupled angular and linear acceleration cues in the pitch-heave and yaw-side acceleration axes as well as pure roll acceleration cues. Mechanization of the base drive equations is tailored to provide realistic onset acceleration cues based upon a pilot opinion study of control inputs during the initial test phase of the approach simulation. Moving base disturbances are also generated in response to atmospheric and carrier wake disturbances. A functional block diagram of the total system is shown in Fig. 8 while a schematic of the moving base and cockpit installation is shown in Fig. 9. Black and white reproductions of the view seen by the pilot during the latter approach phase are shown in Fig. 10.

The airframe, aircraft systems, flight control system, and moving base drive equations are programmed in an analog computer to provide flexibility to the designer. The visual display information, vehicle kinematics, aircraft carrier

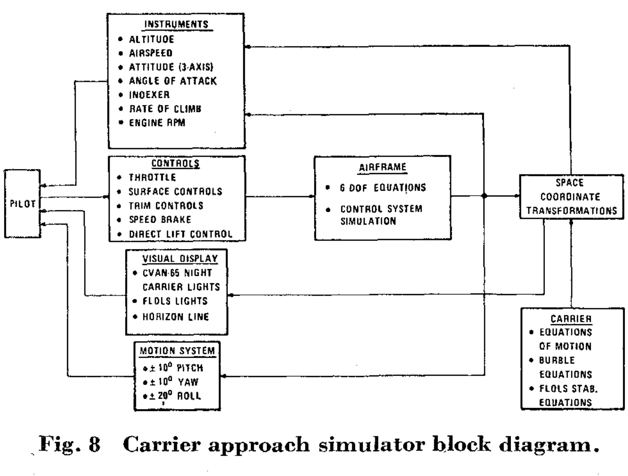

Fig. 8 Carrier approach simulator block diagram.

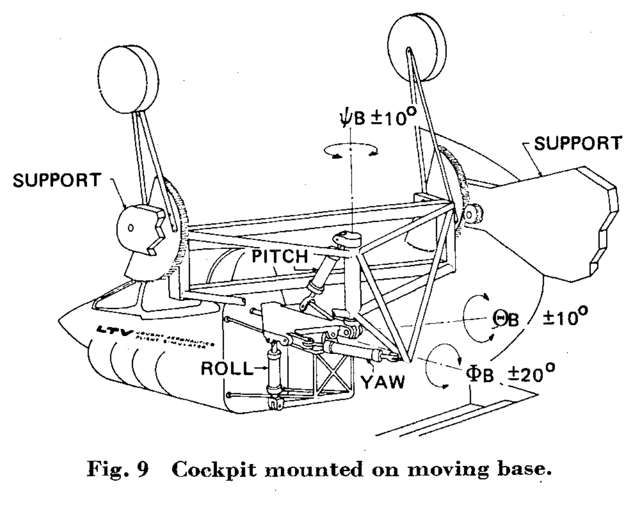

Fig. 9 Cockpit mounted on moving base.

dynamics, atmospheric turbulence, and coordinate transformations are performed in a digital computer.

The carrier approach simulator is used primarily as an engineering design tool to investigate the influence of various design parameters on aircraft handling qualities during carrier approach. Recent areas of investigation have included short period frequency and damping, longitudinal control effectiveness, lift curve slope, direct lift control, lateral control characteristics, speed brake effectiveness, drag polar shape and position on the drag polar, engine response, approach power compensation, and stability augmentation. Alternate tasks such as evaluation of changes in wave-off techniques and limited night carrier landing training exercises have also been performed.

Generally an approach begins with the aircraft trimmed for one G level flight aligned with the ship at approximately two nautical miles, and at an altitude slightly below the low ball glide slope. The pilot's task is to intercept and maintain the glide slope (roger ball) to touchdown. Completion of the approach is related to the real world by an arrestment, bolter, wave-off or ramp impact. An arrestment freezes the problem, while a ramp strike freezes the problem and illuminates the cockpit with a red light. Analog strip charts, vertical situation X-Z plot, and a digital printout are provided for each approach. Lateral, longitudinal, and vertical dispersion data with respect to the ramp and intended touchdown point, and touchdown sink rate are the prime rating criteria. Pilot subjective opinion of the various airplane and control configurations provides a supplemental evaluation.

An example of several typical time histories of altitude error from the nominal glide slope during the approach, for several variations in the aircraft configuration, is presented in Fig. 11. These results imply unfavorable coupling characteristics between the direct lift control system and the approach power compensation system mechanized.

