# Advanced Fighter Controls Flight Simulator for All-Systems Compatibility Testing

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**McDonnell Aircraft Company has developed a flight simulator to serve as a test bed for control systems for advanced fighters. The cockpit of the simulator is adaptable to any fighter cockpit configuration and is located on the nose of a hydraulic, electrical and control system test bed. This paper contains a description of how this unique simulation facility was set up, checked out and operated in the all-systems compatibility testing of the F-4 fly-by-wire Survivable Flight Control System (SFCS). Actual SFCS flight hardware and electronics were mated to an existing control system mock up and to a digital computer simulating F-4 flight dynamics. The simulator flights included takeoff, landing, air-to-air and air-to-ground target tracking and system failures, as well as the usual flight test handling quality maneuvers. In addition, normal and emergency procedures were developed. Thus, through testing and training with the simulator, control system and interface problems were corrected and a high level of confidence in the design of the SFCS was established before an SFCS equipped aircraft was flown. These accomplishments, and a capability for rapid response in testing problems and modifications developed during flight test were major factors in keeping the program on schedule and on cost.**

## Introduction

THE increasing sophistication of equipment for driving control systems in high performance aircraft has generated the requirement for quicker and more thorough testing of new designs. The interaction of new systems with existing ones is best determined by operating the actual equipment comprising these systems together. A unique method of testing such interaction as early as the design phase has been provided by the McDonnell Aircraft Co. (MCAIR) Advanced Fighter Control Flight Simulator (AFCFS).

The AFCFS is a tool for evaluating the complete flight control system (including the pilot) of advanced fighter aircraft under controlled laboratory conditions. By combining a modern fixed base simulator, a primary controls test fixture and advanced fighter flight control system electronics, the AFCFS provides testing fidelity heretofore available only with actual flight testing. Although this concept and the simulator are applicable to any new fighter control system, a particularly appropriate system, the F-4 Survivable Flight Control System (SFCS), has been chosen for this paper to illustrate the problem solving capability of the AFCFS.

## Background

The SFCS utilizes quad-redundant flight control channels to provide the F-4 with greater reliability and combat survivability. To assure safe flight testing during the early phase, a mechanical backup was provided in the yaw and pitch axes. An emergency electrical backup mode was also provided for the phases in which the mechanical backup linkages were physically removed from the aircraft. The flight simulation for the early design phases of this program was provided by a fixed base simulator and associated software, along with the special software required to simulate the Survivable Flight Control Electronic Set (SFCES).

To assure compatibility of the design hardware with the actual aircraft equipment, including all the associated non-linearities, a test was planned utilizing a remote crew station simulator, the Variable Geometry Simulator (VAGES), and an F-4 hydraulic and control test bed (Iron Bird). This plan presented major simulation compromises due principally to the fact that the crew station would be remote from the Iron Bird. Several solutions were considered, but the increase in simulation fidelity achieved by mounting the VAGES cockpit directly on the Iron Bird made this solution the most desirable.

## Test Setup

### Hardware

The F-4 Iron Bird with the VAGES installed was used as the test bed for SFCS compatibility testing. The SFCS electronic sets and actuators were installed and completely checked out during the open loop (without pilot or flight simulation) portion of the test. For the closed loop (piloted flight simulation) testing, the SFCS electronics, the VAGES instruments and displays, and the Iron Bird were interfaced with the digital computer flight simulation through the Unit Interface. The SFCS Simulation Functional Block Diagram is shown in Fig. 1 and the facility layout is shown in Fig. 2.

#### *Iron Bird*

The F-4 Iron Bird is normally used primarily in conducting tests on the F-4 aircraft primary control and hydraulic systems. Production aircraft parts are used to reproduce the actual aircraft geometry and dynamics. In the installation of the SFCS equipment (secondary actuators, mechanical isolation mechanism, etc.) care was taken to duplicate the wire and line lengths and routing to be used in the SFCS aircraft. The electronics sets were mounted beneath the crew station using interconnect cables duplicating aircraft wiring.

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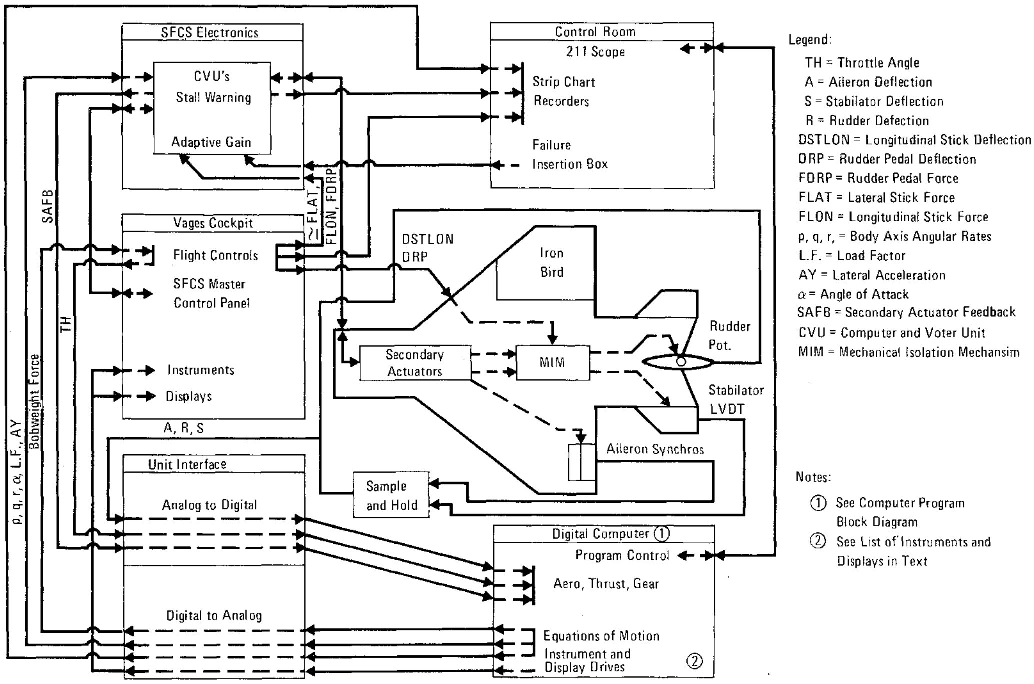



