

GROUND AND FLIGHT TEST EXPERIENCE WITH A TRIPLY REDUNDANT DIGITAL FLY-BY-WIRE CONTROL SYSTEM

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ABSTRACT

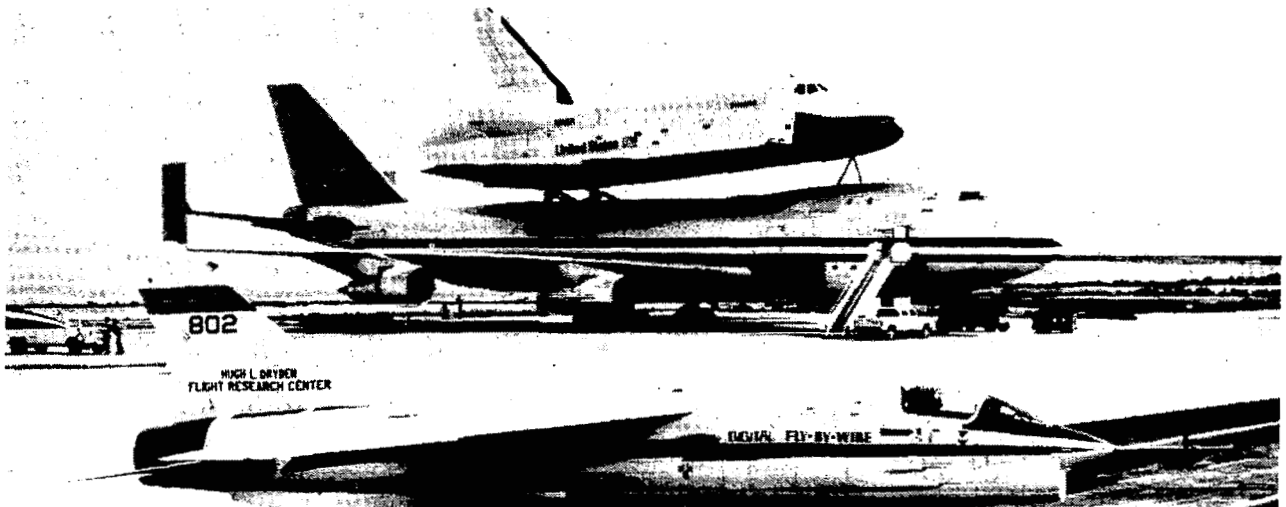
The National Aeronautics and Space Administration (NASA) is conducting research in digital fly-by-wire (DFBW) flight control for aircraft. The primary impetus for this work has come from the projected flight control system requirements for advanced military and commercial aircraft, particularly in the area of active controls. Such systems must have extremely high levels of reliability and computational capacity.

From 1972 to 1980, the NASA Dryden Flight Research Center (DFRC) conducted flight tests of a DFBW control system in an F-8C aircraft.

A triplex digital fly-by-wire flight control system was developed and then installed in the aircraft to provide fail-operative, full authority control. Hardware and software redundancy management techniques were designed to detect and identify failures in the system. Control functions typical of those projected for future actively controlled vehicles were implemented.

NASA F-8 DIGITAL FLY-BY-WIRE PROGRAM

NASA has been conducting research in aircraft digital fly-by-wire control at the Dryden, Langley, Ames, Lewis, and Johnson centers. The primary objective of this work is the development of highly reliable flight control systems that permit the implementation of active control functions, which contribute to energy efficiency and high maneuverability. A major flight experiment at the Dryden Flight Research Center involves the use of a Navy F-8C testbed aircraft that was modified to incorporate full authority digital fly-by-wire controls. The vehicle has a triplex fail-operational digital fly-by-wire primary flight control system and an analog emergency backup control system.



PHASE I 1971-1973


- SIMPLEX SYSTEM
- APOLLO SPACECRAFT COMPUTER
- NO MECHANICAL BACK UP
- ANALOG BACK UP
- FIRST FLIGHT MAY 1972
- PROVED DFBW FEASIBILITY

PHASE II 1974-1980

- TRIPLEX SYSTEMS
- MODERN COMPUTERS
- NO MECHANICAL BACK UP
- ANALOG BYPASS SYSTEM
- FIRST FLIGHT AUGUST 1976
- DEMONSTRATED DESIGN GOALS

F-8/DFBW LIGHTNING SUSCEPTIBILITY TESTS

To learn more about possible lightning effects on digital fly-by-wire systems, a series of NASA-sponsored research programs were conducted by Lightning Technologies Inc. and the Air Force Flight Dynamics Laboratory at Wright Patterson, using the F-8/DFBW aircraft. This research led to development of a nondestructive method, now known as the lightning transient analysis (LTA) test, for determining the level of lightning-induced voltages in aircraft electrical circuits. These test results were widely distributed in industry and prompted positive efforts to design lightning protection into other aircraft being designed with fly-by-wire control systems, including the USAF/General Dynamics F-16, the USN/McDonnell Douglas F-18 and the NASA space shuttle.

