N76-31138

DEVELOPMENT OF AN ACTIVE FLY-BY-WIRE FLIGHT CONTROL SYSTEM

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SUMMARY

This paper presents a summary of the YF-16 flight control system. The basic functions of the flight control system are discussed, as well as the unique features such as Relaxed Static Longitudinal Stability (RSS), Fly-By-Wire (FBW), and Side-Stick Pilot's Controller (SSC). In addition, the basic philosophy behind the selection of the flight control system functions and unique features is discussed.

INTRODUCTION

The YF-16 is the first aircraft developed in which an Active Flight Control System was incorporated from its inception. In the past, the design of a flight control system was undertaken after the basic aircraft aerodynamic design was set and was used mainly to improve handling qualities. This usually involved little more than augmenting pitch and lateral-directional damping. As aircraft handling and performance requirements increased, so did the complexity of the flight control system. The desire to obtain uniform aircraft response to pilot commands results in command augmentation systems being used in the flight control system. Since these systems required large authority surface commands to achieve the desired response, the requirement for highly reliable electronic systems was generated and achieved. The achievement of this reliability has allowed the application of an Active Control System in the YF-16.

SYMBOLS

A.C.	aerodynamic center
An	normal acceleration

C_D	drag coefficient
C_L	lift coefficient
$L_{\alpha_{WB}}$	lift of the wing body due to angle of attack
L_{WBT}	total lift of the wing-body-tail
L_{α_T}	lift of the tail due to angle of attack
L_{δ_T}	lift of the tail due to deflection
LH	left-hand
$M<1$	Mach less than one
$M>1$	Mach greater than one
MAC	mean aerodynamic chord
P_T	total pressure
P_S	static pressure
RH	right-hand
RSS	relaxed static longitudinal stability
SM	static margin
T.E.	trailing edge
W	weight
α	angle of attack
β	sideslip angle
$\dot{\theta}$	pitch rate
δ_e, δ_H	horizontal tail deflection

DISCUSSION

The design of flight control systems has evolved from purely mechanical to active over the past two decades, as depicted in Figure 1. The advent of high-performance airplanes in the mid-1950's that were required to operate over larger performance envelopes necessitated the development of three-axis electronic stability augmentation systems. Originally, the B-58 utilized single-branch electronics in its three-axis augmentation system. The following generation of airplanes, e.g., the F-111, employed triple-redundant electronics in stability and command augmentation system due to the larger authority requirements. However, pilot mechanical controls were retained so that the aircraft could be flown safely in the event of electronic failures.

Limited FBW functions were incorporated into control system such as the spoilers, terrain following radar capability and low speed trim compensator on the F-111. In addition, several specialized airplane research and test programs have used dual, triple and quadruple redundant electronics in their control systems. These include the F-4 SFCS, C-141, NASA F-8, and TWeaD programs. Since only single-failure protection is provided with triple-redundant electronic systems, an active control system must employ quadruple-redundant electronics to provide the two-failure protection that is required. The development of a quadruple-redundant system has been a straightforward and low-risk extension of the 10 years of highly successful triple-redundant electronic application experience on the F-111 program and the quadruple-redundant experience gained during the F-4 SFCS program.

The YF-16 Control System

The functions of the YF-16 flight control system are very similar to those of most other new high performance aircraft. The basic functions of the flight control system that are common are air data scheduled gains, stability augmentation (dynamic), interconnects between roll and yaw axis and command augmentation. The unique features and functions of the flight control system are static longitudinal stability augmentation (RSS), minimum displacement side-stick controller (SSC), total Fly-By-Wire implementation (FBW) and angle-of-attack and normal acceleration limiting.

Why Relaxed Static Stability

For the primary design mission of the YF-16 - air superiority - the importance of maneuverability and range results in the RSS concept providing sufficient benefits to justify its incorporation. The basic RSS concept can be stated in a very simple way:

1. Balance the airplane for optimum performance
2. Rely on the flight control system to provide the desired level of static stability as well as dynamic characteristics.

Illustrations of the differences between a conventionally-balanced airplane and an airplane with relaxed static stability are given in Figures 2 and 3.