SFCS SIMULATION FUNCTIONAL BLOCK DIAGRAM

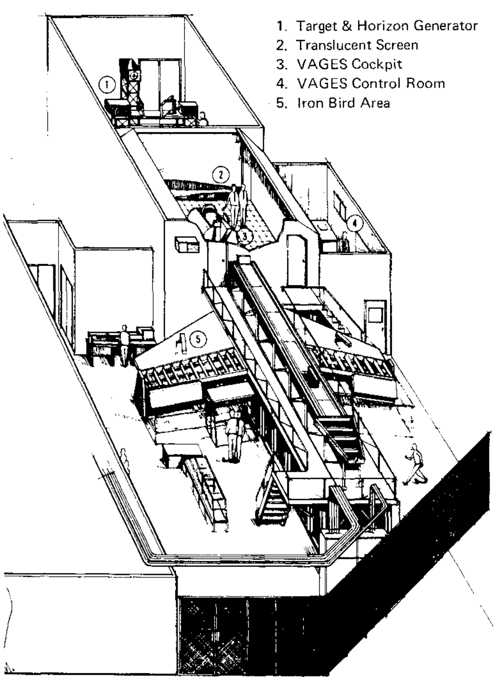
**Fig. 1 SFCS simulation block diagram.**

*Crew Station*

The VAGES was designed so that the cockpit/control geometry could be adapted to various advanced fighter cockpit layouts. It was configured as an F-4 cockpit for the SFCS program (Fig. 3).

*A. Instruments*—Functioning instruments for this study included: Attitude Director Indicator (ADI), Mach/Airspeed Indicator, Angle-of-Attack Indicator, Altimeter, Rate of Climb Indicator, "g" Meter, Engine rpm Gages (2), Hydraulic Pressure Gages (4), Stabilator Position Indicator, Rudder Position Indicator, Aileron/Spoiler Position Indicator (2), Bearing Digital Readout, Range Digital Readout.

*B. Flight controls*—The AFCFS primary flight controls are the same as are in the SFCS F-4 aircraft. In the mechanical backup mode the longitudinal stick and rudder positions are transmitted through the mechanical isolation mechanism (MIM) and operate the surface actuators. In a fly-by-wire mode the MIM shifts to isolate the control positions from the surface actuators. Control is then accomplished through stick force transducers and rudder pedal force pickoffs. The electrical signals representing the pilot's control inputs are summed with aircraft motion feedback signals in the SFCS electronic set to generate




VARIABLE GEOMETRY SIMULATOR LAYOUT

**Fig. 2 Variable geometry simulator layout.**

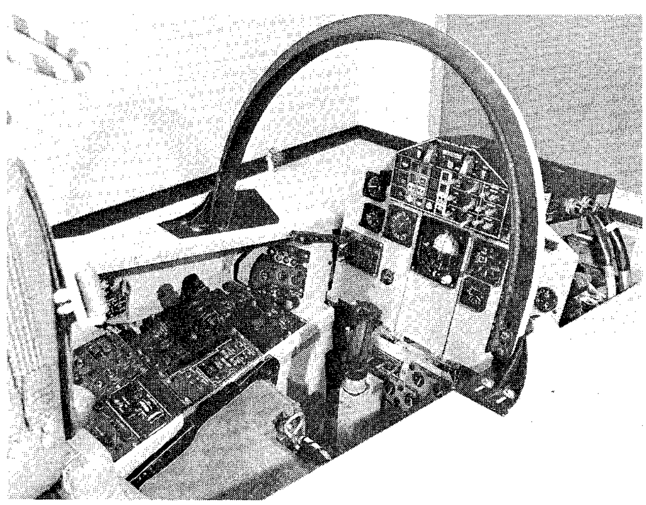


**Fig. 3 VAGES SFCS-configured F-4 cockpit.**

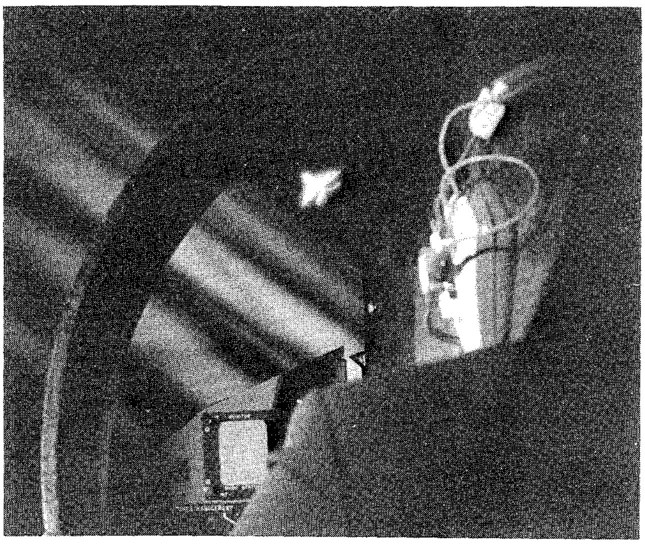


Fig. 4 Target image.

