F-15 ACTIVE (**A**dvanced **C**ontrol **T**echnology for **I**ntegrated **VE**hicles)
Research Program History and Technology

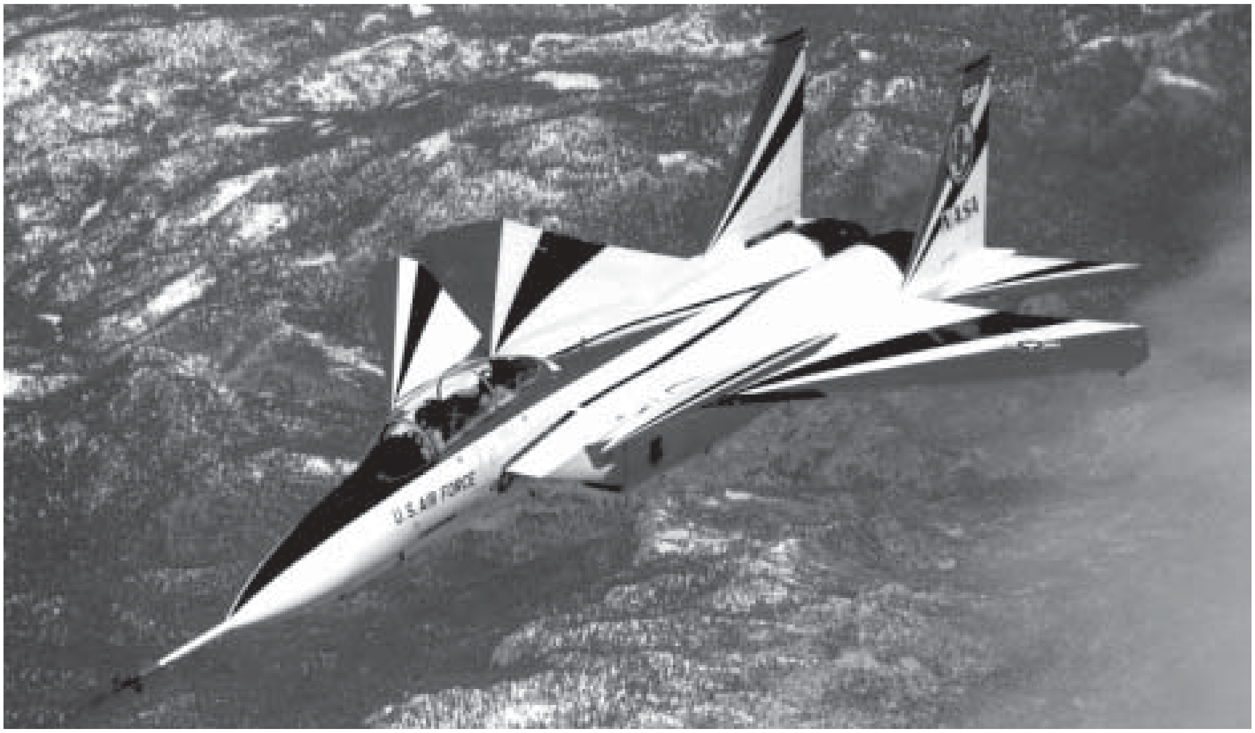


Figure 1-1

F-15 ACTIVE

This highly modified F-15 fighter was just one of the aircraft used by NASA to explore the extreme limits of aerospace technology. The aircraft was built in 1972, and modified for the U.S. Air Force's Short Takeoff and Landing Maneuvering Technology Demonstrator (STOL/MTD) flight research program which lasted from the mid-1980s until 1991. Beginning in 1993 it was involved in a NASA, U.S. Air Force, and private industry flight research program called Advanced Control Technology for Integrated Vehicles (ACTIVE). The F-15 ACTIVE program concluded in 1999. Since then the aircraft has been used as a testbed for "intelligent flight control systems" that enable a pilot to maintain control and safely land an aircraft that has suffered a major systems failure or combat damage.

History and Technical Discussion

Pilots can maneuver an airplane about each of its three **axes,** producing motions called **pitch**, **roll**, and **yaw** (figure 1-2). Pilots steer the airplane’s flight path as desired by controlling pitch, roll, and yaw with a control wheel (or stick) and foot pedals located in the cockpit. These cockpit controls are in turn connected to movable panels, called **flight control surfaces**, attached to the airplane’s structure. These surfaces are named the **elevator**, **ailerons**, and **rudder** (figure 1-3).

