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# EXPERIENCE WITH THE X-15 ADAPTIVE FLIGHT CONTROL SYSTEM

*by Staff of the Flight Research Center*

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16. Abstract

The X-15 adaptive flight control system is briefly described, and system development and flight-test experiences in the X-15 research airplane are discussed. Airplane handling qualities with the system and system reliability are also discussed.

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# EXPERIENCE WITH THE X-15 ADAPTIVE FLIGHT CONTROL SYSTEM

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## SUMMARY

An adaptive flight control system (AFCS) was evaluated during the X-15 research airplane program throughout the flight envelope to an altitude of 354,200 feet (108 kilometers) and a velocity of 5660 feet per second (6209 kilometers per hour) and during atmospheric entries in which angles of attack up to 25° were maintained. The dynamic pressure varied from essentially 0 to approximately 1889 pounds per square foot (90,446 newtons per square centimeter).

During the preflight system development cycle, problems with hysteresis, actuator rate limiting, and structural resonance were experienced.

The AFCS improved the handling qualities of the X-15 airplane in some respects. The most significant improvement occurred during atmospheric entry in which the greatest variation in flight conditions existed.

The system exhibited high reliability during the 65 flights of the test program. In-flight electronic component failures were generally undetected by the pilot because of the system's redundancy, fail-safe monitors, and adaptive gain compensation.

The flight-test program confirmed the following advantages of the X-15 AFCS: (1) Nearly invariant response was provided at essentially all aerodynamic flight conditions; (2) accurate a priori knowledge of aircraft aerodynamic characteristics was not required to design a satisfactory system; (3) aircraft configuration changes were adequately compensated for; and (4) the dual redundant concept provided a reliable and fail-safe system.

The flight-test program also disclosed several disadvantages associated with the system, including the following: (1) Commands by the pilot and other spurious inputs caused gain reduction and degraded performance at undesirable times; and (2) supercritical gain operation existed in flight, which, because of mechanical nonlinearities and electrical saturation, resulted in divergent airplane motions.

## INTRODUCTION

Each innovation by control system designers to advance the technology is made in pursuit of the elusive "optimum" in handling qualities. An invariant airplane response to pilot control commands has been a design goal that has seemed to become more difficult to achieve with the advent of each new manned aerospace vehicle. Some of the problems are increasing range of center of gravity, widely varying control effectiveness, and variable aircraft geometry and configuration. The "self-adaptive" flight control concept was conceived as one solution to the growing problem. This concept was defined in reference 1 (page 2) as "one which has the capability of changing its parameters through an internal process of measurement, evaluation, and adjustment to adapt to a changing environment." In an aircraft, such a system would automatically adapt to flight conditions of varying aerodynamic control effectiveness without recourse to air-data sampling.

Studies by the U. S. Air Force in 1956 established the theoretical feasibility of designing a self-adaptive flight control system. The next step, to establish the practicality of the concept, was undertaken in 1957 with a number of contract studies. These studies resulted in flight-test programs to evaluate adaptive concepts in F-94 and F-101 airplanes. By 1958, the government was satisfied with the practicality of adaptive systems; however, the flight-test results were limited by the flight maneuver envelopes of the test airplanes so that the full potential of the systems could not be evaluated. To more fully prove the concepts, a true aerospace environment would have to be covered in a flight-test program. Therefore, a program was initiated which would result in flight demonstrations in the X-15 airplane, because the rate of change and range of its stability and control parameters, for example, control-surface effectiveness, short-period damping, and frequency, would provide a severe test of the concept. A detailed history of the development of the self-adaptive concept through 1958 was included in reference 1.

In June 1959, the U. S. Air Force awarded a contract for the development of the X-15 AFCS. Although the primary purpose of the program was to test a self-adaptive technique in a true aerospace environment, it was decided to include in the system certain features which had come to be recognized as desirable in aircraft automatic flight control systems. These features included dual redundancy provisions for reliability, integration of reaction and aerodynamic controls, rate command control, and simple outer-loop hold modes in attitude and angle of attack. A prototype of the system was evaluated on the X-15 simulator and in a limited flight-test program with an F-101 airplane.

During the summer of 1961, the AFCS was installed in the X-15 airplane. The first flight was on December 20, 1961. Before the X-15 airplane program was terminated, the AFCS had been used on 65 flights. Much of the development and many of the early flight-test results were reported in references 2 to 8. The present report summarizes the experiences with the AFCS for the entire X-15 flight program.

## SYMBOLS

| | |
|---|---|
| $a_x$ | longitudinal acceleration, g |
| $a_y$ | lateral acceleration, g |
| $a_z$ | normal acceleration, g |

| | |
|---|---|
| $C_{l_\beta}$ | variation of rolling-moment coefficient with angle of sideslip, per degree |
| $C_{m_\alpha}$ | variation of pitching-moment coefficient with angle of attack, per degree |
| g | acceleration due to gravity, 32.2 feet per second$^2$ (980.7 centimeters per second$^2$) |
| h | altitude, feet (kilometers) |
| $K_p$ | damper gain in the roll axis, degrees differential horizontal-tail surface deflection per degree per second of roll rate |
| $K_q$ | damper gain in the pitch axis, degrees of average horizontal-tail surface deflection per degree per second of pitch rate |
| $K_r$ | damper gain in the yaw axis, degrees of rudder surface deflection per degree per second of yaw rate |
| $L_{\delta_a}$ | roll-control effectiveness, per second$^2$ |
| p | rolling angular velocity, degrees per second |
| q | dynamic pressure, pounds per foot$^2$ (newtons per meter$^2$) |
| t | time, seconds |
| $\alpha$ | angle of attack, degrees |
| $\beta$ | angle of sideslip, degrees |
| $\delta_a$ | differential horizontal-stabilizer surface angle, obtained as the difference between the left and right horizontal-stabilizer deflections (aileron deflection producing a right roll is positive), degrees |
| $\delta_h$ | average horizontal-stabilizer surface angle, obtained as one-half the sum of the left and right horizontal-stabilizer deflections (trailing edge down is positive), degrees |
| $\delta_r$ | rudder surface angle, trailing edge left is positive, degrees |
| $\delta_\varphi$ | roll-control stick position, degrees |
| $\theta$ | angle of pitch attitude, degrees |
| $\varphi$ | angle of roll attitude, degrees |
| $\psi$ | yaw or heading angle, degrees |

Subscript:

L left

## AIRPLANE AND SYSTEMS

### X-15 Airplane

The X-15 was a single-place, rocket-powered airplane (figs. 1 and 2) designed for flight research at hypersonic speeds and extreme altitudes. It was carried aloft under the right wing of a B-52 airplane and launched at an altitude of approximately 45,000 feet (13.7 kilometers) and a speed of approximately Mach 0.80. After launch, a powered flight mission was performed, followed by an unpowered deceleration glide and a landing at Edwards Air Force Base, Calif. With this operational technique, the airplane was capable of attaining a Mach number of 6 and could be flown to and recovered from an altitude in excess of 350,000 feet (106.68 kilometers). The duration of an average free-flight mission was approximately 12 minutes.


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*Figure 1. X-15 airplane.*

Flights were made with two airplane configurations: ventral rudder on, and ventral rudder off (fig. 2). The stability and control derivatives and physical characteristics of these configurations were presented in detail in reference 9. The static-stability derivatives of the basic airplane (ventral rudder on) indicated that the vehicle would be stable throughout most of the flight envelope; however, at a Mach number of approximately 3.0 and an angle of attack greater than 10°, the airplane was uncontrollable without damping augmentation when normal piloting techniques were used. Analysis revealed that this instability was caused by an unfavorable combination of the

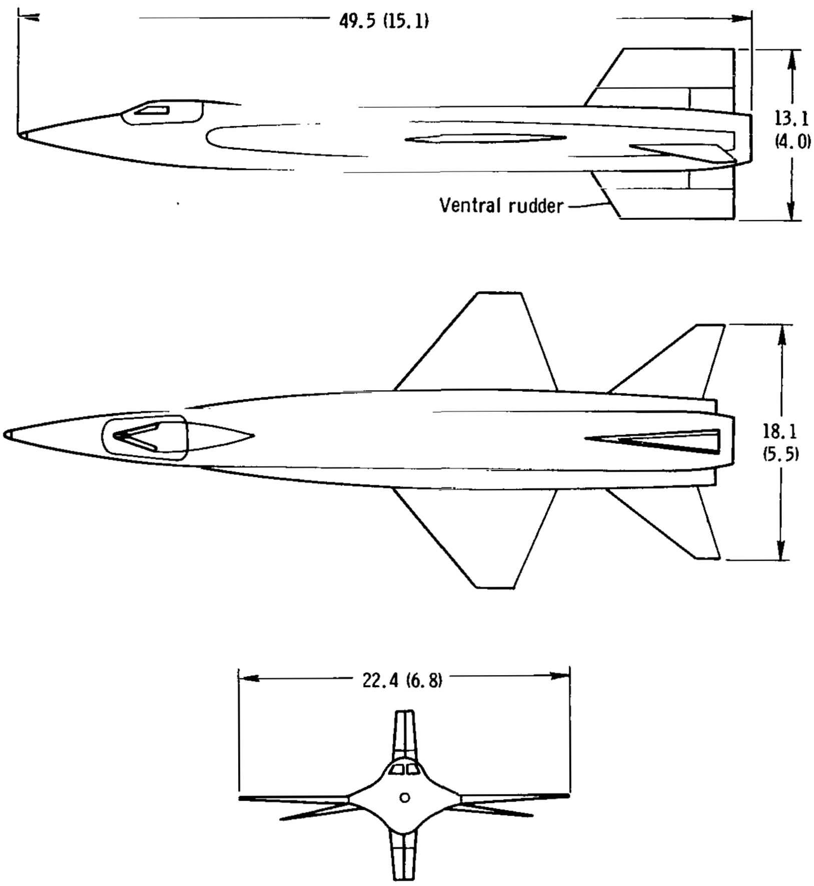


*Figure 2. Three-view drawing of the X-15 airplane. (Dimensions in feet (meters).)*

yawing moment due to aileron deflection and the dihedral effect. This problem was subsequently alleviated by removing the ventral rudder (refs. 10 and 11). Although the change produced lower static-directional stability and rudder effectiveness, it resulted in a more controllable airplane with stability augmentation inoperative, particularly at high angles of attack.

