

## HYBRID SIMULATION OF AN AIRCRAFT ADAPTIVE CONTROL SYSTEM

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**ABSTRACT:** Aircraft adaptive control is simulated in real time by a hybrid system (HYDAC\* 2000) consisting of a general purpose analog computer and parallel digital logic and conversion components. The proposed adaptive technique utilizes predicted as well as measured past information on aircraft behavior to calculate optimum controller parameters. The optima are determined by a systematic search procedure in parameter space. The search program is under the direction of the logic elements and employs an analog computer model of the aircraft system, solved at high speeds for prediction purposes. Fast adaptation to environmental disturbances is shown to be realizable.

## THE ADAPTIVE CONTROL PROBLEM

The general concept of adaptive control has become well known, and the objectives and various types of adaptive systems have been classified.<sup>1</sup> In particular, for adaptive control of a high performance aircraft, it is desired to alter the feedback control parameters in the basic linear control system to correct for unknown, unanticipated, or unaccounted-for changes in the aircraft's operating characteristics, inputs, or criterion of performance.

A typical adaptive scheme to accomplish this purpose measures and evaluates the aircraft's performance over some recent time interval, makes decisions regarding any necessary control loop parameter modifications, and implements these changes.

Of interest is the speed of adaptation. The time required in the adaptive process above (for a reasonable quality of adaptation) is usually much longer than the characteristic time constant of the system.<sup>2</sup> It is suggested here that faster adaptations would obtain if the evaluation of system performance were made on the basis of predicted future

aircraft performance as well as measured past performance.

Accordingly, an adaptive scheme is proposed wherein environmental changes are reflected in an on-board model of the aircraft control system. The model, in turn, is used to predict future aircraft performance and, in conjunction with an optimization program, to determine optimum controller parameters. Prediction is done via high-speed integration of the model equations; therefore, optimization is rapid, and a new set of controller parameters can be instituted almost as soon as a measurement of performance indicates a need for change.

The feasibility of using a predictive technique of this sort is to be determined by means of a hybrid simulation. Of particular interest is the quality of adaptation, i.e. the magnitude of departures from optimum performance in the face of environmental upsets. Since a hybrid approach is applicable to problems requiring both logical calculations and high-speed iterative solution of differential equations, its use is justified in this problem, where these requirements are imposed by the optimization technique.

## THE HYBRID SYSTEM

One of the major forms of hybrid computation to emerge in recent years is the association of a general purpose analog computer with a complement of general purpose digital logic, memory, and conversion components. The genesis of this type of computational system began with a desire to exploit the high-speed integration capability of the analog computer. The consequent need to control and change the analog's program on the basis of previous results and external inputs and at correspondingly high speed led to the adoption of the parallel digital devices, programmed to exercise the necessary logical control, timing, and data storage functions.

Applications of this type of hybrid computation include iterative calculations, automatic production of a sequence of analog runs, and solutions of partial differential equations via techniques requiring function storage and iteration.<sup>6</sup> The additional capabilities of this system to perform automatic optimization of system parameters and to simulate systems containing digital devices are of interest in this problem.

The adaptive control problem imposes computational requirements of two-speed integration of the system equations with iterations of the high-speed solution under direction of the digital logic elements. These latter are also programmed to automatically test the results of analog iterations, make logical decisions from evaluations of these results, and execute commands aimed at determining optimum system parameters. The analog computer provides the simulation of the aircraft and control system, their models, and also of a dynamic reference model which provides a criterion for evaluating system performance. The parallel digital elements, in addition to their role in directing the optimization, are programmed to act as master control of the entire simulation. With the exception of the representation of the actual aircraft and control system, the simulation is regarded as one of a potential on-board adaptive control system. The simulation itself is considered to be representative of those in which the full speed capability of the analog computer is utilized.

## THE OVERALL ADAPTIVE CONTROL SYSTEM

The elements essential to the adaptive technique are shown in Figure 1 and comprise:

1. an Aircraft Control System whose feedback control parameters  $\bar{\lambda}$  (vector nomenclature) are the objects of adaptation,

2. a Performance Criterion in the form of a dynamic reference model (with parameters  $\bar{q}$ ), arbitrarily specified but known to produce a desirable response  $\bar{x}_{RM}(t)$  to pilot inputs  $i_p(t)$ .

3. Auxiliary Models (heavy black boxes in Figure 1), having parameters  $\bar{\lambda}_M$ ,  $\bar{p}_M$ , and  $\bar{q}$ , corresponding to actual system parameters, to be used to calculate (via high-speed integration) the predicted responses  $\bar{x}_M(t)$  and  $\bar{x}_{RM}(t)$  for use in the optimization program.

4. a Predicted Index of Performance, E, defined by

$$E = \int_t^{t+\tau} \left| \bar{x}_{RM} - \bar{x}_M \right| dt \quad (1)$$

where  $\tau$  is the prediction interval.

5. Adaptive Process No. 1, an automatic optimization program, which computes  $\partial E / \partial \bar{\lambda}_M$  and the optimum  $\bar{\lambda}_M$ .

6. Adaptive Process No. 2, a parameter tracking program, which calculates optimum  $\bar{p}_M$  from measurements of actual system performance.

The form of the Performance Criterion and the use of Auxiliary Models are suggested by the "Model-Reference-Adaptation" technique of Whitaker<sup>3</sup> and an "auxiliary system" concept of adaptation as discussed by Widrow<sup>2</sup>, respectively. The approach taken here, however, is different from both of these in its utilization of high-speed prediction.

The predictive technique operates as follows. Adaptive Process No. 1:

1. makes small perturbations in  $\lambda_{Mi}$  (each component of  $\bar{\lambda}_M$ ).
2. measures E over a prediction interval with the perturbed  $\lambda_{Mi}$ .
3. calculates  $\partial E / \partial \bar{\lambda}_M$  (approximately).
4. alters  $\bar{\lambda}_M$  so that E will be reduced.

Successful modifications of  $\bar{\lambda}_M$  initiates identical modification in  $\bar{\lambda}$  (via lighter line in Figure 1). High-speed repetition of this process produces the optimum  $\bar{\lambda}$  in a very short time interval (typically much less than one second for a system whose major time constant is about three seconds).