In the subsonic flight regime (Figure 2) the conventionally-balanced airplane is shown to have its wing-body lift acting forward of the center of gravity and the total lift acting aft of the center of gravity. Since in a stable system the moment produced by the wing-body lift as a function of angle of attack must be less than that produced by the tail, the tail must be deflected in a direction to reduce the total tail lift in order to trim the system. Therefore, the total trimmed lift available at a given angle of attack is reduced for a conventionally-balanced aircraft. The RSS-balanced aircraft has both the wing-body and the total lift acting forward of the center of gravity. In this case the moment produced by the wing-body lift as a function of angle of attack is greater than that produced by the tail and the tail must be deflected in a direction to increase the total tail lift in order to trim the system. Therefore, the total trimmed lift available at a given angle of attack is increased for an RSS configuration

In Figure 3, the same information is shown for a supersonic flight condition. In this case, both the conventionally-balanced and RSS airplanes have both the wing-body and total lift acting aft of the center of gravity. Because the RSS airplane has a farther aft center of gravity than the conventionally-balanced airplane, the down load on the tail required to trim the system is much smaller. Therefore, the RSS aircraft has a higher total lift available than a conventional balanced aircraft at the same angle of attack.

Now what this all means is improved maneuverability and range. Representative trim requirements for the conventionally-balanced and RSS configurations are shown in Figure 4 for both subsonic and supersonic Mach numbers. The benefits that are obvious from this illustration are: (1) higher trimmable lift coefficient, and (2) lower trim deflections with attendant drag reduction and lower tail loads.

The trimmed drag polars shown in Figure 5 are illustrative of the trim drag reduction attributable to the RSS balance. The reduced trim drag results in higher sustained load factors and increased range. Note that the benefits are most pronounced at the higher lift coefficients, which is an extremely important region for the YF-16. A secondary benefit of the RSS balance is a somewhat reduced weight because of reduced tail loads.

Why-Fly-By-Wire

The decision to employ the CCV concept of relaxed static stability (RSS) for the YF-16 brought with it the responsibility for providing a reliable, full-time-operating, three-axis stability and command augmentation system. Since a reliable stability and command augmentation system is required, adequate electronic redundancy is necessary to fulfill this requirement. Therefore, the decision to be made is whether pilot commands should be transmitted via mechanical components (linkage, bellcranks, etc.) or electrical signal paths. If mechanical components are chosen, electrical components are still involved to implement the command augmentation system. It follows then that the retention of mechanical components for transmission of pilot stick commands is unjustifiable, since an unstable airplane cannot be controlled in flight without the benefit of a full-time-operating stability and command augmentation system. Therefore, fly-by-wire (FBW) is a natural outgrowth of a redundant electronic control system required for an augmentation system in an unstable (i.e., RSS) airplane.

An active control system offers four benefits which the YF-16 airplane enjoys: (1) precision control and optimum response; (2) design flexibility, offering growth capability and easy acceptance of design changes; (3) improvements in a maintainability and survivability as a result of simplified equipment installations; and (4) improved airplane performance, since the introduction of CCV concepts is compatible with FBW.

How The Flight Control System Basically Works

The YF-16 quadruple-redundant system employs four independent signal branches, i.e., each input signal source (pilot, inertial sensors, etc.) originates as four signals, designated Branches A, B, C, and D. This redundancy concept is depicted for the pitch axis only in Figure 6. Each of the four branches are processed independently in the Flight Control Computer. This computer contains various functions which modify input signals from each of the three control axes, e.g., control dynamics, structural filters, gain-scheduling, selectors, power monitors, and various interconnecting electronic circuitry between the three control axes. Once the input signals have been gain-adjusted, filtered, and amplified, the resulting output signals are sent to each of the five large-authority, high-response, command servos. Each servo, in turn, drives its respective surface power actuator, as shown in Figure 6. The basic location of the hardware components of the flight control system is shown in Figure 7.

Flight path control is achieved through the actuation of an all-movable, differential horizontal tail for pitch and roll control, wing-mounted flaperons for roll control, and a conventional rudder for yaw control. Maneuver capability at high angles of attack is enhanced by automatic positioning of the full-span leading edge flap.

Important Design Considerations

The decision to employ an active control system in lieu of a conventional control system required the addressing of several important design considerations peculiar to these systems. These include: electronic circuit failure monitoring, electrical power failures, engine failures, command servos, surface actuators, and branch separation.

