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USAF TEST PILOT SCHOOL
EDWARDS AIR FORCE BASE, CALIF. 93523

DEVELOPMENT & FLIGHT TEST OF ADAPTIVE CONTROLS FOR THE X-15

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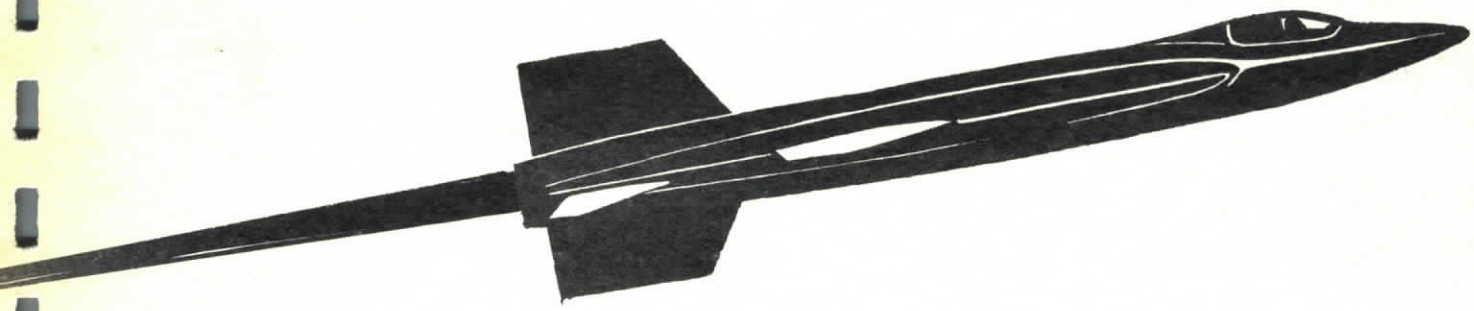


Honeywell
Military Products Group

USAF TEST PILOT SCHOOL
EDWARDS AIR FORCE BASE, CALIF. 93523

F O R W A R D

The Honeywell adaptive flight control system developed for the No. 3 X-15 is capable of optimum performance over a wide range of flight conditions.

The adaptive control changes its own gain through an internal process of measurement, evaluation and adjustment to provide optimum system performance in a changing environment. Two hundred and thirteen flights in an F-101, amounting to 300 flight hours plus 1300 ground test hours, have gone into proving the concept. Test pilots from NASA, Air Force, McDonnell and the Navy have flown a total of 78 evaluation flights. The comments of these pilots throughout the development phase has played a major part in the final design of the adaptive system now installed in the No. 3 X-15.

This advanced control technique is available today largely due to the forward thinking of the Flight Control Laboratory, ASD; NASA scientists, Honeywell research and development efforts and to the comments of Navy, Air Force, NASA and civilian engineering test pilots.

This paper was presented at the Supersonic Transport Symposium by the Society of Experiemental Test Pilots 29 and 30 September, 1961, Beverly-Hilton Hotel, Beverly Hills, California.

DEVELOPMENT & FLIGHT TEST OF ADAPTIVE CONTROLS FOR THE X-15

INTRODUCTION

The X-15 with its extensive flight envelope and the accompanying large changes in performance characteristics presents a broad challenge to the flight control system designer.

The conventional design approach would begin with a detailed analysis of the theoretical aircraft characteristics to pre-determine a set of optimum control parameters for each flight condition. These pre-determined parameters then would be scheduled into the control system by means of a complex air data sensing device which identifies the flight condition. However, predicted flight characteristics of a vehicle under development are not accurate enough for pinpoint determination of control system parameters. Even with extensive flight testing certain compromises will inevitably exist in the final design. Also from a time and cost standpoint it is no longer practical to optimize system gain scheduling by flying to all points of the flight envelope and sampling performance. This is true for the supersonic transport as well as the X-15 research vehicle.

Six years ago the Flight Control Lab., ASD, recognizing the need for more advanced control concepts, awarded Honeywell a study contract to investigate advanced control techniques.

The objective of Honeywell's advanced flight control study program was to develop a system which could provide satisfactory control through extreme changes in flight environment without the need for:

1. Accurate knowledge of the vehicle's characteristics.
2. Air data scheduling.

3. Extensive flight testing.

Early in 1958 the advanced control study program being conducted at Honeywell Research produced encouraging results, and it was decided to mechanize the fundamental idea and test it in an aircraft. Thus was launched a series of programs and efforts that have brought us to the installation of an adaptive flight control system in the No. 3 X-15 at Edwards Air Force Base.

My responsibility in this program has been to coordinate system design with pilot capability and characteristics in a way that would promote maximum efficiency in mission accomplishment. To assist in this pilot input to system design, and to preclude the dangers of a one-pilot technique, a select group of pilots was scheduled, at various stages in the development, to evaluate and comment on the breadboard X-15 system in the F-101A test vehicle. Among these pilots were Joe Walker, Major Bob White, Major Bob Rushworth and Neil Armstrong, to name just a few. These engineering test pilots have had a strong say in the final control system configuration that is now being installed in the X-15 by Honeywell.

Honeywell believes that our future successes in space will be with manned craft as well as with missiles, and that mans selective judgement coupled with proper control techniques will prove to be a significant factor in accomplishing this success.

In this paper I have two points of discussion to cover:

1. Proving the feasibility of the adaptive concept.
2. Development of the X-15 adaptive system.

PROVING THE FEASIBILITY OF THE ADAPTIVE CONCEPT

Early in 1958, Honeywell installed the first adaptive hardware in a fully instrumented F-94C jet aircraft in Minneapolis for feasibility testing. This was the culmination of a research study effort entitled "A Study to Determine an Automatic Flight Control Configuration to Provide a Stability Augmentation Capability for a High Performance Supersonic Aircraft." The project was administered under the direction of the Flight Control Laboratory, Wright-Patterson AFB. The objective of this effort was to develop a stability augmentation system that would not be dependent on complex scheduling of system parameter gains.

The flight test program in the F-94C was successful in proving the feasibility of the Honeywell adaptive concept and corroborating the results of earlier studies. When the Minneapolis phase of the flight test study was completed, the aircraft and equipment went to Wright-Patterson AFB for continued development testing and final evaluation. Capt. Gus. Grissom, USAF, was assigned as project pilot to conduct the flight test evaluation of the system at Wright-Patterson AFB.