## Displays

A photograph of the pilot's instrument panel is shown in figure 3. The three-axis attitude indicator (shown in the center of the panel) was the primary instrument for displaying airplane pitch, roll, and yaw attitude to the pilot. A pitch-attitude vernier was provided on the left side of the indicator to give a more accurate indication of pitch attitude. An instrument showing dynamic pressure was located above the attitude indicator, and a timer which displayed elapsed engine thrust time was positioned immediately above the dynamic-pressure display. Errors (difference between preset value and actual value) in angle of attack and angle of sideslip were presented on the crossbars of the three-axis attitude indicator. The angle-of-attack bar was used as a vernier to establish a desired angle of attack. At high altitude, where the indications of angle of sideslip and angle of attack were unreliable, the sideslip bar was usually switched to present heading error. Actual angle of attack was presented on a dial gage to the left of the attitude indicator. Above the angle-of-attack indicator was a presentation of normal acceleration.

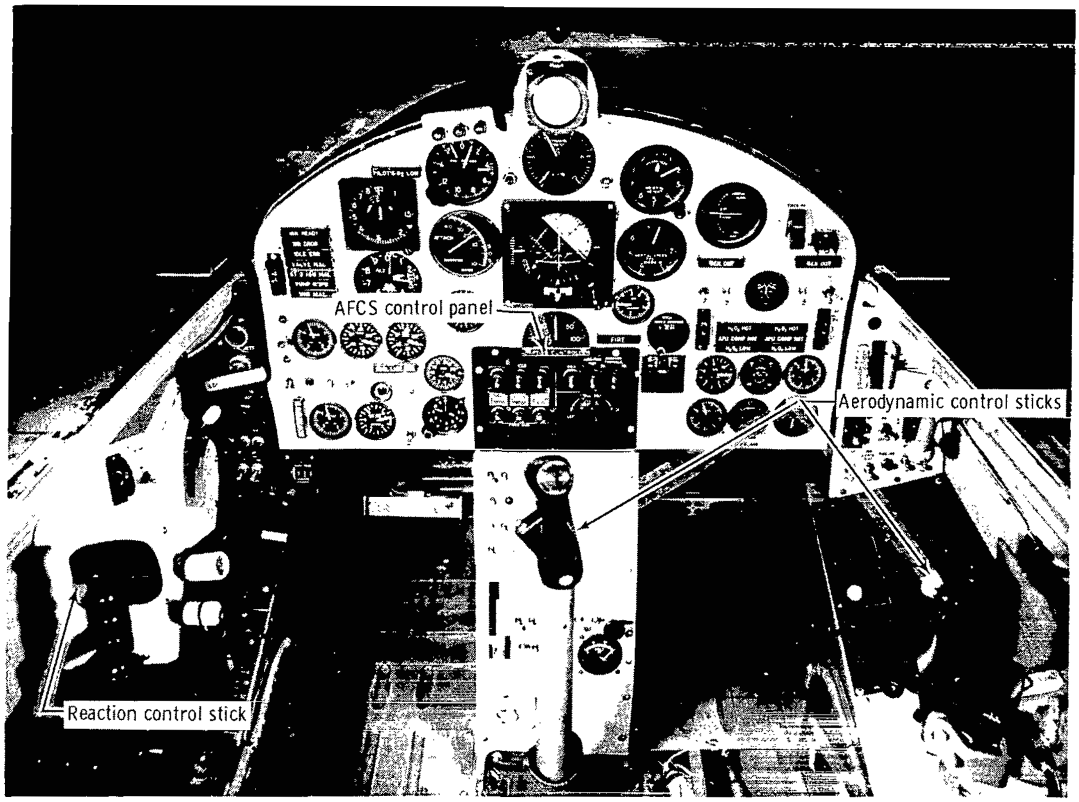


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*Figure 3. X-15 cockpit.*

Conventional pressure-derived airspeed and altitude were displayed to the left of the angle-of-attack dial. These quantities were used at Mach numbers of less than 2 and altitudes of less than 80,000 feet (24 kilometers). Velocity, altitude, and rate of climb, derived from the inertial reference platform, were displayed in the upper-right corner of the panel. A display of roll rate (below the attitude indicator) was included as a secondary display. The AFCS control panel was located on the forward panel to facilitate pilot monitoring.

For several special-purpose flights late in the X-15 program, the cockpit display was varied somewhat from the arrangement described.

## Mechanical Controls

Aerodynamic control was provided through the empennage control surfaces using the all-movable rudder surfaces for directional control and the all-movable horizontal tail for both pitch and roll control. The aerodynamic control surfaces were actuated by irreversible hydraulic systems. Artificial feel was provided by force bungees. A conventional center stick, a controller located on the right side of the cockpit (slaved to the center stick), and rudder pedals provided aerodynamic control. The side-located controller, although designed for use in high-acceleration environments, was used by the pilots throughout the aerodynamic flight region. This control system was described in detail in reference 12.

### Jet Reaction Controls

Small monopropellant rocket motors were used on the X-15 airplane to produce control torques in all three axes when the aerodynamic control surfaces became ineffective at high altitudes. This system was discussed in detail in reference 13. Manual pilot control of the reaction control rockets was provided by a single, three-axis control stick located on the left-hand console, as shown in figure 3. The stick was mechanically connected to proportional propellant-metering valves which regulated the propellant flow for the attitude control rockets.

### X-15 Adaptive Flight Control System

The X-15 AFCS was a model following, adaptive variable gain, rate command augmentation system and autopilot. The system was described in detail in references 2 to 8, thus only a brief description is included here. The AFCS was installed in series with the basic X-15 hydromechanical control system in the same general arrangement as the basic X-15 stability augmentation system which it replaced (refs. 12 and 14). The components unique to the AFCS weighed less than 110 pounds (50 kilograms). The system had a dual redundant mechanization throughout, excluding the servoactuators.

The simplified diagram in figure 4 illustrates the basic concept of the system. Commands were introduced to the control-surface actuators through conventional mechanical inputs and simultaneous electrical inputs which were proportional to pitch- and roll-stick displacement. The electrical input to each axis was shaped by a simple network (model) which had the dynamic response desired of the airplane in that axis. The X-15 models were first-order lags with time constants of one-half second in pitch and one-third second in roll. The difference in pilot rate command (model output) and the achieved rate was then used as an error signal in the high-gain loop of the system. The system operated on the principle of using sufficient lead in series with a high forward loop gain, acting on this error signal, so that the response of the aircraft would be approximately that of the model.

The AFCS was designed to provide a bandwidth three to five times greater than that of the model, thus insuring that the airplane would follow the model closely. The gain was automatically increased until the system began to oscillate at the verge of instability. (This gain was the "critical" gain.) The gain changer, shown in figure 4, operated by monitoring the limit-cycle amplitude and adjusting the gain to maintain the amplitude at less than a preset level. The limit-cycle frequency, which was determined by the lead compensation, was higher than the aircraft's natural frequency but lower than the lowest structural frequency.

A number of ancillary functions were included in the system that are not shown in figure 4. Because the X-15 servoactuator had a limited authority ($\pm 15^\circ$ of surface about a trim position), a longitudinal trim followup loop was included to provide the system with full surface authority. The autopilot functions were additional outer loops

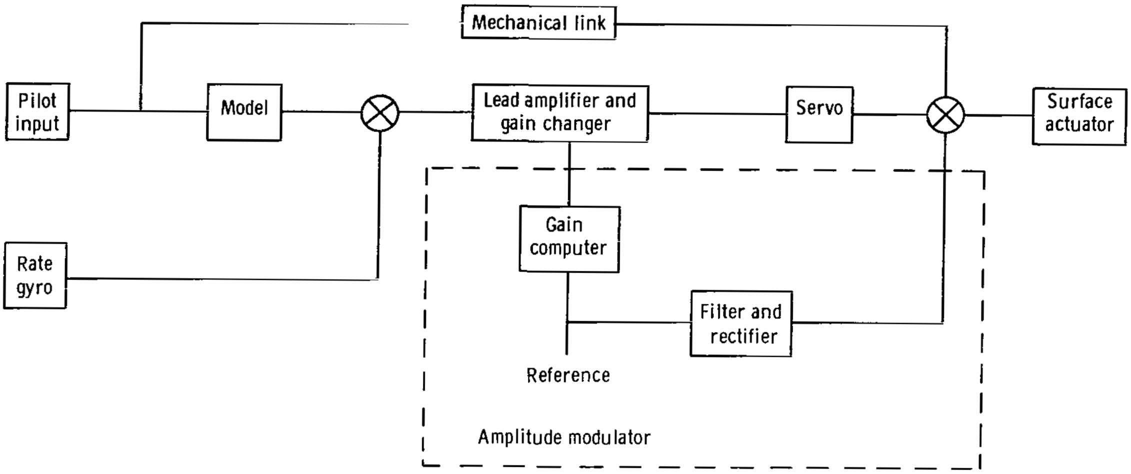


*Figure 4. Simplified block diagram of basic concept of X-15 AFCS.*

($\alpha$, $\theta$, $\varphi$, and $\psi$ hold) which the pilot could select to assist in controlling the airplane. The attitude control rockets were automatically blended with the aerodynamic control surfaces to provide continuous control into the high-altitude regions where commands required their use. Automatic limiting of normal acceleration was available to make entries from high altitude easier.

