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SELF-ADAPTIVE FLIGHT-CONTROL STUDIES

APPLICABLE TO DYNA-SOAR

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INTRODUCTION

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This paper presents a summary of the requirements for, and the advantages to be obtained from, a self-adaptive flight-control system. A review of a research program to design and build a self-adaptive system for the X-15 is made. This program, while not directly connected with the Dyna-Soar program, will furnish information that will be of value in resolving Dyna-Soar flight-control design problems.

DISCUSSION

During the past several years there has been a growing realization that development programs were not producing optimum flight-control systems. This condition exists because of the greater extremes of environment through which aircraft are operating. These extremes cause changes in the aircraft-response characteristics, as shown in the previous paper by A. H. Lee and L. J. Mason, which must be compensated for by changes in the autopilot parameters if satisfactory response is to be maintained at all flight conditions.

Several methods are available to change these autopilot parameters. At present, in most operational supersonic aircraft, the required changes are made in a predetermined fashion based upon air-data measurements as shown in figure 1. Several inadequate features of these adjustments should be emphasized. First, accurate and detailed information about the aircraft stability derivatives is required for the entire flight regime. Second, the capability must exist for measuring air data for <u>all</u> flight conditions. Third, the calculation of the required adjustments is a long process and must be confirmed by flight-test data. Fourth, subsequent changes in airplane configuration, such as a change in vertical-tail area to improve performance, will require additional autopilot testing and adjustment. After flight test the autopilot will

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work satisfactorily at the conditions at which it was tested provided degradation of components, such as the hydraulic servo valve, is held to a minimum.

When the flight profile is sufficiently well known, for instance, that of an ICBM, the changes in autopilot parameters can be made as a function of time and, thus, eliminate the need for accurate measurement of air data; however, because of unknown factors regarding the exact stability derivatives, the autopilot must be designed with some margin for stability. Thus, the system will not operate to its full capability at all flight conditions. In each of the systems described, there is no guarantee of true relationship between the changes in autopilot parameters and vehicle stability other than flight test.

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Obvious problems concerning the design of flight-control systems for advanced vehicles arise. A vehicle such as the Dyna-Soar must perform satisfactorily on the first flight. The vehicle must operate through regions where air data are not available, and the flight profile cannot be predetermined for time-based parameter changes. Also, there is the problem of maintaining dynamic performance through unexpected changes in structure from hard-to-predict sources, such as aerodynamic heating.

In order to solve these problems, the Air Research and Development Command (ARDC) initiated a program in 1956 to determine methods of adjusting autopilots in a closed-loop fashion, which required no air-data measurements, by direct measurement of system performance. These systems have been called self-adaptive controllers. A self-adaptive system is defined 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, either external or internal to the vehicle under control (ref. 1).

Several self-adaptive techniques were studied under WADD contracts and some of these have been flight-tested in century-series aircraft to demonstrate their practicality. A flight test of one system developed by the Minneapolis-Honeywell Regulator Company has shown that the effect of aerodynamic-parameter changes on the performance of a flight-control system can be minimized by raising the loop gain to increase the system bandwidth. Figure 2 shows a technique for keeping the system gain at the highest possible value without incurring system instabilities. Note that this technique uses no air-data scheduling. Figure 3 illustrates how the gain controller operates. A nonlinear high-gain characteristic $K_{\dot{\theta}}$ is furnished by a variable-gain amplifier with clipped outputs. The filter and lead network insure that the first element to become neutrally stable as the loop gain is increased will be the hydraulic servo. When the gain has been raised to its critical value, the servo will exhibit a

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characteristic motion or limit cycle. This motion is picked up by the band pass filter, demodulated, and compared with a fixed reference. Any difference in these signals will cause the gain to be lowered or raised through the integrator gain control. In the absence of any input from the servo, the reference bias will slowly drive the loop gain up until limit cycling occurs. In this manner, the system can be operated at the highest gain possible for all flight conditions.

Because of the high loop gain the response of the flight-control system is much more rapid than that which A. H. Lee and L. J. Mason showed in the previous paper would be desired by the pilot; therefore, an electronic model or prefilter is inserted as shown in figure 2. This model is a simple second-order system which is set at the natural frequency and damping ratio desired by the pilot. Note that this system does not require the usual gain margin associated with conventional systems because the closed-loop gain-changing feature permits operation just below the critical level throughout the flight regime. Operation at a higher gain produces a significant improvement in dynamic performance and makes the control system far less sensitive to changes in vehicle characteristics.