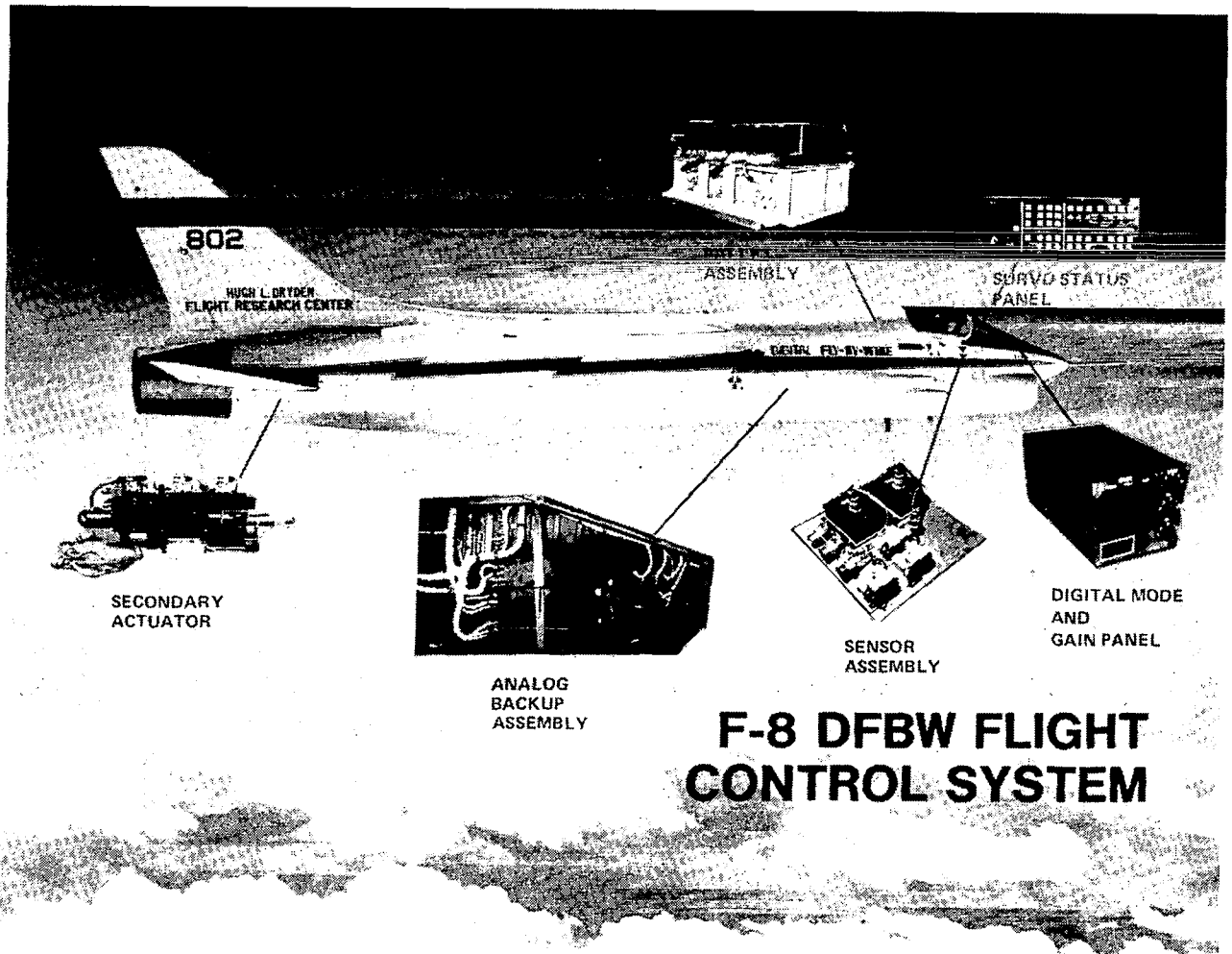


**50,000 Volt Simulated Lightning
Strike Induced on Nose Boom
Of Digital-Fly-By-Wire Aircraft**

**F-8/DFBW LIGHTNING
SUSCEPTIBILITY TESTS**

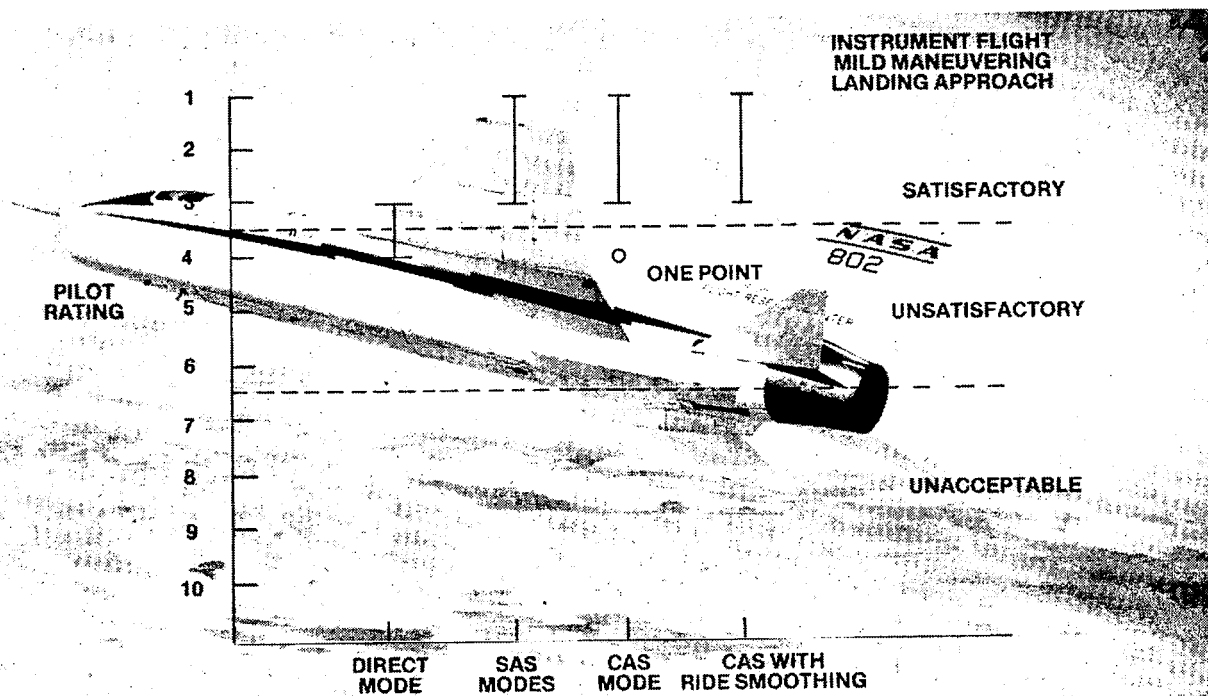
F-8/DFBW FLIGHT CONTROL SYSTEM MAJOR COMPONENTS