When employing redundant electronic systems, consideration must be given to the problem of proper signal selection and failure monitoring. The F-111 airplane utilizes triple-redundant electronics with middle-value signal selection. With more than 350,000 aircraft flight hours, there has been only one known dual electronic failure experienced. (The pilot landed the airplane without incident). With reliance on demonstrated operational service, the YF-16, quadruple-redundant system likewise utilizes middle-value signal selection on the processed input commands (which result from the four separate electronic branches) that are ready for outputs to the command servos. To illustrate, signal Branches, A, B, and C are compared. The middle value is selected and then quadrupled so that four identical signals are available as output commands. If, for example, signal Branch B varies a predetermined amount from the other two, then Branch D is substituted instantaneously for B. If one of these three subsequently fails, say A, then the minimum value signal of C or D is chosen. By using this type of failure monitoring and signal selection, the control system is protected against dual failures.

The system is fully protected against power losses. Multiple electrical power sources are provided by an engine gear box-driven generator, a standby hydraulically-driven generator, and from multiple battery power as a last source. The standby generator, hydraulically driven by either the engine or emergency power unit (EPU), is automatically activated in the event of improper generator voltage or frequency. If both generators are lost, the batteries provide approximately 10 minutes of power. The end result is that the system receives uninterrupted regulated power with automatic or manual power switching capability. In addition to the above normal electrical protection, further protection relative to engine failure is provided by the EPU which automatically protects against low hydraulic system pressure.

Another consideration which is absolutely essential to the successful operation of an active control system is the conversion of electrical command signals to mechanical signals for commanding each surface power actuator. Each control surface is powered by a tandem valve-on-ram power actuator. In conventional airplanes, pilot stick and pedal inputs are summed mechanically with trim actuator and damper (stability-augmentation) servo inputs to command each power actuator's valve through conventional linkage. In the YF-16 active control system, the inputs are summed electrically and fed to a command (secondary) servo which provides a mechanical input to a power actuator's valve through a very short linkage run, as indicated in Figures 6 and 7.

Why Side Stick Controller

When the decision was made to adopt the fly-by-wire feature of the control system, the door was opened for simple implementation of any one of a number of new pilot-controller concepts. Should the control stick be retained in the conventional center location or would it be more effective on the side? Should it be a displacement stick or a force-sensing stick? With these questions in mind, several studies and research programs were undertaken to determine the best solution for the YF-16.

After researching SSC installations that had previously been tested on such aircraft as the B-47, B-26, B-58, F-4, F-8, F-104, F-105, F-106, A-4, A-6, A-7, X-15 and others, General Dynamics built a flight control simulator to check out ideas and designs. A number of center-stick and side-stick hand controller designs were evaluated in a flight control simulator. Included in these were finger-type controllers, palm controllers, conventional grips with unconventional axes of rotation, and force-sensing controllers with both low and high feel-forces. The studies and evaluations showed that the force-sensing, side-stick controller was superior to all of the other approaches, including displacement and force-sensing center sticks and displacement-type side sticks.

The most widely recognized advantages of the force-sensing side-stick controller are: (1) improved high g tracking (based on results from the NASA Langley dual-mode simulator and the NASA bly-by-wire F-8 aircraft), (2) improved access to the instrument panel and increased panel area, (3) ease of implementation of pilot inputs in the computer (electrical signals proportional to stick force), and (4) pitch and roll axes better oriented to the pilot's arm and shoulder muscles.

The fly-by-wire aspect of the flight control system is particularly compatible with a force-sensing controller. Advantages of this combination include: (1) no linkage dynamics or friction felt at the controller, (2) no linkage balancing problems, (3) enhanced system survivability, (4) greater freedom in airframe design (including ease of change), and (5) potential for weight and cost reduction.

The pilot's controller shown in Figure 8 is a force-sensing (minimum deflection), side stick, mounted on and extending above the right-hand console. The location was developed to ensure easy access for the 5th through 95th percentile pilot. An adjustable arm support is provided to enhance pilot control. The arm support adjustments are vertical, fore and aft, and tilt. The force-sensing element, which contains quadrex transducers in both the pitch and roll axes is identical to the stick-sensing unit employed in the A-7 aircraft, except for the level of redundancy since there is also mechanical linkage. The sensing element has been adapted to an F-111 grip.

The pilot introduces pitch and roll commands by applying appropriate forces to the stick. The forces imparted to the stick by the pilot cause electrical signals to be produced by the transducers located in the lower portion of the stick; these signals are input to the flight control computer. The trim button on the top of the stick grip allows the convenient and conventional input of pitch and roll trim commands. Other stick grip switches are provided to control elements of the armament system, nose-wheel steering, and aerial refueling.