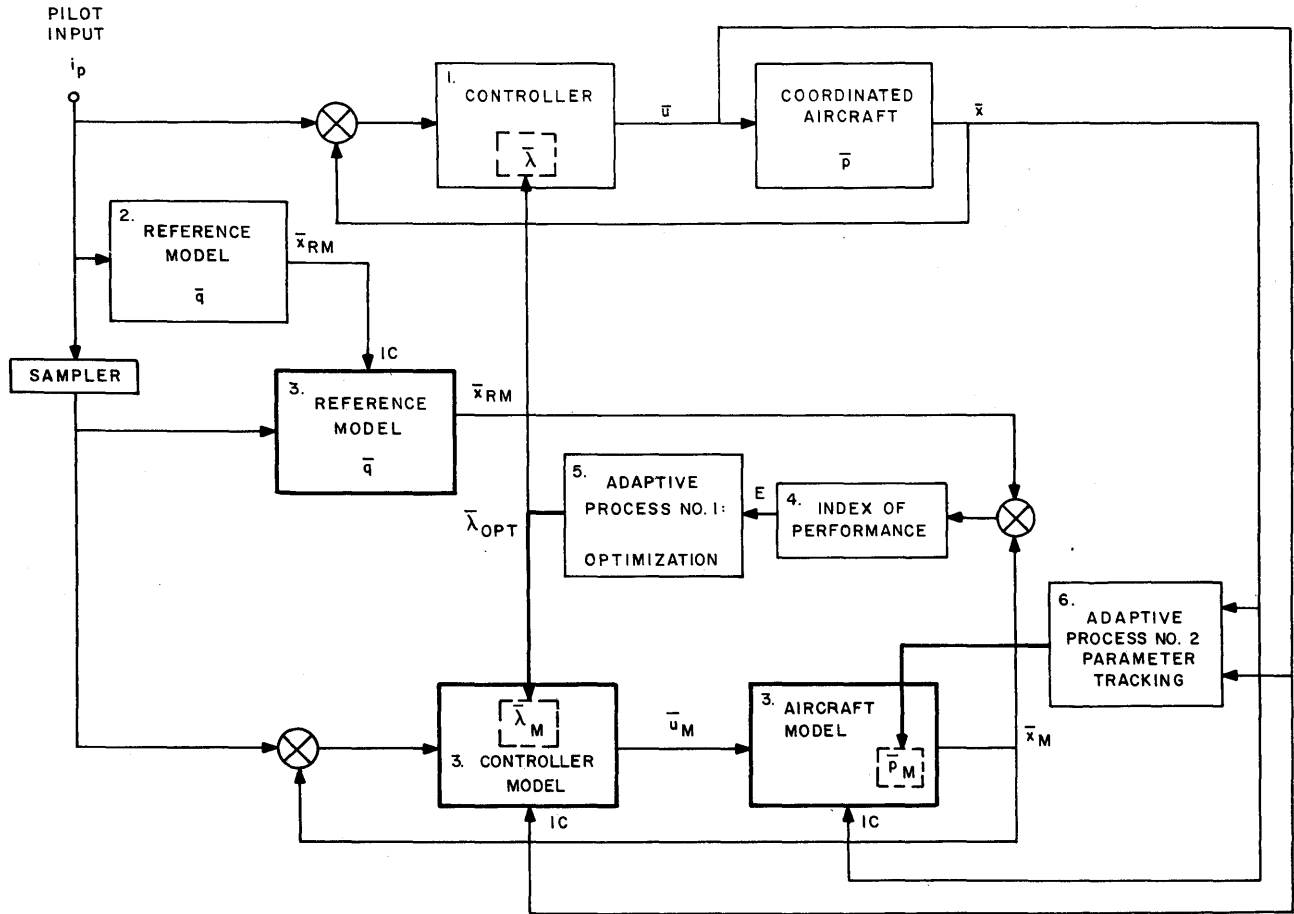


Figure 1: Adaptive Control Scheme

By itself, adaptive loop no. 1 does not provide complete adaptive control. A second adaptive process is necessary to track the parameters  $\bar{p}_M$ , updating the predictive model in an attempt to match aircraft performance. Thus, variations in the operating characteristics or inputs to the actual aircraft occur as parameter changes in the aircraft model, the objective being to alter or force the predictive loop to imitate the actual aircraft as closely as possible. The effects of environmental perturbations also appear in the auxiliary model via the transfer of information on the current state,  $\bar{x}$  and  $\bar{u}$ , of the aircraft and its feedback control system. This information is used as initial conditions in the iterative prediction calculations. In summary, adjustment of  $\bar{p}_M$  allows prediction and hence optimization of  $\bar{\lambda}_M$  on the basis of the current estimate of the aircraft transfer function; and state variable transfer permits prediction from the correct current state.

It should be evident from the above that the determination of the optimum  $\bar{\lambda}$  by calculation of  $\partial E / \partial \bar{\lambda}_M$  presumes the constancy of parameters  $\bar{p}_M$  and  $\bar{q}$ , pilot input  $i_p$ , and state variables  $\bar{x}$  and  $\bar{u}$

over the prediction interval  $\tau$ . Since this condition does not necessarily prevail due to changing environmental conditions, unpredictable pilot behavior, or changing performance criteria, it is necessary to constantly re-evaluate  $\partial E / \partial \bar{\lambda}_M$  and the optimum  $\bar{\lambda}$ . This is a reasonably simple task in the system at hand, since  $\bar{p}_M(t)$ ,  $\bar{q}(t)$ ,  $i_p(t)$ ,  $\bar{x}(t)$ , and  $\bar{u}(t)$  will presumably be low-frequency functions and essentially constant during a few high-speed evaluations of the gradient. (Special consideration of  $i_p(t)$  is made later.) The need to re-evaluate the optimum emphasizes, however, this fundamental characteristic of predictive adaptation schemes: current optima are calculated on the basis of extrapolated present information and represent the best estimate that can be made; they are not necessarily the true optima which could have been implemented given a priori information on the nature of the system changes and perturbations. The adaptive scheme can thus be visualized as a means for tracking the true optima on the basis of current measurements of performance. It attains the true value only when environmental perturbations no longer appear, i.e. when predicted and actual performance coincide.

Other non-predictive adaptive schemes are, of course, faced with similar problems of current "optima" lagging the true optima. This is due to the time lag between the measurement of performance and implementation of correction.<sup>3</sup> Generally these schemes have much longer lag times than the predictive techniques. Note for comparison purposes that both adaptive processes of Figure 1 operate very rapidly so that corrective action can begin essentially as soon as environmental perturbations become evident in the aircraft outputs. This delay is determined by various aircraft system time constants and the nature of the perturbations.

Although corrective action is fast, the quality of adaptation may be suspect if predicted response differs significantly with actual future performance, or if repeated evaluations of the optima are ineffectual in producing necessary corrections. Such situations can conceivably exist when:

1. the aircraft model and actual aircraft are described by significantly different transfer functions, and the mismatch cannot be compensated by parameter tracking.
2. parameter tracking and state variable transfer is ineffectual in transferring to the model sufficient information on the nature of the actual disturbance.
3.  $\bar{i}_p$  and  $\bar{p}_M$  vary drastically over the prediction interval.