commands for the secondary actuators. The secondary actuators then operate the surface primary actuators. The entire fly-by-wire system, from the pilot input and motion sensors to the secondary actuator, is quad-redundant in both electronics and hydraulics. The longitudinal feel system of the SFCS F-4 differs from that in the production F-4 in that the SFCS does not have a q-bellows for varying the stick force gradient with airspeed. The longitudinal feel system in the AFCFS is identical to the SFCS F-4 which has a fixed single gradient spring cartridge arrangement with an eddy current damper and a bobweight. The contribution of the simulated bobweight of the AFCFS to stick force is generated by a servo controlled from the digital computer. The simulator lateral control system also has a simple spring cartridge for stick feel but does not have a mechanical backup feature; that is, the ailerons/spoilers are fly-by-wire only. A side stick controller (SSC) mounted on the right console operates in parallel with a fly-by-wire force transducer control from the center stick.

Secondary simulator controls include throttles with speed brake switches, gear handles and three-position flap switches. All controls are read by the digital computer to obtain the appropriate thrust and aerodynamic effects. The generator, hydraulic and master caution lights are operable to warn the pilot of aircraft system failure.

The SFCS Master Control Panel mounted on top of the instrument panel contains switches for selecting fly-by-wire modes and gains, and for inserting various failure modes. It also has lights for monitoring the status of the system. A Discrete Function Generator Panel is located on the center pedestal for inserting step inputs to the stabilator, rudder or ailerons. A three-axis trim panel is located on the left console for aircraft trim while in the fly-by-wire mode. Also on the left console are the MIM switches, the speed stability mode switch and the aileron disengage switch. All of the control system and SFCS equipment are actual flight hardware.

C. *Displays*—Out-of-the-window visual displays are provided for the pilot to fly air-to-air gunnery, air-to-ground weapons delivery, and for takeoffs and landings, The translucent rear projection screen is mounted in front of the pilot, covering his forward 60° field-of-view, Two projectors are located behind the screen. One projects a cloud horizon or terrain map translator video directly onto the screen. The other projects video of an all-aspect target model aircraft onto a gimballed mirror. The mirror is positioned to project the target image at the proper line-of-sight location (relative to the pilot's eye) on the screen (Fig. 4). An additional 360° attitude cue is provided for the pilot by a horizon projector mounted behind his headrest in the crew station. This horizon projector puts a ground image on the interior walls of the simulator room and is gimballed to move in pitch and roll. A sound simulator provided cues for engine and aerodynamic noise plus the sound effects for noises made by extendable items such as flaps, gear and speed-brakes.

## Unit Interface/Controller

The Unit Interface is located near the Control Data Corporation (CDC) 6600 computer and serves as a link between the computer and the several Unit Controllers located at the actual simulator crew stations. The Unit Controller contains the converters, both Analog-to-Digital (ADC) and Digital-to-Analog (DAC), plus some control and monitoring functions. The Unit Controller transmits and receives only digital data to and from the CDC 6600, thereby eliminating the need for long, noisy analog signals paths. The accuracy of the interface system is frequently checked by running calibration signals from the CDC 6600 through the Unit Controller DAC's and back to the computer through the ADC's. Discrepancies greater than 0.3% are detected and pinpointed for quick corrective action.