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Since June 1959, the Minneapolis-Honeywell Regulator Company has been studying, under the sponsorship of WADD, some of the automatic flight-control problems associated with boost-glide weapon systems. The first phase of this effort was to determine and to define the type of pilot-assist modes which would be of value and how they would be used in a mission profile. The next phase is to design a self-adaptive autopilot employing the technique previously described to furnish those modes which could be flight-tested in an X-15. The last phase would be to build and flight test such a system in an X-15.

In previous research aircraft, such as the X-15, the flight-control philosophy has been to design a simple, reliable damper system to assist the pilot. In future military vehicles which will follow the Dyna-Soar, a system of this type falls far short of what is required. The pilot will have to perform duties other than flight control, such as energy management, navigation, and a military mission. In order to secure sufficient time for these other duties, an automatic flight-control system will be required. It is such a system which is now being designed and built for flight testing in the severest flight-control environment available, the X-15. Figures 4 to 6 are tentative block diagrams of the X-15 self-adaptive system now being designed.

The X-15 flight-control system is composed of three subsystems. The minimum-flight system (MFS) furnishes stability augmentation, includes the self-adaptive feature, integrates reaction and aerodynamic control in one stick, and permits the pilot to put mechanical inputs

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into the flight-control system. The piloted-flight system (PFS) contains the pilot-assist modes, control-stick steering (CSS), angle of attack, altitude, and altitude holds. The basic stability loop utilizes a pitch-rate feedback, and normal acceleration is blended with this in the CSS mode. The proposed automatic-flight system (AFS) is being studied and designed under separate procurement and would include onboard computing equipment to provide such functions as energy management and automatic approach and landing.

Figure 7 shows the control modes and the control variable utilized throughout the different flight phases. For example, in the first phase of flight the MFS utilizes high-passed pitch rate, roll rate, and high-passed yaw rate plus lateral acceleration for stability augmentation. The pilot command mode of the PFS is accomplished with normal acceleration plus pitch rate and roll rate.

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The flight-control system being designed for test in the X-15 must have more than good dynamic performance. It must demonstrate high reliability. A reliability analysis based on a 1-hour mission of the MFS pitch channel shows a mean time between failure (MTBF) of 515 hours for single-channel operation. If a redundant configuration such as the one shown in figure 8 is used, the MTBF is increased to 925 hours. This reliability is in effect the reliability of the hydraulic servo which is a series element in the control system. This reliability figure is based on the premise that not more than one failure of the hard over or shorted type will occur in the triple redundant networks. It can be postulated that the gain changes will compensate for up to two open or "dead" type failures or one hard over failure with no loss in system performance. Most electrical failures are of the open or "dead" type (ref. 2). This capability is achieved because any one electrical network can provide the maximum required signal and because the gain changer will raise the gain of any remaining channel to compensate for failures. Even in the case of a single remaining channel or a non-redundant system, the self-adaptive feature will compensate for deterioration, to the point of failure, of components by raising the forward loop gain.

A three-axis self-adaptive system similar to the one described for the X-15 has been flight tested on an F-101. This system was built by the Minneapolis-Honeywell Regulator Company and is presently being flight evaluated by WADD, NASA, and AFFTC pilots. The WADD pilots have reported the system performance as excellent. It has given constant response at all flight conditions, and the pilots have not been able to detect the limit cycle operation. Figure 9 is a flight recording taken from this aircraft showing step commands into the roll axis. Note the operation of the roll and pitch gain as the limit cycle appears on the aileron and pitch servos and the difficulty of detecting the limit cycle from the system noise. Actually, amplitudes of the noise and limit cycle are almost identical;

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however, the limit cycle can be detected by looking for its characteristic frequency of 4 cycles per second. Flight data have demonstrated the operation of the gain changer in compensating for the deterioration of components. Thus, one reason besides dynamic performance for the use of a self-adaptive technique would be increased reliability.