The consequence of 3. above is evident upon consideration of  $i_p(t)$ . Values of this function are sampled at the start of each prediction calculation and assumed to prevail over the entire prediction interval. It is true, however, that the optimum  $\bar{\lambda}$  depends not only on the present value of  $i_p(t)$  but on its functional nature as well. To assume a form for the function, namely  $i_p(t) = \text{constant}$ , even though the constant is updated from prediction to prediction, may lead to an inaccurate calculation of the optimum. This situation may be overcome by extrapolating the recent past history of  $i_p(t)$  over the prediction interval. Such a modification would allow for greater utilization of present information in predicting future performance.

The  $i_p$  sampler at the input to the auxiliary system now has a dual purpose. It prevents discontinuous pilot inputs from affecting the prediction during the course of a run (pilot inputs are regarded here as being piecewise continuous with low frequency content over continuous segments), and it becomes part of the extrapolation system.

A yaw control system for a supersonic transport (Figure 2) as presented by Whitaker<sup>4</sup>, was chosen to demonstrate the adaptive technique.

The aircraft control system is expected to perform satisfactorily over extremely wide ranges of speed and altitude. The attendant changes in performance characteristics and a variety of environmental conditions make modification of the controller gains necessary. In the system the pilot's input yaw rate is monitored by a yaw integrating gyro which produces a control action causing the vehicle to roll until a component of its angular velocity about its yaw axis is equal to the yaw rate command. (More detailed descriptions of this system are given in reference 3.) The same basic fifth-order representation was used for both the actual aircraft control system and its model, although nonlinearities and additional inputs were frequently included in the actual system in order to test the adaptive scheme.

Three control loop gains are to be adjusted:  $\lambda_1$ ,  $\lambda_2$ ,  $\lambda_3$ , corresponding to gains in the forward loop, the roll angle stabilization loop, and the roll rate damping loop, respectively.

The reference model is seen to be a third-order system with three parameters,  $q_1$ ,  $q_2$ ,  $q_3$ , which are time constant, frequency, and damping factor, respectively. These parameters define the desired response and may be altered at will.

A single aircraft output, the yaw angular velocity,  $W$ , is taken as a measure of aircraft performance. It is assumed that delays in measuring all output variables are negligible.

INDEX OF PERFORMANCE

A single index of performance given by  $E = \int_t^{t+\tau} |W_{RM} - W| dt$  was used to adjust the three parameters. This was later found not to be optimum due to the existence of local minima, insensitivity to certain parameter changes, and parameter cross-coupling, but is retained here for the sake of exposition of the technique. A better approach employs several E's defined by:

$$E_i = \int_{t+\tau_{1i}}^{t+\tau_{2i}} |W_{RM} - W| dt \quad i = 1, 2, 3 \quad (2)$$

where  $\tau_{2i} - \tau_{1i}$  is a portion of the prediction interval. The values can be chosen to minimize the interactions of the three parameters. This form has been suggested by Whitaker.



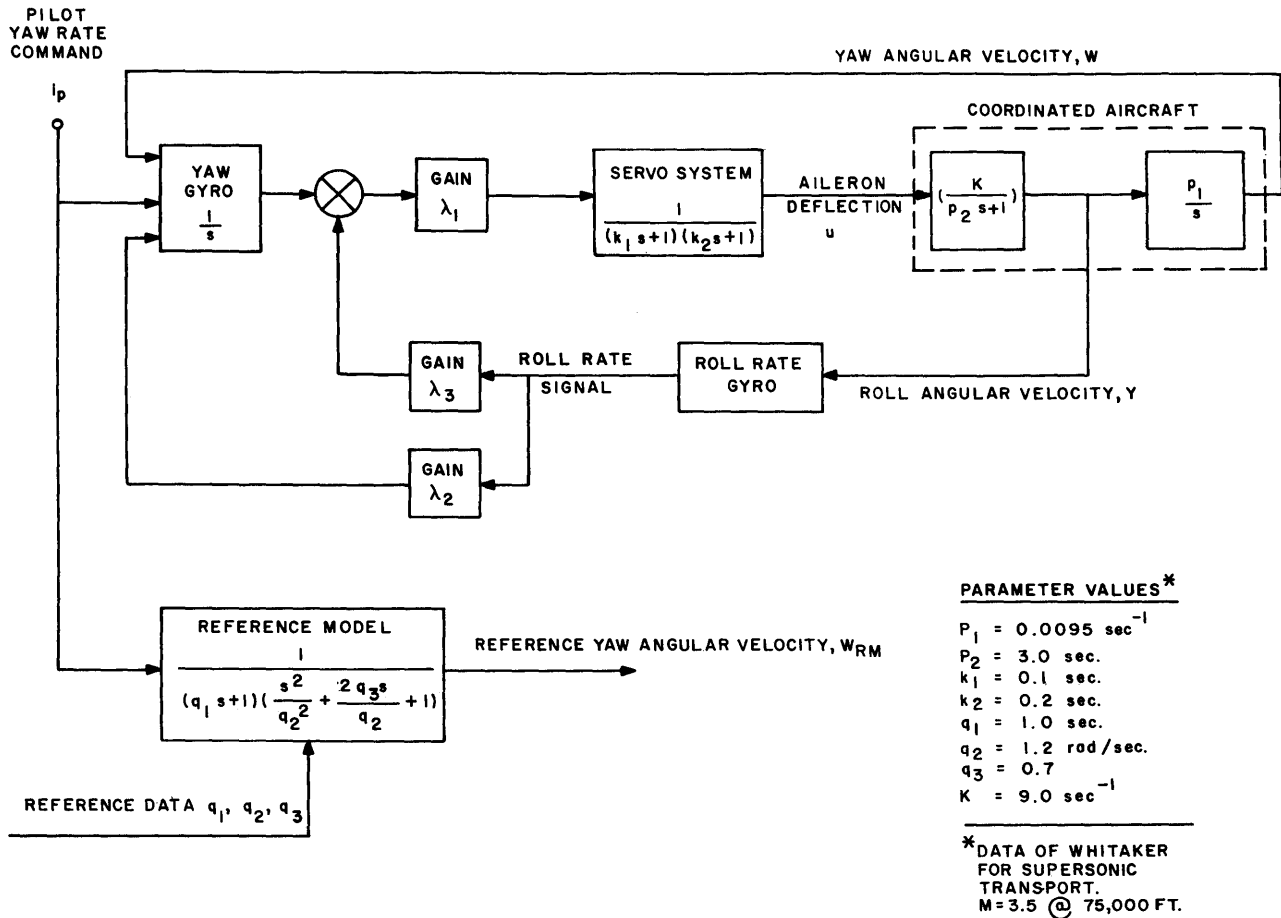


Figure 2: Aircraft Control System Block Diagram  
(Form of System and Parameter Values According to Whitaker)<sup>4</sup>