### Software

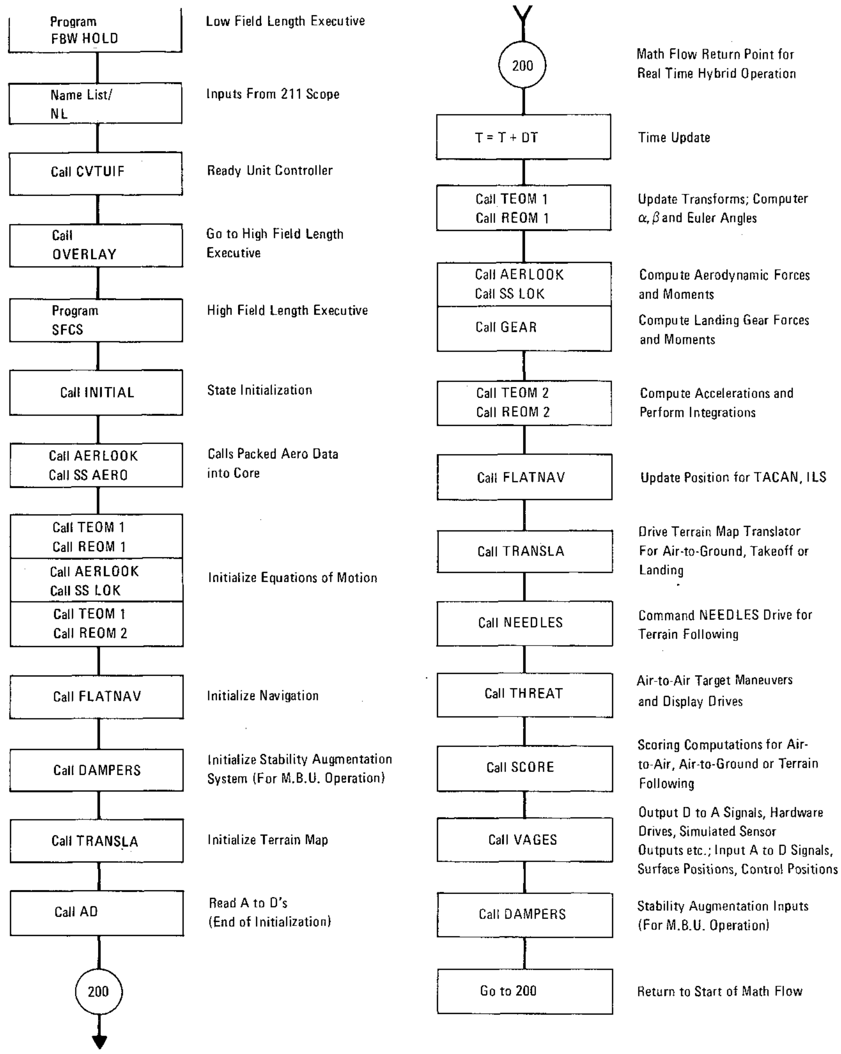
The digital computer simulation features a central executive program which calls each operation from a package of subroutines. Communication between the subroutines is accomplished through a large common block called an F-Array. There is direct access to the computer through the display station (CDC 211 Scope) located in the simulator control room. Initial conditions and many program options can be typed in on the 211. At any time during flight, the simulation can be put in "Hold" and any variable in the F-Array called out to the scope. This capability for on-line examination of the program's inner workings greatly facilitates checkout and troubleshooting. (See Fig. 5 for program block diagram).

#### *Aerodynamics*

Two separate aero data packages and aerodynamic computation subroutines are employed; one for normal flight, and one for spin-stall. Both aero programs employ one, two, and three-dimensional stored data of thrust limits and stability derivatives.[1] The data includes flexibility effects. The aerodynamic forces and moments are computed using these derivatives and other appropriate terms. The effects of wing rock and buffet are optional as separate increments. Thrust response to the pilot's throttle input and hinge moment limits to ailerons are computed in the aero subroutines. The rudder hinge moment has to be physically applied to the Iron Bird rudder by a servo because the F-4 rudder is a reversible system and the pilot can have some mechanical rudder authority with the pedals.

#### *Equations of Motion*

A set of machine language standard subroutines, common to many simulation problems, is available as a part of the computer system. The "standard" equations of motion (Subroutines TEOM1, REOM1, TEOM2, REOM2) are employed in this simulation. The forces and moments (aero, thrust gear) are inputs, and the accelerations, rates, Euler angles, angles-of-attack, sideslip, transform matrices, etc., are outputs. The integration is accomplished with quarternions to avoid singularities. The quarternion correction factor is monitored and never deviates by more than 0.1% even during the most violent departures and spins.




COMPUTER PROGRAM BLOCK DIAGRAM

**Fig. 5 Computer program block diagram.**

*Navigation*

Aircraft position is updated in subroutine FLATNAV for use in TACAN, ILS and target relative geometry computations. The drive signals for the terrain map translator are computed in subroutine TRANSLA. In landing approaches there is a ceiling at which the video is switched from the cloud horizon to the terrain. This ceiling and any wind condition is selectable as a NAMELIST input to the program.

*Operational Tasks*

Display generation computations for takeoff, landing, and air-to-ground weapons delivery are done in subroutine TRANSLA. The terrain following task is accomplished with no visual reference to the ground. The pilot maneuvers to keep the command steering needles on the ADI centered. The needle action is set up in subroutine NEEDLES to simulate command steering over moderate rolling terrain.

The air-to-air target maneuvers are programmed in subroutine THREAT. Two target options are available. The evasive target maneuver consists of a target which starts dead ahead of the attacker and then goes into a series of dives, turns and speed changes. The other option is a level target flying S-maneuvers at constant speeds and constant g's.

Scoring of the pilot's tracking error during terrain following, air-to-air and air-to-ground is done in subroutine SCORE. The errors are computed for each iteration and sorted according to magnitude. At the end of each run the error distribution total and percentages are printed out.

*Stability Augmentation System*

Since the SFCS aircraft has a normal F-4 stability augmentation system (SAS) when in the mechanical or electrical backup mode, it was necessary to include this feature in the simulation. The SAS rate gyro and accelerometer simulation must be accomplished in the digital computer since these dynamics could not be obtained from hardware on the non-moving Iron Bird. Thus the SAS is modeled in the digital program (Subroutine DAMPERS), and the SAS contributions to surface deflections are added to the actual Iron Bird surface deflections before the deflections are used in the aero subroutines. It is also necessary to restrict the SAS contribution to rudder deflection to the amount of rudder deflection actually available within hinge moment limits.