The heart of the F-8/DFBW flight control system is the triplex computer and interface unit assembly mounted on a removable pallet for easy access. A digital mode and gain panel located in the cockpit provides the pilot with system status information. Similar data are provided for the redundant actuators on a servo status panel. Analog backup electronics are located in the aircraft fuselage section as are the redundant rate gyro and accelerometer sensors. Each aircraft control surface is operated through a redundant servoactuator assembly that is commanded via the digital computers.



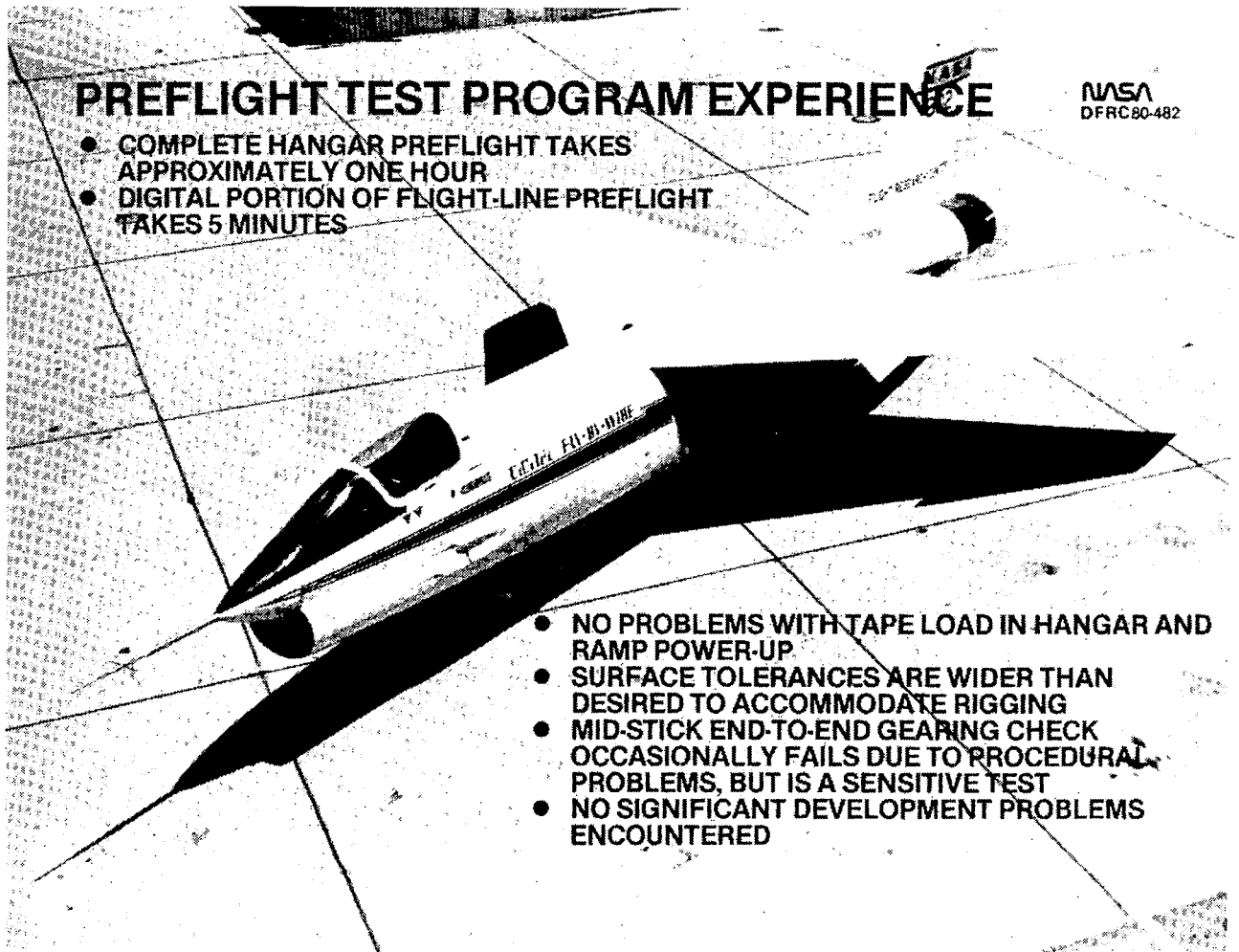
F-8/DFBW HANDLING QUALITIES SUMMARY

Handling qualities ratings by pilots for all control modes, based on the Cooper-Harper rating scale, have been satisfactory and above for all augmented modes and borderline for direct modes with no augmented feedback parameters. Ratings did not tend to vary for instrument flight, mild maneuvering and landing approach tasks.