### ADAPTIVE PROCESS NO. 1

The optimization technique used is a modification of the method of steepest descents according to Witsenhausen<sup>5</sup>. A search to find the minimum of  $E(\lambda_{M1}, \lambda_{M2}, \lambda_{M3})$  from an arbitrary initial starting point  $\lambda_{M1}^0, \lambda_{M2}^0, \lambda_{M3}^0$  and  $E^0$  proceeds as follows:

1. By perturbing the  $\lambda_{Mi}$  values by a small amount  $h$  calculate approximate partial derivatives

$$\frac{\partial E}{\partial \lambda_{Mi}} = \frac{\delta E^+ - \delta E^-}{2h} \quad (3)$$

where

$$\delta E^+ = E(\lambda_{M1}^0, \dots, \lambda_{Mi}^0 + h, \dots, \lambda_{M3}^0) - E^0$$

$$\delta E^- = E(\lambda_{M1}^0, \dots, \lambda_{Mi}^0 - h, \dots, \lambda_{M3}^0) - E^0$$

This requires six high-speed prediction runs.

2. Store the results of all partial derivative determinations. This is done in quantized form to place the storage load on the digital computer. The quantization is done by comparing the partial derivatives with a quantity  $L$ , arbitrarily but carefully specified, and determining a new quantity  $Z_i$ :

$$\begin{aligned} Z_i &= +1, (\delta E^+ - \delta E^-) < -2hL \\ &= 0, -2hL < (\delta E^+ - \delta E^-) < 2hL \quad (4) \\ &= -1, (\delta E^+ - \delta E^-) > 2hL \end{aligned}$$

The unit vector  $Z$  defines a direction in  $\lambda$ -space in which a decrease in  $E$  is probable.

3. Adjust the parameters to  $\lambda_{Mi}^0 + Z_i \Delta$ , where  $\Delta$  is some fixed quantity.
4. Test for an improvement in  $E$ . If  $E$  is lower, continue updating all parameters in the direction found, until no improvement occurs. When this happens, repeat 3

with a smaller  $\Delta$ . When this also fails, repeat the whole process starting from the new position in  $\lambda_M$  space.

5. Stop the optimization procedure when either all  $Z_i = 0$  or when at least one improvement cannot be obtained with the smaller  $\Delta$  proceed steps.

The information flow for this procedure is given in Figure 3. Note the automatic recycle feature provided to continuously re-evaluate the optimum following its initial determination. The recycle is started automatically following a stop condition, provided that a manual stop command has not been issued by the operator. It is very important upon recycling to re-evaluate the reference error  $E^o$  by making a run with the  $\lambda_i$  currently in effect. Failure to do so may result in a "locked-in" condition, wherein a new optimum cannot be achieved because the new minimum E is greater than the  $E^o$  just determined. Such a condition can

occur because environmental upsets in effect "shift" the E hypersurface.

Refinements in the basic program, as suggested in Reference 5, were made in order to decrease convergence time.

#### ADAPTIVE PROCESS NO. 2

The actual aircraft can be described by some vector function of the form

$$\bar{x} = \bar{f}(\bar{x}, \bar{p}, \bar{u}, \bar{I}) \quad (5)$$

where  $\bar{I}$  refers to environmental inputs. The aircraft model is defined by

$$\bar{x}_M = \bar{g}(\bar{x}_M, \bar{p}_M, \bar{u}_M) \quad (6)$$

We seek the values for  $\bar{p}_M$  for which the actual system outputs and model outputs coincide as well as possible. This optimum is obtained directly by

