F-16 & A-10A OFT SIMULATORS
FLIGHT SYSTEMS DEVELOPMENT & TEST

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ABSTRACT

This paper discusses flight systems development and test issues of the Air Force's F-16 and A-10 Operational Flight Trainers (OFT) for flight controls, performance, and stability and control. Brief descriptions of the aircraft, simulators and their hardware, and flight systems software are presented. The basic design data base is described; simulator test techniques are presented; and some of the more interesting flight system simulation test problems and their resolutions are discussed. Probably the more basic reason for many of the A-10 OFT flight systems initial problems relates to the minimal involvement of user pilots during data development and flight system logic design operation. Conversely, the success of initial government flight systems testing of the F-16 OFT was aided by early user pilot involvement in system design and operation. This paper also contends that the greatest amount of transfer of training (simulator to aircraft) for flight systems operation and performance is obtained with a design philosophy which replicates cockpit features, visual cues, and the performance of the actual aircraft. The paper concludes with suggested future methods to improve simulation performance and test efficiency.

NOMENCLATURE

AOA	angle of attack
$C_{L\delta e}$	lift coefficient due to elevator
DAC	digital to analog converter
DPS	degrees per second
FS/g, $\delta e/g$	stick force and elevator per load factor
HST, PWT	high speed tunnel, polysonic wind tunnel
I/O	input/output
S/W	software
VVI	vertical velocity indicator

F-16A AIRCRAFT

The F-16A is a single-engine, single seat multirole tactical fighter with full air-to-air and air-to-ground combat capabilities. It has a wingspan of 33 feet with wing tip missiles and an overall length of 49.5 feet. With full internal fuel, full ammunition and two AIM-9 missiles, the gross weight of the aircraft is approximately 23,500 pounds. The maximum gross landing weight is 27,500 pounds and the maximum gross takeoff weight is 35,000 pounds, which permits the carriage of almost 11,000 pounds of external stores. The F-16A aircraft is powered by the F100-PW-100 turbofan engine, which is in the 25,000 pound thrust class. The fuselage is characterized by a large bubble canopy and an underslung engine air inlet. The wing tail surfaces are thin and feature moderate aft sweep (40°). The wing is a NACA 64A204 airfoil which has leading edge flaps that are deflected automatically to enhance performance over a wide speed range. Flaperons are mounted on the trailing edge of the wing and combine the functions of flaps and ailerons. The horizontal stabilizers have a small amount of anhedral (10°) and provide pitch and roll control through differential deflection. The vertical tail, augmented by twin ventral fins, provides directional stability. The primary flight control system is a full fly-by-wire system which does not use mechanical linkages or control cables between the cockpit and the control surfaces. This systems provides three-axis flight path control through the use of a side stick controller and rudder pedals.

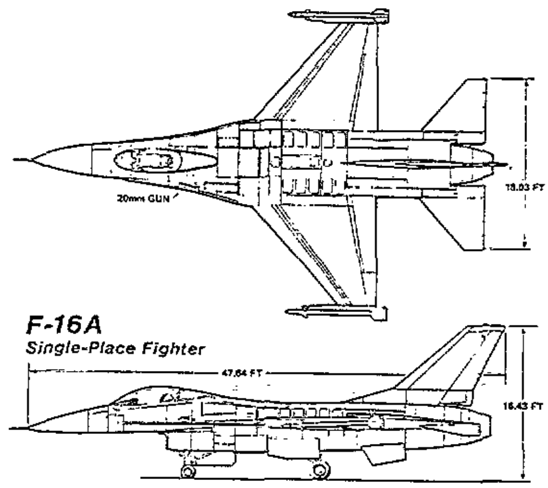


Fig 1 F-16A Aircraft

F-16 OPERATIONAL FLIGHT TRAINER

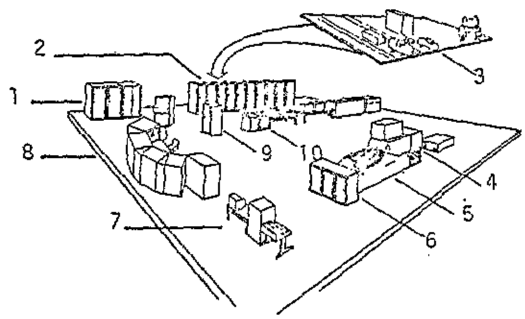
The F-16 Operational Flight Trainer (OFT) is currently nearing the end of a four-year production program and is being installed at various training sites throughout the United States, Europe, and Asia. The F-16 OFT is designed and built by the Singer-Link Corporation in Binghamton, New York and is intended to provide pilots with flight training that is directly transferrable to the F-16 aircraft. Through the use of the trainer, experience can be gained in the operational use of all aircraft systems. Pilots are able to practice tactical missions, both air-to-air and air-to-ground, with all possible weapon loadings. Emergency procedures can safely be practiced and the trainer can be "flown" to the limits of the aircraft's flight envelope to provide increased confidence and survivability.