Since the simulation includes the downwash turbulence created by the deck edges and island, thrust modulation is required while translating through the "rooster tail" turbulence. The ballooning effect close to the ramp shows the airplane emerging from the downwash area and the pilot reducing thrust to maintain an optimum sink rate.

V/STOL Assault Transport Simulator

Another recent program wherein simulation played a significant role during design and development was that of the XC-142A aircraft. The XC-142A is a prototype assault transport designed to evaluate the operational problems of VTOL flight. The control and stabilization systems of the XC-142A were designed to permit instrument flight rules operation (IFR) through all vertical, transition, and normal flight modes. The requirement for completely blind vertical takeoff and transition established the sophistication of the

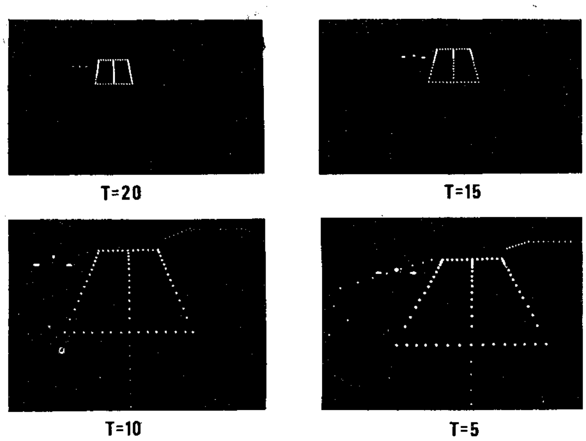

Fig. 10 Pilot's view of carrier (T = time to touchdown).

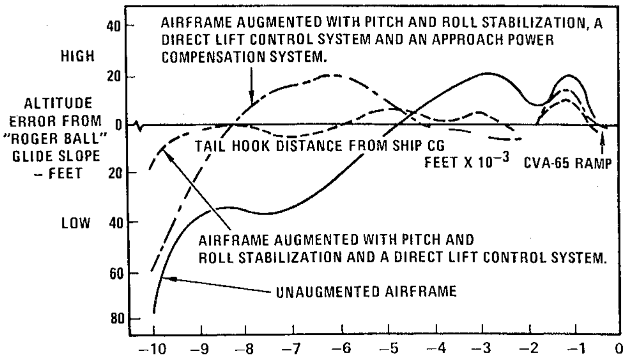

Fig. 11 Altitude error during landing approach.

automatic stabilization system designed into the XC-142A. Designing to this IFR requirement was accomplished by making use of two simulation devices.

The two simulators involved were a Flying Qualities Simulator, used from early in the design phase until all systems were blueprinted and a Flight Control System Simulator used extensively between the completion of design and the first flight of the airplane. The Flight Control System Simulator was also used during the flight test program for pilot familiarization, exploration of new regimes, and the verification of any design changes found necessary in flight. The philosophy behind the design and use of the simulators will be discussed.

At the time of preparation of the XC-142A Detail Specification, there were no VTOL flying qualities specifications. Airplane requirements were fairly well defined by MIL-F-8785 and helicopter requirements by MIL-H-8501A. A flying qualities specification for the XC-142A was forged by combining these two specifications with such additional requirements as were learned from the NASA VTOL test beds. Requirements for the transition area which, of course, include all STOL operation were, at best, vaguely defined. In addition, few requirements had been established for helicopter IFR flight.

Because of the fact that transition dynamic requirements were not firmly pinned down, especially under instrument flight conditions, an XC-142A flying qualities simulator was put together quite early in the program. This simulator consisted of a fixed base XC-142A cockpit mockup coupled with a combined analog-digital representation of the airplane dynamics and proposed control system. Variable control feel was provided by electro-hydraulic force servos. The original task of this simulator was to set design requirements for the control system in the hover and transition region under instrument flight conditions. These requirements were, of necessity, based primarily on pilot opinion. As the control system design progressed, the simulator was used to evaluate design compromises and system performance with simulated hardware performance.

Since the Flying Qualities Simulator included no airplane hardware, its sophistication lay in the computer mechanization of the airplane aerodynamics, engine and propeller dynamics, structural dynamics and control subsystem dynamics. As the aerodynamics of the XC-142A are heavily influenced by power (slipstream), a high-speed digital computer was used to simulate the forces and moments on each airplane part as a function of altitude, air speed and power setting. The total forces and moments generated by the digital computer were integrated by the analog system to provide a continuous solution of the aircraft flight motions. Continuous flight from hover through transition was possible. Gusty wind conditions were produced by superimposing random gusts from Gaussian noise generators and mean winds. Gust spectra representative of low altitude ground turbulence were used for hover and transition simulation.

