FLIGHT TEST EXPERIENCE WITH ADAPTIVE CONTROL SYSTEMS

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1. INTRODUCTION

The NASA Flight Research Center has followed closely the development of adaptive control systems for the past ten years. Valuable experience has been obtained from flight evaluation of the adaptive system in the X-15 aircraft. The adaptive control systems evaluated in flight have been either experimental or prototype systems, and each was functionally used to accomplish, in most cases, unrelated research investigations. No serious attempt was made to optimize system performance or to define the systems' total capability. The flight evaluation of these systems has, therefore, been primarily concerned with reliability, performance, and compatibility with the flight environment.

First, this paper will briefly summarize our flight experience and some general pilot reactions to the adaptive features and other aspects of the specific adaptive systems tested. A second objective of the paper is to describe spme unexpected occurrences that identify areas of required improvements if the adaptive feature is to be used in future systems.

2. RELIABILITY AND PERFORMANCE

The reliability of the adaptive systems tested in flight has been excellent, regardless of the fact that they were not production systems. The X-15 adaptive system, for example, experienced only two persistent failures during 65 flights, and each of those failures involved only one axis. Several other momentary failures were experienced in one or more axes: however, in each 'instance, the adaptive mode could be re-engaged following the transient disturbance. It appears obvious that black-box technology is capable of providing a high degree of reliability through redundancy and improved electronic hardware. It must be admitted, however, that the quality of maintenance and caliber of technical support were excellent.

The performance of these systems has also been good. Figure 1 shows actual system gains versus predicted gains for a typical X-15 flight. Non-critical gain operation is evident, but the effects of these deviations on handling qualities are not perceptible to the pilot. Excessive pilot control activity, airplane motions. or turbulence can substantially reduce the adaptive gains and thus noticeably degrade system response and vehicle handling qualities; however, the minimum gain levels in the systems tested still provide acceptable handling qualities.

3. PECULIAR HANDLING CHARACTERISTICS AND PILOT IMPRESSIONS

The adaptive flight control systems which have been evaluated were designed to provide invariant aircraft response characteristics throughout the aircraft's atmospheric flight envelope. High levels of aircraft damping were maintained by varying system gains as required, and the pilot was provided with invariant control response through rate command or rate and normal acceleration command control loops. These systems also provided the pilot with a variety of autopilot or hold modes, such as angle of attack, pitch attitude, and roll hold. In theory, the pilots should have been completely satisfied. In real life, however, this was not necessarily true. Figure 2 lists some of the features and unusual characteristics peculiar to these systems, along with pilot opinions. As can be seen, the pilots were not completely happy. Before discussing these items, however, it should be emphasized that many of those listed are not unique to an adaptive system. In fact, most of the unusual handling characteristics which stimulated pilot comments are a result of the rate-command control feature and not the adaptive system *per se.* Since most of the existing adaptive flight control systems utilize rate command to some extent, the general discussion and pilot comments would appear to be appropriate.'

The pilots did appreciate the idealized artificial-feel characteristics available in these systems as well as the variety of autopilot and hold modes which can be readily included. The invariant aircraft response characteristics, optimum in theory, are not readily apparent to the pilot. Figure 3 shows pilot Cooper Scale ratings for a number of different flight phases for both the adaptive system and a conventional fixed-gain system installed in the other X-15 airplanes. These flight phases cover a wide range of altitude, Mach number, and dynamic pressure. The response characteristics of the X-15 equipped with a fixed-gain system are thus varying, and yet the pilot ratings do not vary appreciably, nor are they substantially different from those for the adaptive system except in the relatively low dynamic pressure flight phases. This can be explained to some extent by the fact that both systems provide effective deadbeat damping (damping ratios in excess of 0.3) at reasonable dynamic pressures. Whether the damping ratio is variable but no lower than 0.3 as in the fixed-gain system, or held constant at 0.5 as in the adaptive system, is immaterial to the pilot, since he still considers both to he deadbeat.