An important consideration in the design of any autopilot is the amount of attention required of the pilot for satisfactory performance in mission profiles. Figure 10 shows the pilot workload for an X-15 profile with self-adaptive stability augmentation only. Note that
L workload does not indicate the effort required of the pilot, either
1 mental or physical, but rather the time spent in performing a function.
1 The self-adaptive stability augmentation furnishes constant performance
1 at all flight conditions and has blended aerodynamic and reaction con-
4 trol. Figure 11 shows the same mission profile flown with a complete autopilot including control-stick steering and altitude, attitude, and angle-of-attack hold functions. There is a sharp decrease in the amount of pilot workload required to accomplish the mission with the complete autopilot; thus the pilot is free to direct or oversee the operation of other equipment required for a military mission.

The results of the X-15 study and simulation and the F-101 flight test have shown that a self-adaptive flight-control system will provide the response required for mechanization of these outer loops without scheduling and will permit reduction of pilot workload.

Before initiating the program described, it was first necessary to establish that the range of dynamic conditions and the control problems encountered in the X-15 test vehicle would be comparable enough with the Dyna-Soar and other future vehicles to make the results of a test program of practical value.

A two-degree-of-freedom short-period comparison of the natural-frequency-and-damping ratio of the X-15 and a typical Dyna-Soar vehicle was made (ref. 3). The X-15 trajectory chosen for study is a typical maximum-altitude flight. The X-15 was boosted to a peak velocity of 6,400 ft/sec and an altitude of 250,000 feet. The boost phase of the Dyna-Soar trajectory was not studied, since differences in the two vehicle configurations do not permit sound comparisons. The Dyna-Soar trajectory used had a peak velocity of 24,000 ft/sec at an altitude of 250,000 feet and followed an $(L/D)_{MAX}$ trajectory, modified through the heating range to keep the temperature within specified limits. A 9,000-pound vehicle with a delta-wing area of about 330 square feet was used as a representative Dyna-Soar. Perfect lateral stability was assumed for both the X-15 and Dyna-Soar.

Figure 12 shows a comparison of dynamic-pressure variations with time for the X-15 and the Dyna-Soar at the critical reentry regions along the respective trajectories. It can be seen that the dynamic pressure of the X-15 changes much more rapidly than that of the Dyna-Soar and has a greater total variation.

Another important criteria affecting autopilot design is the product of ζ the damping ratio and ω_n the undamped short-period natural frequency. This product can be used to compare the speed of response of the airframes, and as shown in figure 13 the product varies over a wide range for both vehicles. The stability derivatives used to calculate ω_n and ζ time histories were estimated from data supplied by North American Aviation, Incorporated, and the Dyna-Soar contractors.

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It can be seen from figures 12 and 13 that the total variations of two of the control parameters which are normally specified for autopilot design are greater for the X-15 than for the Dyna-Soar during reentry and change more rapidly for the X-15. This rate of change will be a factor in determining what type of self-adaptive autopilot technique should be selected. Since the rate of change of $\omega_n\zeta$ is much greater for the X-15, a self-adaptive technique capable of adjusting to the changing parameters of the X-15 should work for the Dyna-Soar.

In orders of magnitude of period and damping, the Dutch roll case is comparable to the longitudinal short-period mode and the same general conclusions are applicable at low angles of attack for both vehicles.

From this analysis, it was concluded that a self-adaptive control system was feasible for the X-15 and that flight test of such a system would gain data of value for use on later vehicles such as the Dyna-Soar.

The present schedule (fig. 14) calls for installation of the adaptive equipment in an X-15 in February of 1961 with flight test of the system starting in May of 1961. This airborne equipment will be supported by a complete set of ground-support equipment for checkout and maintenance. Presently, the system to go in the X-15 has been breadboarded and is being operated on the X-15 simulator. At the conclusion of these tests this month, design and fabrication of the airborne equipment will start.

The operation of this equipment during the summer of 1961 should provide timely information for confirming design techniques of a flight-control system which could be used in the Dyna-Soar.

CONCLUDING REMARKS

A self-adaptive control system has several advantages over a linear control system even when the design dynamic performance of both is acceptable.

A self-adaptive system furnishes more margin for error regarding the knowledge of stability derivatives and the effects of aerodynamic variations and structural heating not yet fully defined.

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The system integrates aerodynamic and reaction control and provides the possibility of greater reliability through redundancy. It provides a stable, nonvarying inner loop which permits the design of outer loops without scheduling, which will relieve the pilot workload and permit operation of more sophisticated onboard computing systems.