The elevator produces pitch up or down when the pilot moves the control stick backward or forward. Ailerons cause the airplane to roll right or left corresponding to right or left movement of the control stick. The rudder produces right or left yaw corresponding to right or left rudder pedal movement.

A recent flight control design incorporated in the F-15 ACTIVE (figure 1-1) is the use of **thrust vectoring** to also produce pitch, roll, and yaw. Here, the jet engine’s exhaust **nozzle**

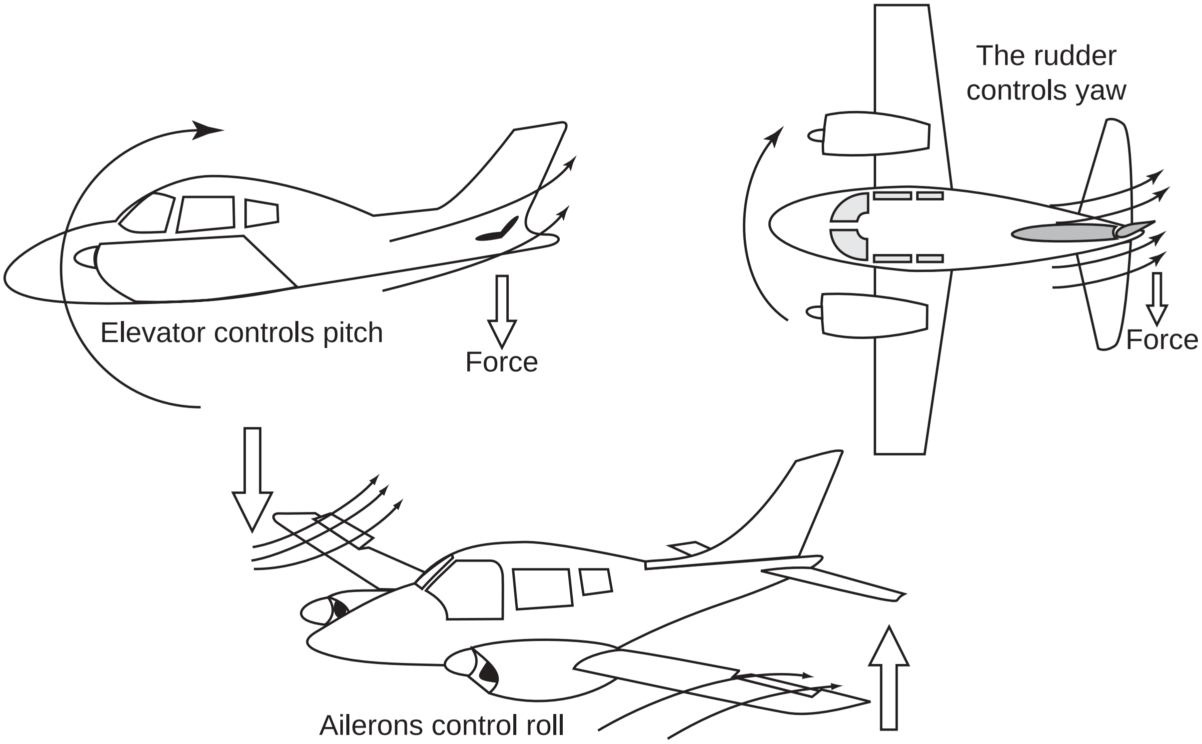


Figure 1-2

Three axes producing motions called pitch, roll, and yaw.

Figure 1-3

Supermarine Spitfire

moves as well as the flight control surfaces when the pilot moves the control stick. This movable nozzle deflects the exhaust stream to produce the desired motion. Thrust vectoring causing a nose-up pitching motion is illustrated in figure 1-4. Deflecting the exhaust stream upward causes a reaction force that moves the tail down (and nose up), complementing the usual nose-up motion due to elevator deflection.

“Vectoring” for jets simply means pointing the engine exhaust in various directions (direction + magnitude = vector) to change the direction of the aircraft’s flight path. You may have driven a small boat by pointing an outboard motor to steer the boat; it’s much the same idea.

Here is a more formal definition of thrust vectoring: the manipulation of jet engine exhaust such that the resultant reaction forces augment, or in some cases, replace, those forces normally generated by the aerodynamic control surfaces.