TRAINER HARDWARE

Computation System. The current F-16 OFT consists of a computational system which comprises a complex of hardware units and structured software programs (Fig 2). The main computer consists of a central Nord-10/s 16 bit processor expanded four 32 bit Nord-50 processors. The Nord-10/s provides central control and supervision for all system I/O and program execution. The Nord-50 processors are dedicated to simulation system processing under control of the central Nord-10/s. The Nord-50 processors run in parallel, each contributing an uninterruptible one-fourth of the total Nord-10/50 computing power. Additionally, two Link-developed linear function interpolators (LFIs) are used to provide the aerodynamic data for flight handling characteristics of the trainer. Other hardware includes two disc drives, one a backup for the other, a Night Only Calligraphic Image Generation (NOCIG) visual system, signal conversion equipment (SCE), an actual F-16 Delco Magic 362F Fire Control Computer (FCC), a mechanoreceptor subsystem (MRCS) and a Sander's display system driving three CRTs, a light pen and three keyboards at the F-16 OFT instructor station.

Student Station. The cockpit of the simulator is an exact replica of an F-16 aircraft cockpit. It includes actual aircraft hardware for items such as the side stick controller, the Head-Up Display (HUD), the Radar/Electro-Optic (RDR/EO) system and the Fire Control Navigation Panel (FCNP).

All motion is simulated with a mechanorecptor cueing system (MRCS) consisting of 30° reclined g-seat, anti-g suit, and a seat shaker. Unlike previous simulators, there is no hydraulic control loading because, just as in the aircraft, the simulator employs a fly-by-wire flight control system which interacts via signals from the stick and rudder pedals' force transducers through the signal conversion equipment directly to the flight control system software model to provide all necessary flight dynamics. Realistic aircraft and environmental sounds are reproduced by an aural cue system.



1. Power Cabinet
2. Nord Computer
3. Hydraulic/Pneumatic Pumps
4. NVS Display
5. Student Station (Cockpit)
6. Cockpit Peripheral Cabinet
7. NVS Support Equipment
8. Instructor Operating Station (IOS)
9. Mechanoreceptor Cabinet (MRCS)
10. 75 M-BYTE Disks

F-16A Trainer Simulator

On several, but not all, trainers a Night Visual System (NVS) provides visual cues for the pilot to fly take-offs, approaches, landings, air-to-ground weapons delivery, air-to-air intercepts, and and limited air refueling. It employs a conventional beamsplitter CRT display with an instantaneous field of view (FOV) of ±22.6° horizontally and +13° and -15° vertically.

Instructor Operating Station. Finally, all of this is orchestrated at the instructor Operating Station (IOS). Designed to be operated by one instructor, the IOS includes three 21 inch alphanumeric CRT displays with a light pen, a radar/EO repeater with controls, selected flight avionics (repeater), a NVS repeater, functional keyboards, a three-axis joystick, and a communication system. Each CRT can provide real-time information of cockpit conditions, system malfunctions, instrument/navigation procedures, threats, or weapon delivery results.

FLIGHT SOFTWARE

The software is organized into modules which interact in a real-time simulation environment (Fig 3). The majority of the software is written in FORTRAN with some assembler language for better efficiency.

Each module is small (i.e., 100 to 200 statements) and has a well defined function such as module F500, Drag Coefficient. The Drag Coefficient Module calculates the total drag force coefficient due to aerodynamics including the basic aircraft and any perturbations from the clean configuration. The output of this module and several other aero coefficient modules interracts with the atmosphere module and equations of motion module to provide the flight dynamics for the simulator. Other modules are similarly grouped to provide engine dynamics, navigation, and weapons delivery simulation.

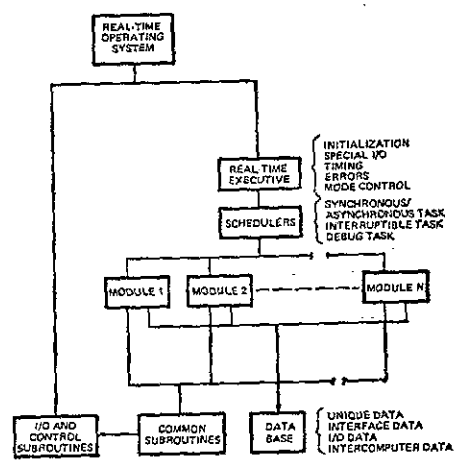


Fig 3 Software Organization

SIMULATOR DEVELOPMENT

Once the contract is let for the simulator, a large effort is spent in gathering data (Fig 4). Usually, sufficient data does not exist or there are anomalies in the data. Some examples for the F-16 OFT were: insufficient F-100 engine data, incomplete non linear rudder and flaperon effects, and incorrect aeroelastic modeling equations. Additional data must then be generated to cover voids.

This is expensive and time consuming. Once the data base is correlated, a software model is generated, debugged and refined.