Why Angle-of-Attack and Normal Acceleration Limiting

Since by definition an air superiority aircraft is highly maneuverable over its entire operting envelope, there are areas in which it is easy to obtain large values of angle-of-attack or normal acceleration. There are several ways that the pilot can be protected against such occurrences rather than requiring him to spend his time looking at cockpit instruments. One of these ways is to build in the required protection during aircraft design by putting on large enough aerodynamic surfaces (i.e., big vertical tail) and enough structural weight to assure that the pilot cannot spin or break the aircraft, no matter what he does with the stick. As you might surmise, this approach would severely penalize the aircraft's basic performance from a weight and drag standpoint.

Another method to protect the pilot is to build in enough aerodynamic resistance to stall throughout the usable angle-of-attack range and enough structural weight to obtain the required "g" plus a 1.5 safety factor and depend on the pilot to keep the aircraft within limits. The third method is to use the flight control system to limit angle-of-attack and normal acceleration which results in the lightest, best performing aircraft, but a very complex control system.

For the YF-16 we chose to use a combination of methods two and three which resulted in an aircraft with excellent performance characteristics with a minimum of complication in the flight control system. Using the above approach, i.e., minimum size surfaces and structural weight combined with angle-of-attack and normal acceleration limiting, has resulted in a high performance fighter type aircraft which the pilot may truly maneuver with "Complete Abandon."

YF-16 Flight Test Status

Thirty-one flights have been made by YF-16 No. 1 between 2 February and 13 April 1974 accruing 33:45 total flight time with 1:39 being supersonic. Six pilots (2 contractor, 2 AFFTC and 2 TAC) have flown to date with USAF pilots making their first flights on flight Nos. 4, 12, 16 and 28.

Pilot acceptance of the advanced technology items, such as side stick control with force inputs, fly-by-wire flight controls with relaxed longitudinal aerodynamic stability and maneuvering leading edge flaps, has been enthusiastic. Typical comments are "performance and agility exceptional, easily and precisely controllable, impressive roll response with almost immediate stop at release of stick, comfortable and enjoyable to fly immediately, no difficulty experienced in adapting to the side stick controller."

Confidence in the redundant active control system had been so firmly established during simulation, ground tests and checkouts, that all flights (including takeoff and landing) have been made in a statically unstable configuration with the normal c.g. for all flights to date being 36½% MAC (aircraft aerodynamically unstable in pitch at subsonic and transonic conditions).

Some of the significant items demonstrated to date include:

1. Level flight acceleration to Mach numbers in excess of 1.6
2. Wind-up turns to 7+ g's at subsonic and supersonic speeds
3. Flight to angles of attack of 22° at low subsonic speeds and 18° at high subsonic speeds, and 9° sideslip.

Conclusions and Remarks

Although the YF-16 flight control system represents another in a long line of advanced control system concepts, its implementation has been accomplished using current state of the art techniques and hardware. The reliability of the hardware to date has been exceptional as well as the pilot's acceptance of the system. The flying qualities and performance of the flight control system have been outstanding and we feel have provided the Air Force with an outstanding air superiority fighter prototype.