A self-adaptive system requires less redesign and will adjust and operate correctly with less performance testing when vehicle configuration changes are made; thus it has greater growth potential.

A self-adaptive system designed and flight-tested in the X-15 will provide useful information for the Dyna-Soar program.

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2. Connors, A. J., and Ekern, H. O.: Comparison of Dyna-Soar and X-15 Longitudinal Dynamics. WADC TN 59-213, U.S. Air Force, June 1959.

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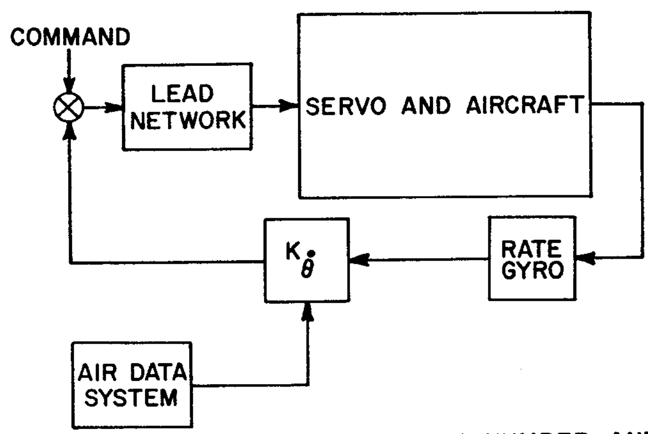
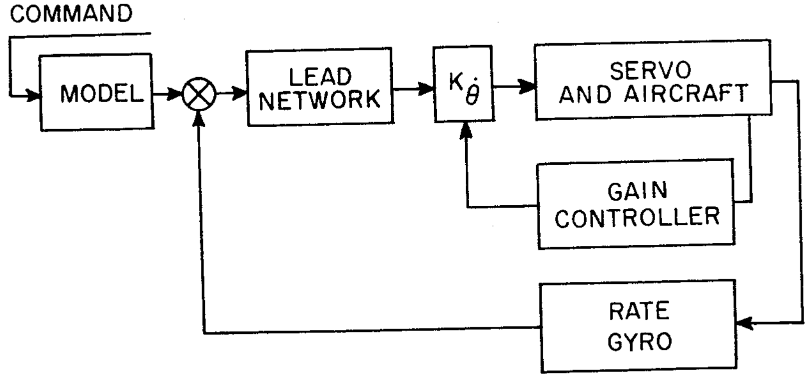
LINEAR DAMPER