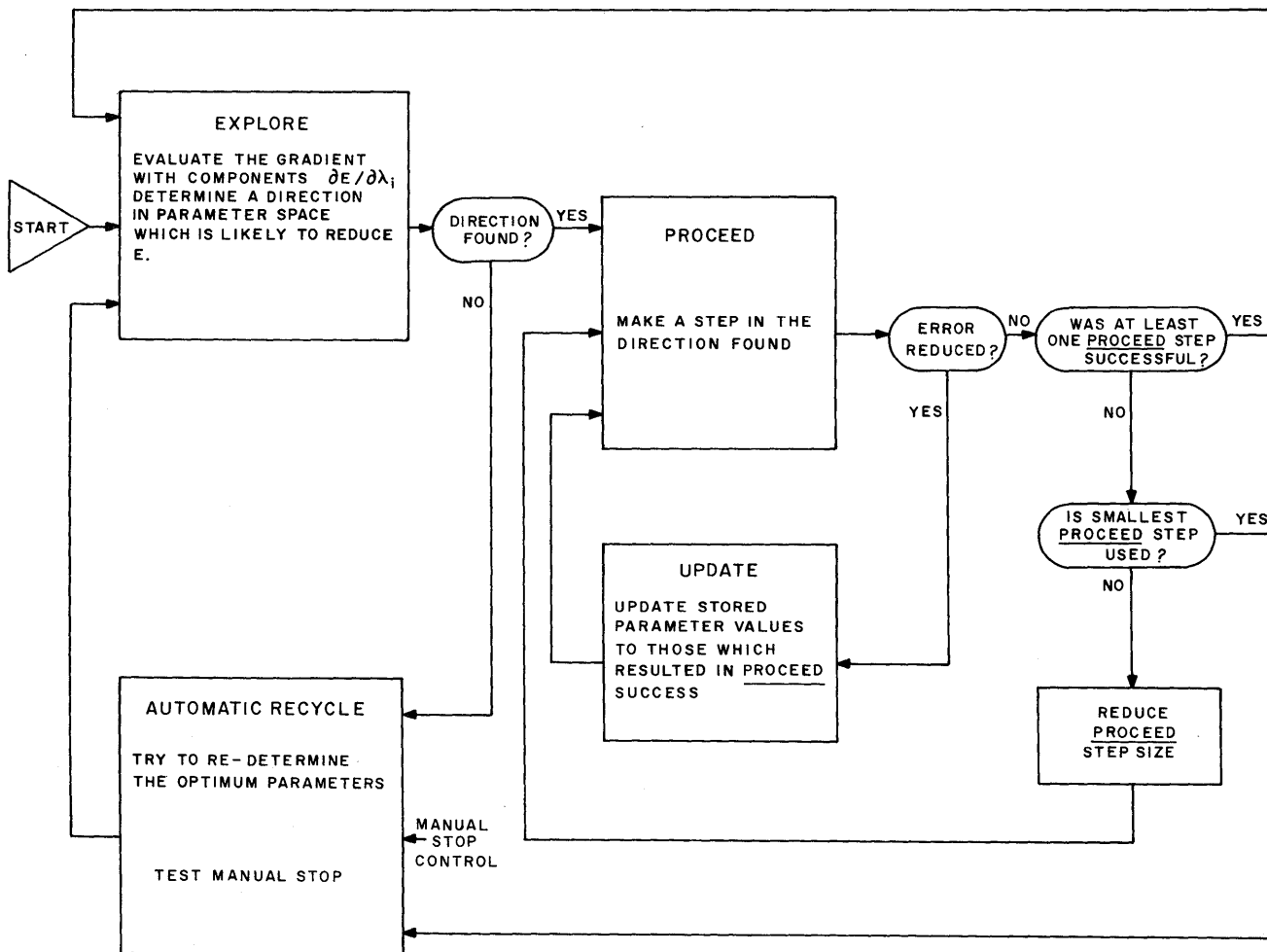


Figure 3: Optimization Procedure (Simplified)

substituting  $\bar{x} = \bar{x}_M$ ,  $\bar{u} = \bar{u}_M$ , and  $\bar{\dot{x}} = \dot{\bar{x}}_M$  into equation (6) and solving the resulting algebraic expression for  $\bar{p}_M$ . This technique is valid if the number of components of  $\bar{p}_M$  are equal to or less than the number of components of  $\dot{\bar{x}}_M$ . It also is based on the assumption that the necessary state variables and control variables can be measured. It may be necessary to differentiate (and filter) aircraft outputs to obtain certain components of  $\dot{\bar{x}}$ .

It is of interest to note that differences between the actual aircraft and its model ( $\bar{f} \neq \bar{g}$ ) or the existence of environmental inputs ( $\bar{I} \neq \text{zero}$ ) are reflected in the model via changes in  $\bar{p}_M$ .

For the system under consideration equation (6) is

$$\begin{aligned} \dot{W}_M &= p_{M1} Y_M \\ \dot{Y}_M &= \frac{1}{p_{M2}} (K_M u_M - Y_M) \end{aligned} \quad (7)$$

where  $K_M$  is taken to be constant. The optimum  $p_{M1}$  are given by

$$\begin{aligned} p_{M1} &= \dot{W}/Y \\ p_{M2} &= (K_M u - Y)/\dot{Y} \end{aligned} \quad (8)$$

A difficulty in determining these quotients occurs under steady state conditions, when numerators and denominators become zero but  $p_{M1}$  and  $p_{M2}$  are determinate. A division circuit using the method of steepest descents<sup>7</sup> affords a solution to the problem and was used in the simulation. Initial values for  $p_{M1}$  and  $p_{M2}$  were obtained from a knowledge of  $p_1$  and  $p_2$  under assumptions that  $\bar{f} = \bar{g}$  and  $\bar{I} = 0$  initially.

The roll rate  $Y$  is measured by a roll rate gyro as part of the basic control system.  $\dot{W}$  and  $\dot{Y}$  would have to be determined by differentiation of aircraft outputs  $W$  and  $Y$ . The main servo output  $u$  could be measured easily.

Other, more sophisticated parameter tracking techniques could be used.<sup>8</sup> The possibility of time-sharing the optimization techniques of Adaptive Loop No. 1 was also considered. These alternatives are feasible, but require considerable additional computation. The technique used provided satisfactory results with a modest expenditure of computational equipment.

#### ALLOCATION OF TASKS IN THE HYBRID PROGRAM

The hybrid system was an Electronic Associates HYDAC 2000 computer consisting of a PACE® 231-R

general purpose analog computer and a digital operations system (DOS 350). The 231-R was equipped with a high-speed electronic mode control unit (MLG). The allocation of computational tasks are shown in Figure 4.

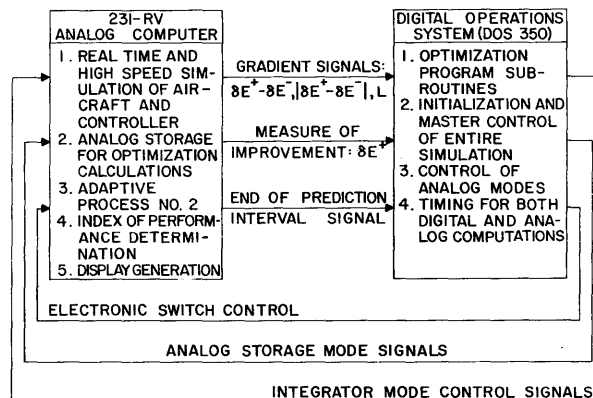


Figure 4: Allocation of Computer Tasks

#### THE ANALOG PROGRAM

An unscaled schematic for the basic aircraft system is given in Figure 5. Two of these circuits are required, one operating in real time to represent the actual system, the other at high speed (1000 times faster) for prediction. Noise inputs, failure conditions, and changes in the structure of the circuit were applied only to the real time circuit. The parameters  $p_1$  and  $p_2$  were fixed in the actual system circuit, but variable (as determined by the tracking process) in the predictive circuit. Initial conditions for the actual system were taken to be zero; the initial conditions for integrators in the predictive circuit were taken from outputs of their corresponding real time integrators. The parameters  $\bar{\lambda}_M$  and  $\bar{\lambda}$  were determined for the two circuits by different logic programs: the  $\bar{\lambda}_M$  were modified to evaluate  $\partial E / \partial \lambda_{Mi}$  but  $\lambda_i$  were changed only if prediction with  $\lambda_{Mi}^0 + Z_i \Delta$  yielded a smaller  $E$ . (Note that  $\lambda_{Mi}^0$  is equivalent to  $\lambda_i$ .)

Proper scaling of the gains  $\lambda_{Mi}$  and  $\lambda_i$  was essential for the optimization process. Use of a single, fixed exploration step size,  $h$ , depends on this. Improper scaling results in a gain between  $\partial E / \partial \lambda_{Mi}$  and  $\lambda_{Mi}$  that is either too high or too low, causing the optimization to stop at a non-optimum point or produce unstable solutions. A few simple trial-and-error experiments on the computer permitted determination of appropriate scale factors.