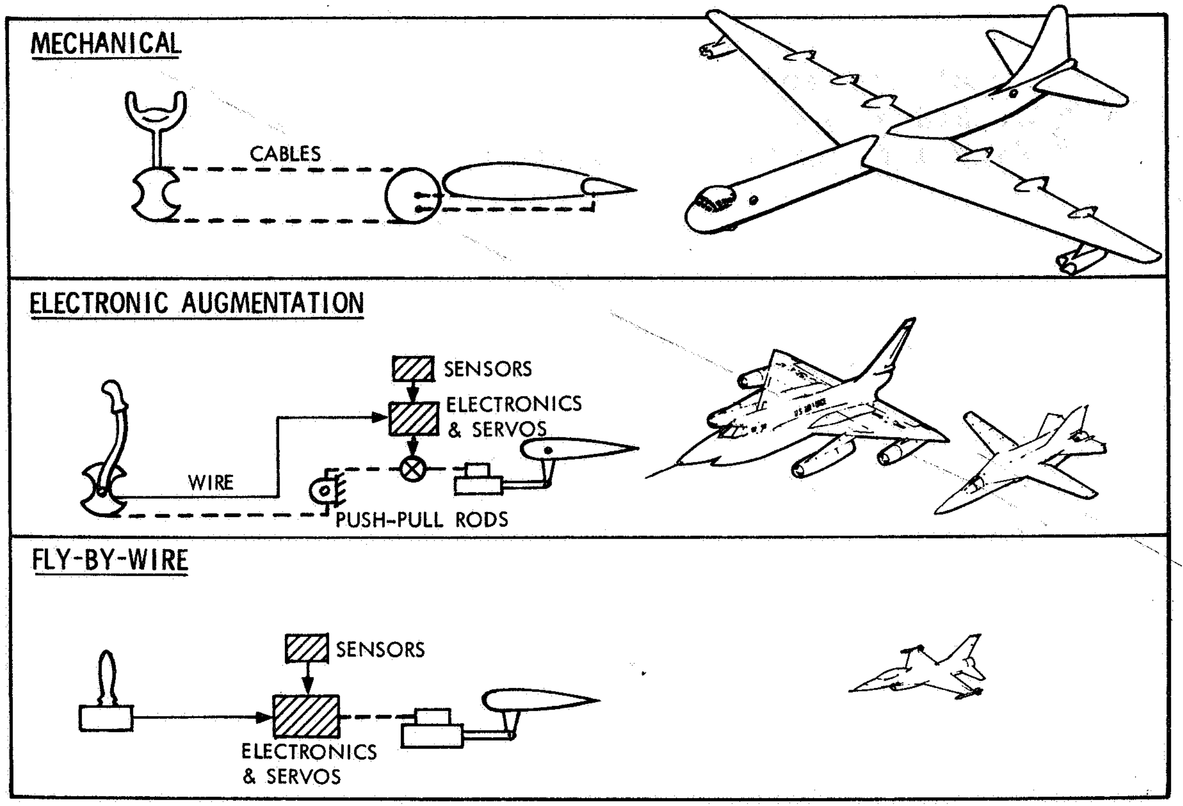

Figure 1 FLIGHT CONTROL SYSTEM EVOLUTION

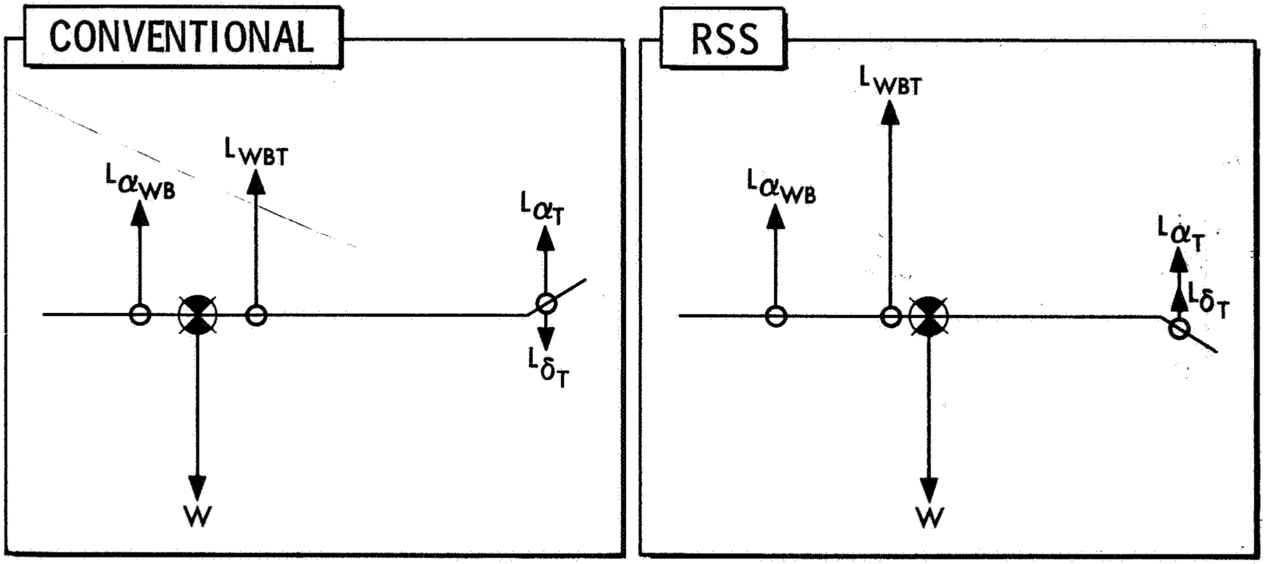

Figure 2 SUBSONIC BALANCE COMPARISON