$K_{\dot{\theta}}$ IS A FUNCTION OF MACH NUMBER AND ALTITUDE

Figure 1

ADAPTIVE DAMPER



$K_{\dot{\theta}}$ IS VARIED AUTOMATICALLY AS A FUNCTION OF SYSTEM PERFORMANCE

Figure 2

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DIAGRAM OF ADAPTIVE LOOP

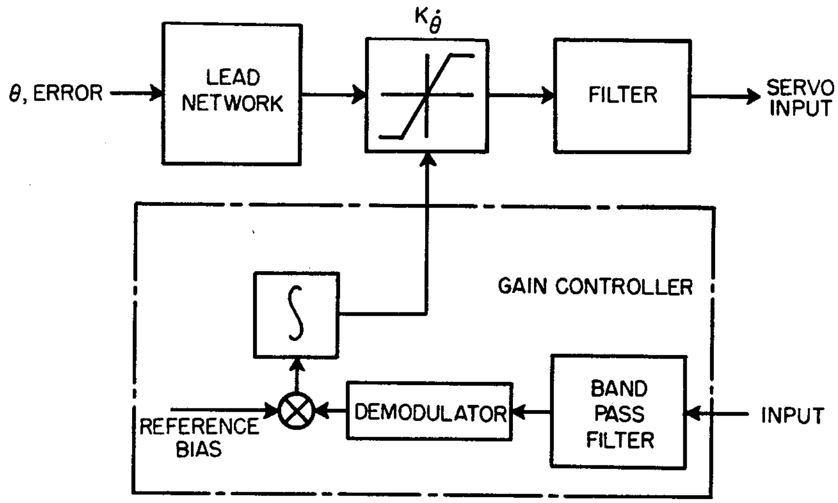

Figure 3

X-15 PITCH AXIS CONTROL SYSTEM

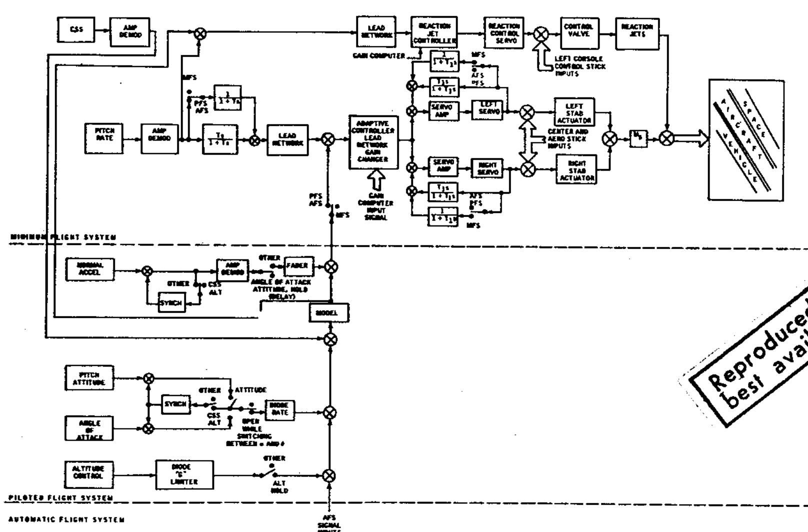

Figure 4

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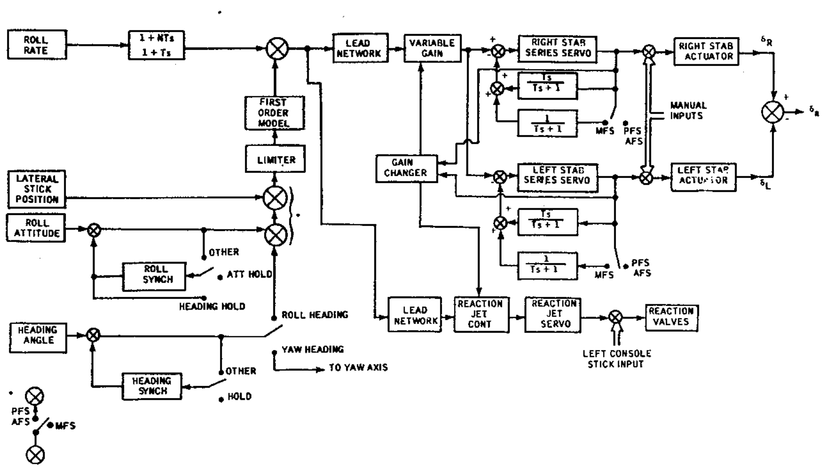

Figure 5

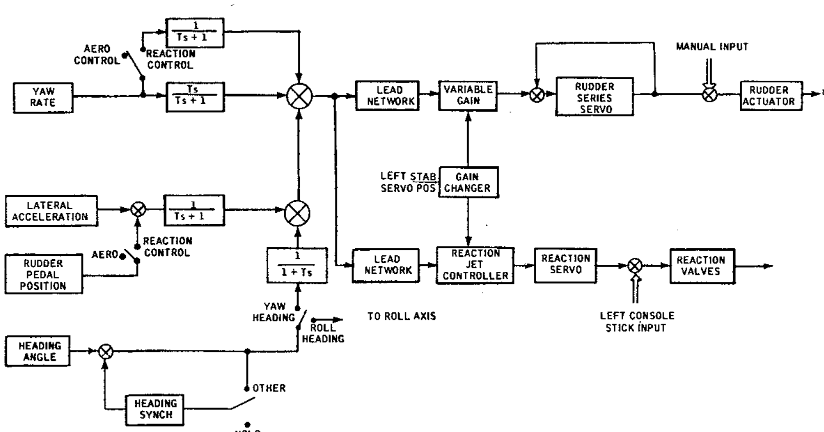

Figure 6

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CONTROL MODES

$\dot{\theta}_H$ - high-pass pitch rate
P_H - high-pass roll rate
r_H - high-pass yaw rate
a_y - lateral acceleration
n_z - normal acceleration
$\dot{\theta}$ - pitch rate
P - roll rate
CSL - command signal limiting (α, n)
θ - pitch attitude
α - angle of attack
ϕ - roll attitude
ψ - yaw orientation