As soon as possible during development, highly qualified pilot(s) should be brought in to perform a modified functional check flight of the simulator in order to identify any deficiencies in the flight regime. This was done with the F-16 OFT with excellent results.

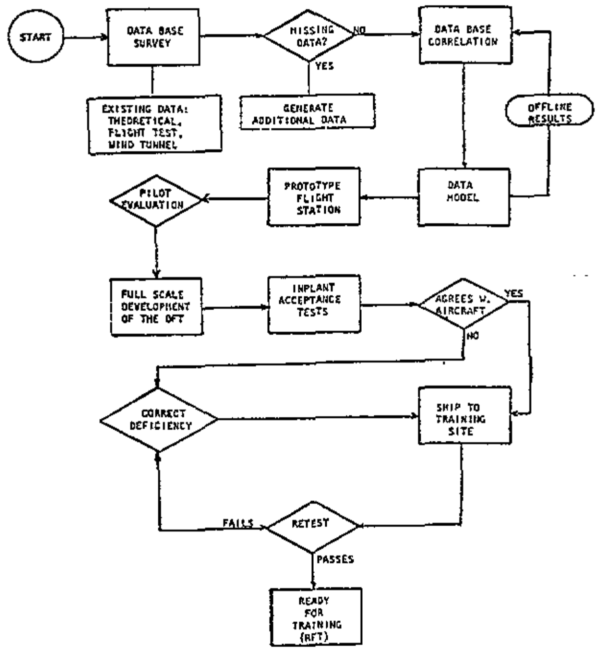


Fig 4 Simulator Development

Once Full Scale Development (FSD) and Quality Control (QC) checks are complete, extensive inplant acceptance tests with unit pilots begin. Several halts will probably occur as technical problems arise and are cleared by the contractor. If all goes well, the simulator passes several critical tests and is shipped to the appropriate training base. If all does not go well, then one or more technical deficiencies exist. If the deficiency is minor and does not effect training it will probably be waived for shipment and fixed prior to the ready for training date (RFT). If the deficiency is major then it must be corrected inplant. For the F-16 OFT follow-on simulators, retesting consisted of condensed testing of the necessary areas to ensure a complete and accurate system.

TEST PROCEDURES

In order to evaluate the complete F-16 OFT system over 4,000 pages of Acceptance Test Procedures (ATP) were written and incorporated into ten volumes. One of these volumes, volume seven, contained the performance evaluation tests. It consisted of: weight and balance checks, atmosphere checks, speed power tests, engine performance, and both static and dynamic flight characteristics.

Weight and balance tests were rather straightforward readouts of gross weights, centers-of-gravity, and moments of inertia for several F-16 configurations. Similarly, the atmospheric checks evaluated proper temperature lapse rates, airspeeds and mach numbers for standard (+15°C) and nonstandard days (-20°C, +40°C) and also checked for correct wind, turbulence, and gust effects.

The Speed Power tests provided the first detailed comparison of the performance of the simulator with that of the aircraft. These tests consisted of level accelerations/decelerations, rates-of-climb, and times-to-climb. The level acceleration tests were run at several fixed altitudes from sea level to 50,000 feet at maximum and military power settings. These tests are highly dependent upon an accurate engine model for thrust and inlet ram drag, and an equally accurate model for aircraft drag. The rate-of-climb (R/C) tests were run differently in the OFT than in the aircraft. R/C curves were generated for three different gross weights at sea level, 10,000 feet, and 30,000 feet. The trainer was then evaluated against them by freezing the altitude and allowing the pilot to vary the true airspeed by changing the pitch attitude. Thrust was kept constant at either military or maximum power settings and gross weight was maintained by freezing the total fuel. These tests became more difficult at the higher altitudes and gross weights due to its sensitivity to airspeed and pitch changes in this regime. The time-to-climb tests were more dynamic and, therefore, similar to those in the aircraft. Two tests were run, one in military power and one in maximum power. Both were run from sea level but timing was not started until the trainer passed 10,000 feet in order to allow the pilot to stabilize his climb attitude. The pilot initially maintained a constant airspeed (400 KIAS for military power; 550 KIAS for maximum power) until reaching 0.9 mach (mil power) or 1.5 mach (max power) and then held constant mach until completion of the test. Again, as in the R/C tests, it became difficult to match the data at the high altitudes primarily due to lower thrust available, pitch sensitivity, and pilot technique. Longitudinal maneuvering flight characteristics were evaluated using constant airspeed fixed altitude wind-up turns to 7 g's to determine control surface variations with load factor. Several gross weights and configuration were analyzed at 10,000 and 30,000 feet. As the angle of bank and the g-loads increased most pilots had difficulty maintaining mach number/airspeed even with altitude frozen. Repetition improved the pilot's ability and the test results. Longitudinal trim checks were also made for various configuration changes such as gear, flaps, and speed brakes extension and retraction. Lateral trim checks were performed by steady-state sideslips in which the pilot maintained a wings level sideslip of constant rudder pedal force. The rudder pedal force was varied up to full rudder deflection for each of several airspeeds, altitudes, and configurations. Results for sideslip angle ( ), rudder deflection, and differential flaperon were then compared with the aircraft data. Lateral trim was also checked for asymmetrical loads.