The greatly simplified block diagram in figure 4 is typical of the roll and pitch axes. The yaw axis did not include an electrical pilot input. The mechanical connection, linking the pilot's control stick with the surface actuators, was not changed from the basic aircraft configuration, so that control of the unaugmented airplane was unchanged. Under certain circumstances, the presence of this mechanical pilot input capability could have been detrimental to the AFCS performance.

## INSTRUMENTATION

During the initial flight-test program, parameters pertinent to evaluation of the X-15 AFCS were recorded on standard NASA oscillograph recording instruments which were synchronized at 0.1-second intervals by a common timer. Later in the program, the data recording system was converted to a pulse-code-modulation tape system. The following parameters were recorded:

Airspeed and pressure altitude

Normal, longitudinal, and transverse accelerations

Pitch, roll, and yaw angular accelerations, velocities, and attitudes

Angles of attack and sideslip

Cockpit control positions and forces

Control-surface deflections

Control servoactuator deflections

AFCS gain computers

AFCS autopilot reference errors

AFCS command signals

Attitude control rocket-chamber pressures

An inertial platform supplied velocities, heights, and attitudes. A ball-nose flow-direction sensor provided angle of attack and angle of sideslip. A tracking radar and a conventional air-data system were also used to obtain velocity and altitude information. Internal recordings were accurate within 3 percent of full-scale values for each sensor.

## DISCUSSION

### General Experience

The flight-test program with the X-15 AFCS began in December 1961. The first seven flights constituted the acceptance-test portion in the evaluation program. These flights were discussed in detail in references 6 and 7. System deficiencies were expected during the acceptance tests; however, before the fifth flight, all known or suspected deficiencies had been eliminated, and the remaining three flights were used for contractual demonstration and acceptance of the system. A high-altitude flight for performance evaluation terminated the acceptance-test sequence. The AFCS had met all the requirements of the performance specifications to which it had been designed.

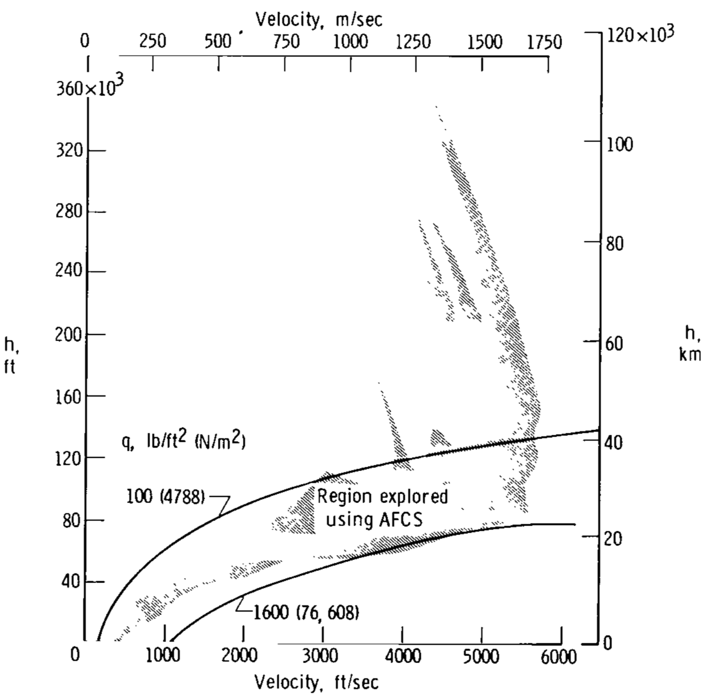


*Figure 5. X-15 flight envelope for the AFCS evaluation.*

After the acceptance-test program, the system was used on 58 flights by nine pilots to fly to a maximum altitude of approximately 354,200 feet (108 kilometers) and was evaluated with variations in dynamic pressure from 1889 pounds per square foot (90,446 newtons per square centimeter) to near 0 pounds per square foot (fig. 5). Although no serious attempt was made to optimize system performance or to define the total capability of the system, valuable impressions and experience were obtained. Much of the experience was not unique to the "adaptive" concept, however. Most of the unusual handling characteristics, which stimulated pilot comments, were results of the rate-command control feature rather than the adaptive concept.

## Development Experience

Early development of the X-15 AFCS was discussed in references 2 to 8; only the significant developmental experiences subsequently found in flight are reviewed in this report.

Although much study and experience went into the design of the X-15 AFCS in the form of analog-computer studies and F-101 flight-test experience with a system having the same concepts, several problems were encountered when a breadboard of the AFCS was connected to the ground-base X-15 flight simulator (fig. 6). The simulator consisted of a full-size operating mockup of the complete control system: cockpit, control sticks, cables, linkages, electronic equipment, servoactuators, power actuators, and simulated control surfaces. Complete six-degree-of-freedom airplane motion was computed with an analog computer, which enabled complete missions to be "flown" from launch to landing. When the actual AFCS hardware was used with the simulator, the first difficulties with the system became apparent.

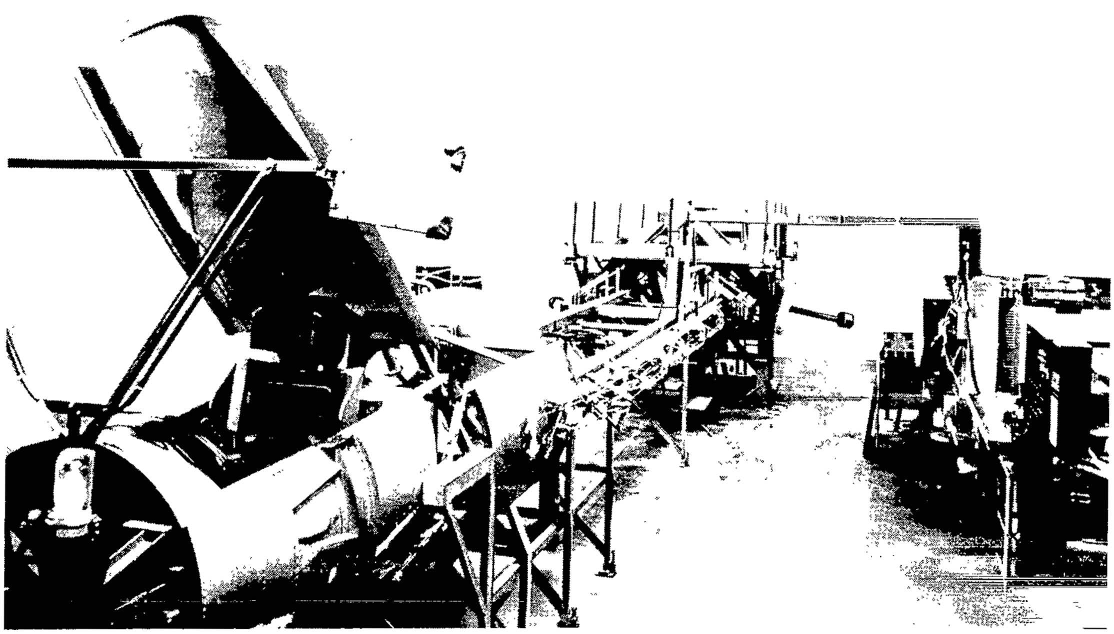

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*Figure 6. X-15 flight control simulator.*

The hysteresis or lost motion in the X-15 control system was large compared with that of the F-101 and, therefore, presented a problem, particularly during entry maneuvers from high altitudes. At high altitude the gains were, of course, driven to their maximum values in trying to compensate for the almost complete lack of aerodynamic control effectiveness. During entry, the aerodynamic control effectiveness increased beyond the value for loop stability with the AFCS gain at maximum, but, because of the lost motion, the loop was not closed until a disturbance exceeded the hysteresis. Considerable movement of the pilot's controls resulted from these supercritical gains, because the servos moved so rapidly that the surface actuators could not follow. The movement was passed upstream by the mechanical system to the pilot. This problem also occurred to a lesser extent at other flight conditions when, because of the lack of motion, the gains drifted to supercritical values and caused a brief period of shaking when the motion exceeded the hysteresis. An example of this is shown in figure 7. By putting flow restrictors in the servoactuators to make their maximum rate of operation more consistent with that of the surface actuators (26 deg/sec), shaking of the pilot's controls was essentially eliminated. In addition, the dynamics of the gain computer were changed so that the gain was rapidly reduced to a subcritical value before the shaking could develop enough amplitude to be noticed by the pilot.