The F-94C adaptive feasibility study was so successful that Honeywell decided to fabricate and flight test, in a supersonic aircraft, a complete three-axis adaptive AFCS. When thisprogram was considered there was little military funding available. In keeping with the confidence we at Honeywell have in manned space vehicles, company funds were obtained to support the design, and flight test of the MH-90, a three-axis adaptive system. The Flight Control Lab. made available a JF-101A (S/N 53-2422) at Minneapolis for a test vehicle.

The goals of the MH-90 program were:

1. Demonstrate the three axis AFCS adaptive concept in a supersonic aircraft.
2. To develop satisfactory outer loop control (attitude hold, heading hold, altitude control and control stick steering) without use of air data scheduling.
3. To match the adaptive system to optimum pilot control technique.

The objectives of the MH-90 program were met successfully, and the adaptive concept was proven conclusively. The program required approximately 12 months to complete and included 48 developmental flights.

Major J. J. Knight, USAF, and Capt. H. K. Wimberly, USAF, evaluated the system at the conclusion of the program.

Now with two flight test programs on the adaptive completed, we at Honeywell are confident that the self evaluating adaptive is the answer to the control problems of vehicles such as the Supersonic Transport, Dyna Soar, and the X-15.

DEVELOPMENT OF THE X-15 ADAPTIVE SYSTEM

In July 1959 Honeywell was awarded a contract for the development of an adaptive system to be flight tested in the X-15 space flight research vehicle by the Flight Control Lab, ASD, (AF33(616)-6610). The system proposed by Honeywell for the X-15 used the concept and many of the components developed in the MH-90 program.

The JF-101 test bed with the first complete adaptive hardware created considerable interest on the part of AF and NASA pilots and engineers. As a result of this interest, a series of flight demonstrations of the MH-90 were performed in Minneapolis by the following impressive group of evaluation pilots:

Major W. F. Daniel, USAF AFFTC Edwards Air Force Base

Major R. M. White, USAF X-15 Project Pilot

Capt. R. A. Rushworth, USAF X-15 Pilot

Capt. S. H. Nelson, USAF AFFTC Edwards Air Force Base

Capt. N. C. Evans, USAF AFFTC Edwards Air Force Base

Joe Walker, NASA, X-15 Project Pilot

Neil Armstrong, NASA X-15 Pilot

LCDR Tex Birdwell, USN, NATC, Patuxent River

LCDR Taylor Brown, USN, NATC, Patuxent River

The comments of these pilots were carefully studied and evaluated, and where appropriate, changes were made in the MH-90 system. The evaluation of this select group of pilots at this time was exceptionally valuable and the final X-15 adaptive configuration has many features reflecting their input.

Honeywell, in order to evaluate more effectively the adaptive mechanization planned for the X-15, modified the MH-90 to the electrical equivalent of the aerodynamic portion of the X-15 adaptive system. The system was now the electrical equivalent of the X-15 adaptive although it did not include the redundant networks with the associated comparators and monitors, the reaction control circuitry, the fixed gain fail safe circuits or the facility for automatic pre-flight checkout.

No mechanical changes in the aircraft were necessary. This particular JF-101A control system includes an autopilot series servo integrated with the aileron and rudder power actuators. The stabilator is controlled by a parallel servo for gross motions or commands, and a series servo for fast damping motions. Therefore, only long term pitch commands are reflected back to the center stick.

In the X-15, control is accomplished by utilizing right and left horizontal stabilizer series servos for control of the upper and lower vertical stabilizer power actuators. These differences in control system mechanization did not affect the autopilot tests as the end result in aircraft response was the same.

The JF-101 test bed, Figure 1, was equipped with a number of special flight test provisions to provide an efficient, easily maintained system for autopilot development testing. These provisions included a special gain adjust panel available to the pilot (see Figure 2), an aircraft cabling junction box for making cabling modifications (see Figure 3) and a test panel for checking all autopilot signals. In order to make the most effective use of flight time, an analog simulation of the aircraft was used for ground checking. This closed-loop test procedure provided an accurate measure of system operation prior to the actual test flights.

Now I will discuss the adaptive principles used in the X-15 system. I will support my statements with slides showing actual flight recordings made in the F-101A.

The adaptive principles can best be discussed by considering a single axis control system as shown in Figure 4. The MODEL defines the response of the system and is composed of a simple electrical network which shapes the command signal to represent the desired response of the aircraft.

The ADAPTIVE CONTROLLER slaves the aircraft to the output of the model and is the fighting heart of the adaptive system. The ability of the controller to follow the model requires that the system gain, rate of control surface motion, be continuously held at or very near the maximum gain that the system will tolerate without being driven to instability. As the flight condition changes,

the basic aircraft gain changes. Now, if the adaptive controller is to command the aircraft as prescribed by the model, it must vary its gain to maintain the loop gain at or near the critical level. When the system is at the critical gain level, a small amplitude oscillation called a "limit cycle" will occur. The frequency of this "limit cycle" is determined by the compensation network in the adaptive controller. Gain changing is accomplished in the following manner. The residual motion is "sensed" by a limit-cycle amplitude detector which is comprised of a bandpass network followed by a rectifier. The output of the rectifier is compared to a "set point" which establishes the level of the limit cycle to be sustained. This level is kept comparable in magnitude to the always-present control system dead spot.

Since a constant amplitude limit cycle identifies critical gain, any tendency of the system to operate at any other gain level is reflected by either too small or too large an amplitude of limit cycle. The system will immediately initiate corrective action to re-establish and sustain critical gain. The limit cycle frequency in this system is approximately 4 cps, and the set point amplitude is about 0.1 degree (double amplitude) of elevator position. This is not discernable to the pilot because it occurs at random intervals and seldom exceeds more than 2 full cycles at 4 cps before the gain changer reduces the gain. Simulator studies and actual flight tests show that this adaptive feature causes the gain control to vary as an inverse function of the control surface effectiveness.