Dynamic stability flight characteristics were evaluated by first comparing the longitudinal short period dynamics with those of the aircraft. A strip chart recorder was used to record longitudinal stick force, stabilator position, pitch rate and attitude, angle of attack, and load factor while the automatic test features of the computer were used to input a pitch force doublet. Tests were run at three basic configurations, three different altitudes and several airspeeds. Similar procedures were used to evaluate the roll mode. Again the automatic test feature was used with the strip chart recording roll force, differential flaperon, roll rate, and roll attitude. From these tests, times to roll 90°, 180° and 360° for several airspeeds, weights, and configurations were compared with flight test data. Finally, the Dutch Roll mode was investigated using a rudder doublet (automatic function) and recording rudder pedal force, rudder deflection, yaw rate, roll attitude, sideslip angle, lateral acceleration, roll rate and differential flaperon.

Tests were also performed to evaluate 1-g stalls and take-off and landing performance. The last test performed was an overall pilot evaluation of the entire flight envelope. This was performed by a highly qualified F-16 flight test pilot whose comments were used to further improve the simulator data base.

TEST RESULTS/PROBLEM AREAS

One technique which has provided Air Force engineers with insight into potential problems in the flight handling area is to have the pilots "fly" simple profiles during their first time in the simulator. This allowed discrepancies, which might not otherwise be evident, to surface. One such discrepancy was noted by several pilots. Their comment was that the simulator required excessive force to "unstick" from the runway during rotation and lift-off. Contributing factors were a limited field of view visual system which may not have provided sufficient cues for rotation and lift-off and a fixed-stick controller which the pilots were not accustomed to using. The primary cause, however, was a non-linear load curve for the main landing gear which was approximated by linear equations. Additional break points were required in order to "smooth" the curve to fit the actual aircraft performance.

Another discrepancy was noted during the landing phase. Just prior to touchdown almost all pilots entered a rolling PIO (pilot induce oscillation) on their first landing in the simulator. This was also noted initially on the A-10 simulator. As the number of approaches and landings increased, the rolling tendency decreased to zero. The primary cause for this appears to be a lack of visual cues near the terminal phase of the approach. The pilot then overcontrols the roll axis. As experience grows, the pilots "learn" to slow their roll inputs during this phase to effectively eliminate this problem.

As mentioned previously, it was difficult to test the time-to-climb above 40,000 feet due to its sensitivity to airspeed and pitch. Several iterations of this test were required before satisfactory results were achieved. In this case, the data was correct but the test procedures were difficult to follow.

Perhaps the area of highest risk was in the software development for the F-100 engine. The actual F-100 engine in the F-16 aircraft is operational throughout a very broad flight envelope with rapid changes in engine demands. In order to properly handle this, a cycle analysis design approach was used to model the dynamics of each engine section. From the onset this effort was beset with problems ranging from missing data, especially transient data, to personnel changes. Two years were required to perfect the engine simulation.

A second problem area of the engine development existed in the Back-up Controller (BUC) which provides the fuel flow rate to the engine in the event of failure of the primary Unified Fuel Control (UFC). Both hardware and software problems occurred to hamper testing. Once the hardware was fixed, pilot comments became very important in isolating software problems and additional data was then sought to correct them.

A-10A AIRCRAFT

The A-10 aircraft is a single place close air support aircraft built by Fairchild Republic Company, Farmingdale, New York. It is powered by General Electric TF34-GE-100 engines having a maximum installed thrust of 9,000 pounds per engine. The maximum gross weight of the aircraft is 47,500 pounds. The engine is a high bypass turbofan with a single fan rotor, fourteen stage compressor and six turbine stages (See Fig 5). The aircraft has a length of 53.5 feet, a wing span of 57.5 feet, and a wing area of 405 square feet. The wing airfoil is an NACA 6716 inboard of the landing gear pods and an NACA 6713 outboard. The wing contains four panel, three position flaps, aileron and aileron tab surfaces, and eight pylon weapon stations; three additional pylon stations are located on the fuselage. The ailerons consist of upper and lower panels which also function as speedbrakes when moved symmetrically. The empennage consists of twin vertical rudders, a horizontal stabilizer, and elevators with elevator tab surfaces. The horizontal stabilizer and vertical stabilizer are NACA 64A013 airfoils. The armament system includes a 4,000 round per minute 30mm seven barrel gun. The flight control system is designed to operate with single or dual hydraulics shut down; the latter case is called Manual Reversion. Without hydraulic power, roll control mechanically transfers from aileron surface control to aileron tab control by means of a roll tab shifter device near the control surfaces. Mechanical disconnect devices, in both the pitch and roll control axes, free the control stick to operate in one of two separate paths in both pitch and roll in the event of a mechanical linkage jam.