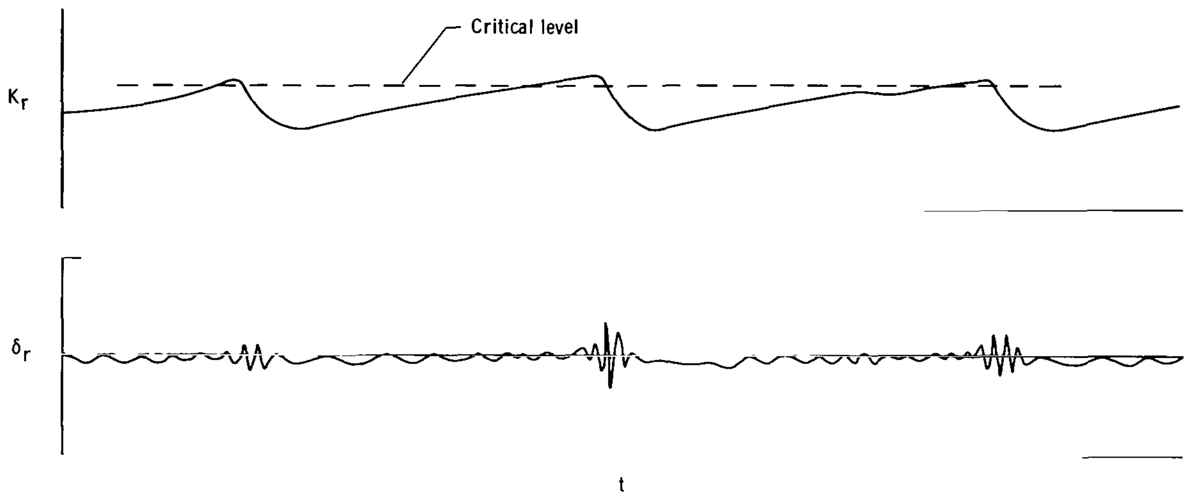



*Figure 7. AFCS gain operation and surface activity.*

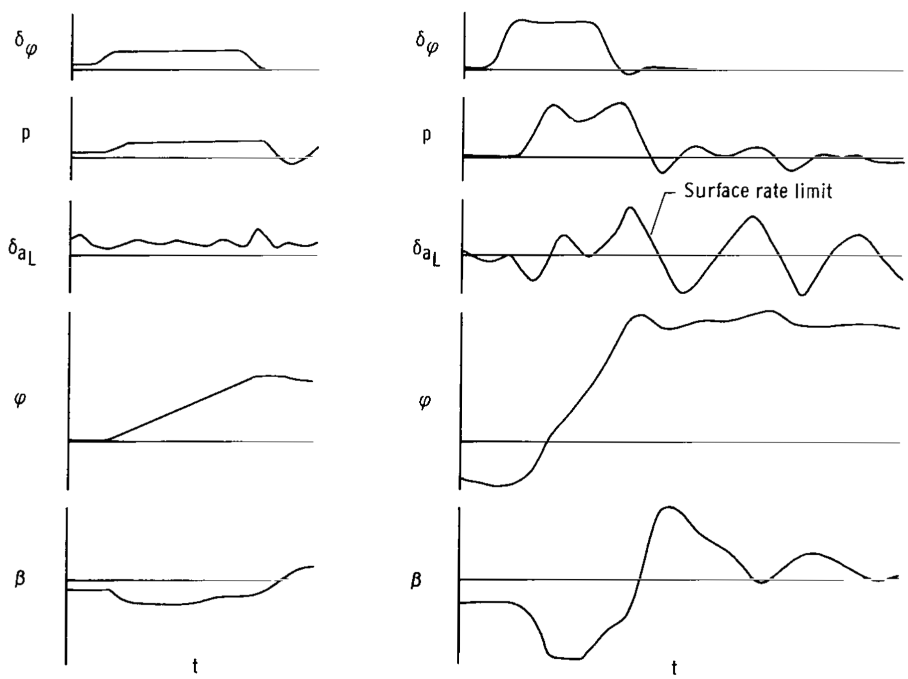
Maintaining the gain at a near-critical value when pilot inputs tended to drive it down momentarily was also a problem. This was most apparent in ballistic flight, because the gain values were used to automatically engage (blend in) the reaction controls (refs. 2 and 3). At altitude, a sharp pilot input could drive the gain low enough to disengage the reaction controls momentarily, until the gain worked its way back up. This problem was eliminated by adding a high-pass filter and limiter to the servo signal used by the gain computer. In this way, the effect of the low-frequency, but large-amplitude, pilot inputs was greatly reduced without affecting the small-amplitude, high-frequency signal necessary for proper gain adjustment. In addition, the reaction control engage logic was changed to allow for dips in the gain values, thus preventing premature disengagement of the reaction controls.

Operation of the automatic followup trim system presented a problem, particularly at high altitude. The trim system slowly oscillated, which caused the control stick to wander. This was alleviated by reducing the rate at which the trim actuator functioned, thereby reducing the gain of that particular loop.

Very late in the development of the X-15 AFCS, but prior to flight, a problem was encountered during a flight in which the relatively low-gain basic stability augmentation system caused structural resonance of the horizontal stabilizers (refs. 14 and 15).

Because of its much larger gain values, it was obvious that the AFCS would require an extremely deep notch filter to avoid the structural resonance. The high order of the notch filter required an extensive modification (ref. 5). The large additional phase lag of the notch filter introduced another problem: limit cycles. A compromise had to be found, because phase lag had to be reduced to reduce the effect of the limit cycles. To do this, it was necessary to increase the gain at the structural frequencies. An acceptable compromise was found only after the maximum and minimum gains were reduced; that is, the variable gain range was shifted downward.

Surface rate limiting, mentioned previously, produced another problem. Even in the modified system, it was possible for the servo velocity to exceed that of the actuator and thereby force the actuator to move at its rate limit. When this occurred, the surface no longer produced the response requested by the servo, and the airplane was unable to maintain the commanded rate, particularly for large inputs on high-gain conditions. In the small roll step shown in figure 8(a), vehicle response followed the command very well. In the large roll step (fig. 8(b)), rate limiting occurred, as evidenced by the slope of the surface position trace, and the response deviation from the model was significant. These deviations were also reflected in the coupled axes,




*(a) Small roll step.* *(b) Large roll step.*

*Figure 8. Surface rate limiting (X-15 simulator).*

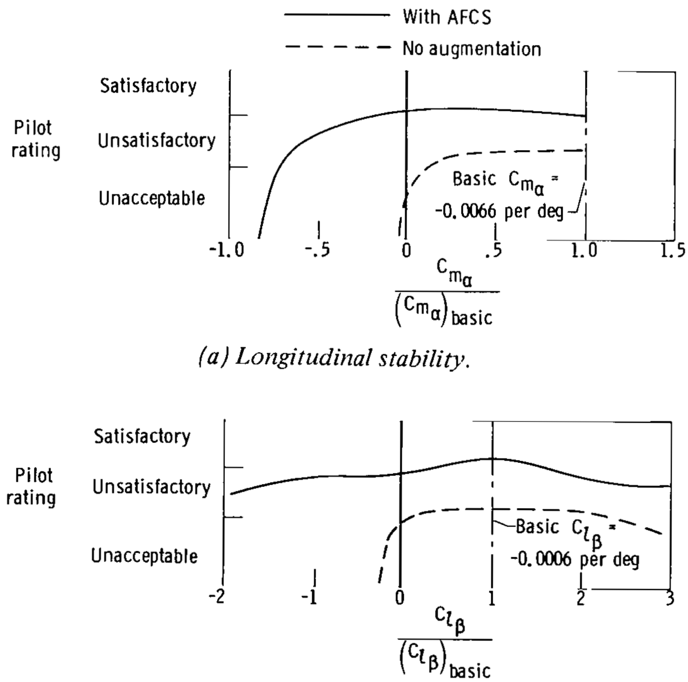
as indicated by the large sideslip excursion. In some critical areas this saturation could have resulted in loss of control, particularly if the rate limiting had occurred because of large pitch-axis commands, which would also have left the aircraft without roll control or damping or both. This was peculiar to the X-15 airplane because the horizontal stabilizers provided pitch and roll control simultaneously.

Operational Experience

On the first flight, in December 1961, some deficiencies were found in the X-15 AFCS. These deficiencies were associated with airplane and systems interface, so that the system did not need to be changed functionally. The only functional change—the deletion of two functions—during the entire program was made prior to the tenth flight. The yaw-rate-to-roll (YAR) and the lateral-acceleration-to-rudder (LAR) loops were initially included in the system to compensate for an adverse dihedral effect which existed in the unaugmented airplane at high angles of attack when the ventral rudder was installed. These lateral-directional characteristics were discussed in detail in references 10, 11, and 16. When the AFCS was operating near critical gains, the YAR and LAR loops offered little improvement in handling qualities; however, they were thought to be necessary if the system gains were greatly subcritical. When the decision was made in September 1962 to fly the X-15 airplane without the ventral rudder, the YAR and LAR loops were deleted from the AFCS. In the airplane ventral-rudder-off configuration, simulator experience had indicated that these loops tended to destabilize the Dutch roll mode. These experiences refuted the contention that the X-15 AFCS would be relatively insensitive to airplane configuration changes. Subsequently, the LAR loop was reactivated, flown for several flights, and found to have no measurable effect on airplane stability. Thus, it was removed again, supporting the contention that the X-15 AFCS could accommodate configuration changes.

Other minor configuration changes were made during the X-15 AFCS program which also had no effect on the airplane's handling qualities. Wing-tip pods were added and removed; one horizontal stabilizer (one panel) was replaced with a distorted stabilizer which had been removed from another airplane after causing a roll mistrim; and one horizontal stabilizer was coated with about one-half inch (1.27 centimeters) of experimental ablative material, producing an airfoil 1 inch (2.54 centimeters) thicker than the standard airfoil on the opposite side of the airplane.

A more conclusive configuration sensitivity study was conducted with the X-15 simulator in an attempt to determine the benefits that could be achieved by using an "adaptive" control system. Basic X-15 aerodynamic derivatives were varied to determine the compensation an adaptive system could provide. It was readily apparent that the AFCS was extremely tolerant of variations in the levels of basic aircraft control effectiveness and stability. Figures 9(a) and 9(b) show the effect on pilot rating of varying the magnitudes of two basic derivatives,




*(a) Longitudinal stability.*

*(b) Dihedral effect.*

*Figure 9. Augmentation effectiveness of AFCS (X-15 simulator).*

the longitudinal stability derivative $C_{m_\alpha}$ and the effective dihedral derivative $C_{l_\beta}$, through sufficiently wide ranges to render the aircraft unflyable without augmentation. The derivative values are expressed in multiples of the basic X-15 values. The dashed lines represent the unaugmented aircraft which, for negative values of static margin and dihedral effect, was impossible to control. As shown, the AFCS could absorb substantial deviations of these parameters from the design levels and still provide acceptable handling qualities. These two examples are typical of the experience with the X-15 AFCS when it was operating near critical gain.

The AFCS did not operate near critical gain most of the time. An indication of how well the gain changer maintained the system gain at its critical value is shown in figure 10 in which the actual gain wanders to either side of the critical value. During entry from high altitude, the airplane aerodynamic control effectiveness increased rapidly from a value near 0, which should have caused the system gain to drop correspondingly from its maximum value. Because of the mechanical control system hysteresis, the drop in system gain was delayed, as indicated by the large values of airplane gain while the system gain remained at its maximum value. When there was pilot control activity, electrical noise, turbulence, structural vibrations, or rapid aircraft motions, the gains were often reduced below the critical gain value.