Pitch Axis - The pitch control operates in any of four modes:

1. Damper with or without acceleration feedback.
2. Pitch attitude-hold
3. Angle of attack-hold.
4. Altitude-hold.

When operating on damper with acceleration feedback, the pilot commands a combination of pitch rate and normal acceleration, the sum of which is proportional to the force applied to the control stick. Combining normal acceleration and pitch rate feedbacks in the inner loop provides excellent pilot handling qualities in aircraft response. At the high dynamic pressure flight condition, the amount of normal acceleration relative to pitch rate experienced during maneuvering flight is large. Consequently, the pilot is primarily commanding normal acceleration, and the resulting acceleration dynamic response is essentially ide tical to the model output.

At the low dynamic pressure flight conditions, the amount of pitch rate becomes large relative to the normal acceleration that the aircraft experiences. The pilot now primarily commands pitch rate, and the resulting pitch-rate dynamic response is essentially identical to the model output.

When operating on damper with the normal acceleration switched out the inner loop operates on pitch rate only.

When on attitude hold or angle of attack hold, the inner loop is controlling pitch rate. This permits the use of a fixed pitch attitude or angle of attack feedback gain, since the relationship between pitch rate and pitch attitude or angle of attack is independent of flight condition.

The altitude control, although not a part of the final X-15 system, is disussed here since it was mechanized in the F-101A developmental system and proved to be very successful.

When the altitude hold mode is engaged, normal acceleration is the inner loop feedback configuration. The normal acceleration response of the basic inner-loop configuration is sufficiently invarient with flight condition to permit the

use of fixed outer-loop altitude displacement and rate gains. Altitude displacement and rate signals are supplied by an altitude "blender" which has inputs of static pressure, rate of static pressure change, and normal acceleration. At low rates of change, altitude information is supplied by the conventional pressure sensors; but at high rates, the altitude information is supplied by integration of normal acceleration. This scheme eliminates the undesirable effects of dynamic lags and transients associated with pressure sensing and transmission, and reduces the noise level of the altitude rate signal.

Figure 5 shows two actual flight recordings of altitude control performance involving engagements in ascents and descents. Particular attention is called to the smoothness of the recoveries. Performance of the altitude control has been outstanding through the entire program. The excellence of performance is attributed to the high inner loop gain provided by the adaptive system and addition of the acceleration signal to the "blender". Altitude retention during accelerations and decelerations at 10,000 feet from 200 to 550 KIAS caused deviations of only ±40 feet.

Roll Axis - The roll axis of the MH-90 operates on any of three modes:

1. Damper
2. Roll-attitude-hold
3. Heading-hold

The adaptive gain controller is identical to that used in the pitch axis. When operating in the damper mode, the pilot commands roll rate which is proportional to the force applied to the control stick.

The use of a roll rate inner loop having a response that is uniform for all flight conditions enables the simple application of a fixed-roll-attitude-hold mode. For this mode, a fixed-gain, attitude error signal is applied to the

model input. Since the roll-rate response is uniform for all conditions, the roll attitude response also is uniform.

The heading-hold mode permits the pilot to "lock-on" to any desired compass heading, after which the system will hold the selected heading. The existence of a heading error will command a proportional bank angle until corrected.

Figure 6 shows actual flight recordings of a series of roll attitude steps made a various flight conditions. Note the uniform aircraft response at all flight conditions.

Yaw Axis - The yaw axis has only one operating mode, using a combination of lateral acceleration and high passed yaw rate to provide turn coordination and yaw damping. The adaptive gain controller is the same as in the roll and pitch axis.

Summarizing the flight test program conducted in the F-101 on the X-15 adaptive system, the goals set forth at the start of the program were achieved successfully:

1. The adaptive concept feasibility was proven conclusively in a three axis AFCS in a supersonic aircraft. Adequate flight data was taken showing invariant response of the system in all three axes at all flight conditions.
2. Excellent outer-loop control was achieved without use of air data scheduling. Altitude control according to evaluation pilots, is the finest ever tested.
3. Pilot acceptability is attested to by 78 evaluation flights performed by 18 pilots representing NASA, Navy, AF, The Boeing Company and McDonnell Aircraft.

The developmental breadboard adaptive system in the F-101 has totaled up the following operating record:

1300 hours of system ground time

300 hours of system flight time

213 total flights*

78 evaluation and demonstration flights

135 development and research flights

*Number of flights and system operating hours includes those made on electric side stick development program.

During this operating period reliability was excellent. No malfunctions in the adaptive feature occured which were not caused by human error. The adaptive mechanization has not shown any unusual characteristics detrimental to the aircraft control system.

The adaptive system developed and evaluated in the F-101 was limited to the electrical equivalent of the X-15 adaptive. It was not practical to test or evaluate in the F-101 such features as reaction controls circuitry, fixed gain, etc. However, the entire X-15 adaptive system was extensively evaluated on the North American Aviation X-15 simulator.

Features of the X-15 system checked out on the NAA X-15 simulator are discussed briefly in the following paragraphs.

Fixed Gain - Dual fixed-gain channels parallel the dual adaptive channels in each axis. These provide an emergency, or backup, system which will permit control of the aircraft to be maintained if the adaptive channels fail. The fixed gains are set at approximately the lowest critical gains in the flight envelope. For increased reliability, the fixed-gain channels are operative at all times eliminating switching if a failure occurs.

Control in both the aerodynamic and reaction control regions is provided by the fixed gain system.

Reaction Controls - Automatic transition from aerodynamic to reaction controls is provided allowing the pilot to maneuver the aircraft throughout the entire flight envelope with a single control stick. As the altitude increases, the system gains increase to maintain the limit cycle. When the gains reach about 80 per cent of their maximum values, at about 130,000 feet, the reaction controls are energized. Due to a large deadspot the reaction controls will not necessarily be used immediately after being energized. Instead, the aerodynamic surfaces will continue to provide a large part of the control with the reaction controls operating only when the system errors exceed the deadspot values.

During re-entry, as dynamic pressure increases, the limit cycle will be resumed at about 130,000 feet and the reaction controls will be de-energized when the gain decreases to 60 per cent of maximum. The system thus uses a minimum of reaction control fuel since maximum use is made of the aerodynamic controls.

Redundancy and Failsafety - Each axis of the system is mechanized in a parallel redundant manner to provide fail safety. The redundant mechanization includes several comparators and limitors which allow the system to remain operative on the adaptive loop for 90-95% of all failures. A failure in one axis will not disengage any other axis. Furthermore, a hardover in the outer-loops will revert the system to the damper mode and a hardover in the adaptive loop will at worst revert that axis only to the back up fixed circuitry.