In the lower dynamic pressure flight phases, the adaptive control system was obviously better. For example, during an X-15 atmospheric re-entry, the adaptive system is effective much earlier in the re-entry, because of its higher gain, and has damped out most of the re-entry misalinement transients before the 'g' onset and rapid increase in dynamic pressure really begin. The fixed-gain system, on the other hand, has usually not eliminated these induced oscillations in the earlier phases of re-entry. Aircraft oscillations that persist until the rapid 'g' onset begins are very disturbing to the pilot, since he cannot readily damp them manually because of the rapidly changing frequency of the oscillation as dynamic pressure increases. If he does attempt to manually damp an oscillation during this phase of the re-entry, he can instead easily aggravate the motions by a poorly timed or improper control input. The X-15 adaptive system also provided the pilot with hold modes and blended aerodynamic and reaction control which reduced the pilot's workload during exo-atmospheric flight and re-entry. For these reasons, the X-15 with the adaptive control system was considered to be superior to the X-15 airplanes with Conventional fixed-gain systems for flights out of the atmosphere.

The invariant response characteristics of the adaptive system are not obvious to the pilot, since pilots do not normally think of desired response in terms of stick deflection. Before a pilot makes a control input, he has already decided what airplane response he wants. If the initial control input does not provide the desired response, he modifies the input to obtain that response. It is doubtful that any pilot is ever aware of the amount of control-stick deflection used during a major portion of any flight. The only time a pilot is really aware of stick motion is when large abrupt control inputs are required or intentionally made or when the airplane response is too sensitive or too sluggish. Adaptive or rate-command flight control systems can virtually eliminate the problem of oversensitivity but cannot guarantee a minimum level of invariant response, because of the practical limits of control authority. In our experience the aircraft equipped with adaptive control systems did not have excessive control-sensitivity problems, and therefore this potential advantage was not apparent to the pilot.

Since invariant aircraft response did not particularly impress the pilots, the question might be asked: What characteristics did stimulate pilot comments? Referring again to Figure 2, two of these characteristics were immediately apparent to each pilot: the compensation for aerodynamic trim changes, and the lack of speed stability. Both of these characteristics are a result of the rate-command feature rather than the adaptive feature. Trim changes normally associated with extension or retraction of landing gear, landing flaps, speed brakes, or other variable-configuration devices are automatically compensated for by a rate-command system and are thus masked to the pilot. Variations in longitudinal center-of-gravity position are also not apparent to the pilot, since trim is automatically adjusted and response characteristics do not vary. Transonic trim changes are also masked. Lateral or directional asymmetries are masked to the pilot and the yawing and rolling moments due to loss of thrust on one or more engines on one side of a multiengine aircraft are automatically compensated for within the limits of the system control authority. Although the pilots generally appreciate this automatic trim-compensation characteristic, they do feel somewhat uncomfortable about the loss of hitherto familiar cues. The trim change usually accompanying extension or retraction of landing gear or landing flaps served as a positive indication of response to the movement of the particular control lever.

An aircraft equipped with a rate-command control system does not respond in a conventional manner to changes in airspeed or dynamic pressure. The aircraft attitude will not change unless the pilot commands it to change. As a result, the nose of the aircraft will not fall through in a conventional manner as airspeed decreases nor will it pitch up as airspeed increases. Thus, the aircraft has no apparent speed stability. This characteristic, by itself, would not be too disturbing to the pilot if the other cues normally associated with changes in airspeed were available. These other cues, however, are also missing. There is no change in stick force, stick position, or aircraft response to control inputs. The aircraft thus feels completely solid to the pilot right up to the point at which loss of control occurs. In maneuvering flight, the pilot must either monitor airspeed or angle of attack or depend on other cues such as buffet to warn him of loss of airspeed. The lack of speed stability is particularly noticeable during the landing maneuver. The pilot has the impression that the aircraft does not want to land.

Figure 4 shows a typical X-15 altitude plot during landing. Stick force is also presented for the conventional fixed-gain system and for the adaptive system. Airspeed is constantly decreasing during and after flare at a rate of approximately 4 knots per second. In the X-15 airplanes equipped with conventional fixed-gain control systems, the pilot is continually working on a positive stick-force slope and is usually pulling back on the stick and occasionally retrimming as speed decreases during the level deceleration after flare. This appears to be quite normal to the pilot. In the X-15 equipped with the adaptive control system, however, there is no obvious requirement for the pilot to continually pull back on the stick as airspeed decreases, since once the flare is completed and the aircraft is in a near-level attitude, the control system will, on its own, maintain that attitude. In addition, at the instant of flare completion, the pilot has to actually push abruptly, as shown in the time history, to Prevent the aircraft from ballooning, because, at the instant of flare completion, the aircraft has a higher angle of attack and thus higher pitch attitude than required to maintain 1g flight. If the pilot simply releases the control stick, the system will maintain that attitude and the aircraft will begin to climb. After flare, the pilot is actually working on a negative stick-force slope, as shown in the lower plot, which feels very unnatural. The pilots of the X-15, with the rate-command system, have resorted to trimming-in a nose-down pitch rate before the flare to preload the stick and thus achieve some semblance of speed stability.