Flight Control Design

Mechanical Flight Controls

From the Wright Flyer through most World War II airplane designs, the pilot’s stick and rudder pedals were connected to the flight control surfaces with steel cables. Thus, these designs are often called “manual” or “mechanical” flight control systems.

In such a design, pressure of the airflow over the airplane’s flight control surfaces resists movement of the cockpit control stick. Since faster speeds produce higher air pressures, it becomes progressively harder for the pilot to physically move the stick as **airspeed** increases.

Hydraulic Flight Controls

To allow the pilot to be able to move the control stick at very high speeds, hydraulically powered flight control systems were introduced. Here, a hydraulic actuator moves the control surface and essentially multiplies any force the pilot applies to the stick many times over as it positions the control surface. While permitting supersonic flight, hydraulic flight control systems posed new problems for pilots in controlling these airplanes. It was often difficult for the pilot to predict how much stick force was necessary to produce the desired response. Control forces, which were natural and predictable in a mechanical flight control aircraft, were reproduced artificially in the hydraulic aircraft. Optimizing the various devices involved over the entire **flight envelope** proved difficult, and it was not uncommon for pilots of these highly

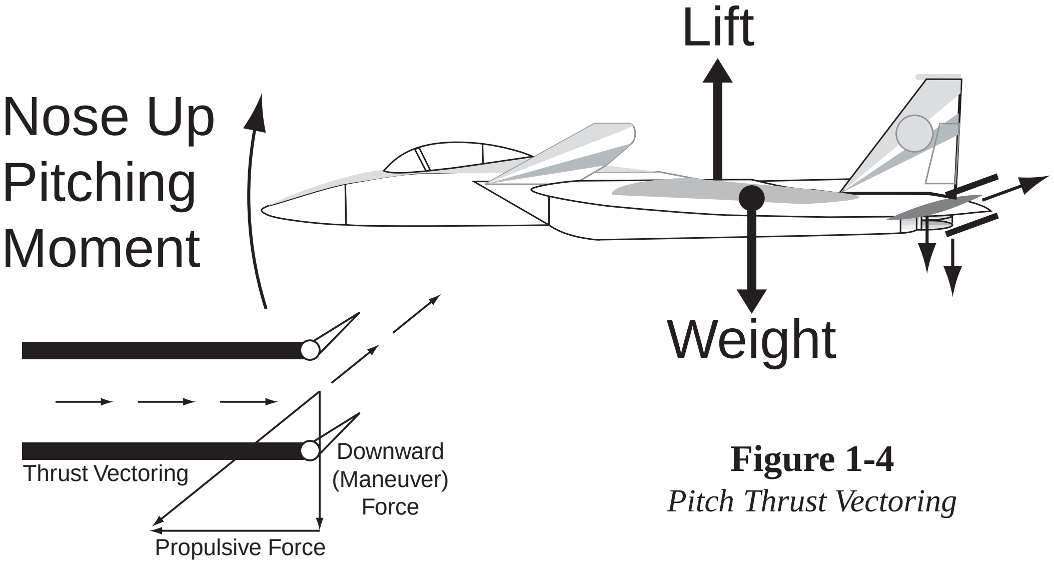


Figure 1-4

Pitch Thrust Vectoring

maneuverable aircraft to lose control. Additionally, failures of the hydraulic system, such as ruptured fluid supply lines or overheated pumps, plagued these designs.

Fly-By-Wire Flight Controls

In the 1960s, designers turned to electronics and computer technologies to overcome many of the problems associated with hydraulically powered flight controls. Hydraulic actuators were still necessary, but fly-by-wire meant that the pilot's control stick movements were now transmitted electronically to the actuators. Also, a computer allowing much-improved flight path control precision could control the airplane's response. NASA research was the driving force for the successful development of fly-by-wire aircraft.

The NASA Digital Fly-By-Wire (DFBW for short) research aircraft, a modified U.S. Navy F-8 Crusader, was one of the most significant research programs in NASA history. On May 25, 1972, NASA 802 became the first aircraft to fly completely dependent upon an electronic flight control system (no mechanical backup). It used a computer from the Apollo spacecraft to operate the flight controls. The DFBW F-8 validated the concepts of the fly-by-wire flight control systems now used on nearly all modern high-performance aircraft, military and civilian transports, and the Space Shuttle flight control system.[1] The F-15 ACTIVE research aircraft is equipped with a digital fly-by-wire flight control system.