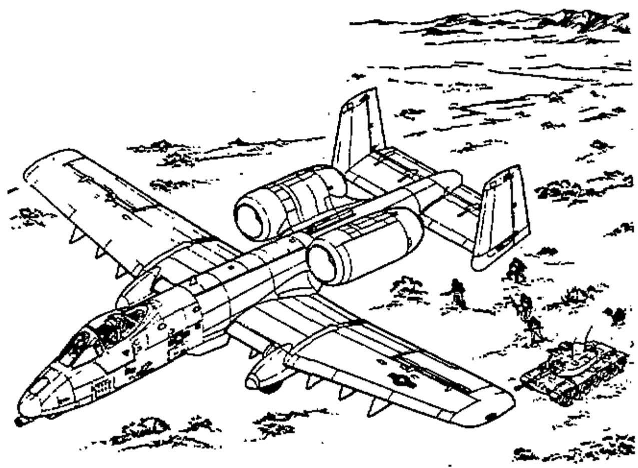


Fig 5 A-10A Aircraft

A-10A TRAINER SIMULATOR

Reflectone, Inc., of Tampa, Florida builds the A-10A Operational Flight Trainer for the Air Force through an initial 1976 contract with the Simulator Systems Program Office. The principal mission of this trainer is to provide the capability of procedures and proficiency training to pilots required to fly the A-10A aircraft in fulfillment of its mission to navigate, seek out and destroy ground targets. The trainer provides the means of developing proficiency in all phases of instrument flight, including ground operations, takeoff, enroute navigation, holding, penetration, approach, and landing under both normal and emergency conditions. The visual system permits practice in normal and emergency procedures under simulated night visual conditions. Experience will also be gained in selection and release procedures associated with the basic armament system and simulated electronic warfare (EW) equipment.

TRAINER HARDWARE

The trainer hardware and floor layout are shown in Figure 6. The primary computer capabilities consist of: Three System Electronics Laboratory (SEL) 32/55 computers (Units 1), an MDEC Vital IV system consisting of a Varian Image Generator Processor and Visual Display Unit (Units 7 and 2), an LSI-11 Minicomputer, aft of the cockpit station, for control loading modeling (Unit 8). Additional hardware systems are the Instructor Station (Unit 3), the Electronic Warfare Simulation Cabinet and Console (Unit 4), Audio Cabinet System (Unit 5), and Hydraulic and Electrical Power Equipment (Unit 6).

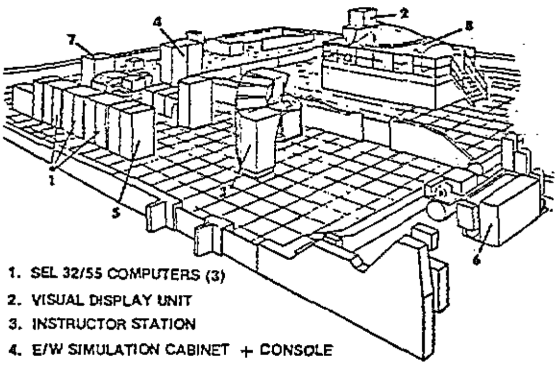


Fig 6 A-10A Simulator Facility

FLIGHT SOFTWARE

The software is primarily coded in Fortran with some assembly coding for the non-real-time programs. The trainer S/W system contains approximately 300,000 lines of code of which all are disc stored. The flight control system for the A-10 trainer simulator is a digital control loading system (DCL) designed and built inhouse by Reflectone, Inc., of Tampa, Florida. The DCL represents a novel method for simulating the control systems of an aircraft. The traditional method has been a system consisting of sensors, mechanics, hydraulics, drive electronics, and modeling ties together with some I/O interface to a host CPU. In this design, the modeling electronics (basically an analog computer) was replaced with a digital computer. The control system modeling of the aircraft is then performed by the digital computer software. I/O interchange to the host SEL computer is now performed by direct memory address (DMA) exchanges between the LSI-11 digital control loader computer and the host CPU.