Two steepest-descent division circuits, of the type shown in Reference 7, were implemented to calcu-

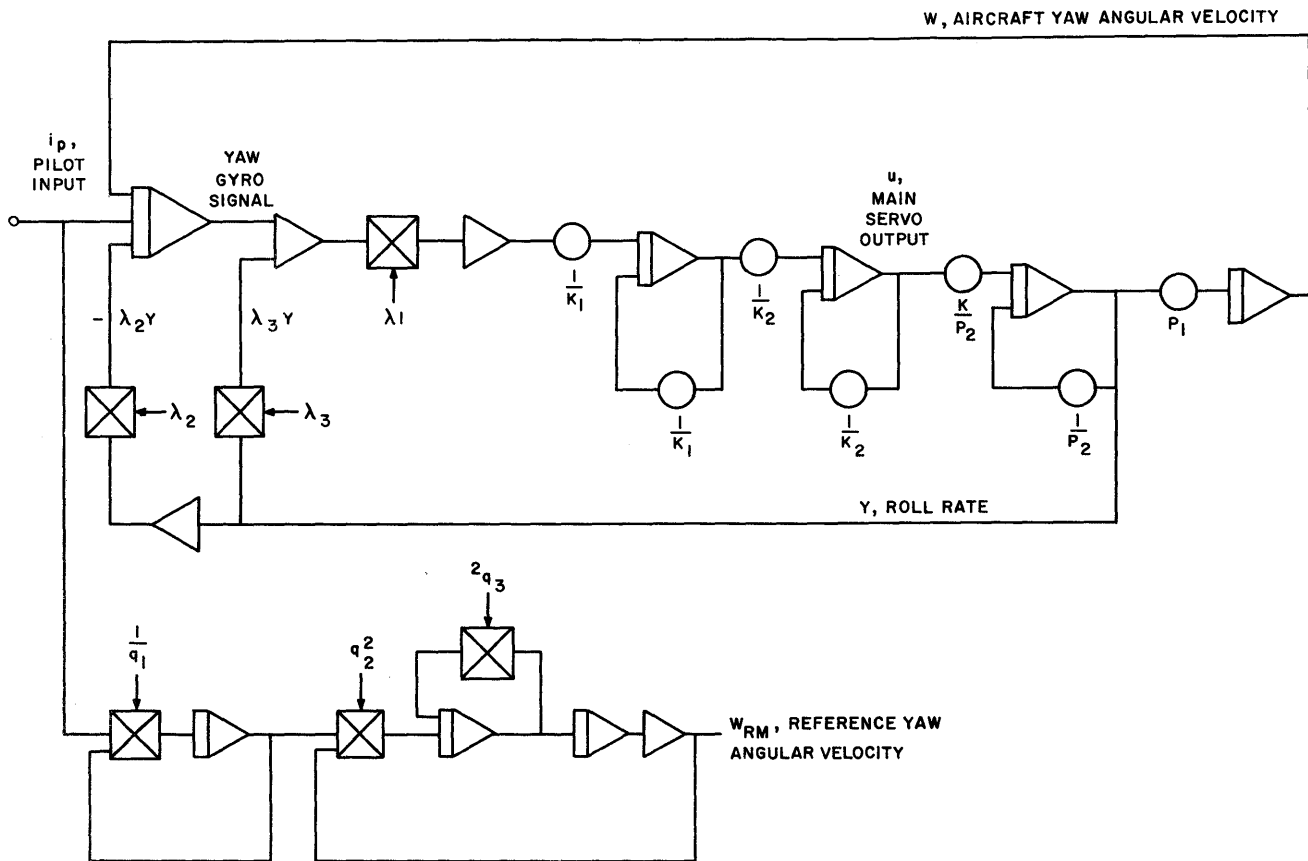


Figure 5: Analog Circuit for Aircraft, Controller, and Reference Model (Unscaled)

late  $p_{M1}$  and  $p_{M2}$  according to equation (8). In the simulation the derivatives  $\dot{W}$  and  $\dot{Y}$  appear as explicit voltages and need not be determined by differentiation.

#### THE DOS PROGRAM

The DOS consists of a collection of programmable, parallel digital logic, memory, and conversion components. Only the logic and some conversion components were used in this problem. These include logic gates, clocked flip-flops, shift registers, monostables, counters, comparators, and electronic switches, which can be interconnected on a patch panel in a manner similar to analog computer programming. Propositional and sequential logic calculations are handled by the gates and flip-flops, respectively, or by packaged combinations of these (shift registers, counters, etc.). The comparators and electronic switches provide the analog-to-logic and logic-to-analog conversions. In addition, logic levels on the DOS can control electronic switches in the analog circuits, the modes of analog integrators, and the

modes of track-hold analog storage units. The operating details of these devices as well as their program symbols are considered elsewhere.<sup>5,6&9</sup>

In this simulation the DOS directs the entire optimization program. The mechanization of the program, including circuit diagrams, has been given by Witsenhausen.<sup>5</sup> It suffices here to note the program structure—a set of subroutines, appropriately interlocked, whose functions are to:

1. select the step sizes  $h$ ,  $\Delta_1$ , and  $\Delta_2$  and set the appropriate switches accordingly. (See Figure 6.)
2. test for stop - recycle conditions.
3. initiate a high speed analog run to determine  $E$ , with a single parameter augmented by  $+h$ , then  $-h$ , repeating this for all three parameters.
4. evaluate  $Z_i$  according to equation (5) and store the results in digital form during the determination in step 3.



5. initiate a high-speed analog run with the appropriate  $Z_i \Delta$  modifications in all three parameters and test for improvement.
6. update the  $\lambda_i$  and  $E^o$  analog storage units to the values of  $\lambda_{Mi}$  and  $E$  that resulted in improvement.
7. repeat steps 5 and 6 until no improvement is obtained or until a preset number of "proceed" steps have occurred.
8. repeat steps 3 - 7 until a stop - recycle condition occurs.
9. clear the results of previous logic calculations when a stop - recycle condition exists, make another analog run with the present  $\lambda_{Mi}$ , and store the resulting value of  $E$  as the new  $E^o$ ; start with step 1 again.

The hybrid program is shown schematically in Figure 6 with emphasis placed on the interface. Various portions of the analog program are represented symbolically by a single integrator; parameters are represented by a potentiometer symbol. High-speed portions of the program are indicated by a slash line drawn through the integrator sym-

bol. The storage units employed analog integrators, programmed as accumulators. Selection of the magnitude and sign of the  $\lambda$  perturbations ( $\delta\lambda_i$ ) was done by electronic switches under control of the DOS logic elements. Control outputs of the DOS subroutines are indicated; their interconnections are given in reference 5.

## RESULTS

Responses of the adaptive control system to a variety of test conditions are presented in Figures 7 - 11. The standard aircraft and reference model parameters given in Figure 2 were used unless otherwise specified.