The lack of speed stability in an aircraft can at times be advantageous. For example, at the higher Mach number and altitude cruise conditions of current operational aircraft, significant atmospheric changes cap be encountered in a relatively short time. If the effects on aircraft performance are disregarded, it is undesirable for the aircraft to respond to these variations, since these atmospheric changes could initiate and sustain a continuous phugoid oscillation. An aircraft equipped with a rate-command system, however, will not respond to the atmospheric changes.

Some other subtle results of the use of a rate-command system are the reduction of the influence of ground effect and the elimination of normal dihedral effect, since aircraft attitude will not change in response to external forces. This again can surprise an unsuspecting pilot.

In summary, although these systems have certain peculiar characteristics, the pilots have been able to adjust to them. The pilots, however, still have mixed feelings concerning these systems. When first exposed, the pilots tend to distrust the systems and occasionally have the feeling that the system, rather than the pilot, is controlling the aircraft. With experience, they begin to appreciate some of the obvious benefits, such as the improved aircraft damping and the automatic hold modes that are available. Other pilots have been "bitten" by the system and have again learned to distrust it. Regardless of their experience level, each of the pilots is somewhat apprehensive about the amount of control authority allocated to the system, since a malfunction could be disastrous. The pilot also knows that, regardless of the manner in which gain scheduling is accomplished, non-critical gain Operation is a possibility. Experience shows that non-critical gain operation is the rule rather than the exception; however, only extremes of non-critical gain operation are of any significance.

4. ADAPTIVE SYSTEM POTENTIAL

In analyzing the results of the Flight Research Center flight experience with adaptive flight control systems, it became obvious that these systems offered no substantial improvement in handling qualities, even for a vehicle with the performance capability of the X-15, In an attempt to determine what possible benefits could be achieved by using an adaptive control system, a brief investigation was made on the X-15 simulator. Basic X-15 aerodynamic derivatives were varied to determine what compensation the adaptive system could provide. It was readily apparent that the adaptive system was extremely tolerant to variations in the levels of basic aircraft damping, control effectiveness, and stability. Figure 5 shows the effect on pilot rating of varying the magnitudes of two basic derivatives, $C_{m\alpha}$, the longitudinal stability derivative, and $C_{l\beta}$, the effective dihedral derivative, 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 lower line in each instance represents the unaugmented aircraft which, for negative values of static margin and dihedral effect, is impossible to handle. The adaptive system, it is seen, will absorb substantial deviations of these parameters from the design levels and still provide acceptable handling qualities. The implication is, of course, that a system of this kind can be designed for a statically neutral or even unstable aircraft and could, therefore, offer a more versatile approach in the design of the aircraft.

5. OPERATIONAL PROBLEMS

Before discussing operational problems, let us briefly review the gain-changer operation and mechanization of one adaptive system. The basic design philosophy for this system is the desire to vary the system gain in a manner that allows the system to ogerate with a minimum (nearly zero) gain margin for the servo-actuator loop, thus providing the highest possible system gain at all times. This system gain should be inversely proportional to the aircraft control effectiveness, so that the gain increases as control effectiveness decreases - thus, invariant response. To implement this philosophy, the system (shown in Figure 6) was designed so that the gain changer would be controlled by the amplitude of the oscillation at the natural frequency of the servo-actuator loop. The bandpass filter should assure the exclusion of oscillations at all other frequencies that are higher or lower than the natural frequency of the servo-actuator loop, The bandpassed signal is rectified to give a direct-current voltage proportional to the oscillation amplitude. This rectified signal is then compared with a fixed-reference signal to generate a gain error signal which, in turn, controls the gain-changer motors to reduce the gain error to zero. In theory, this mechanization responds only to oscillations at the desired servo-actuator natural frequency. The real world, however, is not as clear cut. Almost all random oscillations contain frequency components that are within the range of the bandpass filter. Therefore, such factors as turbulence, structural modes, electrical noise, and pilot control movements all have some effect on the gain changer. The effect, in most instances, is to fool the gain changer into believing the gain is too high, thus causing it to reduce the gain below the critical value.