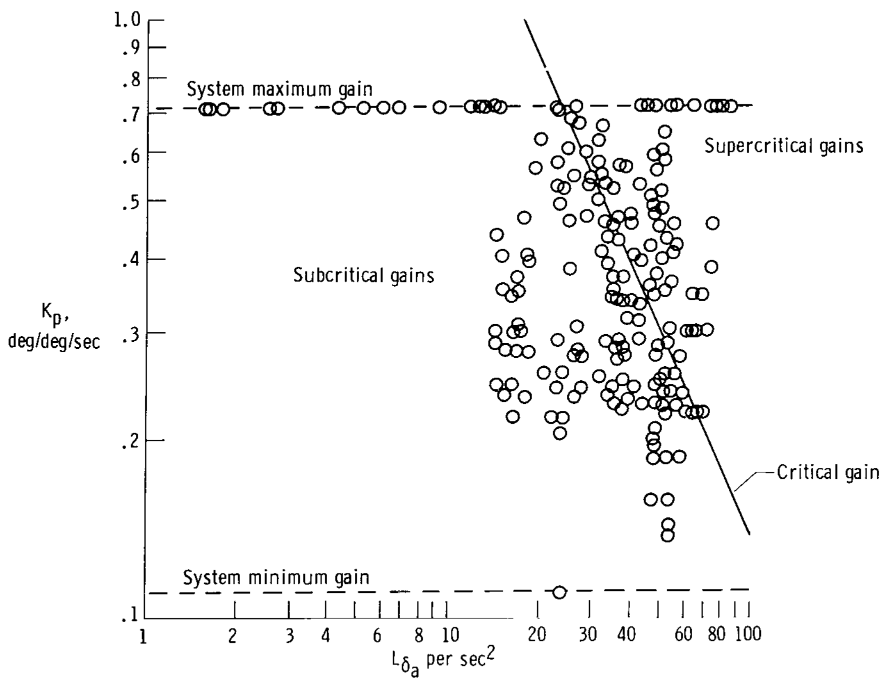
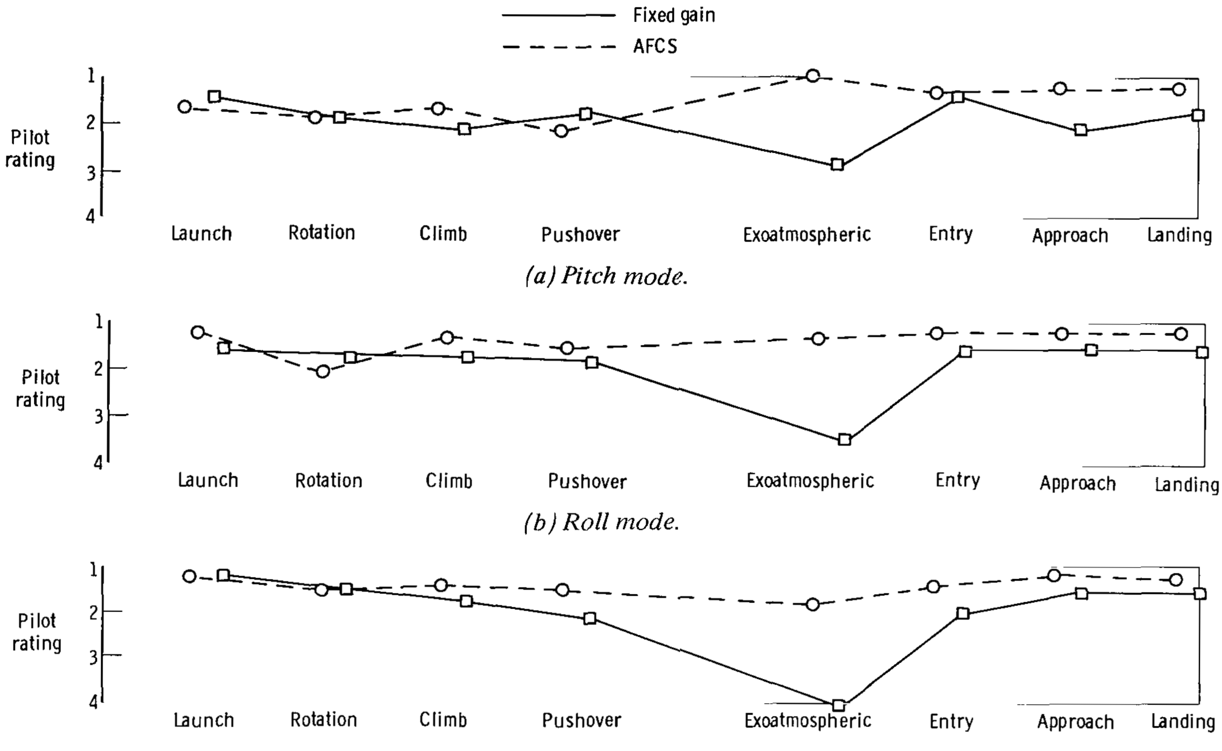



*Figure 10. AFCS gain-changer operation.*

The effects of the deviations from critical gain on the airplane's handling characteristics were not usually perceptible to the pilot. Figure 11 shows pilot ratings (ref. 17) for a number of different flight phases for both the X-15 AFCS and a conventional fixed-gain system installed in the other two X-15 airplanes. These flight phases covered a wide range of altitude, Mach number, and dynamic pressure. Thus, the




*(a) Pitch mode.*

*(b) Roll mode.*

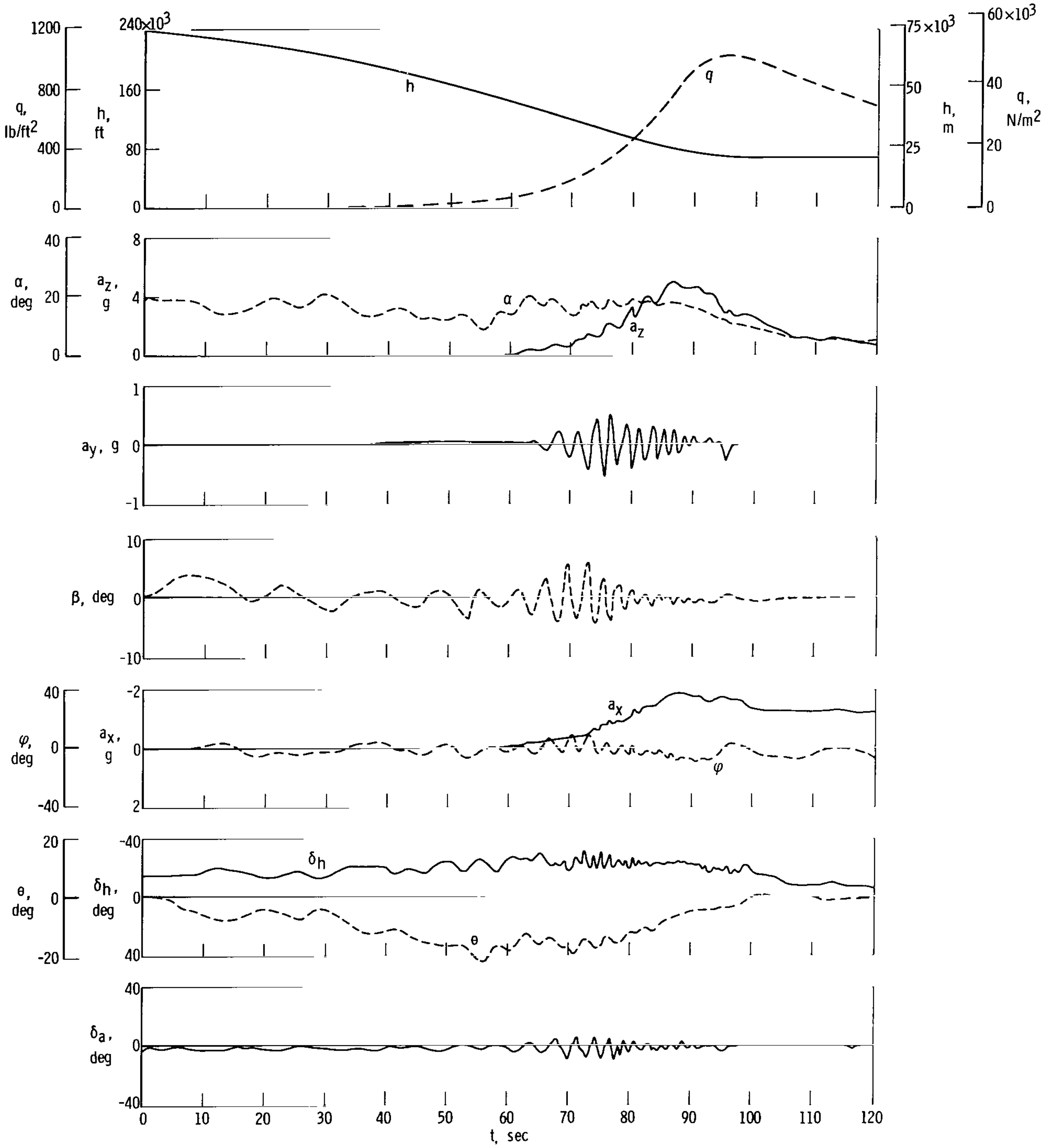
*(c) Yaw mode.*

*Figure 11. Comparison of the pilot ratings of the AFCS and a fixed-gain system.*

response characteristics of the airplanes equipped with the fixed-gain system varied. yet the pilot ratings did not change appreciably nor were they substantially different from those for the AFCS except in the flight phases with relatively low dynamic pressure. This can be partially explained by the fact that both systems provided effective deadbeat damping (damping ratios in excess of 0.3) at reasonable dynamic pressures. It was immaterial to the pilot whether damping ratio was variable but no lower than 0.3, as in the fixed-gain system, or held constant at 0.5, as in the AFCS; he considered both to be deadbeat.