Digital flight-control systems were able to incorporate "multi-mode" flight control laws with different modes, each optimized to enhance maneuverability and controllability for a particular phase of flight. Earlier mechanical or electronic flight control systems could be optimized for only one particular set of flight conditions, such as supersonic flight, weapons carriage, or perhaps takeoff and landing. But the DFBW designs could "flip a switch," giving a separate set of software **control laws** for each flight phase the aircraft would encounter. Thus, a design might have a takeoff and landing mode with its set of control laws, a cruise mode with a different set of control laws, a weapons delivery mode, supersonic mode, and so on. Development of thrust vectoring control laws is part of the F-15 ACTIVE research.

Thrust Vectoring and Fly-By-Wire Combined

Thrust vectoring produces greater agility and maneuverability, especially at slow airspeeds and at a high **angle-of-attack** (relationship between the aircraft's wings and actual flight path). Whereas aerodynamic control surfaces lose their ability to produce pitch, roll, or yaw at slow airspeeds, thrust vectoring still remains quite effective. This is because the pressure of engine thrust against the nozzles stays relatively constant while the air pressure on control surfaces goes down exponentially as airspeed decreases. In fact, aerodynamic surfaces can lose effectiveness altogether if the angle-of-attack gets too high (called a **stall**).

Fly-by-wire computers do the job of properly blending the amount of control surface deflection and thrust vectoring needed. This allows the pilot to simply move the stick in the desired direction, so that flying a thrust vectored airplane is no more difficult, or different, than flying a conventional airplane.

Other design benefits include less **drag** from **elevator/stabilator** deflections for **balance** (**trim drag**); that is, the use of thrust vectoring instead of control surface deflection for balance requirements. This in turn results in better fuel efficiency (due to less trim drag) and reduced operating costs. Thrust vectoring makes possible new, more aerodynamically efficient configurations, such as tailless aircraft with reduced weight due to replacement of control surface area. Safety can be improved by preventing stalls and loss of control and with reconfigurable flight controls using thrust vectoring to replace a malfunctioning control surface. Finally, slower landing speeds are possible, allowing shorter, less expensive runways to be used.

Related Programs and Research

Harrier "Jump Jet" Operational Experience

One of the first operational aircraft to use thrust vectoring was the Harrier, flown by the British Royal Air Force, British Royal Navy, and the U.S. Marines. The first flight of the prototype, called the Kestrel, was in 1960. The Harrier uses four movable engine exhaust nozzles that may be rotated downward, as illustrated in figure 1-5, for vertical takeoff or landing. Its thrust vectoring capability was not designed for in-flight maneuvers other than takeoff and landing.

MATV, HARV, and X-31

NASA research explored thrust vectoring at extremely high angle-of-attack on the High Alpha (angle-of-attack) Research Vehicle (HARV), a modified F-18. The F-16 Multi-Axis Thrust Vectoring (MATV) research program made significant contributions to understanding thrust vectoring design requirements and agility benefits. The X-31 research aircraft is continuing to help NASA learn about the benefits of thrust vectoring (figure 1-6). Whereas a small airplane like those you might see at the local airport might stall and lose control at about 15 degrees angle-of-attack, the X-31 has demonstrated controlled flight to 70 degrees angle-of-attack as well as flight with the vertical stabilizer and rudder completely removed (figure 1-7).

F-15 S/MTD

The F-15 S/MTD (STOL [Short Take Off and Landing]/Maneuvering Technology Demonstrator) testing focused on short takeoffs and landings as well as on enhancing pitch maneuvering capabilities. The first flight with the vectoring nozzles was in May 1989 and flight testing lasted until late 1991. The program demonstrated significantly shorter runway requirements of about 50 percent over production