PREFLIGHT TEST PROGRAM EXPERIENCE

All test flights are preceded by preflight tests comprised of hangar tests to verify system gains and scale factors, and automated flight-line tests that take approximately 5 minutes. The flight software program is generally loaded into the redundant computers during the hangar test, but can also be loaded during flight-line operations. Automated flight-line tests generally require pilot participation for switch operations and control inputs. No significant problems have been experienced with the integrity of the preflight procedures.



PREFLIGHT TEST PROGRAM EXPERIENCE

- COMPLETE HANGAR PREFLIGHT TAKES APPROXIMATELY ONE HOUR
- DIGITAL PORTION OF FLIGHT-LINE PREFLIGHT TAKES 5 MINUTES

NASA
DFRC80-482

- NO PROBLEMS WITH TAPE LOAD IN HANGAR AND RAMP POWER-UP
- SURFACE TOLERANCES ARE WIDER THAN DESIRED TO ACCOMMODATE RIGGING
- MID-STICK END-TO-END GEARING CHECK OCCASIONALLY FAILS DUE TO PROCEDURAL PROBLEMS, BUT IS A SENSITIVE TEST
- NO SIGNIFICANT DEVELOPMENT PROBLEMS ENCOUNTERED

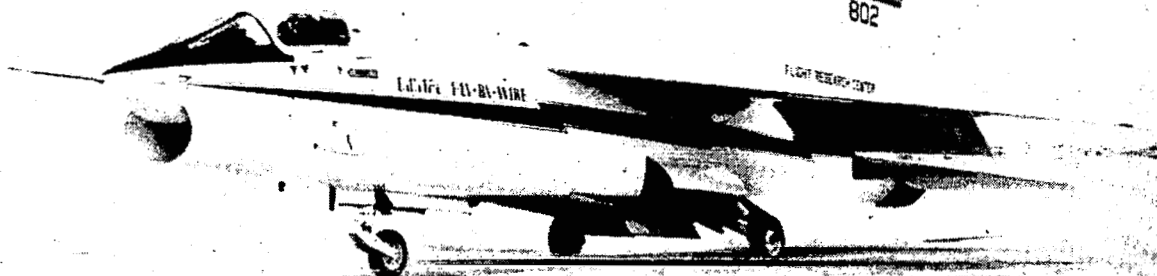
GROUND AND FLIGHT QUALIFICATION TESTS

The iron bird facility was used to a much greater extent than the actual aircraft for ground and flight qualification testing. The actual aircraft was used primarily to validate results established using the iron bird, except for ground resonance and structural coupling testing which required the presence of valid vehicle structural modes. The importance of an iron bird facility as a cost effective means of accomplishing these types of tests cannot be over emphasized.

PERCENTAGE OF TESTING IRON BIRD AIRCRAFT

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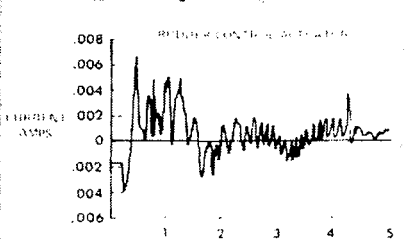
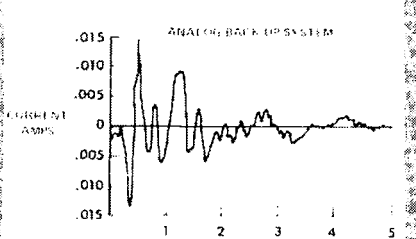
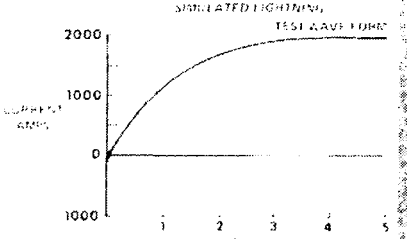
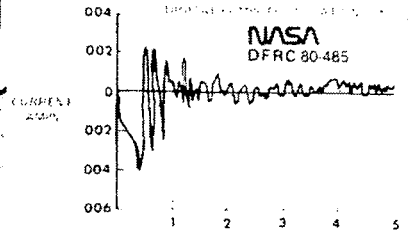
● SOFTWARE VERIFICATION	98	2 (PREFLT TEST)
● FMEA DEMONSTRATION	90	10
● SYSTEM INTEGRATION	75	25
● GROUND RESONANCE		100
● PILOT FAMILIARIZATION	95	5
● EMI	90	10
● LIGHTNING SUSCEPTABILITY		100



INDUCED-CURRENT MEASURED DURING F-8/DFBW LIGHTNING TRANSIENT ANALYSIS TESTS

A wide range of lightning test conditions were applied to the F-8/DFBW aircraft, reaching potentials of up to 50,000 volts and simulated lightning currents of up to 8,000 amps. One of the more significant findings of this first series is that at the instant test voltage is applied to the aircraft, traveling wave currents are established that "ring" back and forth along the aircraft at the speed of light, much as mechanical vibrations are set up in an airplane when it encounters a gust of wind. These currents precede the flow of return stroke current and are considerably higher than it in frequency. The magnetic fields produced by these high frequency currents thus induce higher voltages in internal electrical circuits.