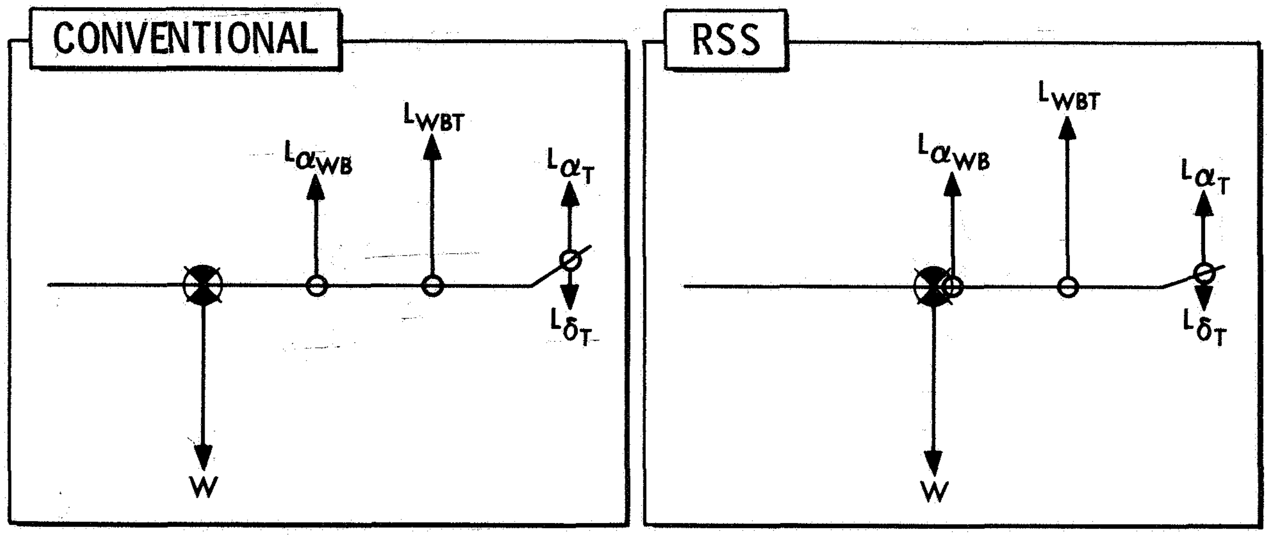

Figure 3 SUPERSONIC BALANCE COMPARISON

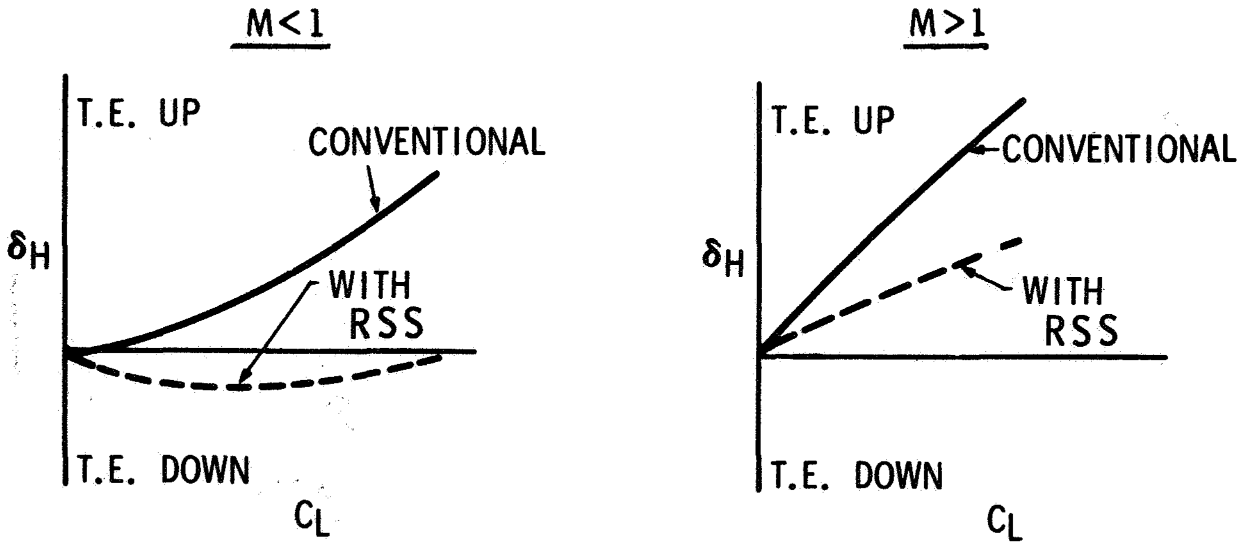

Figure 4 REDUCED TRIM REQUIREMENTS