*Interface*

All of the digital-to-analog and analog-to-digital operations are done in subroutine VAGES. The calibration data for the airspeed, Mach, and angle-of-attack instruments are contained in data tables. A table look-up extracts the desired driving voltage from the table. It is then transmitted to the instrument on one of the Unit Interface digital-to-analog convers (DAC's). The rest of the instruments and all of the display drives have linear driving voltage relationships and are scaled, biased and transmitted to DAC's.

The six dynamic signals simulating outputs from actual gyros, accelerometers, and the angle-of-attach probe are generated in VAGES for input to the SFCS Computer and Voter Units (CVU). Several of the strip chart recorder variables are also computed in VAGES.

The analog-to-digital signals such as throttle position voltage, translator follow-up and secondary actuator feedback are read into the program on analog-to-digital converters (ADC's), filtered, if necessary, and scaled appropriately in VAGES for use elsewhere in the program.

*Control System*

The computer simulation of the SFCS equipment and aircraft hardware was retained as a special option which permitted the simulated aircraft to be flown without having an operational Iron Bird and SFCS hardware. This option allowed checkout of the simulator cockpit and displays before the hardware installation and checkout were completed.

## Hybrid Checkout and Verification Tests

### Software Tests

Verification of the computer simulation of the aircraft's aerodynamic behavior involved a series of data checks and response tests.

*Data Verification*

The aero data points were taken from published data and loaded into the computer.[1] Through a technique referred to as "data packing," the computer storage requirement for the aero data was cut by 75%. Instead of using an entire 60 bit word for each data point, four data points were packed into each word. This gave 15 bit accuracy for each point and resulted in no sacrifice of significant digits. The data tables were checked by having the computer go through the actual table look-up routines used in the aero programs and redraw the curves with a Calcomp plotter. The Calcomp curves were then compared with the original curves to check the accuracy of the loading and look-up routines. Bad points would show up as obvious spikes or discontinuities in the curves.

*Aerodynamic Transient Response*

The next check was that of the aero and equations of motion to step inputs. Before this was begun, the trim initialization was verified to assure that the trim stabilator checked with the published trim curves and that, after starting the flight, the pitch transients were minimal (less than 0.05 °/sec).

The pitch response was checked by stepping the stabilator one degree from the trim position. Calcomp plots of angle-of-attack, load factor, pitch rate, and pitch angle were made for flight conditions covering the entire envelope. The response compared favorably with a small perturbation three-degrees-of-freedom program.

For the lateral-directional check cases the digital simulation runs were started with an initial five-degree sideslip ($\beta$) and the airplane response to that initial disturbance was recorded. Calcomp time history plots of sideslip, roll angle, yaw rate, roll rate, heading and lateral acceleration were made. The control power was checked by inserting steps of aileron, spoiler and rudder. These results also showed good agreement with results from the separate small perturbation program.

*Spin Test*

The spin stall aero data included data for side-slip angles as large as 40° and for angles-of-attack up to 104°.[2] Data points were packed, plotted back, and checked as described for the normal flight aerodynamics above. A check case was set up to duplicate the flight profile of an actual F-4 spin test. At an altitude of 45,000 ft and Mach 0.58, pro-spin controls (full back stick, full right stick. and full left rudder) were applied. Time histories of pitch rate, yaw rate, roll rate, angle-of-attack, sideslip, pitch angle, roll angle and number of turns were plotted along with the same parameters from the flight test spin. The simulation stall, departure and spin entry followed the test flight behavior closely, but the simulation did not settle into the same stabilized high yaw rate spin. For this simulation the discrepancy was not considered detrimental since the stall departure and spin entry were the portions which were critical to the evaluation of the SFCS Stall Warning System.

*SAS Response*

The frequency response and damping of the stability augmentation system (SAS) simulation model was checked by driving it with various sinusoidal inputs. The stabilizer responses to pitch rate frequencies of 1.0, 2.0, 5.0, 10.0, 20.0, and 30.0 rad/sec were recorded. The peak amplitude of the pitch rate oscillation was ±2.5°/sec. Rudder SAS responses to yaw rate inputs of the same frequencies and amplitude were also checked. The results agreed with separate analysis results for F-4 SAS responses. SAS authority limits were temporarily removed for this verification test to facilitate linear analysis.

*Hardware Tests*

Setting up the VAGES for its first actual use in a hybrid simulation required extensive efforts in calibration of all instruments, displays and control system.

*Instruments*

All of the instruments were bench tested and calibration curves obtained prior to installation in the crewstation. The calibration data were used in the VAGES subroutine to compute the driving voltage output signal.

*Displays*

Routine parallax and scale factor calibration was performed on all displays drives including the horizon pitch and roll, target mirror gimbal pitch and yaw, target model pitch, roll and yaw, and target camera roll and range. Since accuracy of these servos affect scoring they are subject to daily calibration. Calibration of the target range (apparent range as seen by the pilot) was obtained by measuring the target's wing span on the projection screen for different target camera range drive voltages. Apparent range was linear out to about 3000 ft. Beyond this range, target size determination was degraded by TV resolution (raster lines).

The terrain map translator was also calibrated on a daily basis to assure proper positioning and camera sightline orientation. The rear screen projector was adjusted to align the translator zero sight line with the pilot's eye. The video horizontal and vertical size was set to give the pilot the same field of view as the TV camera.