The gain changer can also be fooled by direct-current or low frequency signals that are large enough to saturate the electrical limits and mask signals lying within the bandpass frequency range. In these cases, the gain will increase to values exceeding the critical gain and the servo-actuator loop will go unstable. The unstable oscillation Will then increase until the actuator rate limits are reached, at which time a limit-cycle oscillation will develop and sustain itself. A situation of this type has occurred in flight.

The manner in which these (or most other) command augmentation systems are "married" to an airplane has a significant bearing on how well the system will behave and what the eventual handling characteristics are likely to be. In most aircraft, the command augmentation adaptive systems, with their limited authority servo-actuators, have been installed in series with a basic mechanical or hydromechanical control system. With this arrangement, system command and authority limits have no real meaning. since larger commands can be made by the pilot through the basic control system. Such commands Will immediately saturate the electronic command augmentation system, and when these commands are large and inadvertent or unwarranted, the consequences can be serious in the potential effect on the gain changer, as indicated earlier. An obvious, but not always practical, solution would be the use of only the electrical command control, that is, "fly-by-wire".

Also, several of the adaptive command augmentation systems, which have been in service, were "married" to airplanes which utilized the same aerodynamic surfaces for control in both the pitch and roll axes. In this situation demands on the system (either for damping or command control) in one axis will compromise and even prevent effective operation in the other axis. If saturation were to occur in one axis, complete loss of control would result in the other.

All of these potential problem areas, while not uniquely associated with high-gain adaptive systems, are magnified when high-gain adaptive concepts are used to solve the stability and control problems of the airplanes in which they are installed. When all of these problems occur at the same time, the consequences can be disastrous.

Data from the last flight of X-15 airplane number 3, with the adaptive control system, show examples of non-critical gain operation and how such a system can be compromised or fooled. Figure 7 is a time history of this flight. The flight was scheduled as an altitude flight to 250,000 ft. Shown in the time history are aircraft altitude, pitch and roll attitude, right horizontal stabilizer servo-actuator position, and adaptive pitch gain level. Adaptive pitch gain is the only gain shown; however, it is generally representative of the gains in the other two axes.

The system performed normally after launch for approximately 60 seconds. At that time, an electrical disturbance occurred in the aircraft that subsequently affected the operation of all systems. This electrical .disturbance probably emanated from an experiment carried in a wing pod. Although the adaptive flight control system was supposedly isolated, the elctrical disturbance did influence system operation. The major effect of this electrical disturbance on the flight control system was its influence on the gain changer. Throughout the flight, while the electrical disturbance persisted, the system gains were frequently driven below the critical gain level and were also retarded in their return to higher values. The electrical noise was severe enough at one point to cause a disengagement of the pitch and roll servo-actuators; however, the pilot re-engaged them within about 5 seconds.

The electrical noise and its effect on system gains would, during atmospheric flight, have been of little consequence, since, as mentioned previously, acceptable handling qualities exist even at minimum gain. It was of significance on this high-altitude flight, however, since it affected the operation of the normal reaction control system.,

The normal reaction control system is blended with the aerodynamic controls using one cockpit controller to simplify the piloting task .on high-altitude flights. The normal reaction controls are activated and deactivated automatically as a function of average system gain to conserve reaction control fuel. The switching levels for arming and dearming the normal reaction controls were established on the basis of flight experience at the 90 per cent and *60* per cent level, respectively, as shown on the time history.

The pilot could have overridden the automatic arming-dearming feature or could have resorted to use of the dual manual control system. The fact that he took neither of these actions could be attributed to a lack of recognition of the problem (no indication is given to the pilot), a number of other distractions, and the subtleness of the problem. For instance, when the normal reaction controls were first dearmed automatically the aerodynamic controls were still momentarily very effective and the loss of reaction controls would not be perceptible. Subsequently. each time the pilot was scheduled to perform a specific maneuver or control task, the normal reaction controls had just rearmed and the aircraft responded, In any event, the normal reaction controls were dearmed throughout the entire ballistic portion of the flight except for the brief periods shown on the time history.