Induced Currents Measured During F-8/DFBW Lightning Transient Analysis Tests



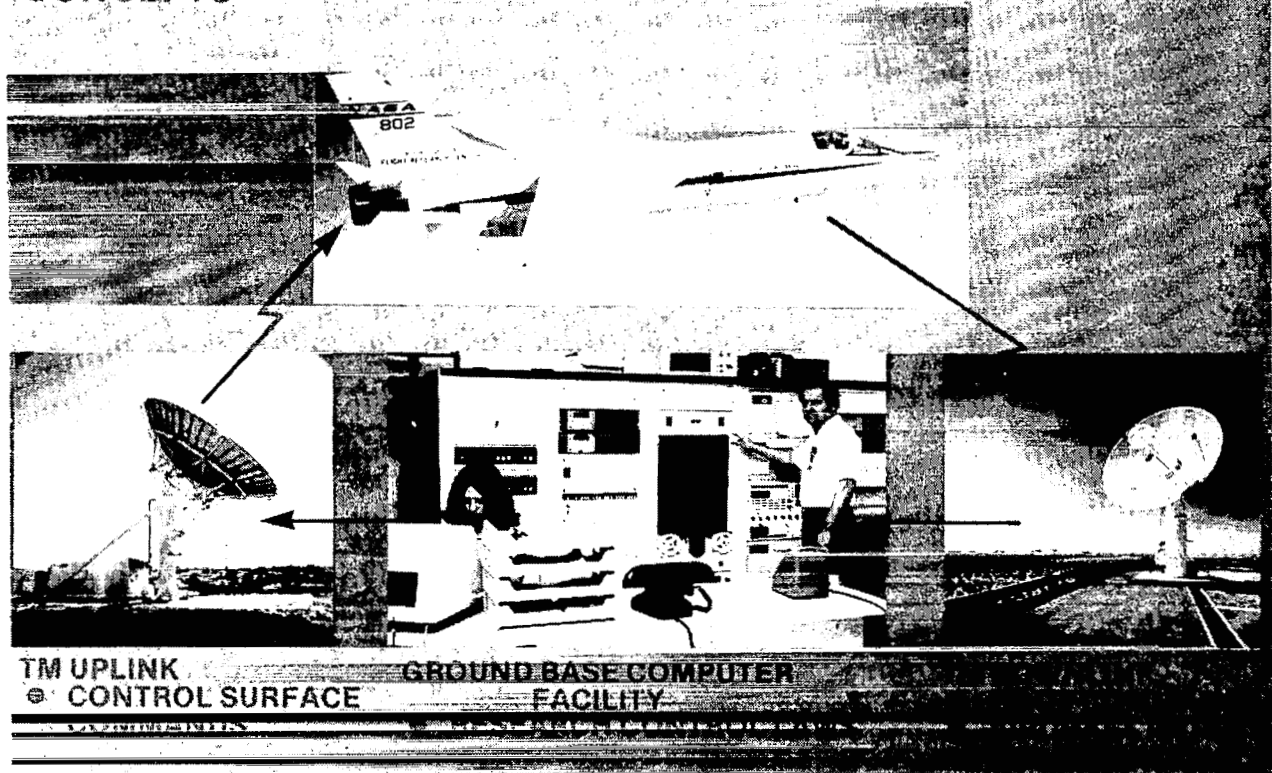
REMOTELY AUGMENTED VEHICLE TEST FACILITY

The F-8/DFBW aircraft can also be operated in a unique control law evaluation mode. By selecting special on-board software, the pilot can bypass the on-board flight computer, and have his normal control commands transmitted via downlink to a special receiving antenna. The commands are then processed in special control law algorithms programmed on a ground-based computer, and computed surface commands are uplinked to the aircraft. The pilot, in effect, flies the aircraft through the ground-based control laws. This approach greatly simplifies the level of verification required to man rate research control laws for flight test purposes and becomes a very low cost means of flight testing advanced control law algorithms.