*Control System*

The control system gains and responses from the stick to the surfaces were completely checked during the open loop (non-piloted portion) of the SFCS compatibility tests. However, those portions of the control system peculiar to the hybrid simulation were not included in the open loop tests and had to be tested separately.

The main problem with the hardware setup was that of obtaining surface position pick-offs free of noise and deadband. This problem was eliminated by using sample and hold circuits and by correcting a persistent slippage between the rudder bellcrank collar and the rudder torque tube of the Iron Bird.

A 2.91 lb/g bobweight servo was calibrated and found to give a reasonably linear force output up to 20 lb (measured at the stick grip). The response and stability were good but the 20 lb limit meant that the bobweight servo force contribution was saturated at 6.8 g's.

*Rudder Loading System*

Operation of the hinge moment limiter was checked by applying full rudder pedal and comparing the resulting rudder deflection to predictions.[3] The agreement was very good over the entire envelope of Mach number and altitude. The rudder had a tendency to enter a moderate oscillation under conditions of high dynamic pressure and full rudder application. This could only be corrected at a sacrifice of hinge moment limiter response in flight regimes of less rudder limiting. Since full rudder pedal at high q is not a frequent control application, it was decided to accept the oscillations in order to retain the limiter response.

*Hybrid Checkout*

Due to the extensive preflight testing of both the hardware and software the initial hybrid flights incorporating the complete SFCS Iron Bird control system were accomplished without major problems.

*Aircraft Performance*

Performance was verified by comparing maximum and military power level acceleration times to the data in Air Force Tech Order 1F-4C-1-1. Turning performance was also checked by flying constant Mach maximum sustained "g" level turns. These maneuvers were flown by hand and therefore exhibited some scatter, but good agreement with the Tech Order was obtained. It was, however, noted that the simulated aircraft was capable of sustaining high turn rates and g-forces at angles-of-attack where the actual aircraft (F-4E) would be rapidly dissipating its airspeed. The normal flight aero program had data to only 20° (22 units) angle-of-attack and the extrapolation used beyond that did not provide entirely realistic behavior. This was not a serious problem since the test plan called for all of the very high angle-of-attack maneuvers to be flown using the spin-stall aero program, which included good data to 104° angle-of-attack.

*Landing Gear Reaction*

Landing gear reaction was programmed in subroutine GEAR (refer to Fig. 5) to give a realistic simulation of aircraft behavior for the ground rotation and takeoff and for landing touchdown and rollout. Accurate modeling of the actual gear dynamics is not feasible for real-time simulation using a 0.04 sec iteration time. The gear reaction during touchdown is over in less than 0.2 sec; thus there would be only about five iterations in which to reproduce the very complex load-stroke behavior of the actual strut. Thus a model was devised to avoid the problems of modeling the actual gear and yet provide realistic ground reaction. Springs with a constant gradient in the actual strut stroke range were used to allow the aircraft to come to rest at its normal ground attitude. Velocity-squared damping was chosen to dissipate the energy of a normal touchdown within the allowed strut stroke. Viscous damping was added to control the rebound and rocking motions.

Brakes and nose wheel steering were not simulated. Directional control during takeoff is not a problem as long as the thrust of the two engines is matched. Aerodynamic rudder control is effective down to about 50 knots.

*Handling Qualities*

The only serious hybrid checkout problem area was the landing configuration handling qualities. The published flap down aero data[2] shows a negative slope on the pitching moment due to angle-of-attack ($CM\alpha$) curves which would indicate negative static stability. The actual aircraft is, in fact, quite stable with the flaps down. More accurate published data was not available so the $CM\alpha$ curves were adjusted in the simulator until several MCAIR test pilots agreed that the longitudinal stability and handling quality closely matched that of the actual F-4E. The increase in $CM\alpha$ required that flaps down stabilator power ($CM\delta$) be increased so that the trim stabilator position would match flight test data. It should be noted here that all of the aero changes were based on simulator flights using the mechanical flight control system. This provided the test pilots with a valid comparison to the F-4 aircraft they were accustomed to flying.

The initial attempts at takeoff (half flaps) revealed that the nose rotation and liftoff speed were too high and that there was a tendency toward over-rotation and pilot induced oscillations (PIO) after takeoff. Ground effects[1] were added since they provide additional lift and some nose-up pitching moment (when the stabilator is full trailing edge up). This addition, along with the changes mentioned above, reduced the rotation and liftoff speeds to the correct values resulting in less tendency toward over-rotation and PIO. The out-of-window terrain map display was inadequate as a pitch reference for rotation due to loss of a distinct horizon as the nose came up and due to the lack of high quality peripheral vision cues. Therefore, all takeoffs were made using cockpit instruments only. With these changes the pilot felt that nose rotation, pitch attitude capture and liftoff were representative of a night takeoff in the actual F-4.

*Test Procedure*

The SFCS operation and aircraft handling qualities were evaluated over the whole flight regime by two MCAIR test pilots assigned to the SFCS project. Pilots were provided with flight sheets which defined the mission profiles and provided instructions. Prior to each flight the pilots were briefed on the flight conditions and maneuvers to be flown and on the items to be rated. However, the flight sheets were used primarily as guides to insure that all areas of the flight regime were examined and the pilots had wide latitude to investigate any area or characteristic of interest. During the test several project engineers were on the intercom system with the pilot to monitor his actions and the aircraft and control system performance.