The rate dampers in each axis are dual channel, incorporating dual rate gyros and servo pickoffs in addition to dual electronic channels. The stick and rudder pedal position transmitters are also dual. Dual fixed-gain channels

parellel to the adaptive channels provide adequate damping to maintain control of the aircraft if the adaptive channels are switched out.

Dual lateral accelerometers are utilized since lateral acceleration is a part of the yaw axis damper system. Dual normal accelerometers are used in the pitch axis to provide protection on autopilot modes. The autopilot inputs themselves (roll and pitch attitude, angle of attack, and heading) are not dual, but are summed into both channels of their respective axis.

Servo monitors will disengage the servos if they fail.

Figure 7 shows location of the various flight control devices in the X-15. Figure 8 shows cockpit location of the pilot function select panels. Figure 9 shows the pilot's center control panel.

1. DAMPER switches -- The pitch, roll, and yaw dampers are engaged by moving the appropriate spring-loaded switch to the DAMPER position. The indicator lights go out when the dampers are engaged.
2. FIXED GAIN Switches -- Fixed gain operation may be selected with the momentary-contact, spring return fixed gain switches. The indicator light will come on and the damper switch remains in the damper position indicating the system is on fixed gain.
3. CONTROL STICK STEERING Switch -- This switch control whether the normal acceleration feedback is switched in or out. CSS switch on provides acceleration feedback.
4. SPARE Switch -- No function at present.
5. REACTION CONTROLS Switch -- Provides pilot option for using automatic activation of reaction controls, reaction controls always activated and controls off.

6. ROLL TRIM Knob -- Pilot adjust of small electrical or mechanical mistrims in roll.

Figure 10 shows pilot's left console control panel

1. ROLL-HEAD Switch -- This switch may be engaged whenever both yaw and roll dampers are engaged. If this switch is engaged when bank angle is less than 7.5 degrees, the aircraft will roll level and lock on to heading. If bank angle is greater than 7.5 degrees, the roll attitude will be retained. The CSS switch on the stick will, as long as depressed, drop out the hold reference.
2. PITCH AND ANGLE OF ATTACK HOLD REFERENCE Switches -- When the pitch damper is engaged either angle of attack or pitch attitude hold may be selected. Depressing the CSS button on the control stick momentarily drops the reference -- release of button locks on the new reference.
3. VERNIER WHEEL -- This wheel provides precise control or adjustment of pitch attitude or angle of attack.

Figure 11 shows the complete automatic flight control system. The box marked Airborne Analyzer is mounted in the B-52 and is used for Pre-flight checkout of the flight control system.

CONCLUSION

For the X-15, Honeywell has developed a system capable of optimum performance over an extensive range of flight conditions with a high degree of reliability and failsafety. There are a number of vehicles in various stages of design and development where these characteristics will be primary considerations in

the selection of a flight control system. One of these, of course, is the supersonic transport; others are the STOL, VTOL and various spacecraft.

The X-15 adaptive is available today due in a large measure to the forward thinking of the Flight Control Lab., ASD and to the rapid strides made in its development at Honeywell. Research and design engineering, joining with flight test into a close knit unit, has resulted in a successful and productive development effort.

We at Honeywell feel that the X-15 represents one of our nation's most significant building blocks in the development of the Supersonic Transport.