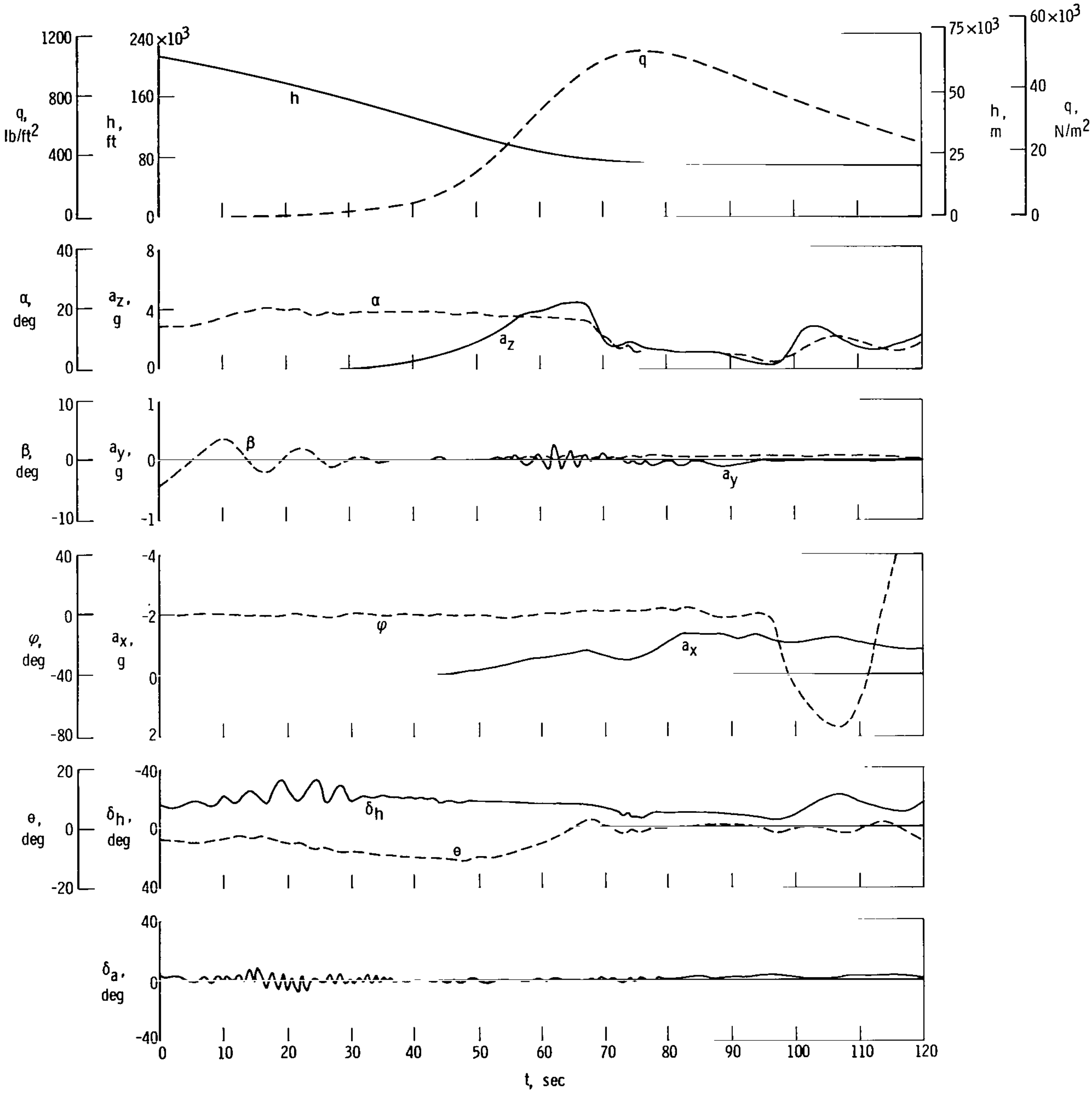
In the low-dynamic-pressure flight phases (refs. 18 and 19), the AFCS provided more effective damping than the fixed-gain system. For example. during an X-15 atmospheric entry (figs. 12(a) and 12(b)), the AFCS was effective much earlier in the entry, because of its higher gain, and damped out most of the entry misalinement transients before the g-onset and rapid increase in dynamic pressure began. The fixed-gain system, on the other hand, usually had not eliminated these induced oscillations in the earlier phases of the entry. Aircraft oscillations that persisted until the rapid g-onset began were disturbing to the pilot. He could not readily damp the oscillations manually because of the rapidly changing frequency of the oscillation as dynamic pressure increased. If he had attempted to manually damp an oscillation during this phase of the entry, he could have instead easily aggravated the motions by a poorly timed or improper control input.

The AFCS also provided the pilot with hold modes and blended aerodynamic and reaction control which reduced his workload during exoatmospheric flight and entry.




*(a) With fixed-gain system.*

*Figure 12. X-15 atmospheric-entry time history.*




(b) With AFCS.

*Figure 12. Concluded.*

For these reasons, the X-15 airplane with the AFCS was considered to be superior to the X-15 airplanes with conventional fixed-gain systems for flights out of the atmosphere. An X-15 pilot's assessment of factors that contributed to the superiority of the AFCS is presented in the appendix.

The invariant response characteristics of the AFCS were not obvious to the pilot, because pilots do not usually think of desired response in terms of stick deflection. Before a pilot makes a control input, he has decided what airplane response he wants. If the initial control input does not provide the desired response, he modifies the input. The manifestation of the invariant rate-command response characteristic of the X-15 AFCS was somewhat subtle. Trim changes normally associated with extension or retraction of landing gear, landing flaps, speed brakes, or other variable-configuration devices were automatically compensated for by the system and were thus masked to the pilot. Variations in longitudinal center-of-gravity position were also not apparent to the pilot, because trim was automatically adjusted and response characteristics did not vary. Transonic trim changes were masked, too, as were lateral or directional asymmetries. The yawing and rolling moments due to the thrust of a misalined engine were automatically compensated for within the limits of the system's control authority. Although the pilots generally appreciated automatic trim compensation, they were somewhat uncomfortable about the loss of familiar cues. The trim change that usually accompanies extension or retraction of landing gear or landing flaps serves as a positive indication of response to the movement of a particular control lever.

Because of the rate-command feature, the AFCS did not respond conventionally to changes in airspeed or dynamic pressure. The airplane's attitude did not change unless commanded by the pilot. As a result, for a neutral control stick position, the nose of the airplane did not fall through in a conventional manner as airspeed decreased, nor did it pitch up as airspeed increased. Thus, the airplane had no apparent speed stability. This characteristic alone would not have been too disturbing to the pilot if the other cues usually associated with changes in airspeed had been available. These other cues, however, were also missing. There was no change in stick force, stick position, or aircraft response to control inputs as airspeed varied. The lack of speed stability was particularly noticeable during the landing. Figure 13 is a time history of a typical X-15 landing approach, with stick force presented for the conventional fixed-gain system and the AFCS. Airspeed constantly decreased at a rate of approximately 4 knots per second during and after flare. In the X-15 airplanes equipped with conventional fixed-gain control systems, the pilot was continually working with a positive stick-force slope. He was usually pulling back on the stick and occasionally retrimming as speed decreased during the level deceleration after flare, which were normal procedures. In the X-15 airplane equipped with the AFCS, however, there was no obvious requirement for the pilot to continually pull back on the stick as airspeed decreased, because, once the flare was completed and the airplane was in a near-level attitude, the control system would automatically maintain that attitude. In addition, at the instant of flare completion, the pilot had to actually push abruptly on the stick (as shown in the time history) to prevent the airplane from ballooning because it was at a higher angle of attack and, thus, higher pitch attitude than required to maintain 1 g flight. If the pilot had simply released the control stick, the system would have maintained that attitude and the airplane would have started to climb. After flare, the pilot was actually working with a negative stick-force slope, as shown in the lower plot, which felt very unnatural. With the rate-command system, the X-15 pilots resorted to trimming-in a nose-down pitch rate before the flare to preload the stick, thus achieving some semblance of speed stability. Other subtle manifestations of the invariant response of the AFCS were the reduction of the influence of ground effect and the elimination of normal dihedral effect.