The following is a description of tasks performed for each flight sheet mission:

*Flight Sheet 1*—Mechanical Back-Up (MBU) Mode Characteristics for General Maneuvering—This test was conducted to evaluate the handling qualities of the SFCS MBU mode at six flight conditions. Maneuvers flown included stick raps, rudder kick, pulls ups, rolls, wind-up turns, trim changes, SAS response, accelerations and decelerations.

*Flight Sheet 2*—Electrical Back-Up (EBU) Mode Characteristics for General Maneuvering—Handling qualities in EBU were evaluated using both the center stick and side stick controller. Stick raps, rudder kicks, pull ups, rolls, wind-up turns, and trim changes were performed at six flight conditions.

*Flight Sheet 3*—Normal Mode Characteristics for General Maneuvering—The pilots investigated the all-up mode handling qualities at 14 flight conditions. The maneuvers flown included stick raps, rudder kicks, hands-off stability, pull-ups, bank-to-bank, wind-up turns, accelerations and decelerations, trim changes and aerobatics.

*Flight Sheet 4*—SFCS Mode Transistion Characteristics—Transition from EBU to MBU, Normal to MBU, and Normal to EBU were made during level flight, wind-up turns, and with full trim applied. These maneuvers were flown at six flight conditions covering minimum to maximum dynamic pressure.

*Flight Sheet 5*—Mode Combinations and Takeoff or Landing (TOL) Function Characteristics—Test pilots flew various combinations of SFCS modes in the pitch, roll, and yaw axes at six flight conditions. Single axis maneuvers such as aileron rolls, rudder steps and pull-ups were followed by cross-axes maneuvers such as barrel rolls and wind-up turns.

*Flight Sheet 6*—Single Channel Failures from Master Control and Display Panel—The pilot inserted each of the twelve possible failures at three different flight conditions. He then maneuvered to ascertain what the system required to detect the failure and what, if any, effect there was on handling qualities.

*Flight Sheet 7*—Single Channel Component Failures—Single components such as hydraulic pumps, generators, and actuators were failed at four flight conditions. The pilots noted failure detection ability and the effect on SFCS performance.

*Flight Sheet 8*—Variable Gain Evaluation for Normal Mode—The project engineers observed the ability of the adaptive gain changer to select the proper gain as the pilot performed stick raps, rudder kicks, pull-ups, wind-up turns, accelerations, decelerations, climbs, dives, and configuration changes for takeoffs and landings. It was found that a more rapid computer iteration rate (0.3 rather than 0.04 sec) was required to assure accurate sampling and aircraft response to the 4 Hz adaptive gain stabilator interrogation signal.

*Flight Sheet 9*—Multiple Channel Failures—Multiple failures in a single axis were applied and pilot corrective action observed. Operation of the demand on mode after triple hydraulic failure was checked as was aircraft handling with double engine flame-out.

*Flight Sheet 10*—Stall Spin Test for SFCS—The aircraft recoverability from stalls, departures, and fully developed spins was investigated using the SFCS normal mode and MBU. Entries were made from both one g and accelerated stalls at various flight conditions. The pilots noted that the simulation of stall and post-stall gyration was very good but that the recovery from the spin using the simulator was easier than that with an actual aircraft. These comments were based on flights using the MBU system; therefore, the difference was a simulation problem and not due to the SFCS.

*Flight Sheet 11*—Operation of SFCS with Secondary Control Inputs—At four flight conditions the operation of pitch and yaw vernier controls was investigated. Airplane response to pitch, roll, and yaw discrete function generator (DFG) inputs was documented.

*Flight Sheet 12*—Survivability Missions—This test was set up to simulate an actual flight test mission. The pilot was given successive failures and as each occurred the pilot aborted or continued the mission based on his assessment of the failure indications and other cues available in the cockpit. Additional failures which necessitated landing in a back-up mode were inserted. Particular attention was paid to the pilot's ability to evaluate the state of the system and choose the proper correction action.

*Flight Sheet 13*—Effect of Stabilator Hinge Moments of SFCS Operation—The objective of this test was to determine the amount of stress in the stabilator power cylinder control rod for normal aircraft maneuvering at flight conditions of maximum hinge moment. This was done by loading the stabilator actuator and applying rapid longitudinal control movements with the center stick and side stick controller.

*Flight Sheet 14*—SFCS Performance During Air-to-Air Tracking—A fixed reticle sight was used for tracking the target aircraft through a series of S-turns. The pilots attempted to hold the sight on the target and fired when a near-solution was achieved. Error data was collected while tracking and firing for statistical reduction at the end of the run. The SFCS "tracking quality" was compared to that of the basic F-4 using the MBU control system.

*Flight Sheet 15*—SFCS Performance During Landing—The pilots evaluated the SFCS system in all modes and gains during multiple TACAN/ILS approaches to full stop and touch-and-go-landings. Various ceilings and cross wind conditions were programmed. The side stick controller and verniers were also evaluated. Particular attention was paid to trim capability during speed and configuration changes.