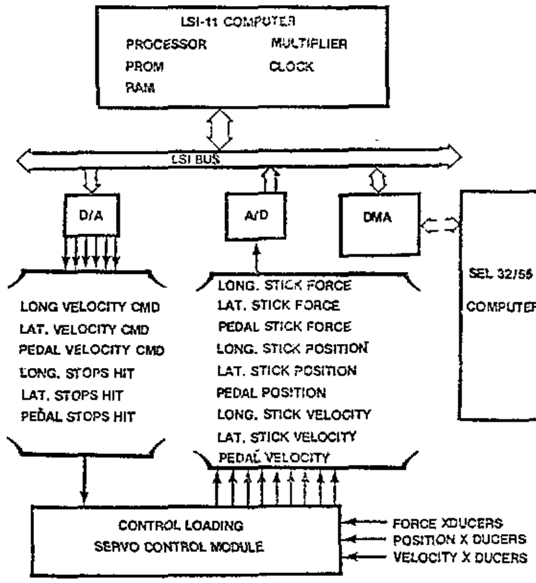


Fig 7 Digital Control Loading Subsystem

The propulsion module consists of approximately 600 lines of Fortran code and is executed at 10Hz with rectangular integration. Its primary outputs are net thrust and ram drag to the aerodynamics module, fuel flow to the fuel systems module, and thrust and engine speed to an aural cue module. The flight module consists of approximately 550 lines of code and performs calculations and summation of all aerodynamic forces and moments acting at the aircraft center-of-gravity. These forces and moments are a function of configuration, control surfaces, engine thrust, angle of attack, sideslip, body angular rates, and environmental conditions. The module data is in approximately 60 percent tabular and 40 percent equation form. The flight equations of motion are computed at 20Hz using a rectangular integration scheme.

DATA BASE

The total system design data base is best appreciated by realizing that a top level document listing the design references contains over 500 individual entries. The flight systems list is 30-40 percent of the total and includes flight test reports from Fairchild Republic Aircraft and the Air Force Flight Test Center as well as aircraft technical orders, engineering reports and drawings. Additional government reports from the Air Force's Tactical Air Command, Flight Dynamics Laboratory, and Human Resources Laboratory were also included in the design data base.

The aerodynamic and propulsion data base is currently a mix of wind tunnel, flight test and data variants due to pilot evaluation. The basic set of data and equations are based upon a cruise configured A-10A. Data changes due to configuration changes, external stores, power and hydraulic status are generally modeled as incremental effects to the cruise configured aircraft. Aerodynamic effects due to buffet, ground effects, and asymmetric controls and malfunctions are also modeled. Wing stall conditions are computed on each wing side individually based on AOA and tip roll rate. Side force due to rudder and lift force due to elevator are modeled as geometric multipliers of yawing moment due to rudder and pitching moment due to elevator respectively. Reductions in lift and a nose down pitching moment due to the absolute value of sideslip are also included. These values are 15 and 10 pounds of lift coefficient and pitching moment respectively per degree of sideslip.

The original aerodynamic data S/W load was based almost exclusively upon wind tunnel data primarily obtained from 1/10 scale model tests of the A-10 in the NASA Langely 7x10 ft HST and the Ames 12 ft PWT. This data resulted in poor lift/moment effects due to power induced flow particularly with secondary control surfaces, i.e., speedbrake and flap deflection. Wind tunnel roll control effectiveness for the cruise configuration was also excessive but identified and documented during flight test. Much of the flight test derivatives identified in AFFTC-TR-77-1 were incorporated into the simulator; however, these derivatives primarily addressed the low angle of attack regime in a cruise configuration. The side force due to aileron and normal force due to elevator were incorrect and not incorporated; the lateral accelerometer location had been mislocated in the computer derivative extraction program resulting in the incorrect side force derivative; wing to elevator center-of-pressure geometric constraints for $C_{L_{\delta_e}}$ computation had also not been entered into the program. The point in mentioning these data discrepancies is that the A-10 aircraft program had a huge aerodynamic data base with inaccuracies and conflicting data which required considerable effort to determine and delete in order to arrive at a data base acceptable for trainer simulation development. Although a huge data base existed, there were also considerable gaps that needed definition; some of these were: (1) external stores mass and inertial properties, and rack and pylon locations, (2) definition of control surface hinge moment characteristics relevant to cockpit control forces during Manual Reversion Flight (no hydraulics).

TEST METHODS

This will be described in a broad sense relating to test effectiveness and efficiency. Air Force simulator acceptance testing has traditionally been very time constrained by comparison with aircraft testing. In this regard, test management coupled with test planning and sequencing along with test techniques and data were very critical to test accomplishments. In reflection, insufficient government involvement during contractor inplant testing of the first article and an abbreviated Test Readiness Evaluation prior to large scale start of government testing resulted in considerable misunderstanding between Air Force and the contractor during subsequent A-10 simulator testing. Also, insufficient use was made of TAC/Test Pilots during contractor inplant testing; results during this period were also not sufficiently documented or remedied. In addition, simulation peculiar test procedures for determining system performance were not sufficiently detailed to allow efficient and large scale official government testing. Detailed flight performance was attempted prior to a thorough computer systems operation checkout resulting in poor flight system test efficiency. Many computer halts and dropouts were encountered which hampered the flight performance evaluation.