REMOTELY AUGMENTED VEHICLE (RAV) TEST FACILITY

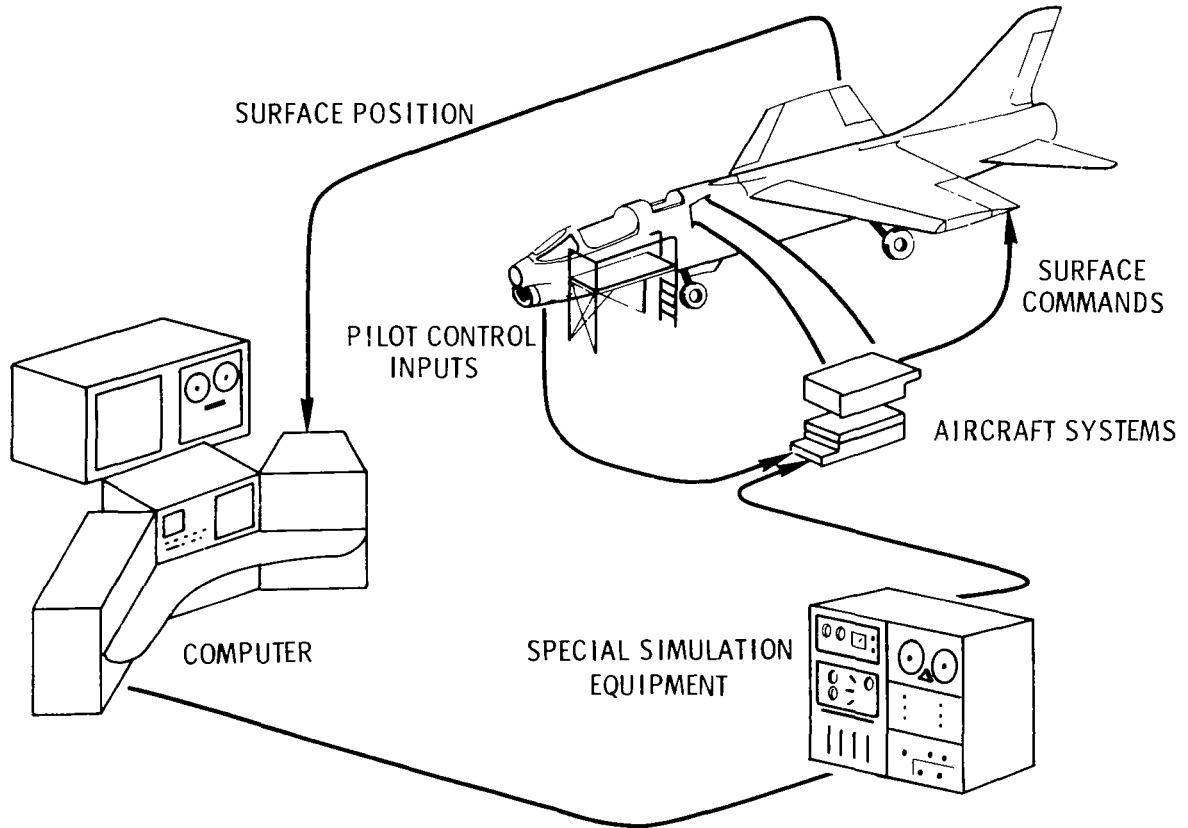
NASA
DFRC 10-88

UNIQUE FACILITY FOR TESTING ADVANCED CONTROL LAW CONCEPTS



IRON BIRD TEST FACILITY

An iron bird test facility was used in carrying out the many tests to support software and hardware verification. The facility consisted of an actual F-8 aircraft and all associated electric, electronic and hydraulic systems. A complete set of DFBW electronics and actuators were installed in the iron bird which was coupled to a six-degree-of-freedom closed-loop simulation of the F-8 dynamics. In addition to supporting ground verification and validation tests, the iron bird was also used for pilot training, pilot-in-the-loop failure mode, effects testing, and EMI testing.

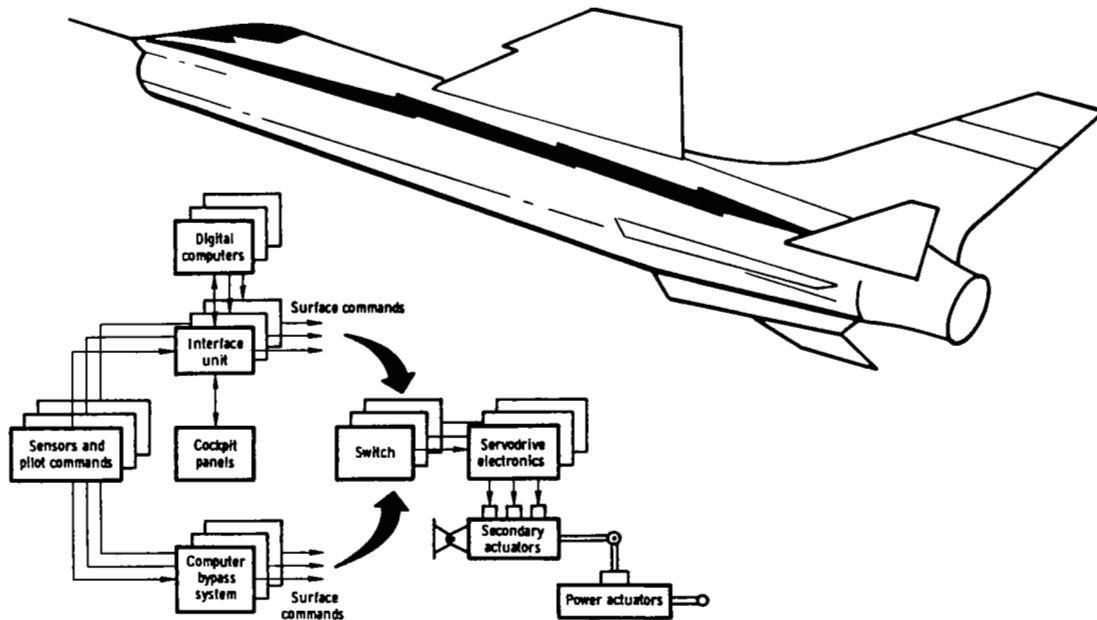


F-8 DIGITAL FLY-BY-WIRE SYSTEM DESCRIPTION

The overall mechanization of the F-8 DFBW control system is shown in this figure. A triplex digital computer set containing control law and system redundancy management software communicates with a specially designed interface unit (IFU). The IFU processes input data, which consist of pilot commands and aircraft sensor signals, and output data, which consist of surface commands, cockpit displays, and telemetry data. Surface commands are routed through a switching mechanism to the servodrive electronics and then to the force-summed secondary actuators, which are installed in series with the existing F-8C power actuators. There are five actuator sets: one for each aileron and horizontal stabilizer surface and one for the rudder.