*Flight Sheet 16*—SFCS Performance During Takeoff—After the aerodynamic simulation problems were resolved as discussed above, the pilots agreed that the takeoffs in MBU were representative of the actual F-4. Different control techniques were tried to develop the best procedure for fly-by-wire takeoffs. Mode reversions were made at critical points during the takeoffs and landings to reveal any possible adverse transients.

*Flight Sheet 17*—SFCS Performance During Air-to-Ground Weapon Delivery—Reasonable scores were obtained from the air-to-ground weapon delivery simulation during the system checkout. However, a failure in the terrain map trans-lator during the time allotted for this test precluded complete pilot evaluation of the SFCS in this task.

*Flight Sheet 18*—SFCS Performance During Terrain Following—Excellent scores were obtained from the command needle steering during terrain following. However, a larger number of runs would have been required to produce any valid statistical information on the relative performance of the backup versus normal modes and side stick versus center stick.

*Flight Sheet 19*—Outer Loop Mode Compatibility for SFCS—Pitch attitude and roll attitude command potentiometers were installed in the VAGES right console to provide autopilot-type attitude-hold command signals to the digital computer. The command signals were summed with the actual roll and pitch attitude of the aircraft, and any error was added to the pitch rate and roll rate gyro feedback signals going to the SFCS electronic set. Test pilots investigated the attitude capture and hold capability of this mode for several flight conditions.

## Data Outputs

### *Pilot Comments*

The primary means of SFCS evaluation was through pilot comments and ratings on the SFCS system operation and aircraft handling qualities. Pilot comments during the tests were recorded on the flight sheets by project engineers. Additional comments and Cooper Harper ratings were obtained during the extensive debriefing that followed each mission.

*Strip Chart Recorders*

Four Brush recorders were used, each having eight analog traces, seven discrete event markers and two time markers. Vehicle dynamic parameters, surface positions, and mode status are typical of signals recorded.

The primary use of the extensive strip chart recorder data was to provide the project engineers with a real-time capability for monitoring the system state and dynamics. The data was retained for further reference and comparison during the flight test phase.

*Computer Printout*

Scoring of the pilot's tracking error during air-to-air gunnery, air-to-ground weapons delivery and terrain following was printed out in an error distribution format to provide a statistical basis for evaluating the benefits of the fly-by-wire concept versus the mechanical system.

## Test Results

The primary objective of this phase of AFCFS simulation was the compatibility testing of the SFCS hardware for all flight conditions and maneuvers. To accomplish this with confidence extensive efforts were carried out to assure that the simulator had correct models of the F-4 aerodynamics. The pilots were able to fly the simulator with the mechanical backup control system and verify that the simulation was, in fact, a very good representation of the basic aircraft. Then, with the SFCS flight hardware mated to a high fidelity simulation of the F-4 aircraft, the system was subjected to exhaustive simulator tests.

During the course of the tests normal procedures were developed for takeoff, landing, and configuration changes as well as for emergency procedures for most possible combinations of aircraft and SFCS failures. The survivability missions were of particular value for training the pilots in system operation and in building their confidence in the redundancy and failure detection capability. The "SFCS Standard and Emergency Operations Procedures" document was based on the experience and training gained during the compatability tests. Several potential problem areas were identified during the simulation. Some problems, such as built-in test failures and Mechanical-Isolation-Mechanism deadband were corrected prior to first flight of the aircraft. Others, such as roll sensitivity, roll-yaw crossfeed and stall-warning implementation were deferred to the flight test phase for further investigation.

First flight occurred on May 4, 1972, with the pilot commenting that the SFCS aircraft flies just like the simulator. The experience and confidence gained in the hardware and personnel during the compatability testing permitted an early progression to full fly-by-wire status over the whole flight envelope.

Several of the potential problem areas identified in the simulation phase turned out to be serious enough to warrant modifications to the control system. Proposed fixes were checked out on the simulator before permanent changes to the hardware were incorporated for flight test. A structural resonance feedback oscillation which occurred in flight could not have been duplicated in the simulator but a corrective filter was rapidly devised and tested in the simulator to insure that it did not adversely affect other flight areas. The simulator has been maintained in a ready to go status throughout the flight test program for quick response to such problems.

The flight test program has progressed to the point where the mechanical backup control system was removed from the aircraft. Again the modifications were completely checked out in the simulator prior to flight in the aircraft. Flight test data correlations runs have been made with very good agreement between simulator and flight test results.

## Conclusions

This program has demonstrated the importance of all-systems-component-compatability testing in development of advanced control systems. A high level of confidence in the hardware and personnel was achieved during the intensive testing and training. Normal and emergency procedures were established and several system discrepancies were discovered and corrected prior to flight. The experience and confidence gained during simulation permitted a rapid progression in the flight test program. The quick response investigation of problems areas and proposed modifications kept the program on schedule and costs down.

## References

[1]"Model F/RF-4B-C aerodynamic Derivatives," Rept. 9842, Feb. 10, 1964, revised Dec. 10 1971, McDonnell Aircraft Company, St. Louis, Mo.

[2]"Model F-4 Spin Evaluation Program," Rept. A0005, Aug. 15, 1969, McDonnell Aircraft Company, St. Louis, Mo.

[3]"Phantom II Flight Control Systems," Rept. F144, Nov. 28 1966, revised June 2, 1969, McDonnell Aircraft Company, St. Louis, Mo.