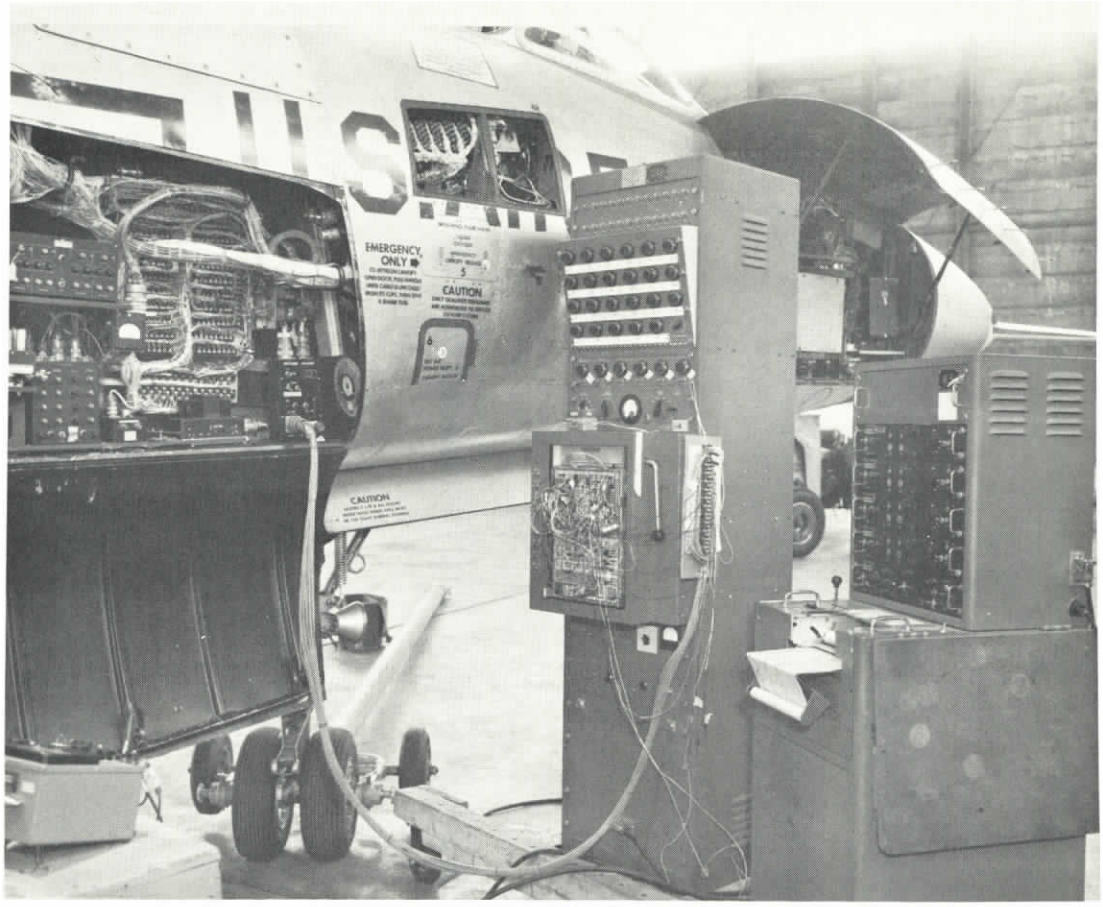


Figure 3 Analog Computer Set Up Next to the F101A

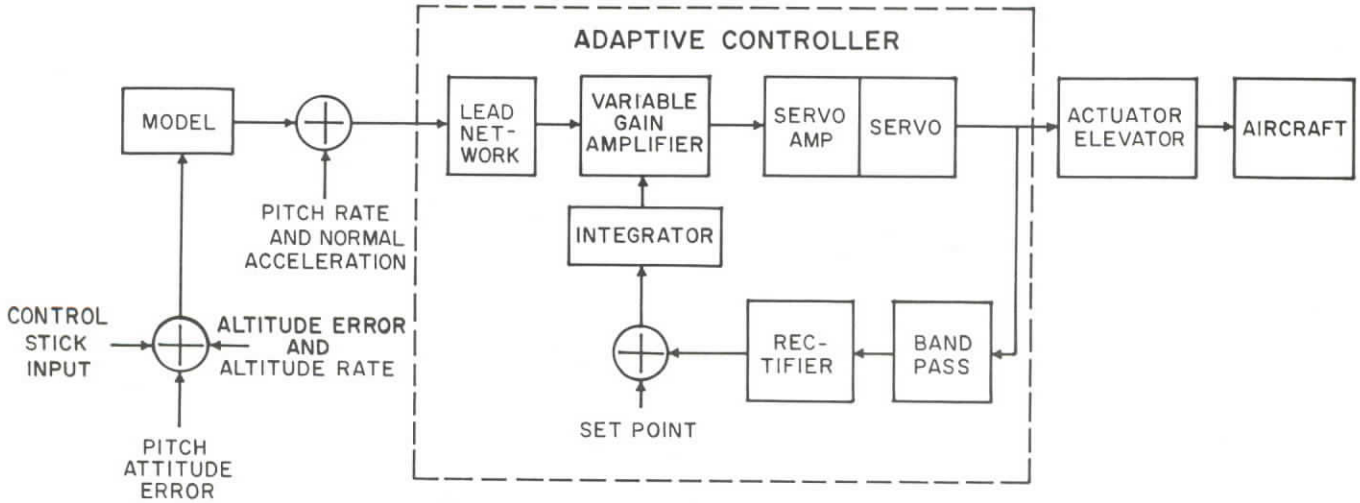
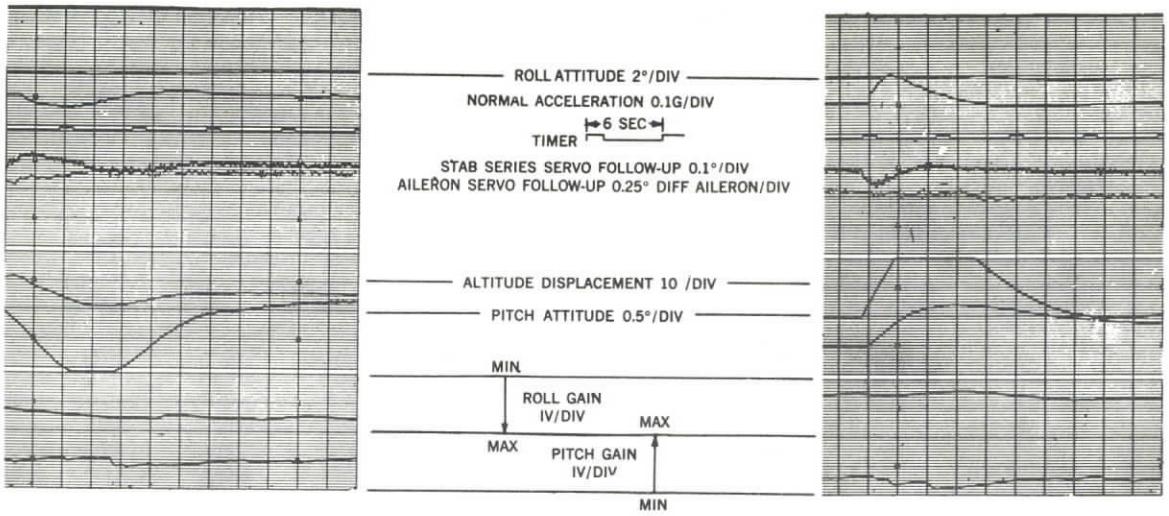