The triplex analog computer bypass system provides the pilot with an emergency unaugmented command path to the control surfaces in the event of a total primary digital system failure. This path was provided primarily to protect against a common-mode software failure in the infant stages of flight test. The switching mechanism allows either the primary system or the bypass system to drive the secondary actuators based on pilot selection or automatically, according to fault status.

Electrical power is provided to three independent flight control buses by an engine-driven dc generator. Each bus is protected by a 40-ampere-hour battery, which would allow approximately 90 minutes of operation in the event of a loss of generator power. Secondary actuator hydraulic power is provided by the aircraft's three hydraulic systems, each of which supplies one of the triple chambers of each actuator.



IN-FLIGHT SYSTEM PERFORMANCE SUMMARY

Over 80 research missions have been flown with the F8/DFBW system. All take-offs and landings have been accomplished with the primary digital system. No automatic reversion to the analog bypass system has ever been required. Four computer hard failures have occurred on separate flights resulting in loss of one of the three digital channels. In each case, the aircraft was operated on the remaining two channels. All failure detection, identification and recovery operations have been according to design.

Although software errors have been discovered after initiation of the flight test program, no software errors have resulted in terminating a flight or aborting a mission, although this could have been the case had the right sequence of events occurred.

Several control law refinements were required to improve overall flying qualities, especially about the roll axis. Roll control was initially extremely sensitive about neutral stick positions for precision control tasks such as formation flying.

Very few cases of sensor failures have been noted, either hard or transient fails.

All failures that have occurred have been detected and properly resolved.

- **ALL TAKE-OFFS AND LANDINGS MADE WITH PRIMARY DIGITAL FLY-BY-WIRE SYSTEM**
- **NO AUTOMATIC REVERSION TO ANALOG BY-PASS SYSTEM HAS OCCURRED**
- **FOUR IN-FLIGHT COMPUTER FAILURES**
- **ONE TRANSIENT FAILURE IN-FLIGHT RESETTABLE**
- **NO FLIGHT ABORTS DUE TO SOFTWARE FAULTS**
- **SEVERAL CONTROL LAW REFINEMENTS NECESSARY**
- **SOME SOFTWARE ERRORS DISCOVERED DURING FLIGHT TEST PROGRAM**
- **VERY FEW SENSOR NUISANCE FAULTS**
- **NO EXCEPTIONS TO FAIL-OP OR FAIL-SAFE DESIGN**

CONTRACTOR AND UNIVERSITY STUDIES/GRANTS

In addition, a large number of supporting studies have been conducted by universities and contractors in support of various advanced concepts addressed by the F-8/DFBW program.

ADVANCED CONTROL LAW CONCEPTS	MIT RENSSELAER INSTITUTE (RPI) COLLEGE UNIVERSITY OF N.Y. (C.U.N.Y.) WILLIAM AND MARY VIRGINIA POLYTECHNIC *CSDL *HONEYWELL
● PHASE II CONCEPTUAL DESIGN	HONEYWELL
● FAULT-TOLERANT COMPUTER DESIGN	ULTRASYSTEMS
● DIGITAL FLIGHT CONTROL ACTUATION	ROCKWELL
● DFBW CERTIFICATION REQUIREMENTS	CSDL

*CONCEPTS FLIGHT TESTED

CONTRACTOR SUPPORT

Over 11 separate contractors have been involved directly in support of the F-8/DFBW program. This broad scope of involvement has contributed greatly to the program's transfer of digital fly-by-wire technology to industry in a timely manner.

CHARLES STARK DRAPER LAB	SOFTWARE AND INTERFACE HARDWARE
DELCO	INTERFACE HARDWARE
IBM	COMPUTER HARDWARE
RAYTHEON.....	COMPUTER HARDWARE
SPERRY FLIGHT SYSTEMS.....	ANALOG BYPASS SYSTEM
HYDRAULICS RESEARCH & MANUFACTURING ...	ACTUATORS
LING, TEMCO, VOUGHT.....	AIRCRAFT INTERFACE
BOEING.....	SNEAK CIRCUIT ANALYSIS
G.E.....	LIGHTNING TESTS
LIGHTNING TECHNOLOGIES, INC.....	LIGHTNING TESTS
AIR FORCE FLIGHT DYNAMICS LAB.....	LIGHTNING TESTS

JOINT NASA CENTER RESPONSIBILITIES FOR PHASE II PROGRAM

Overall program management responsibility for the F-8/DFBW program, including flight qualification and flight testing, rests at Dryden Flight Research Center. Advanced control law and system architectural concepts developed at Langley Research Center have been an integral part of the F-8/DFBW program. Considerable support of the space shuttle control system development has taken place through joint efforts with the Johnson Space Center. A joint NASA/FAA workshop on digital flight controls, sponsored by the Ames Research Center, was also supported by the program in 1979.