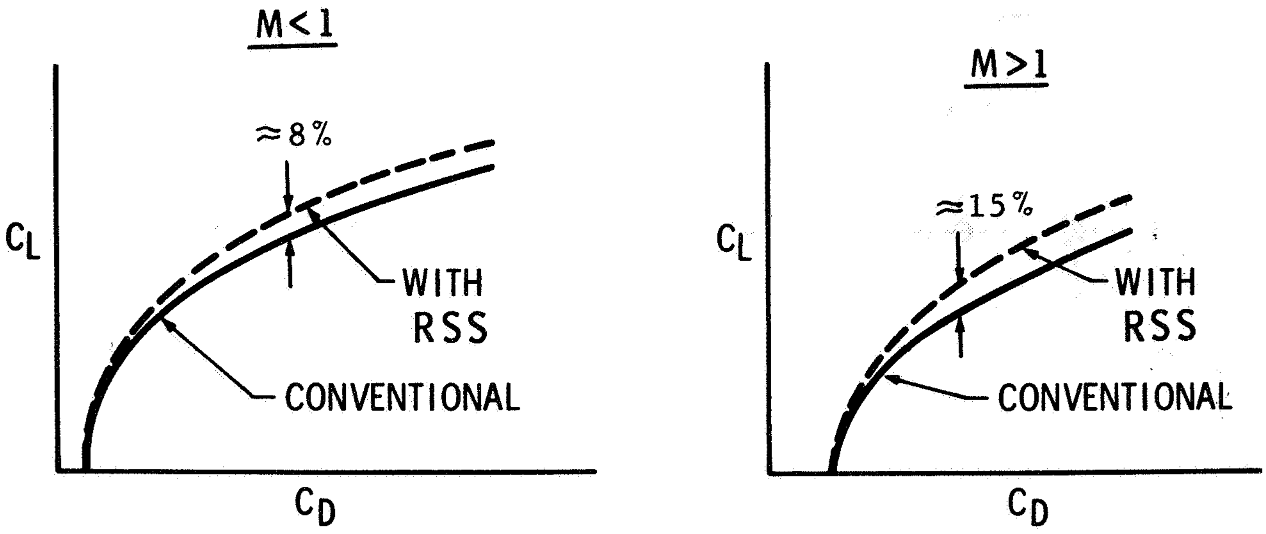

Figure 5 MANEUVERABILITY IMPROVEMENT

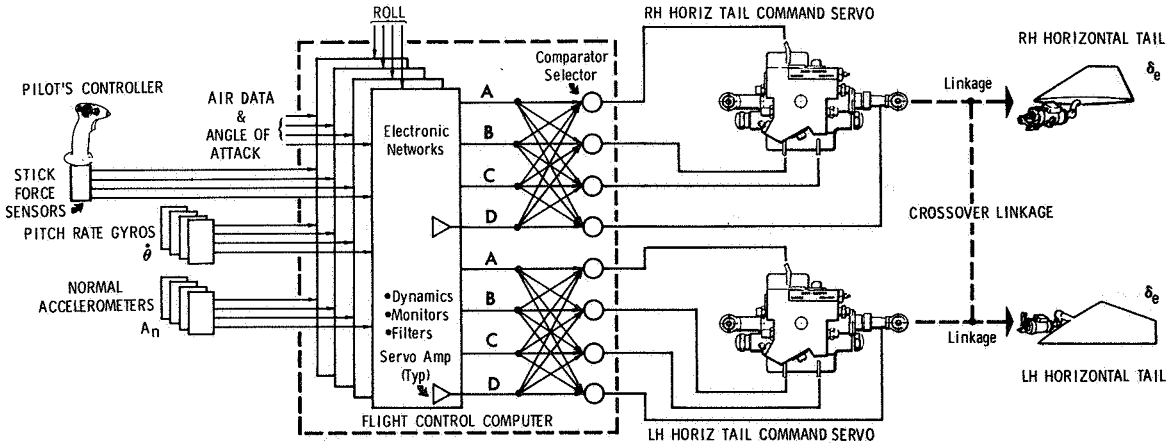

Figure 6 PITCH AXIS REDUNDANCY CONCEPT