Figure 4 Simplified Block Diagram of Adaptive Pitch Axis



Engage Altitude Control at 3000 Feet Per Minute Up — 35,000 Feet, Mach 0.9

Engage Altitude Control at 6000 Feet Per Minute Down 20,000 Feet, Mach 0.9

Figure 5 Altitude Control Flight Records

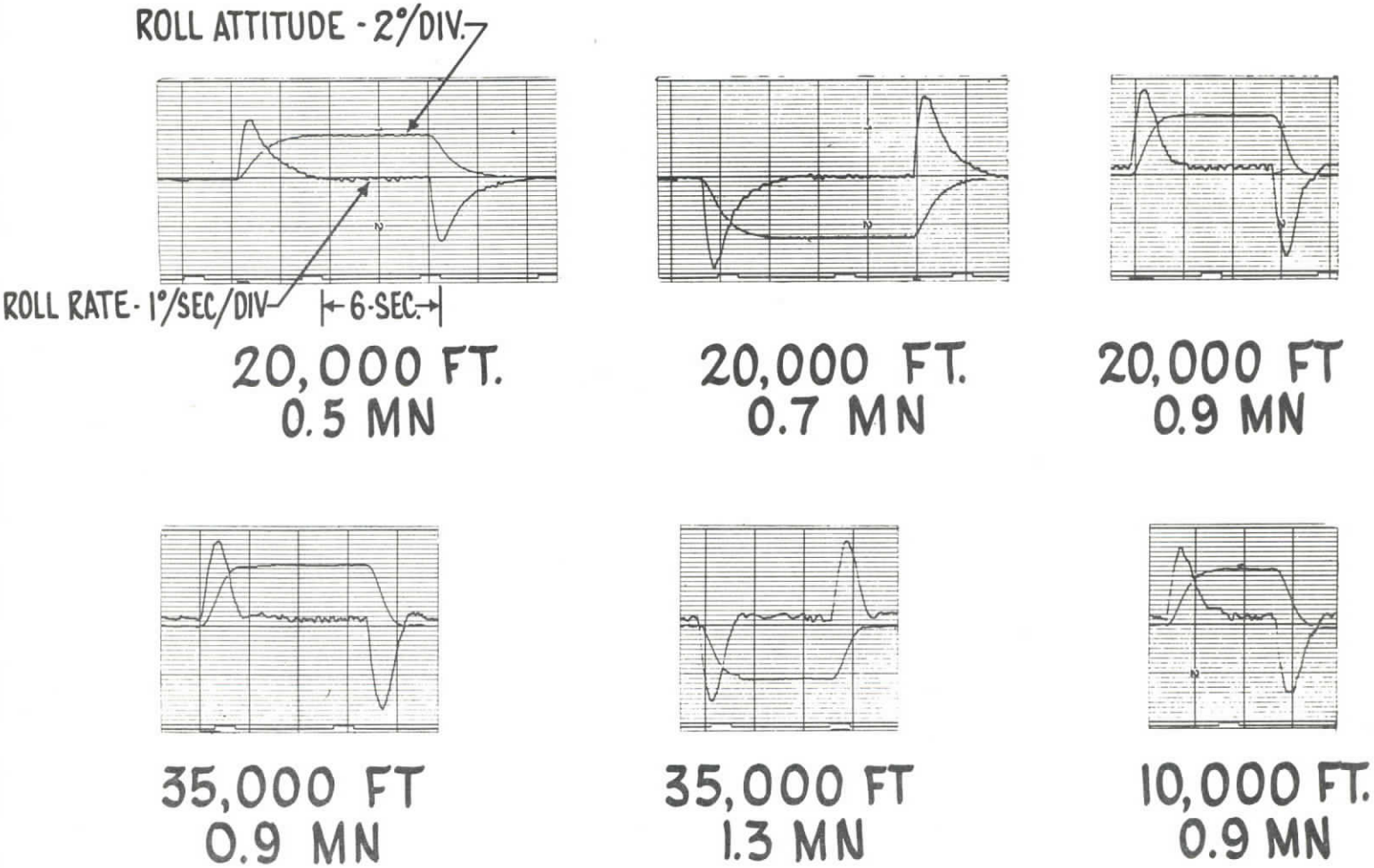


Figure 6 Roll Attitude Steps

1. Q-Ball*
2. Pitch and Yaw Reaction Valves
3. Pitch Trim Actuator* and Pitch Stick Transmitter
4. Right Side Stick CSS and Trim Controls*
5. Center Stick CSS and Trim Controls*
6. Center Pedestal Function Selector
7. Roll Stick Transmitter
8. Left Console Function Selector
9. Rudder Pedal Transmitter
10. Stable Platform*
11. Adaptive Controller and Accelerometers
12. Roll Reaction Valves
13. Rate Gyros
14. Pitch-Roll Servocylinders*
15. Yaw Servocylinder*