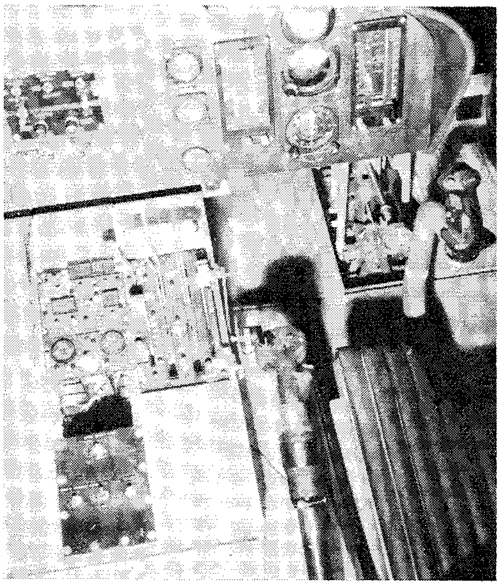

Fig. 12 XC-142A flight controls system simulator cockpit-right-hand station.

As the Flying Qualities Simulator was fixed base, it became apparent that the degree of sophistication required of the automatic stabilization system was influenced by the pilot's ability to readily interpret his cockpit displays. For example, it was found that if quickening were added to the attitude displays in hover, less system damping was required. However, it turned out that quickening gave the pilot great difficulties in gusty air. It was decided to provide a simulation of the best possible IFR instruments in order to not be too conservative in stabilization design. The actual cockpit displays are shown in Fig. 12. The basic instrument group provided an artificial horizon, a horizontal situation indicator, altimeter, rate of climb indicator, airspeed indicator, stall warning and normal acceleration indicator. Tape system displays of airspeed, altitude, rate of climb and angle of attack were used to permit the most precise pilot evaluations. The altimeter display consisted of three tapes normally indicating 1000, 100, and 10 ft per index. These sensitivities could be increased by pilot selection to indicate 100, 10, and 1 ft per index for precise height control in hover and ILS approach tasks. In hover, the horizontal situation display was used to indicate the horizontal location with respect to a fixed ground station. For ILS approaches, this display was changed to show the airplane's vertical and lateral location with respect to the commanded flight path.

After the basic control and stabilization system design was complete, an XC-142A Flight Control System Simulator was built. The Flight Control System Simulator was made up of all of the subsystems which comprise the flight control system of the XC-142A mounted in a structure which simulated the airplane. A picture of this simulator is shown in Fig. 13. A hybrid computer setup, more extensive than that used for the Flying Qualities Simulator was used to simulate the aerodynamic and structural behavior of the airplane. Two series of tests, one open-loop and one closed-loop were run in this simulator. The over-all objective of the tests performed was to verify that the performance of the complete flight controll system was in accord with design requirements and that it was airworthy. Secondary objectives were to provide pilot familiarization before flight and to evaluate any design changes found necessary during the course of the flight test program. System life data for the mechanical portion of the complete flight control system were obtained during the course of the simulator testing.

Since the Flight Control System Simulator occurred in time after the systems were designed one would expect that its role was one of "proof of design." However, valuable system operational characteristics were also obtained. At the time of the closed loop testing all of the wind tunnel tests in support of the XC-142A program were essentially complete. A very accurate evaluation of the actual airplane's handling qualities was made before flight and final system tuning was accomplished. The success of the simulator program may be judged by the fact that only two functional control system design changes were made during flight test. A lateral viscous damper and mass balance were added to the control stick and the yaw axis stabilization system gains were cut to solve an aeroelastic coupling problem that could not be reproduced on the ground based simulator.

In order to indicate the meticulous nature of a modern flight control system simulator, a brief description is in order. The simulator structure was a framework designed to support the control components in the same manner and location and with the same local stiffness as in the actual airframe. Throughout the fuselage simulated segments of floors and bulkheads were mounted to support the airplane control system brackets, fittings and linkages. The fuselage aft section supported the vertical fin and horizontal tail surfaces with the same structural stiffness as the actual airplane aft section. A simulated tail boom extended aft to provide a mount for the tail propeller controls and actuator. All tail surfaces were simplified versions of the airplane structure but with the same structural stiffness. All wing and tail simulated control surfaces had the same chordwise and spanwise stiffness as the airplane control surfaces. All tail surface power control actuators were mounted as in the airplane.