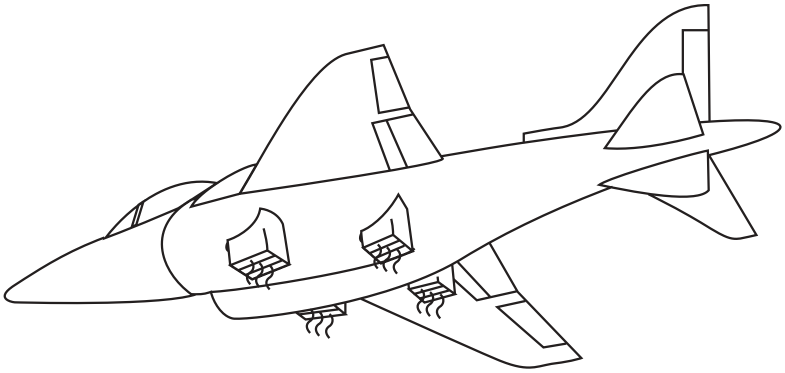
F-15s, inflight use of thrust reversing for deceleration improvement, and enhanced pitching moments with pitch thrust vectoring.[2] The ACTIVE effort evolved from the S/MTD program at the NASA Dryden Flight Research Center.

F-15 ACTIVE Research Program

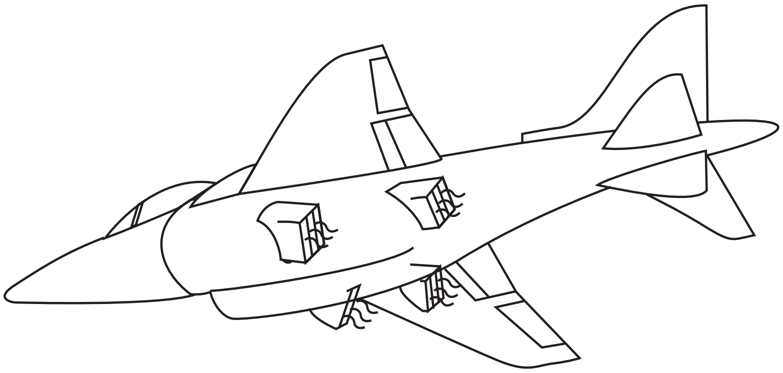
The F-15 ACTIVE research program combined the latest in fly-by-wire flight control system and three-dimensional (3-D) thrust vectoring technologies. While previous programs demonstrated one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) vectoring during very slow speed, high angle-of-attack conditions, the F-15 ACTIVE was used to study the utility of thrust vectoring over a broader spectrum of flight conditions. The overall goal of the F-15 ACTIVE test program was to expand the flight envelope in which useful thrust vectoring is available to enhance aircraft performance, maneuverability, and controllability using production-representative (those that could be mass-produced economically) thrust vectoring nozzles.[3]

Aircraft Description

The test aircraft was a USAF F-15B (two-seat version), tail number 71-0290, and became NASA 837. This aircraft has been through many modifications over the years for various test programs so it is quite different from production F-15 aircraft. It was selected for the ACTIVE research because of the flexibility of its unique, digital, fly-by-wire, integrated flight control and propulsion system. The cockpit



Harrier nozzles pointing down for vertical aircraft movement



Harrier nozzles rotated aft for cruise

Figure 1-5

Figure 1-6

F-18 HARV, X-31, and F-16 MATV
(left to right)

Figure 1-7

NASA X-31 in a tailless configuration

closely resembles the F-15E “glass” cockpits with electronic flight instrument displays and a wide field-of-view Head Up Display. Externally, **canard** flight control surfaces (actually modified F-18 stabilators) were added on the left and right upper inlet areas forward of the wing.

Most importantly, this aircraft had special nozzles for each of the two Pratt & Whitney **afterburning** engines that can vector up to 20 degrees in any direction from the thrust centerline.[3]

F-15 ACTIVE Statistics

Maximum Altitude: 65,000 ft
Maximum Speed: Mach 2.0+
Weight: 54,000 lbs at takeoff,
46,000 lbs empty
Fuel Capacity: 11,520 lbs
(approximately 1,700 gal)
Engines: Two Pratt & Whitney F100–PW-229 thrust vectoring turbofan jet engines
Engine Nozzles: Pratt & Whitney Pitch/Yaw Balance Beam Nozzles (PYBBN)
Wingspan: 42.10 ft
Length: 63.9 ft (excluding the nose boom)
Height: 18.8 ft
Horizontal Tail (stabilator) Span: 28.2 ft
Canard Span: 25.6 ft

The F-15 ACTIVE had nine control effectors: left canard, right canard, left aileron, right aileron, left stabilizer, right stabilizer, rudder (two surfaces counted as one effector since they move together), pitch nozzle, and yaw nozzle (figure 1-8). Flight demonstration of a computer program that can optimize these nine effector movements as well as engine thrust to maximize performance factors, such as range, is a major objective of ACTIVE. The cockpit controls for some these effectors are shown in figure 1-9.