*Components Not Supplied by Honeywell

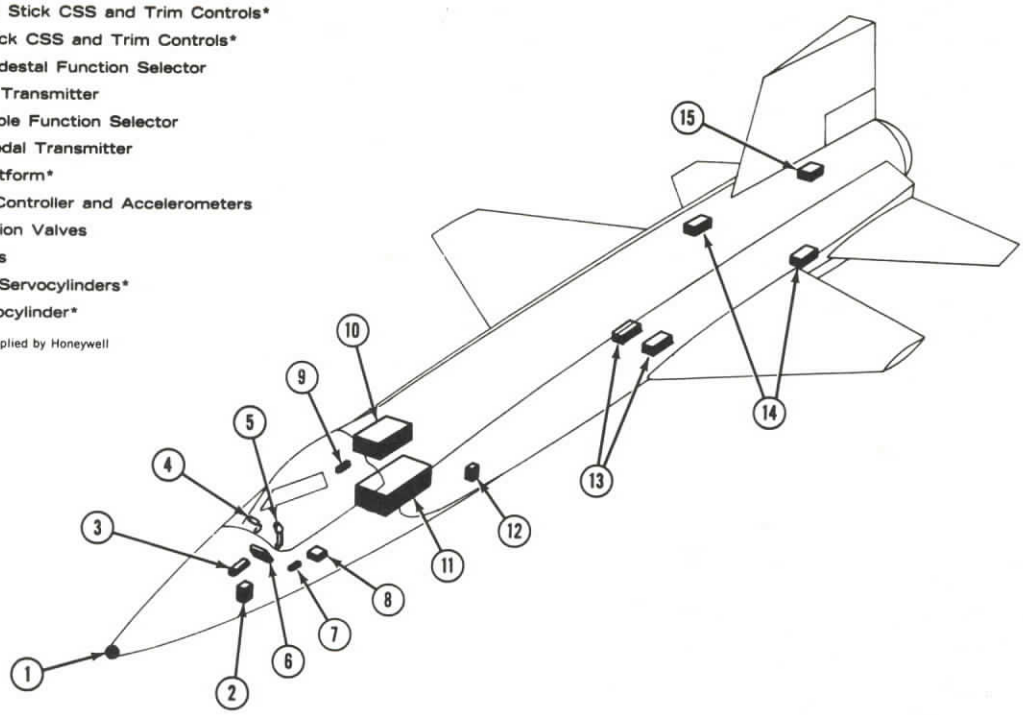


Figure 7 Locations of X-15 Adaptive Flight Control System Devices

FUNCTION SELECTORS IN COCKPIT LAYOUT

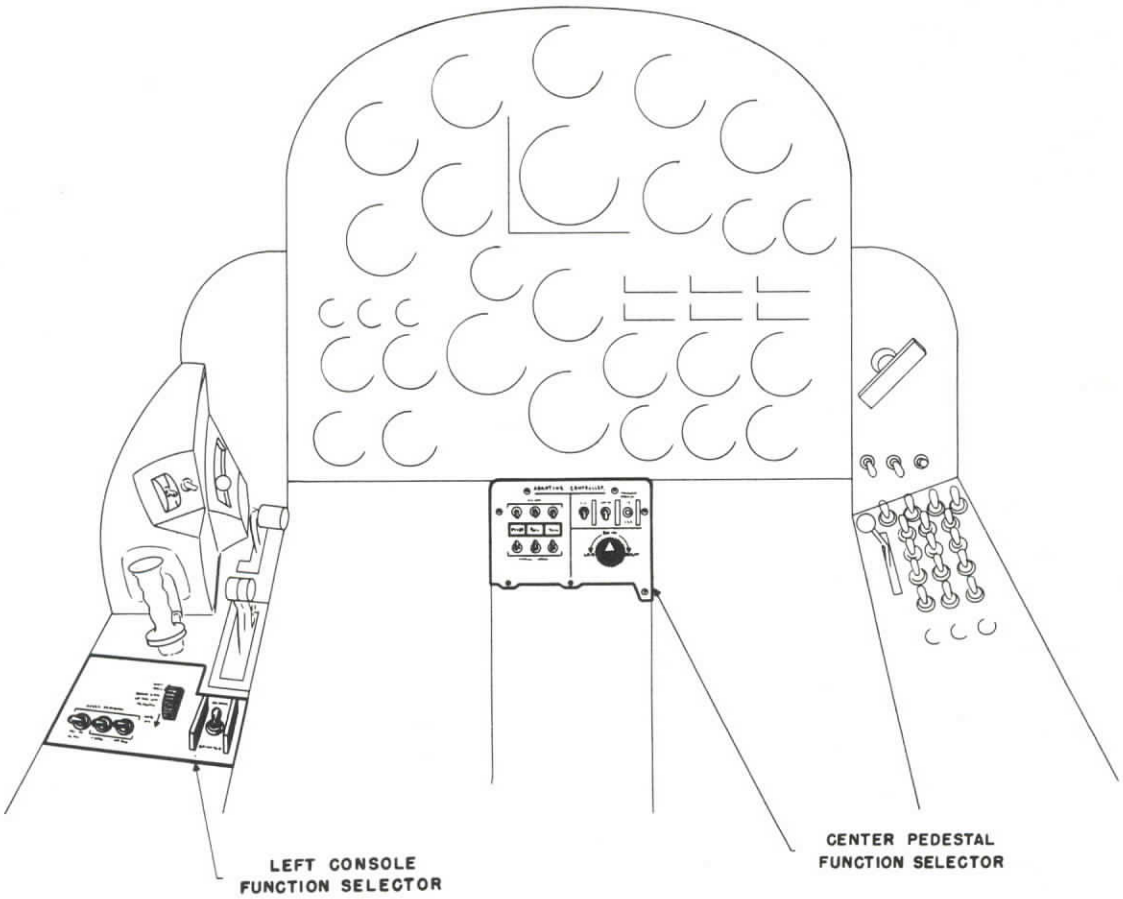


Figure 8 Function Selectors in Cockpit Layout