**Convergence:** Figures 7a and 7b illustrate the speed of convergence to an optimum state from an arbitrary initial set of parameter values. The optimization procedure brought the parameter values for  $\lambda_1$ ,  $\lambda_2$ , and  $\lambda_3$  from 60, 10 and 20 (dimensionless as shown in Figure 7b), respectively, to 70, 18, and 11 in approximately 1.2 seconds. The index of performance  $E$  was reduced to 5.0% of its original value. The input function was a series of steps applied by the pilot in an attempt to perform roll-in and roll-out maneuvers. Although a perfect correspondence between actual

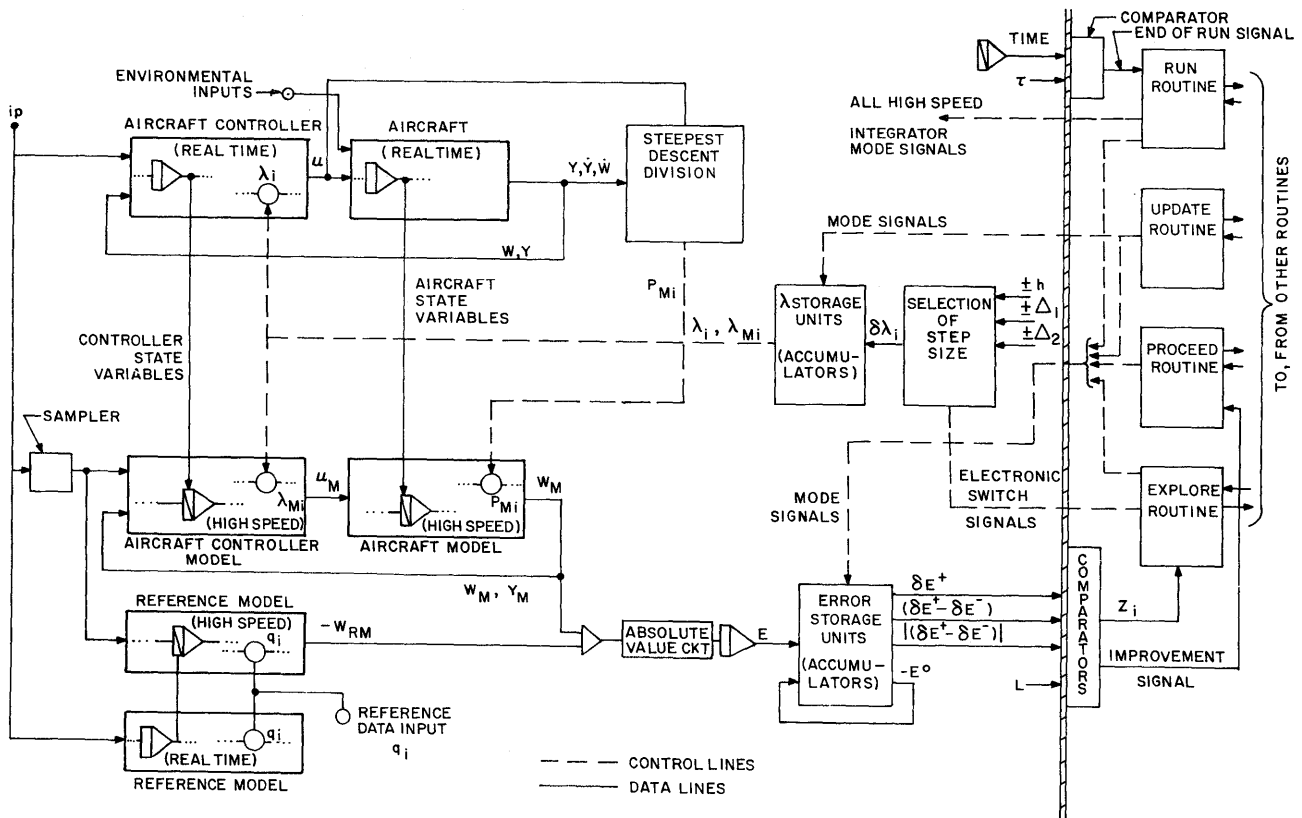


Figure 6: Simplified Schematic of the Hybrid Program

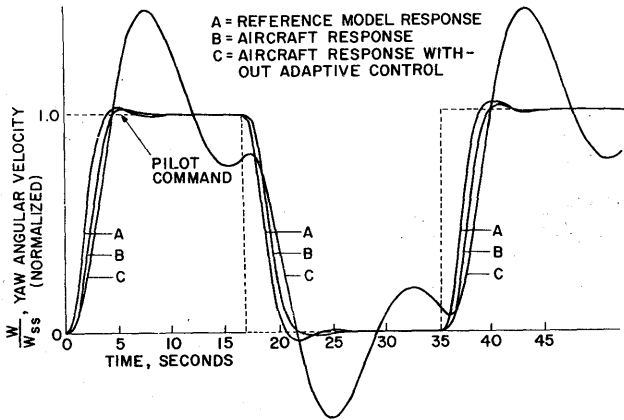


Figure 7a: Aircraft Response to Pilot Inputs, Controller Gains Initially Non-Optimum

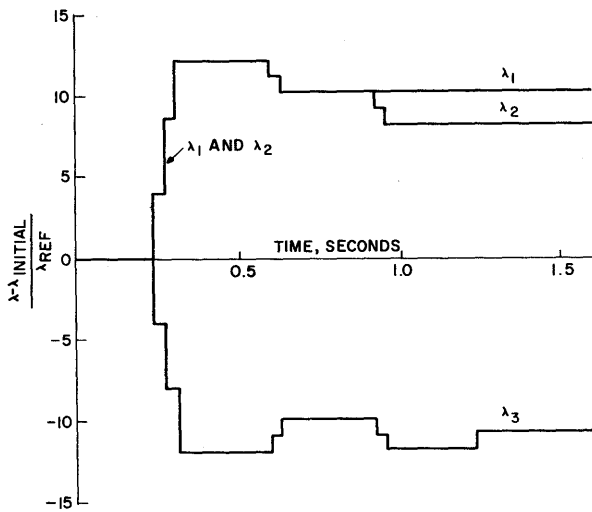


Figure 7b: Adaptation of Gains During a Portion of Response of Figure 7a

and reference model responses was not obtained, the actual response was a drastic improvement over the marginally stable response that would have obtained in the absence of adaptation. Note also that the marginally stable solution is the first response obtained in the iterative optimization program, and the final response is the one shown for the actual aircraft. Approximately 40 high speed prediction runs were made in the intervening 1.2 second period. The prediction was made with  $\tau = 20$  seconds (real time), corresponding to 20 ms of computational time in the high speed loop. The speed of adaptation is seen to be so rapid that actual performance is scarcely affected by the poor initial values of  $\lambda$ . It was assumed in this experiment that  $p_i = p_{Mi}$  and that no environmental effects were operative. The speed of adaptation found here is considerably faster than that reported by Whitaker for essentially the

same aircraft control system but different adaptive technique.