PHASE OF FLIGHT	MFS AUGMENTATION	PFS PILOT COMMAND	PFS HOLD	AFS COMMAND GUIDANCE
PHASE I	$\dot{\theta}_H$	$n_z + \dot{\theta}$	α or θ	
LAUNCH (TAKEOFF)	P	P	ϕ, ψ	AUTO NAVIGATION
EXIT (PULLOUT)	$r_H + a_y$	--	--	AUTO EXIT
BURNOUT		ALTITUDE HOLD OPTIONAL -- CSL		
PHASE II	$\dot{\theta}$	$n_z + \dot{\theta}$	α or θ	
BALLISTIC	P	P	ϕ	AUTO-NAVIGATION
SEMI-ORBITAL	r	r	ψ	ALTITUDE CONTROL
ORBITAL		CSL		
PHASE III	$\dot{\theta}_H$	$n_z + \dot{\theta}$	α or θ	
RE-ENTRY	P	P	ϕ, ψ	AUTO RE-ENTRY
CONSTANT g	$r_H + a_y$	--	--	
CONSTANT α				
EQUILIBRIUM GLIDE		AUTO DRAG BRAKE - q LIMITING CSL		
PHASE IV	$\dot{\theta}_H$	$n_z + \dot{\theta}$	θ	AUTO APPROACH
DECELERATION	P	P	ϕ, ψ	
GLIDE	$r_H + a_y$	--	--	AUTO FLARE-OUT
LAND		ALTITUDE HOLD OPTIONAL -- CSL		

Figure 7

MECHANIZATION FOR RELIABILITY

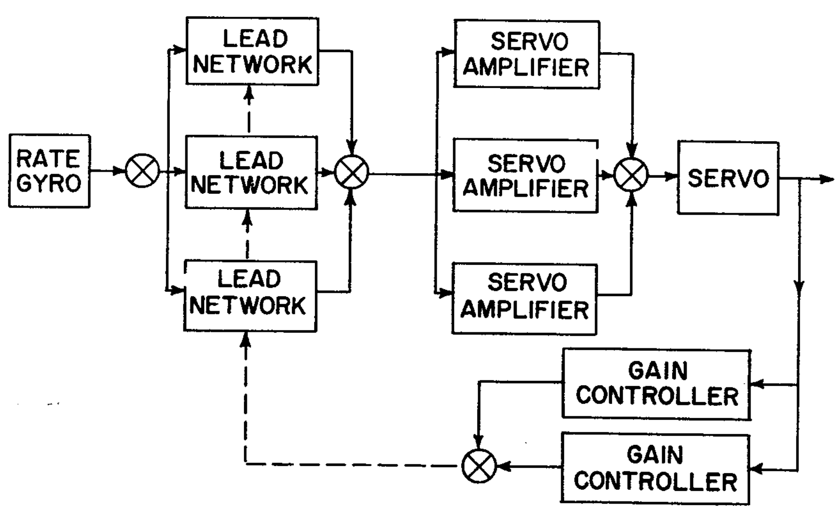

Figure 8

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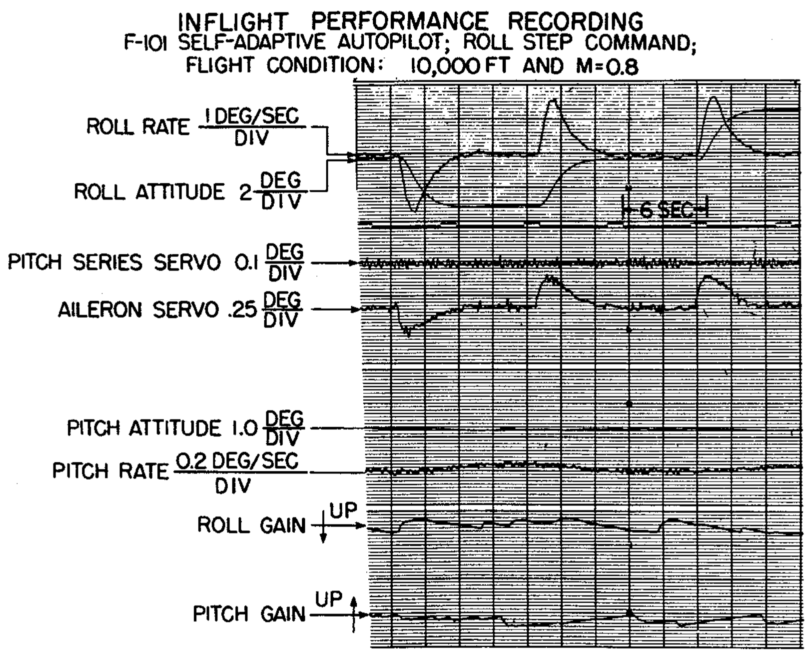