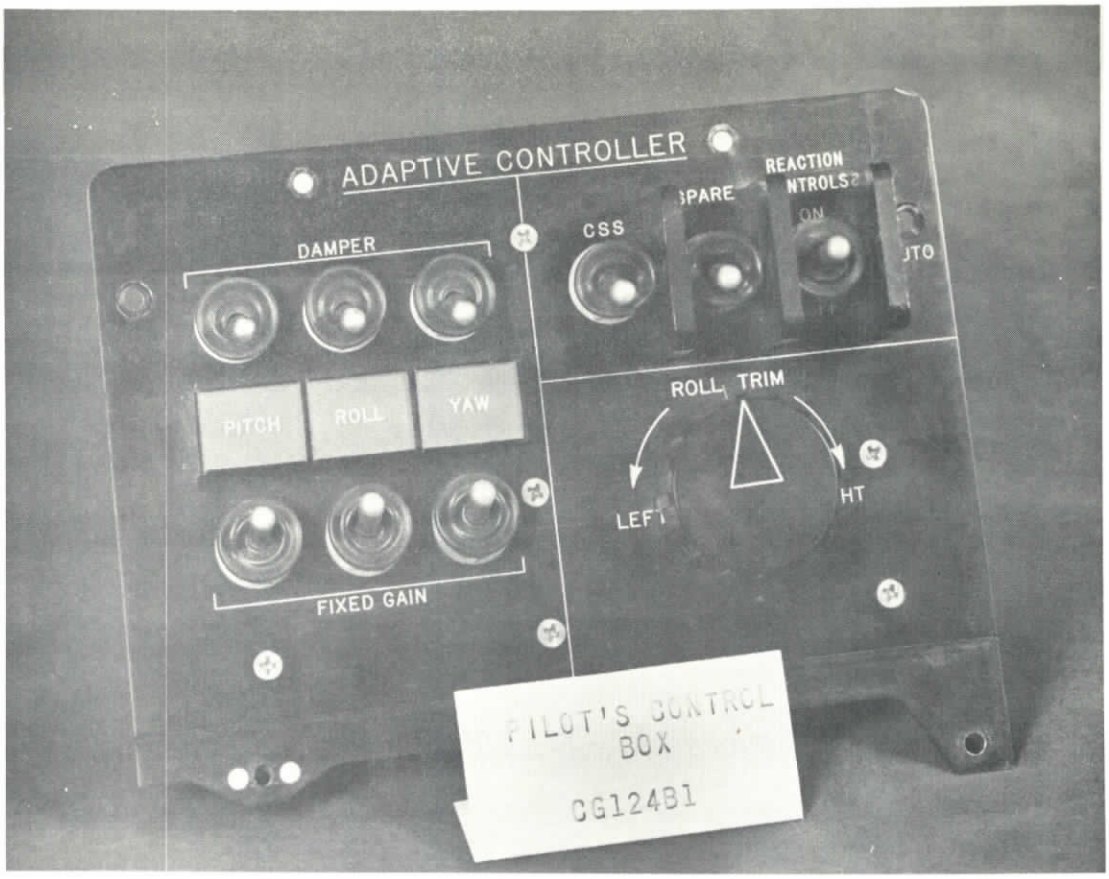


Figure 9 Function Selector Center Console

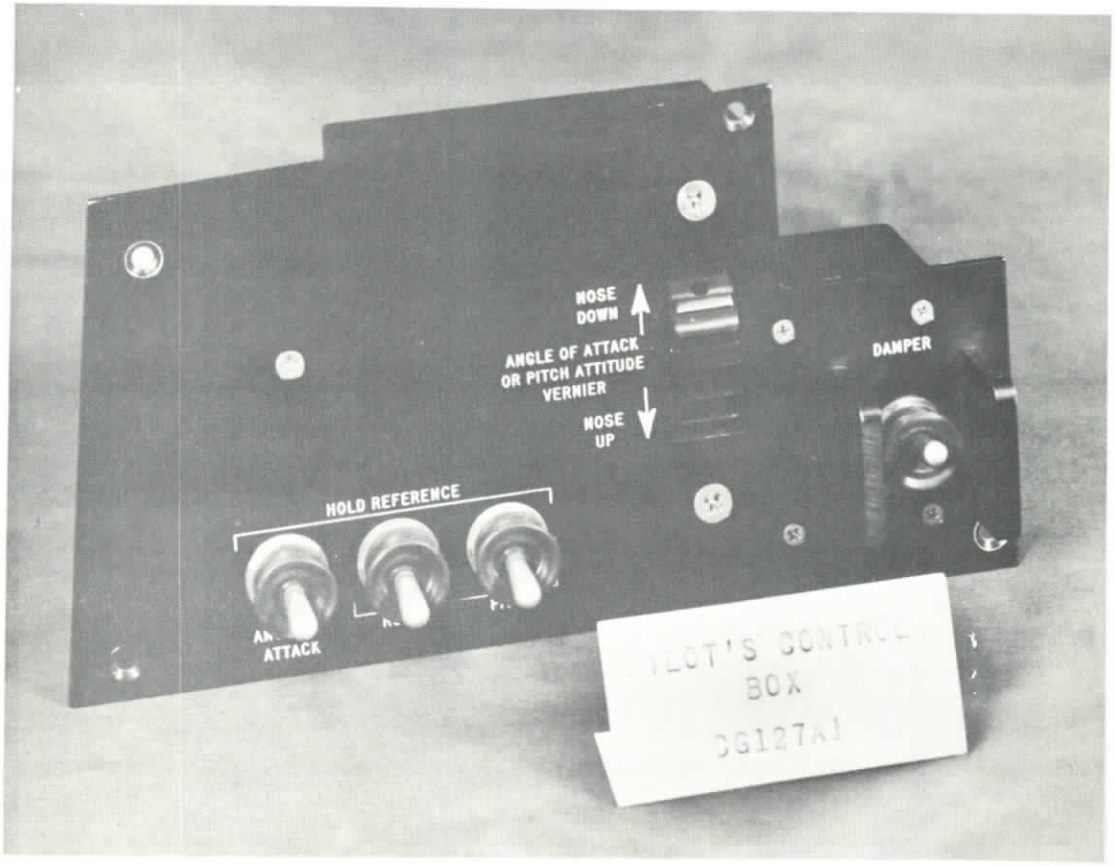


Figure 10 Function Selector Left Console

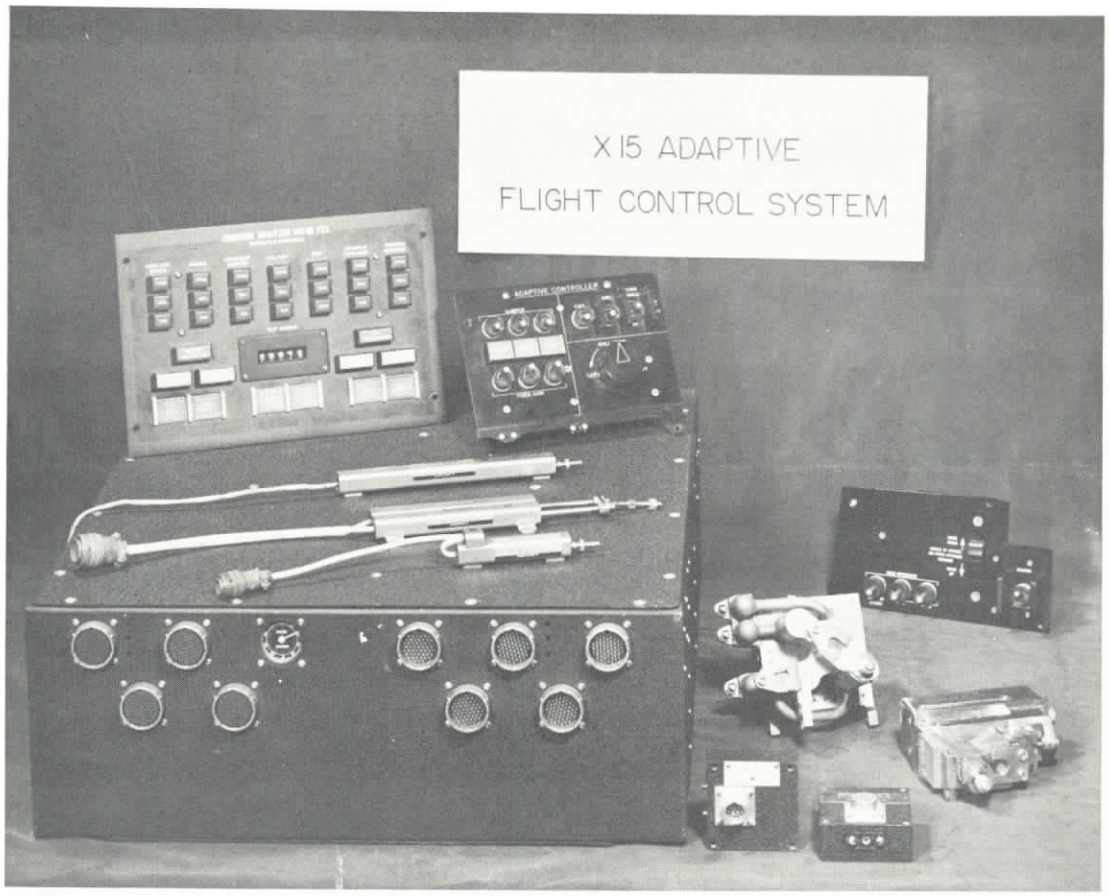


Figure 11 Display of all AFCS Components