The wing was a simulation of the airplane wing torque box with the correct span. In order to match the mass distributions of the airplane wing and locate the hydraulic pumps in the right positions with respect to the system, dummy nacelles were attached to the simulated wing torque box. The nacelles contained the hydraulic pumps, electric drive motors, propeller pitch actuators, propeller pitch control components, and simulated engine fuel controls. The trailing-edge flaps and the ailerons were mounted from the aft beam of the torque box. The wing was mounted on the simulator base in the same manner as on the airplane hinge bulkhead and pivot rib. Airplane wing incidence actuators were used.

The Flight Control System Simulator reflected the fact that the XC-142A control system design involved technical disciplines not ordinarily concerned with conventional airplane controls. For example, the fact that differential thrust is the primary source of roll control power in hover meant that the propeller and engine controls became primary flight controls. The requirement for automatic roll stabilization in hover for IFR flight, led to additional dynamic requirements for the thrust control system. Since the propeller actuators and valves had been through jig development tests in a loaded, rotating environment, it was decided to mount them statically, in the correction position on the simulator. The airplane propeller governor was installed on the simulator.

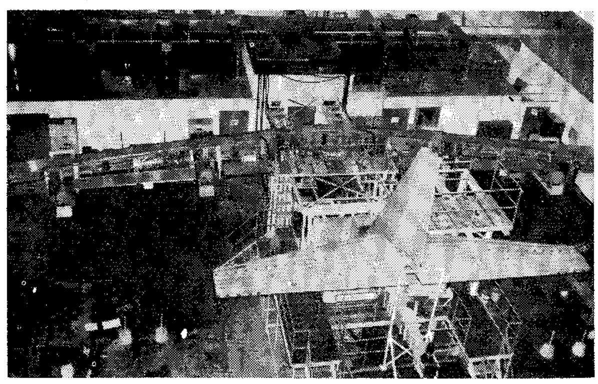

Fig. 13 XC-142A flight controls system simulator.

The engine control cables terminated at potentiometers in the simulated nacelles. From this point input signals were fed to an elaborate computer simulation of the engine-fuel control dynamics.

The same cockpit displays developed for the Flying Qualities Simulator were employed. However, the hybrid computer program was significantly expanded in order to simulate continuous flight to any point in the airplane's flight envelope. This capability enabled the simulation of complete flights including hover, transition, cruise and STOL landings. The computer mechanization included the effects of altitude, Mach number, airframe flexibility, power control system backoff and hinge moment limitations. Simulated flights could be made for any preselected airplane gross weight and cargo distribution and for any atmospheric temperature and gusty wind conditions. All drive signals for the cockpit display instruments and stabilization systems were provided by the computer.

Although, as mentioned, very few design changes were required during flight test because of the intensive simulation program, several design changes were engendered by the simulation program itself. The ability to correct discrepancies on the simulator greatly expedited the flight test program. Typical of the changes that came out of the simulator program were: a) modification of hover height control involving reduction of propeller governor gains, reduction of propeller blade control system hysteresis and modification of the throttle-propeller blade angle interconnect; b) modification of the tail propeller engage/disengage system to eliminate pitch transients; c) modification of roll/yaw control system phasing to eliminate adverse yaw in STOL operation; d) modifications to eliminate pitch stabilization system actuator feedback to the pilot's control stick; e) modification of the rudder pedal feel system phasing to reduce sensitivity; f) redesign of emergency pitch trim to prevent loss of pitch stabilization; g) modifications to the longitudinal feel system to reduce sensitivity in high speed flight.

These changes involved were as a result of discrepancies discovered in nearly every portion of the flight envelope. The sophistication of the hybrid computer mechanization that permitted flight anywhere in the envelope was therefore well justified.

Two other important functions of the Flight Control System Simulator were the evaluation of system malfunctions and the gathering of systems life data. Typical malfunction investigations were of first order failures in the propeller governor, control trim systems and the stabilization systems. The tests proved the ability of the pilot to cope with the failures as well as determining the increase in his work load and the role of the copilot. As the stabilization system is required for IFR VTOL operation a two channel system was provided in each axis; a monitor locks both channels to neutral in case of a discrepancy. The pilot can select each channel individually in order to regain the operable channel in case of a monitor shut-off. The simulator was used to prove the pilot's ability to select the operable channel and continue his flight task to a safe landing. As a final comment the Flight Control System Simulator was invaluable in providing pilot familiarization before first flight.

Concluding Remarks

This paper has presented a summary of several typical man-machine ground based simulation studies conducted in support of aircraft design. Fidelity of the simulators has varied widely, ranging from fixed base IFR to moving base VFR. Each simulation, however, is believed to be adequate for the engineering evaluation conducted and within the constraints of available capability. The establishment of practical simulation fidelity commensurate with the design task depends on engineering judgement and capabilities existing at the time of need.