Figure 9

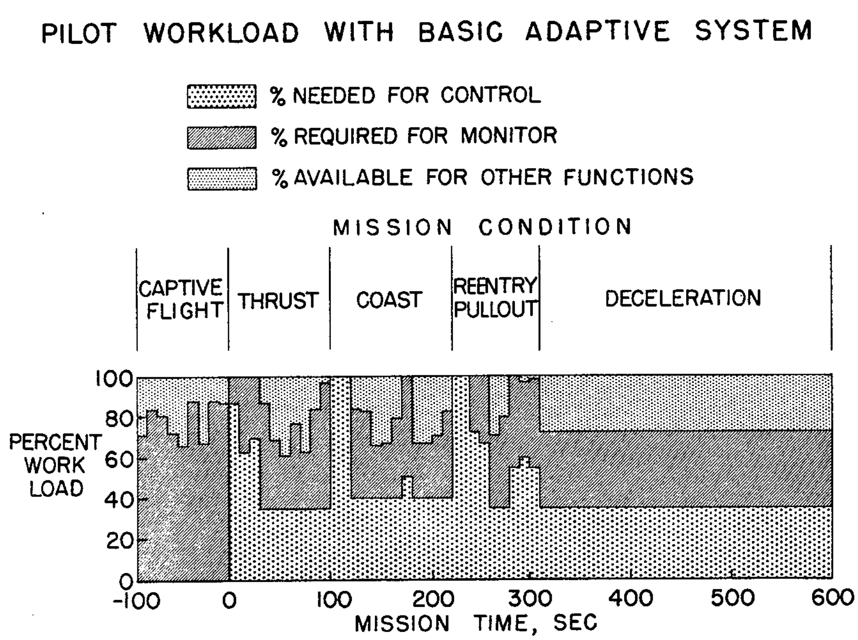

Figure 10

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PILOT WORKLOAD WITH PILOT-ASSIST FUNCTIONS

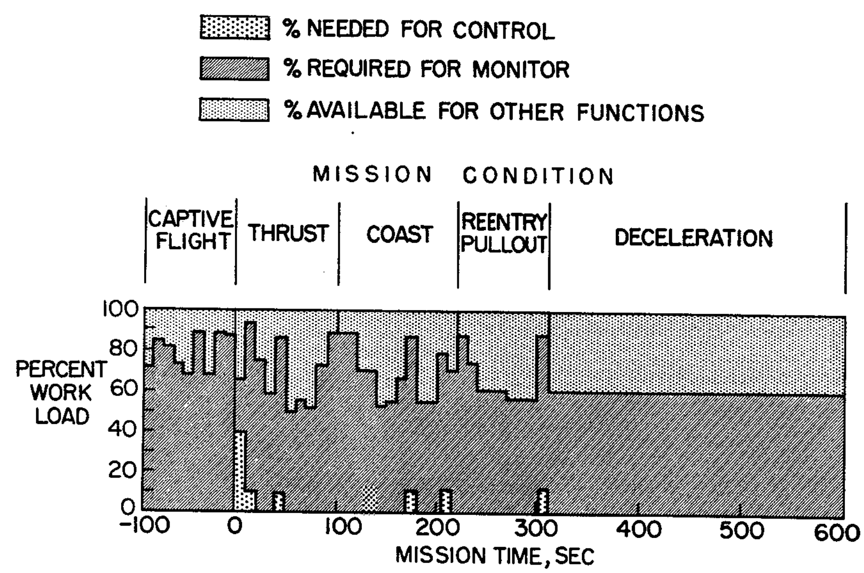

Figure 11

VARIATION OF DYNAMIC PRESSURE WITH TIME