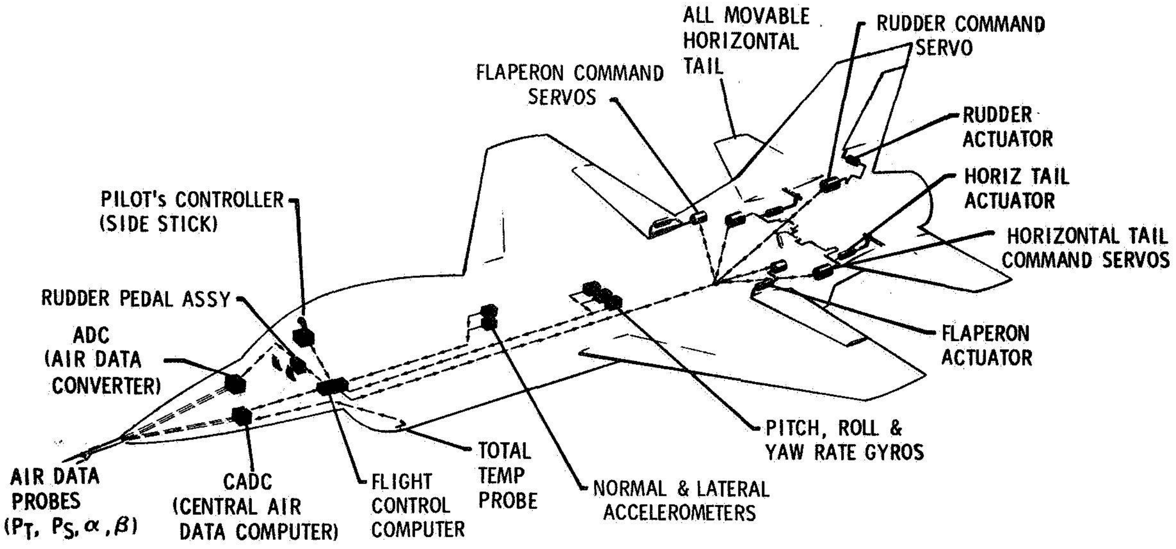

Figure 7 FLY-BY-WIRE FLIGHT CONTROLS

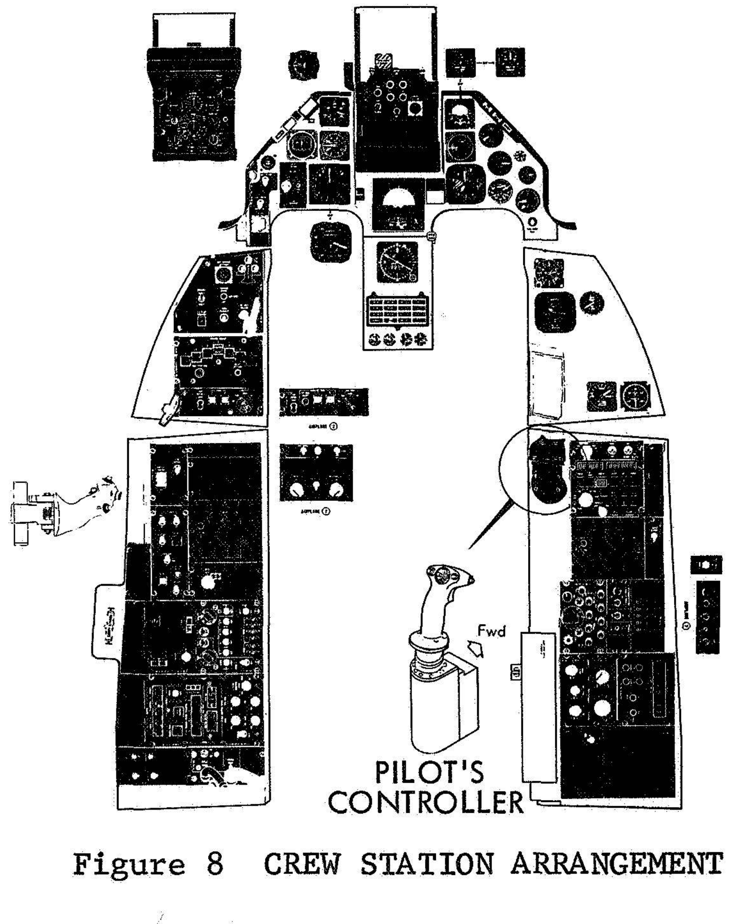

Figure 8 CREW STATION ARRANGEMENT