ACTIVE Testing

F-15 ACTIVE testing was a joint program conducted by NASA, USAF, Boeing Phantom Works (formerly McDonnell Douglas Aerospace Phantom Works), and Pratt & Whitney. As mentioned, the F-15 ACTIVE research used the very same aircraft as the F-15 S/MTD program. The major change to the F-15B test aircraft was the installation of Pratt & Whitney Pitch/Yaw Balance Beam Nozzles (PYBBN for short). PYBBN design has matured to the point where they could be used in a production series of aircraft.[3] The first order of business was to “clear the envelope” to make sure the nozzles would operate as expected throughout the F-15 ACTIVE’s flight envelope (figure 1-10) without causing any unwanted side effects or engine problems. Next was to find out how well the nozzles actually vectored engine exhaust and determine whether the additional loads imparted to the tail end of the aircraft were acceptable. Initial testing also evaluated improvements in aircraft performance due to thrust vectoring.

F-15 ACTIVE flight testing commenced on February 14, 1996, with the first vectoring flight, at 20,000 feet and Mach 0.6, less than one month later, on March 7. The first supersonic pitch vectoring was on April 24, taking ACTIVE to Mach 1.2 at 30,000 feet. This was followed by a “world first” supersonic yaw vectoring at Mach 1.6 and 45,000 feet, on June 13. By November, thrust vectoring had been performed as fast as Mach 1.95 at 45,000 feet and as slow as 200 knots at 30,000 feet with angle-of-attack at 30 degrees.[4] Testing demonstrated successful operation of the PYBBN nozzles and problem-free engine operation.

Additional testing was done to evaluate the impact of the vectored exhaust plume on