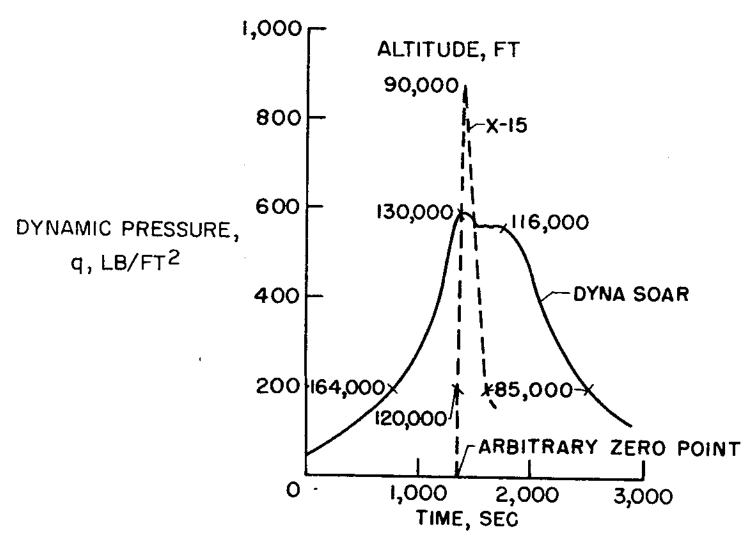

Figure 12

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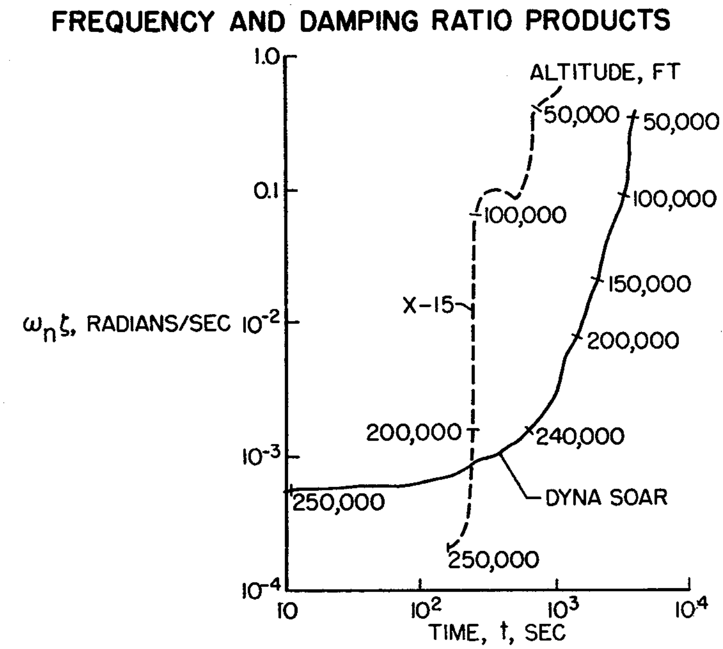

Figure 13

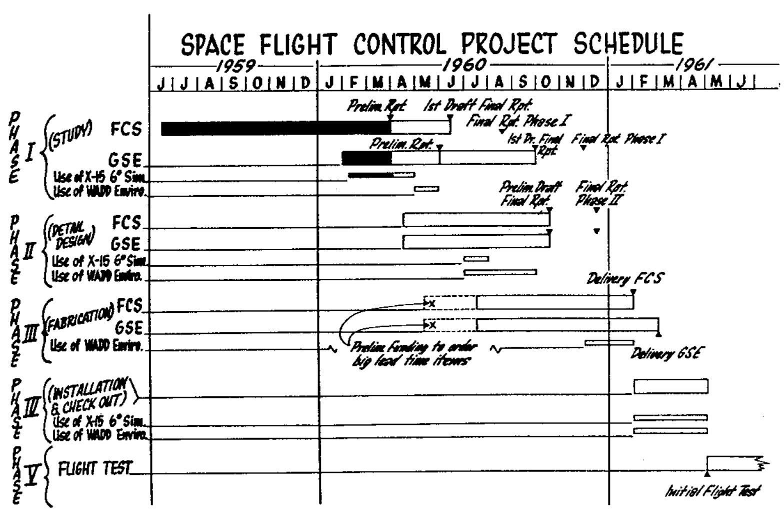

Figure 14

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