TEST EQUIPMENT

Calibrated force gages (load cells) were used by the government to calibrate S/W values for cockpit control forces. A single eight pen strip chart recorder (SCR) was used to provide a continuous record of flight performance and dynamics; a secondary and somewhat unplanned evaluation fallout was its use in identifying sources of computer halts and interrupts. An X-Y-Y plotter was also used and was extremely useful in generating flight control gearing curves of force and position. The plotter graphically portrayed undesirable control force to position "ratcheting" associated with the digital control system implementation. This analog test equipment was provided drive signals by a S/W routine containing 120 internal computer signals; they were converted for display through DACs updated at 2Hz. Additional test display aids were the primary cockpit instruments repeated on the instructor console, i.e., ADI, altimeter, VVI, airspeed, and HSI; these instruments were also repeated graphically on Sanders CRT display pages along with engine parameter bar graphs. This information was very helpful in communicating and understanding pilot evaluations and concerns. There were additional CRT display pages that were very helpful for the evaluation; a control parameter page showing cockpit control and surface positions and a flight parameters page listing weight, configuration, airspeed, engine, environment, and acceleration/rate/attitude response.

TEST TECHNIQUES

Procedures and test results for simulation qualification were contained in a document called the Acceptance Test Document. For flight systems testing this document contained a large assortment of flight test results primarily obtained from two preproduction A-10A aircraft S/N 73-01665 and 73-01667. (These flight test report results are references 1 and 2.) The test techniques used in simulation testing paralleled flight test techniques to a large degree. Flight and simulator sideslip were done with steady heading rather than wings level. For longitudinal and lateral-directional dynamics, actual flight control surface signatures were duplicated and used to drive simulator response. Freezing altitude during many of these tests reduced pilot workload and improved data correlation; this could be done without affecting the calculation or display of velocity or attitude. Prior to these system performance tests, lengthy tests had to be performed to validate the environment, i.e., the atmospheric model, pressure sensitive instruments, and weight and balance. One-G stalls were determined from SCR data of lift coefficient, G's and AOA. These AOA values correlated well with a more easily observable VVI break on repeater instruments during one-G stalls.

Maneuvering stability and stall pitch out were tested during windup turns at constant airspeed. Post-stall gyration, spin, and spin recovery were evaluated against specific flight time history signatures. An attempt to replicate stall/post-stall flight control inputs were done manually with a control input/stick box diagram and written maneuver descriptions.

TEST PROBLEMS

A number of performance differences were observed during testing of the No. 1 simulator unit. As a consequence of this testing, approximately 1,500 test discrepancies were identified, of which 300 were against flight systems; of these, 40 percent were system logic errors, the remainder were system performance errors ranging from the manner in which rudder servo valves shutdown during a single channel SAS malfunction to the dynamic response of the VVI.

Attitude Changes. Slow yaw, pitch, and roll control attitude changes were observed on instruments and the visual system following a controls free, careful one-G trim setup. The motion drift was caused by fluctuating surface control positions from the LSI-11 digital control loader into FFLITE, the aerodynamics module, causing subsequent attitude changes. It was primarily solved by creating a S/W statistical automatic fine tuning loop for the flight control system in pitch, roll, and yaw to account for small varying null positions due to the hardware. This logic looks at stick and pedal velocity, and force over 64 sampling periods (less than one second at a sampling rate of 156Hz) then statistically averages the values and uses them as new and current bias and null forces for servo-value commands. A secondary fix involved a separate hold (clamp) circuit for the control surfaces to eliminate small signal disturbances. Stick position and stick rate, surface control and trim positions are used in the hold circuit logic. When these positions and velocity signals are within a small magnitude level, a new current trim position is used.

Tracking/Strafing. The pilot control workload associated with capturing and maintaining the Head-Up-Display (HUD) gun cross on the target during acquisition and tracking was excessive by comparison with the aircraft workload required. This was an early recognized deficiency of the simulator which was also one of the last problems corrected; it was solved by deviating from design yaw stability augmentation criteria. The design criteria called for an aileron to rudder interconnect (ARI) gain of .2 degrees of rudder per degree above 240 knots along with a yaw rate washout circuit of four seconds (4s/4s+1). This SEL computer circuit was modified during pilot evaluation to a fixed value at all airspeeds of .8 degrees per DPS for the ARI rate damper. This change not only resulted in clearing this discrepancy but also another characterized by excessive yaw and roll during final landing approach. This change appears to be a situation where some undetected (negative) characteristic of the simulator was corrected by an intentional deviation (negative) resulting in a (positive) acceptable performance result. Prior to making this change, the visual brightness of the gun strafing target was poor and was subsequently brightened. This visual change reduced pilot workload but was not of a sufficient nature to preclude this yaw SAS change.

Take-Off Rotation Speeds. Two problems existed which, when recognized as being related, were both corrected with a single design change. The first was the minimum rotation speed at take-off which was higher than the aircraft. The other problem was an excessive pitch down with a throttle chop (the aircraft has negligible initial pitch change with throttle motion). A review of the software model engine line-of-thrust and design data showed that the pitching moment associated with tailpipe curvature (4.5 degrees up) had not been accounted for. Inclusion of this effect in the model solved both the higher rotation speed and the initial pitch up with a throttle chop. An added benefit was the readjustment of C_{mo} values back to magnitudes published in flight test reports. Prior to recognition of the tailpipe curvature effect, the flight values of C_{mo} had been considerably modified to correct trim elevator differences between the simulator and flight results.