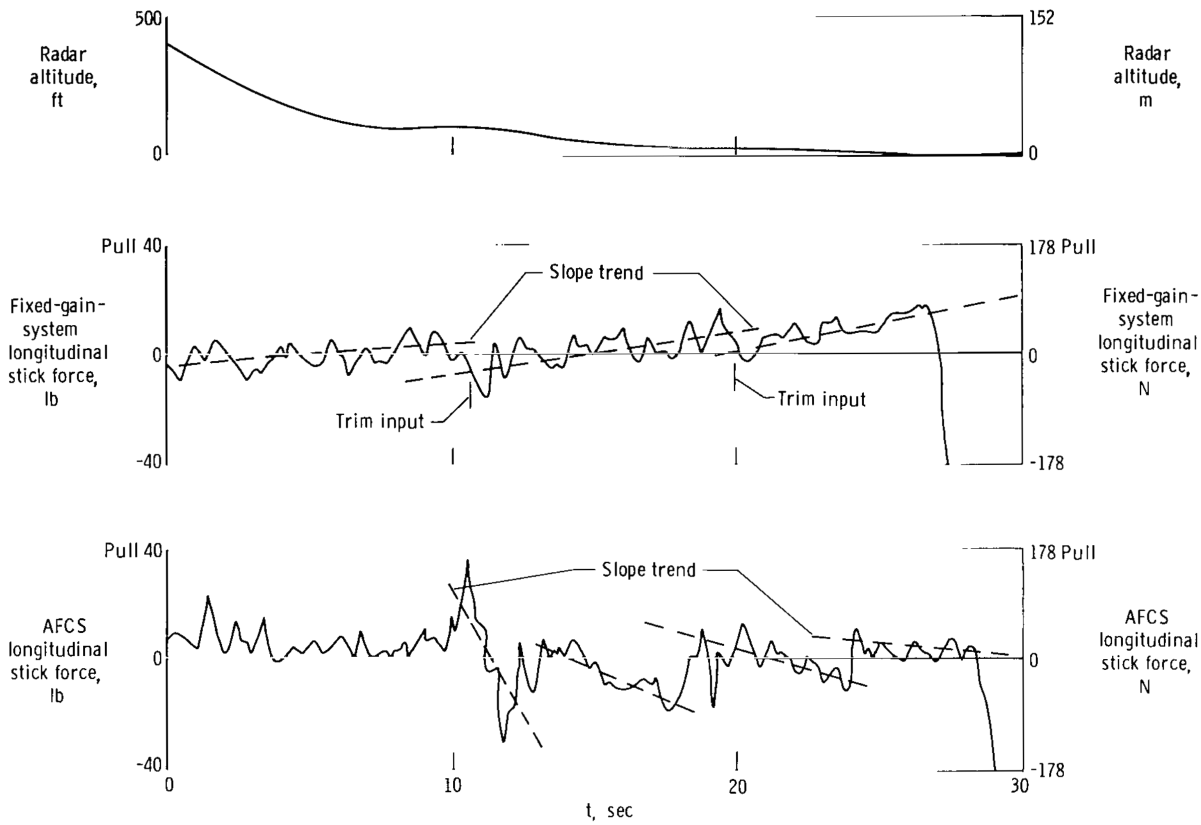



*Figure 13. Comparison of stick force for the AFCS and fixed-gain system during a typical X-15 approach and landing.*

As indicated previously, noncritical gain operation was experienced on all X-15 flights and was usually of no consequence. Occasionally, however, when there was excessive control activity, turbulence, buffet, or unusual airplane motions, the gains were substantially noncritical and noticeably degraded system performance and vehicle handling qualities. An example of gain reduction caused by electrical noise is shown in figure 14. In this particular instance, the performance of the AFCS became so poor that the pilot resorted to the use of the manual reaction control system, rather than continue to use the poorly performing AFCS blended reaction controls.

Early in the AFCS development, it was recognized that large commands from the pilot could not be followed by the control-surface actuators, particularly at high gain. Servo motion was reflected back to the pilot's stick as stick kicks, and system instability was experienced because of the inability of the system to follow the commanded rate. This problem was encountered on two flights in which the airplane became uncontrollable in roll for a short period of time because all available control was being

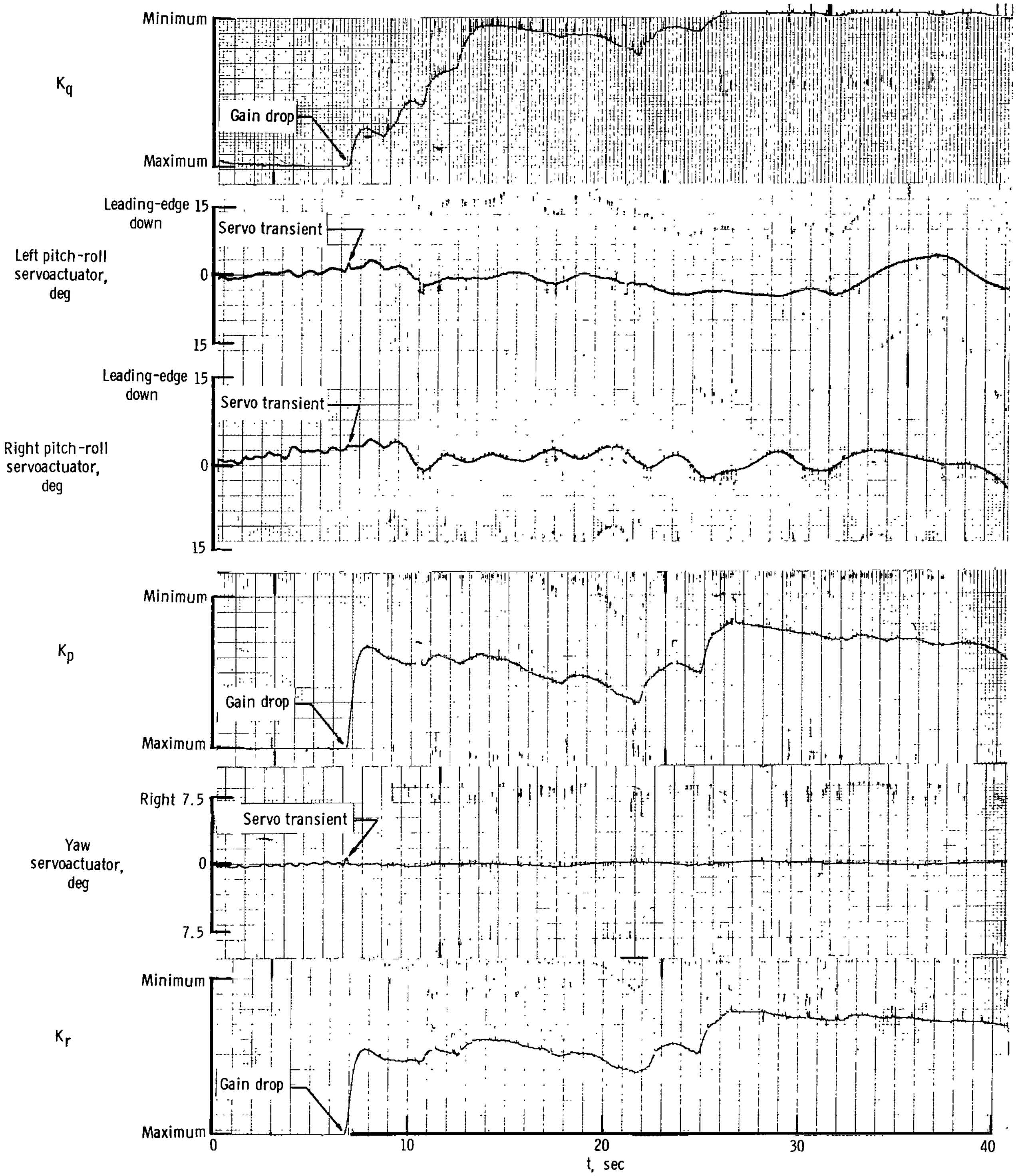



*Figure 14. Time history of control system servoactuator motions and gains showing effect of electrical disturbance.*

used by the pitch axis. A flight record of one experience is presented in figure 15. Roll and pitch rate exceeded the recorder limits during the maneuver, as indicated by the dashed lines. The sawtooth-shaped segments of the time history indicate that the servo rate limit was exceeded. The incident was initiated by the pilot with a rather modest pitch control command and some simultaneous roll command. The resulting rate limiting of the servo in pitch produced a reduction in the pitch-damper effectiveness because of lag and caused the roll axis of the airplane to become unstable. One cause of these incidents was that the pitch gain was at its maximum value, far in excess of the critical gain value for the flight condition, which made electrical saturation possible even for small inputs. Other contributing factors are related to the manner in which the AFCS was "married" to an existing mechanical control system in the airplane. The system was installed in series with the mechanical system and used the existing, limited-authority servoactuator. With this arrangement, system command and authority limits had no real meaning, because the pilot could make larger commands through the basic control system. Such commands immediately saturated the electronic part of the AFCS. When these commands were large or rapid, the effect on the gain changer was serious. In each flight incident, the gain changer was misled by the direct-current or low-frequency signals which were large enough to saturate the electrical limits, thus masking signals within the bandpass frequency range. The gain increased to values exceeding the critical gain, and the servoactuator loop became unstable. The unstable oscillation then increased until the actuator rate limits were reached, at which time the oscillation sustained itself.

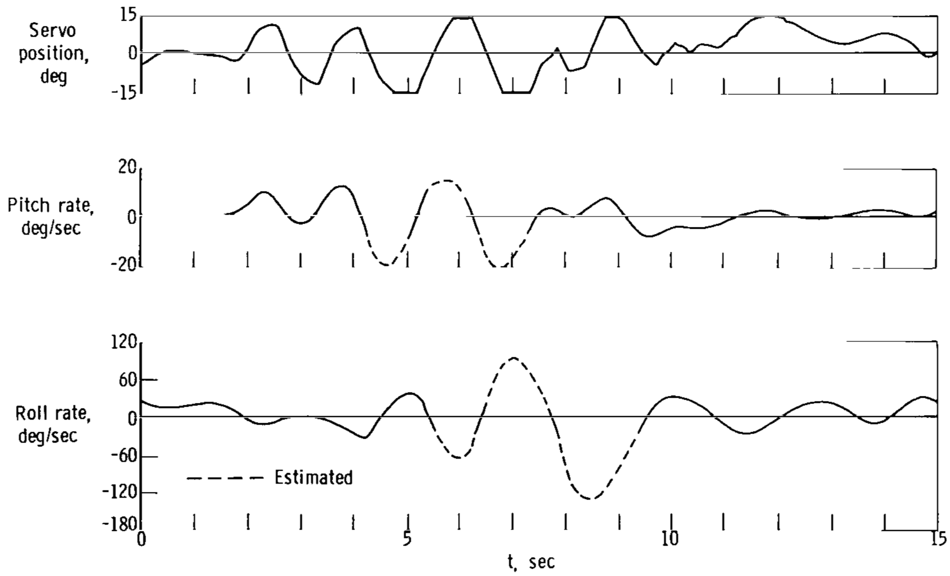



*Figure 15. AFCS saturation instability.*

In addition, the X-15 AFCS was installed in an airplane which used the same aerodynamic surfaces for control in the pitch and roll axes. Demands on the system (either for damping or command control) in one axis compromised and even prevented effective operation in the other axis. Saturation in one axis resulted in complete loss of control in the other axis. This problem occurred immediately following recovery from a high-altitude spin in the last flight of the X-15 airplane with the AFCS. The resulting loss of damping and effective control allowed the post spin aircraft motions in pitch, roll, and yaw to persist until the associated acceleration forces exceeded the aircraft's structural limits. A more detailed account of this incident is included in reference 20.