DRYDEN FLIGHT RESEARCH CENTER

- PROGRAM MANAGEMENT
- SYSTEM SPECIFICATION AND PROCUREMENT
- OVERALL SYSTEMS INTEGRATION
- SOFTWARE VERIFICATION
- FLIGHT QUALIFICATION
- FLIGHT TESTS

LANGLEY RESEARCH CENTER

- ADVANCED CONTROL LAW DEVELOPMENT
- PHASE II CONCEPTUAL STUDY
- DIGITAL ACTUATOR DEVELOPMENT STUDY

JOHNSON SPACE CENTER

- SPECIFY SHUTTLE SUPPORT TASKS
- SUPPORT SHUTTLE SOFTWARE FLIGHT TEST

AMES RESEARCH CENTER

- JOINT NASA/FAA WORKSHOP

F-8/DFBW CONTROL LAWS

Several advanced control law algorithms were developed and implemented in the F-8/DFBW system. The primary objective was to address the type of algorithms that might be applicable to future systems employing active control concepts. The goal was to tax the system as heavily as possible in order to identify limitations encountered in a realistic implementation of advanced control techniques.

ACTIVE CONTROL LAWS

INVESTIGATE PERFORMANCE AND INTEGRATION OF PROJECTED ACTIVE CONTROL FUNCTIONS

- **COMMAND AUGUMENTATION SYSTEM**
- **BOUNDRY CONTROLLER (α -LIMITER)**
- **AUTOPILOT FUNCTIONS**
- **RIDE SMOOTHING SYSTEM/MANEUVER FLAPS**
- **LOW SAMPLE RATE EXPERIMENT**

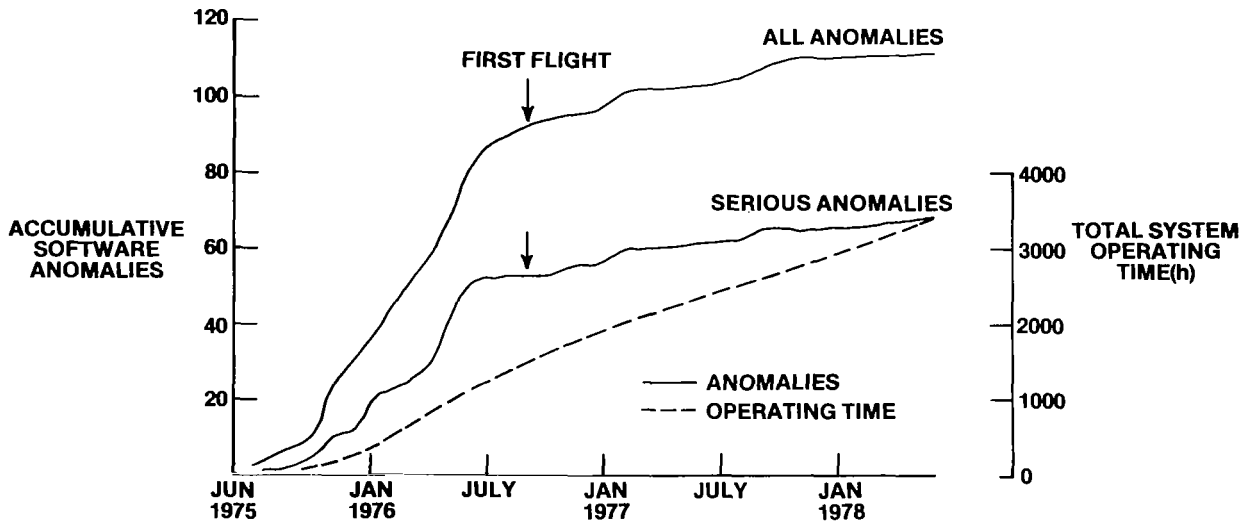
ADAPTIVE CONTROL LAWS

USE MODERN IDENTIFICATION THEORY TO ESTIMATE AIRCRAFT PARAMETERS FOR ADOPTIVE GAIN SCHEDULING

- **MAXIMUM LIKELIHOOD ESTIMATION**
- **ESTIMATE DYNAMIC PRESSURE, α**
- **IDENTIFICATION ALGORITHM ON GROUND COMPUTER**

SOFTWARE ANOMALY EXPERIENCE

Almost one year of verification testing was required before the system reached a level of maturity satisfactory for first flight. 1750 hours of system operating time were required during this period. Of significance is that even after extensive software verification testing, software anomalies occurred after the system was flight qualified, pointing to the fact that it is impossible to tell whether or not all latent software bugs have been identified and corrected.



SUMMARY OF DIGITAL SUBSYSTEM GROUND TEST EXPERIENCE

The amount of ground and verification testing required to bring the F-8/DFBW to a level of maturity was largely underestimated. Many problems requiring software changes and resultant verification were identified. The greatest number of changes occurred after initial integration of all subsystems. Many interrelating effects not identifiable in the early design phase were manifested, resulting in degraded operation.

Sufficient automated testing techniques were also lacking, especially those required to monitor and interrogate simultaneously operating redundant digital computers.

Overall system performance finally achieved, however, was excellent as validated by the flight test results.

- **COMPUTER REDUNDANCY MANAGEMENT EFFORT UNDERESTIMATED**
- **GROUND TEST TOOLS FOUND TO BE LACKING (MULTI-COMPUTER OPERATION)**
- **GENERIC COMPUTER HARDWARE PROBLEMS**
- **FAIL OP-FAIL SAFE OPERATION VERIFIED**
- **CONTROL LAW VERIFICATION ROUTINE ONCE BASIC OPERATIONAL ASPECTS OF SYSTEM MATURED**
- **NO EMI PROBLEMS**
- **NO STRUCTURAL MODE INTERACTIONS**
- **EXCELLENT SYSTEM PERFORMANCE ACHIEVED**