Shortly after passing peak altitude, the pilot apparently realized that a control problem existed, since he began using the left-hand controller, which operated the dual manual reaction controls. During the time the pilot was controlling the aircraft with the manual reaction controls, he apparently misinterpreted the display and inadvertently began to change the aircraft heading. The normal reaction control system would have resisted this heading change if it had been operative. The pilot continued to inadvertently yaw the aircraft until it was misalined 90° to the flight path when descending through 240,000 ft altitude, At this time, the aircraft entered a spin. During the spin the pilot, for the most part, held both aerodynamic and reaction control against the spin. The normal reaction controls also were automatically rearmed during the spin and begain firing almost continuously to oppose the spin rates. The yaw-damper portion of the control system ceased to operate approximately 10 seconds after the aircraft began to spin as a result of a command from a failure-detection circuit in the system. This circuit was designed to detect a failed gyro but was fooled in this case and automatically switched out the yaw-rate gyro input to the system as it was designed to do when the yaw rate exceeded 20 deg/sec. No indication of this action was provided to the pilot,

Some combination of control and the basic aerodynamic stability of the aircraft broke the spin at about 120,000 ft. During the spin, all the system gains had reached a maximum, since the normal gain-reducing stimuli were masked by the large commands from the pilot and by large angular rates. As the aircraft came out of the spin, a pitch-axis servo-loop instability developed due either to commands from the system, or from the pilot, that prevented the gain changer from reducing pitch gain *as* it would normally have done as dynamic pressure increased. The horizontal-stabilizer surfaces were moving symmetrically at their rate limit of 26 deg/sec through a total amplitude of 20° in a sawtooth manner. This control-surface motion initiated and sustained an aircraft pitching oscillation. Once the Servo-loop instability started, the pilot no longer had effective control or stability augmentation in either the pitch or roll axis, since the horizontal-stabilizer surfaces are used for both pitch and roll control. The resulting undamped aircraft motions eventually produced acceleration forces that exceeded the structural limits of the aircraft.

From the simulation studies after the flight, it appeared that a gain reduction either by the system or the of the lack of *any* indication **of** a system problem, the severe aircraft motions, or the 'g' forces, the pilot took no action to manually reduce the system gain, and the aircraft broke into many pieces while descending through an altitude of approximately *60,000* ft.

6. CONCLUDINQ REMARKS

In initial flight evaluations of adaptive flight control systems, the relative merits of adaptive versus fixed-gain systems were not of particular concern since it was assumed that there would be an eventual need for such a system. It was, however, assumed that the adaptive concept was being seriously considered only for advanced flight vehicles, such as a higher-performance research vehicle or a lifting entry vehicle.

Recent developments indicate that this assumption was erroneous. Operational aircraft are currently flying with adaptive flight control systems. The question is; do these operational aircraft need an adaptive System, and on what basis is it justified? . X-15 experience has shown that a conventional control system and fixed-gain dampers provided satisfactory handling qualities to Mach numbers great than 6. There may be certain operational mission tasks that dictate a requirement for more precise control and improved damping than was available in the X-15 airplanes with conventional fixed-gain control systems; however, whether or not an adaptive system is required is st'ill questionable. Recent technological advances and improved hardware offer substantial improvements in fixed-gain system performance over wide ranges of flight conditions. Rate command or rate and acceleration command, auto-pilot, and hold modes can be included in a fixed-gain system if desired, If one gain level will not suffice, gain can be simply scheduled or adjusted at several fixed levels to achieve the desired system performance over the required flight envelope.

Our flight experience indicates that, although the adaptive concept is feasible, the gain-changing logic can be fooled and a number of environmental factors such as turbulence, structural modes, pilot control activity, and electrical interference can compromise the performance of the system and can restrict the usable range of variable gain. The loss of the X-15 aircraft with the adaptive flight control system cannot be attributed solely to the adaptive concept, since there were a number of other factors involved. Elimination of the mechanical backup system and the use of an electric stick could have prevented saturation of the servo-actuators. Higher servo-actuator rates or separate control surfaces for pitch and roll would also have precluded this particular problem. Yet the adaptive feature cannot be absolved, since it was theoretically supposed to operate regardless of these practical or real-life compromises. The system functioned as designed, but the design did not consider this particular and unique combination of conditions and pilot response,,

Before an adaptive flight control system is selected, the aircraft designer should assure himself that it offers distinct advantages over a well-designed simpler flight control system to warrant the additional complexity and the possible occurrence of some of the problems discussed.