### Reliability

A significant feature of the AFCS was the redundancy configuration selected to provide reliability and fail-safety (refs. 2 to 8). Extremely high reliability was required because of the low probability of a successful entry from high altitude without augmentation. Fail-safety was equally important because a large transient introduced in a region of high dynamic pressure would result in destruction of the airplane. Completely dual damper channels, from which either or both channels could control the axis, were provided. The adaptive feature of the circuitry permitted one channel to be lost with little or no loss in system performance, because the remaining gain changer would attempt to provide the additional gain required. The gain computers were interlocked when operative to prevent overcritical gain following a gain-changer circuit failure and to provide a limiting effect for hardover failure. If a model or variable-gain amplifier failed, conventional monitor circuits which disengaged both channels were required. This led to the addition of parallel fixed-gain channels with fail-safe passive circuitry. Because these fixed-gain channels operated simultaneously with the adaptive channels to avoid the reliability and transient penalties of switching, they effectively limited the minimum gain for adaptive operation. These gains were sufficiently high for satisfactory emergency performance throughout the envelope but were less than the critical gain in the regions of high dynamic pressure ($q \leqq 1600$ lb/ft$^2$ (76,608 N/m$^2$)).

Reliability models indicate an AFCS mean time between failures (MTBF) of 200 hours. The basic limitation was the servos, which had no duality. This reliability compares favorably with the fixed-gain system MTBF of 100 hours. It is interesting to note that the AFCS electronics had a predicted functional MTBF of 100,000 hours. The actual reliability of the system in flight was excellent. In 65 flights the system experienced only two persistent failures which affected system performance. Only one of these failures was detected by the pilot, who reported it as a directional mistrim. Eight other electronic component failures occurred during the program but were detected only by maintenance technicians and did not affect system performance in flight.

## CONCLUDING REMARKS

The X-15 adaptive flight control system (AFCS) was evaluated essentially throughout the X-15 flight envelope, which included a maximum altitude of 354,200 feet (108 kilometers) and a maximum velocity of 5660 feet per second (6209 kilometers per hour). The dynamic pressure varied from essentially 0 to approximately 1889 pounds per square foot (90,446 newtons per square centimeter). The AFCS improved the handling qualities of the airplane in some respects. The most significant improvement occurred during atmospheric entry in which the greatest variation in flight conditions existed.

The flight-test program confirmed certain advantages of the AFCS: The concept eliminated air-data scheduling; nearly invariant response was provided at essentially all aerodynamic flight conditions; accurate a priori knowledge of aircraft aerodynamic characteristics was not required to design a satisfactory system; compensation for configuration changes was provided; and the dual redundant concept provided a reliable and fail-safe system.

Several disadvantages associated with the system were also disclosed: Additional design analysis was required because of the high-gain values; commands by the pilot and other spurious inputs caused gain reduction and degraded performance at undesirable times; filters were required to prevent sustained resonance of the structural modes; and supercritical gain operation existed in flight which, because of mechanical nonlinearities and electrical saturation, resulted in divergent airplane motions.

Flight Research Center,
National Aeronautics and Space Administration,
Edwards, Calif., November 3, 1970.

## APPENDIX

## PILOT ASSESSMENT OF THE X-15 AFCS

From a handling-qualities standpoint, the X-15 airplane equipped with the AFCS was vastly superior to the X-15 airplane with the fixed-gain system in ballistic flight and during entry. Because the superiority in these two distinct regions resulted from different factors, these areas of flight are discussed separately.

### Exoatmospheric Flight

The X-15 airplane with the AFCS handled well in ballistic flight for three reasons: (1) attitude hold modes, (2) rate command, and (3) an optimum side-located controller.

The attitude hold modes provided artificial static stability at a time when entry was imminent and proper attitude was vital. When out of the atmosphere, the X-15 with the fixed-gain system was neutrally statically stable. The responsibility for maintaining vehicle attitude and angular rates within relatively narrow limits was paramount; every X-15 pilot had explored, on the simulator, the consequences of allowing vehicle attitudes or rates to exceed these limits and had no doubt about his primary responsibility during exoatmospheric flight.

The rate-command feature in conjunction with an optimum side-located controller provided the capability of achieving small attitude changes accurately at low rates of change and of making even major attitude changes at higher angular rates in one axis at a time.

### Entry

The flight control system characteristics which made the X-15 with the AFCS a more desirable entry vehicle than the X-15 with the fixed-gain system were: (1) blended control systems, (2) high-gain aerodynamic damping, and (3) use of the same optimum controller for ballistic and aerodynamic control.

The blended control system reduced the pilot's workload during entry and reduced the likelihood of overcontrolling either the ballistic or the aerodynamic system. The high-gain damping maintained pitch and yaw excursions during entry at a significantly lower level than those experienced in the X-15 with the fixed-gain system.

### Pilot Observations

The true superiority of the X-15 AFCS was that it unburdened the pilot. The airplane was stable at any dynamic pressure and at any angle of attack. The AFCS inspired confidence and allowed the pilot to spend time cross-checking flight instruments, checking subsystems, and "sightseeing."

# APPENDIX

Although the X-15 with the fixed-gain system was within human controllability limits, the need for the pilot to provide his own static stability during ballistic flight drastically reduced his ability to perform other tasks during this time. During entry, the X-15 with the fixed-gain system usually experienced pitch and yaw oscillations which, while convergent, diverted the pilot's total attention to aircraft control.

During boost and after entry, the X-15 airplanes handled about equally well; no specific examples of the superiority of the AFCS were apparent, other than during ballistic flight and entry.

## REFERENCES


1. Gregory, P. C., ed.: Proceedings of the Self Adaptive Flight Control Systems Symposium. WADC Tech. Rep. 59-49 (ASTIA Doc. No. AD 209389), Wright Air Dev. Center, U.S. Air Force, Mar. 1959.

2. Boskovich, Boris; Cole, George H.; and Mellen, David L.: Advanced Flight Vehicle Self-Adaptive Flight Control System, Part I - Study. WADD Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, Sept. 30, 1960.

3. Mellen, David L.; Cole, George H.; and Lindahl, John H.: Advanced Flight Vehicle Adaptive Flight Control System. Part II - Design of MH-96 System. Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, Feb. 28, 1961.

4. Exby, C. B.; Gray, J. R.; and Harrison, J. W.: Advanced Flight Vehicle Adaptive Flight Control System. Part III - Support Equipment Study. Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, Feb. 24, 1961.

5. Reed, M. W.; Wolfe, J. A.; and Mellen, D. L.: Advanced Flight Vehicle Self-Adaptive Flight Control System. Part IV - Notch Filter Development. Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, June 1962.

6. Lindahl, J. H.; McGuire, W. M.; and Reed, M. W.: Advanced Flight Vehicle Self-Adaptive Flight Control System. Part V - Acceptance Flight Tests. WADD Tech. Doc. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, May 1963.

7. Lindahl, J.; McGuire, W.; and Reed, M.: Advanced Flight Vehicle Self-Adaptive Flight Control System. Part VI - Final Flight Test Report. Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, Oct. 1963.

8. Lindahl, J.; McGuire, W.; and Reed, M.: Advanced Flight Vehicle Adaptive Flight Control System. Part VII - Final Report on Study, Development, and Test of the MH-96 System for the X-15. WADD Tech. Rep. 60-651, Wright Air Dev. Div., U.S. Air Force, Dec. 1963.

9. Yancey, Roxanah B.: Flight Measurements of Stability and Control Derivatives of the X-15 Research Airplane to a Mach Number of 6.02 and an Angle of Attack of 25°. NASA TN D-2532, 1964.

10. Taylor, Lawrence W., Jr.: Analysis of a Pilot-Airplane Lateral Instability Experienced With the X-15 Airplane. NASA TN D-1059, 1961.

11. Petersen, Forrest S.; Rediess, Herman A.; and Weil, Joseph: Lateral-Directional Control Characteristics of the X-15 Airplane. NASA TM X-726, 1962.

12. Tremant, Robert A.: Operational Experiences and Characteristics of the X-15 Flight Control System. NASA TN D-1402, 1962.

13. Jarvis, Calvin R.; and Lock, Wilton P.: Operational Experience With the X-15 Reaction Control and Reaction Augmentation Systems. NASA TN D-2864, 1965.

14. Taylor, Lawrence W., Jr.; and Merrick, George B.: X-15 Airplane Stability Augmentation System. NASA TN D-1157, 1962.

15. Taylor, Lawrence W., Jr.; and Smith, John W.: An Analysis of the Limit-Cycle and Structural-Resonance Characteristics of the X-15 Stability Augmentation System. NASA TN D-4287, 1967.

16. White, Robert M.; Robinson, Glenn H.; and Matranga, Gene J.: Résumé of Handling Qualities of the X-15 Airplane. NASA TM X-715, 1962.

17. Cooper, George E.; and Harper, Robert P., Jr.: The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.

18. Holleman, Euclid C.: Control Experiences of the X-15 Pertinent to Lifting Entry. NASA TN D-3262, 1966.

19. Holleman, Euclid C.: Summary of High-Altitude and Entry Flight Control Experience With the X-15 Airplane. NASA TN D-3386, 1966.

20. Thompson, Milton O.; and Welsh, James R.: Flight Test Experience With Adaptive Control Systems. Advanced Control System Concepts, AGARD Conf. Proc. No. 58, Jan. 1970, pp. 141-147.

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