Pitch/Roll Sensitivity. This problem still exists to some degree on the simulator; it is an excessive attitude response for small pitch and roll control inputs. Previous changes to the simulator have not corrected this issue: the aileron actuator model had been slowed down from a 50 millisecond first order lag to a 120 millisecond lag; in addition, aileron control surface aerodynamic effectiveness was reduced for deflections under five degrees. Design data (wind tunnel and flight test) were generally lacking-only showing roll effectiveness for much larger control deflections.

Flight Test-Simulator Recommended Improvements

In order to improve simulator quality and test effectiveness, we recommend the following improvements in the data base: (1) Surface authorities and maximum rates relative to airloads/airspeed, (2) Identification of any control surface effectiveness reduction for small deflections (e.g., 3 degrees), (3) Cockpit control trim motor transient characteristics relative to surface and stick motion (e.g., no. of clicks to full authority), (4) Flight control system damping and frequency characteristics for normal and degraded hydraulic and electrical power operation, (5) Post stall dynamics and departure characteristics, (6) Control response sensitivity for the power approach configuration, (7) Flight test document expansion of written descriptions of aircraft peculiar characteristics even if the data base does not fully explain the phenomena, (8) Identification of conflicting data between viable sources (flight test vs. contractor), and (9) Improved communication between the aircraft test community and the trainer simulation community.

TEST METHODS

The following recommendations are suggested in simulator and flight test methods to improve simulator efficiency and quality: (1) Combine AOA and control surface trim definition with speed power test during aircraft flight and simulator testing. (2) Freeze simulation altitude while allowing accelerations, velocities, and attitudes to change-to reduce pilot workload during speed stability, maneuvering stability and flight dynamics tests, (3) Better describe how flight test configuration trim changes are performed (e.g., constant attitude, power, altitude). There is an inherent potential for simulation dynamic cue mismatch (e.g., visual, cockpit instruments, flight modules operating at different computational update rates) and fewer (than aircraft) cues available in a simulator. Because of this, additional cockpit instrumentation flight characteristics are required. This cue data should be time tagged to normal aircraft response parameters (e.g., a video camera and recorder). We recommend a cyclic Bode frequency response test at fixed airspeeds. Flight test pilots should also "fly" the simulator as soon as possible to identify deficient areas.

Rather than perform initial flight simulation testing in a segmented classical sense, we suggest that a few aircraft tests be performed specifically structured for simulation use. These tests would be combined expanded functional check flight complied with operational scenarios with a fully instrumented aircraft containing pilot voice recording and a video recorder for instrument response information. This same test profile can then be flown on the simulator in the same manner again recording pilot comments and measuring simulator performance. A method of this nature would allow early identification of significant simulation flight system deficiencies.

PLANNING METHODS

Air Force acceptance of First Article Simulator Systems has been lengthy with unplanned extensions of test schedules because of the unanticipated large number of serious Test Discrepancies. This problem can be minimized if certain concepts are emphasized such as: (1) Providing briefings of system operation and flight characteristics to contractor personnel, (2) Showing, and possibly demonstrating, the aircraft to contractor personnel, (3) Identifying data base milestones within the contract, better organize the design documents, especially their accuracy, currency, and completeness, (4) Assuming that additional aircraft flight data would be necessary for design, thereby dedicating some flight missions for simulation data purposes, (5) Developing a "prototype" flight station as a design tool-between the User pilots and design personnel-for early correction of system operation and flight performance problems.

TRANSFER OF TRAINING

The Air Force spends sizable sums of money to replica aircraft systems operation and displays, flight performance and dynamics, and corresponding motion and visual cues. Questions arise concerning the need for this large design and cost effort. The authors believe that high fidelity flight performance and dynamics are necessary but not sufficient for high Transfer of Training. Some additional and necessary factors are: (1) Training scenarios that reflect an operational mission, (2) Induced psychological stress, and (3) Sufficient visual/motion cues appropriate for a task. If system training requirements are not clearly defined by the USER, or misunderstood by the procuring agency, a trainer can easily be developed with capabilities not totally suited for training. Both the A-10 and F-16 simulators have high fidelity flight performance and weapons capabilities; however, a realistic ground attack or visual landing approaches can hardly be trained properly because of their single window visual systems. Without the possibility of an accident occurring, it's difficult to obtain appropriate stress and workload levels. Minor system performance errors can have large impacts to positive transfer of training for new students who tend more to generalize single issues into poor total system performance. Transfer of training for the Manual Reversion flight now for the A-10 is expected to be less than desirable at this time because force/feel characteristics for trim, configuration, and power changes do not sufficiently reflect the aircraft.

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