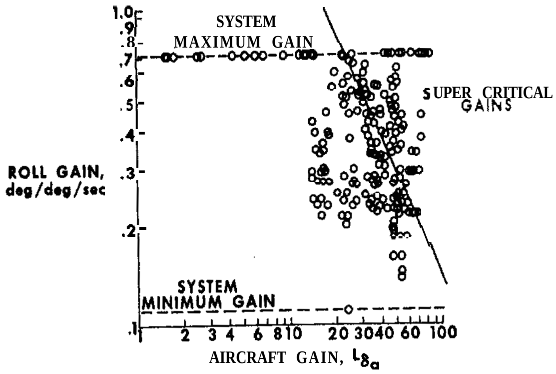

Fig.1 MH-96 system gain-changer operation

SYSTEM CHARACTERISTIC OR FEATURE	LIKE	DISLIKE	MIXED FEELINGS
ARTIFICIAL-FEEL SYSTEM	X		
AUTOPILOT AND HOLD MODES	X		
INVARIANT AIRPLANE RESPONSE			
CONTROL			X
DAMPING	X		
ELIMINATION OF AERODYNAMIC TRIM CHANGES	X		
LACK OF SPEED STABILITY		X	

Fig.2 Pilot impressions

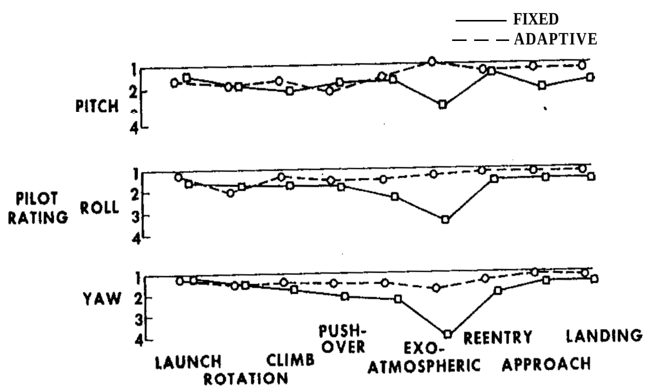