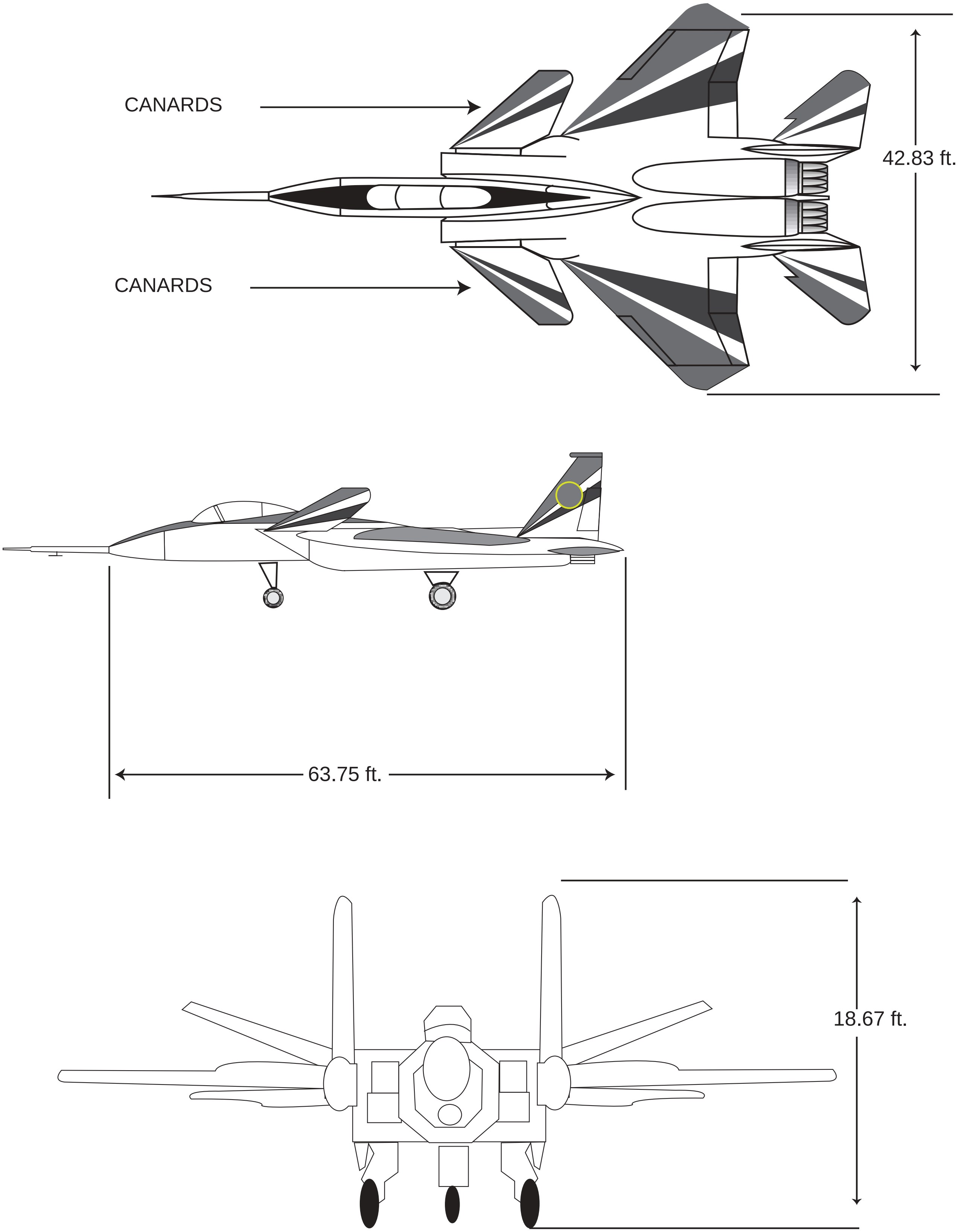


Figure 1-8

Control Effectors of F-15 ACTIVE

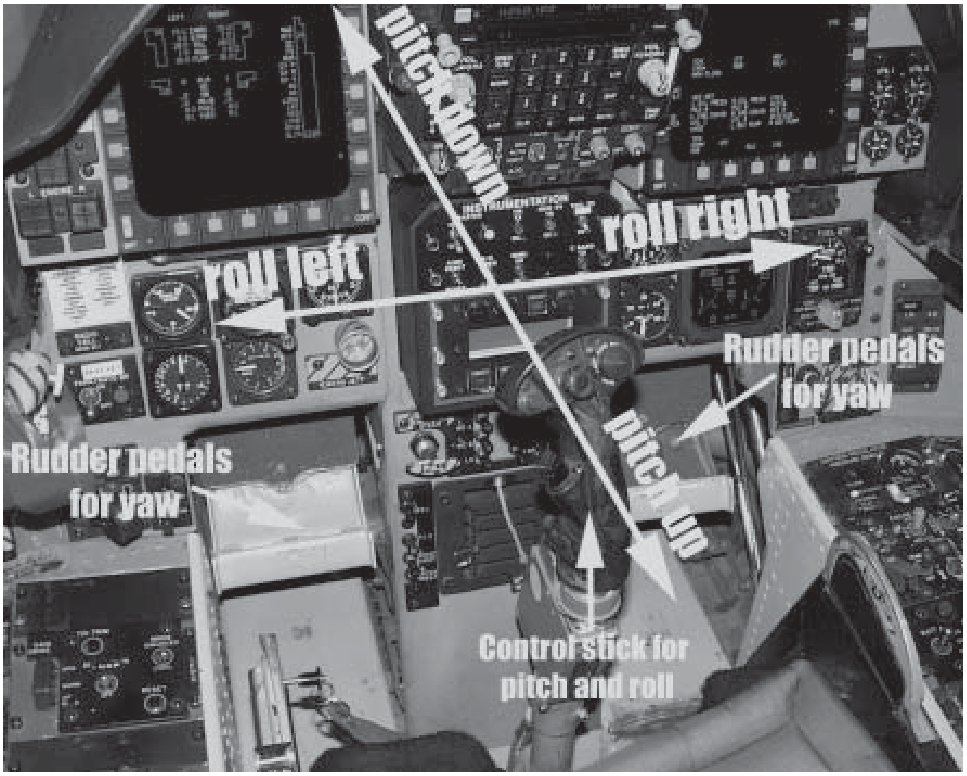


Figure 1-9

F-15 ACTIVE cockpit

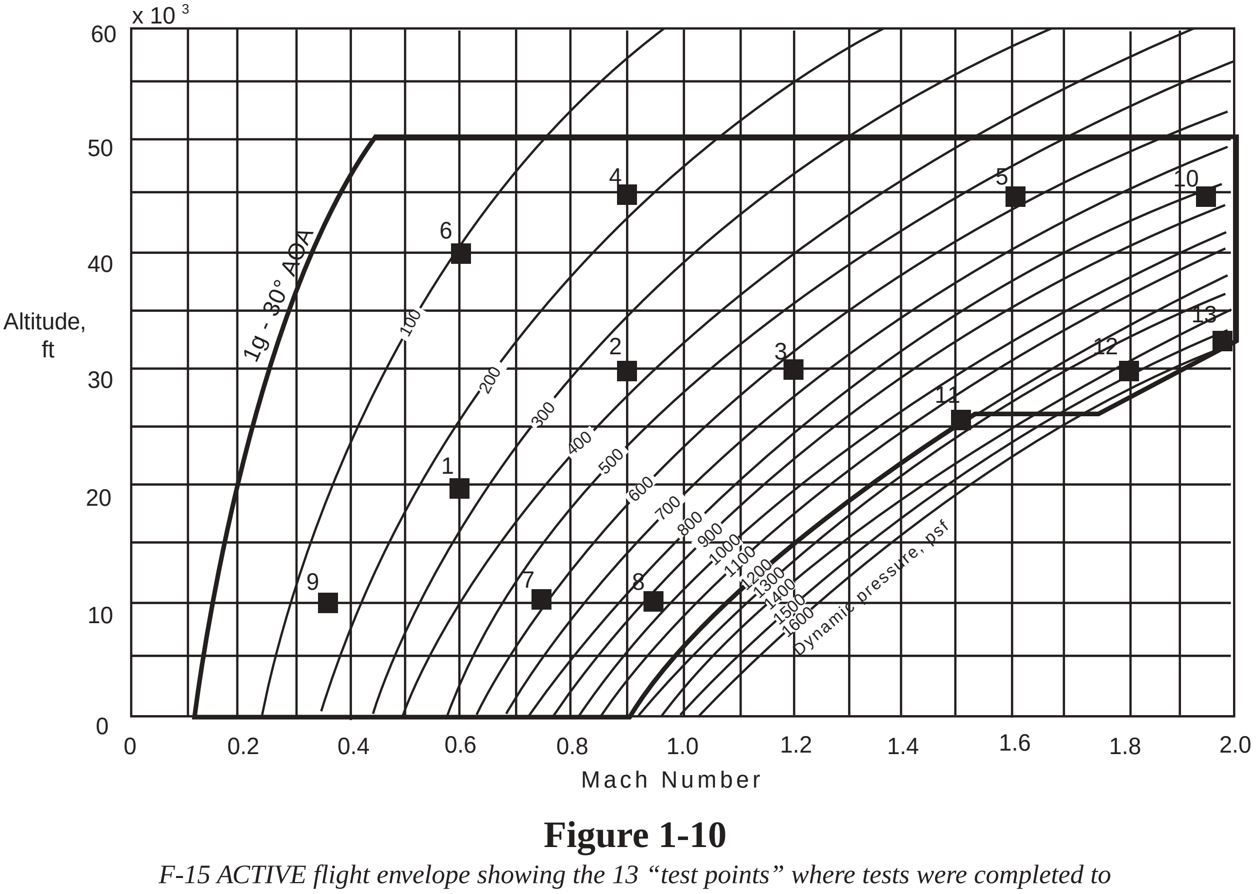


Figure 1-10

F-15 ACTIVE flight envelope showing the 13 "test points" where tests were completed to clear the envelope. Initial flight test results demonstrated successful operations of the PYBBN nozzles up to Mach 2.0 in vectored flight. Engine operation was problem free during vectoring, maneuvering, and throttle movement.

aircraft response and stability. These jet interaction effects were important to define for future aircraft designs such as the Joint Strike Fighter program. Additional tests proved that the PYBBN nozzles did not impact engine operability and that the Pratt & Whitney design was well suited for future ACTIVE research objectives.[4]

Included in the research experiments was an advanced fly-by-wire flight control system called “Intelligent Flight Control.” This system allows the aircraft to automatically adapt to unforeseen changes due to failures or battle damage to flight controls by directing the remaining control effectors to compensate for the malfunctioning ones. This could allow future aircraft to safely land after sustaining major damage or system failures.

This concludes the introduction to the F-15 ACTIVE research program. You should now have an appreciation of aerodynamic design evolution, thrust vectoring concepts, fly-by-wire flight controls, and integration of these technologies as they have influenced the configuration of the F-15 ACTIVE aircraft.

References

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