Fig.3 Comparison of adaptive and fixed-gain systems

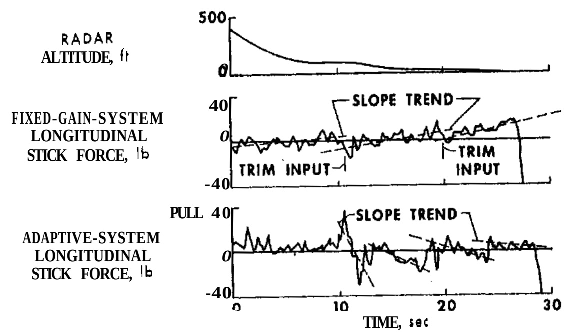

Fig.4 Comparison of stick force during approach and landing

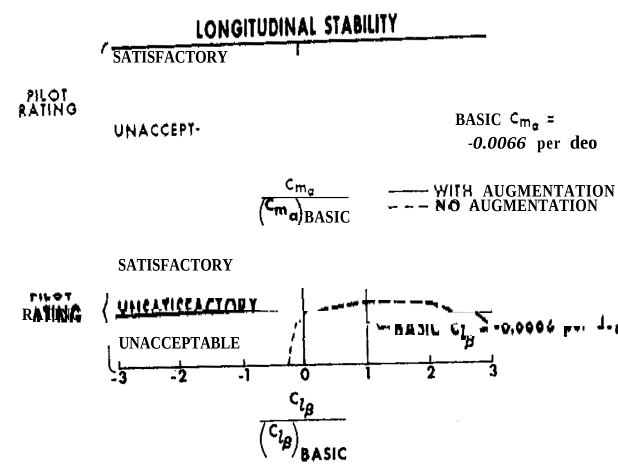

Fig. 5 Augmentation effectiveness, X-15 simulator, M = 6

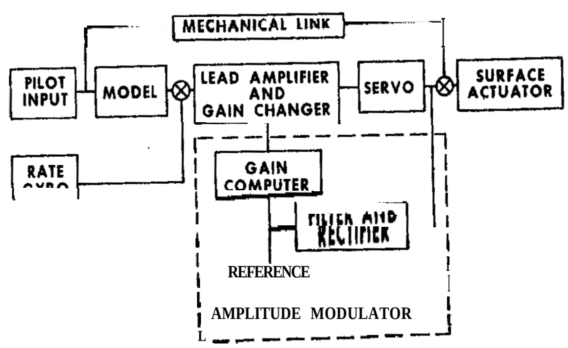

Fig.6 MH-96 adaptive concept

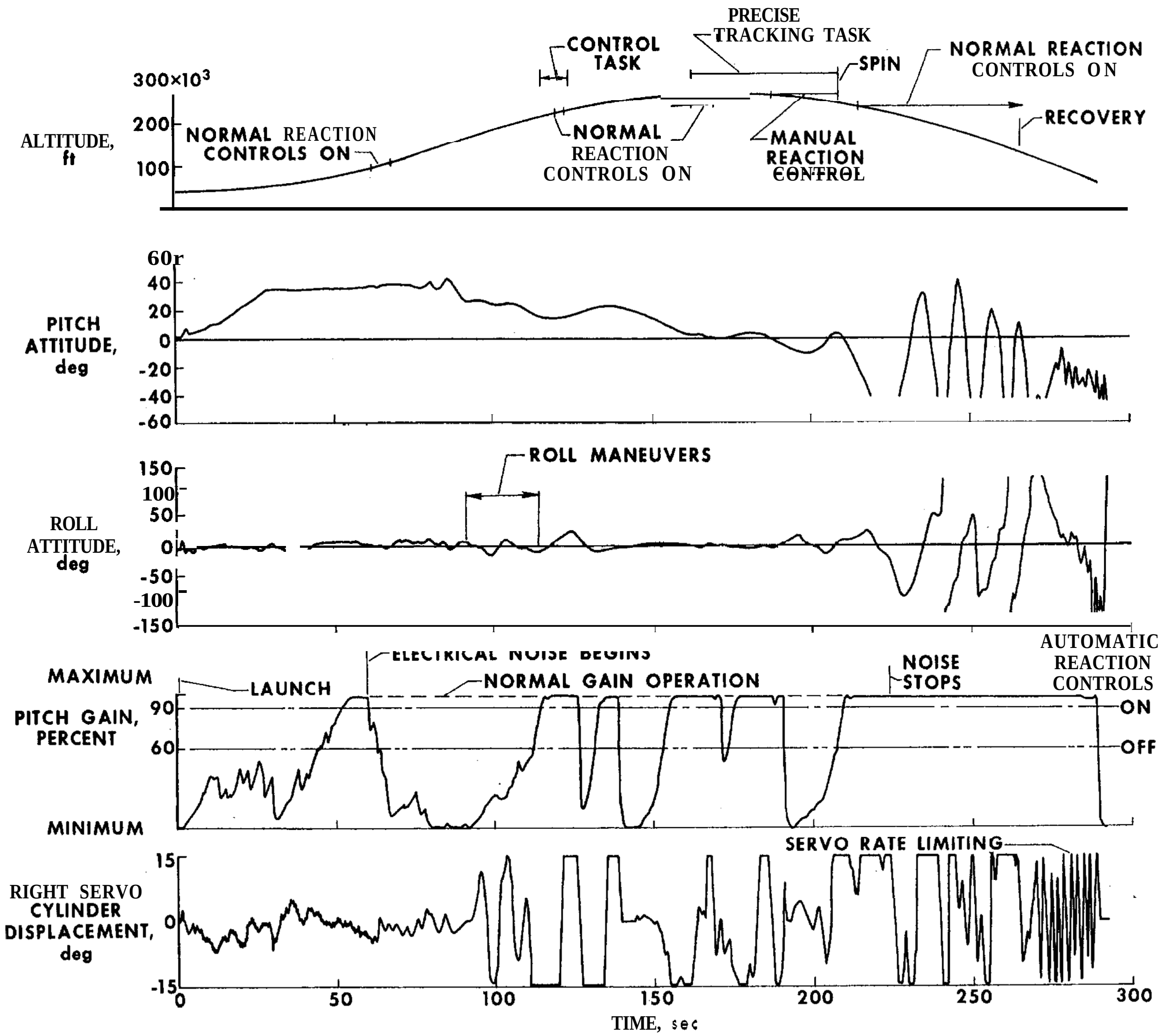

Fig.7 X-15-3 altitude flight