**Environmental Effects:** Using a slightly altered reference model ( $q_1 = 1.25$ ), the response to a change in the aircraft's operating characteristics was obtained. At time  $t = 0$  events occurred within the aircraft leading to a step change in velocity (increase). This change is sensed by Adaptive Process No. 2 in the manner shown in Figure 8a, i.e.  $p_{M1}$  changes. Without this parameter adjustment a poor response would result (curve C). With no adaptive control operating at all a poorer response obtains (not shown).

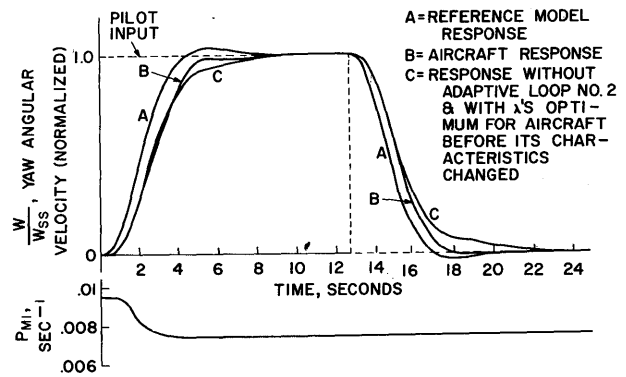


Figure 8a: Aircraft Response to Pilot Inputs, A Change in Aircraft Speed @  $t=0$  Initiates Adaptation

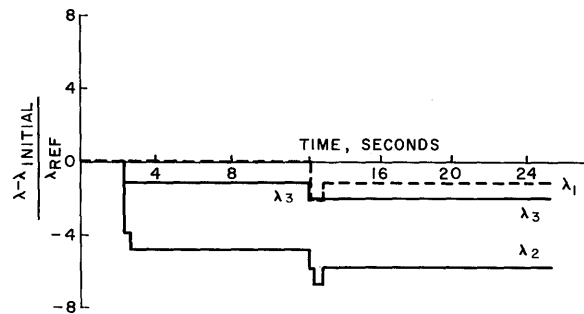


Figure 8b: Gain Adjustments During Response of Figure 8a

The response to an unanticipated input to the aircraft, in the form of a large, constantly applied deflection of the control surface, is shown in Figure 9. This was a most severe test of the adaptive system and demonstrated the need for improvement in defining an index of performance. Parameter cross-coupling with the present E was significant in this experiment. It is felt that the modifications suggested above would constitute a significant improvement. In view of the magnitude of the disturbance and the fact that

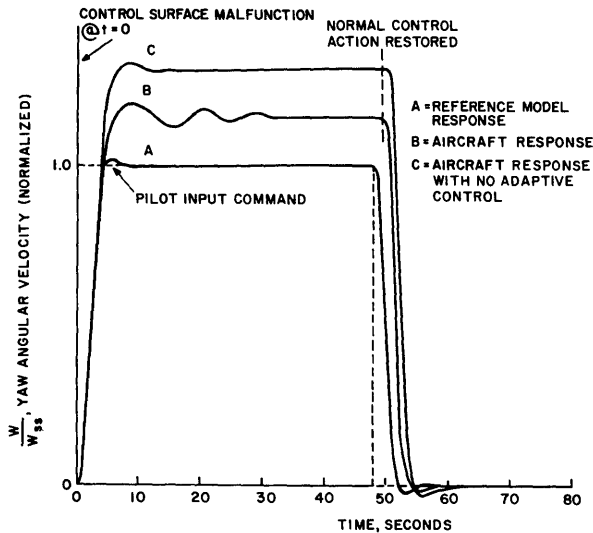


Figure 9: Aircraft Response to Pilot Inputs, Adaptation Initiated by Control Surface Malfunction

exact compensation for an undesirable input may be impossible by adjusting controller gains, the response obtained is considered adequate and

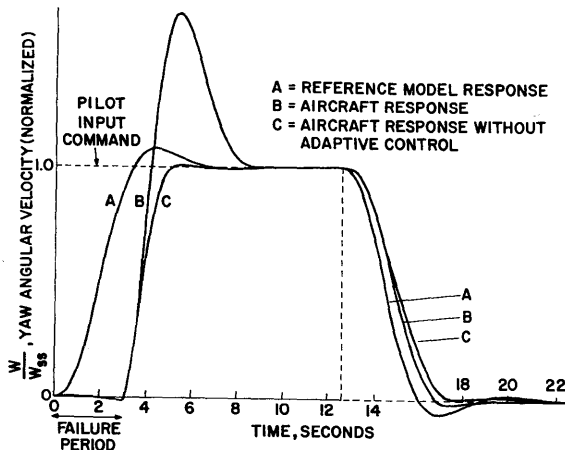


Figure 10a: Aircraft Response to Pilot Inputs when Main Servo Experiences Temporary Failure

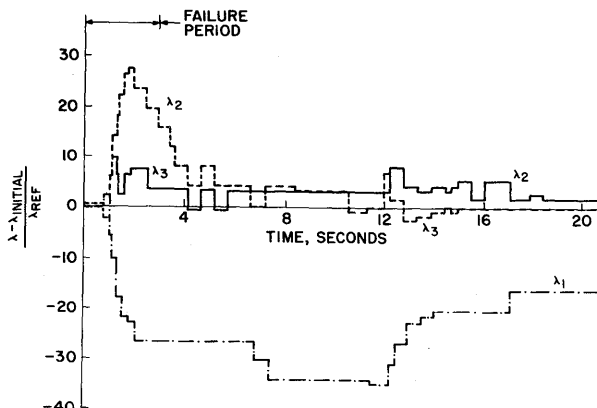


Figure 10b: Gain Adjustments Under Conditions of Temporary Servo Failure

certainly better than that obtained without adaptive control.

The response to a failure condition is shown in Figure 10. At time  $t=0$ , the main servo becomes "locked" in an inactive state and remains in this condition for three seconds. This is an "open-circuit" type of failure. During the three second period the remainder of the control system, which operates correctly, reaches some limit condition, because no feedback signals from the aircraft outputs are forthcoming. At  $t=3$ , the servo operation becomes normal. The response of the system from the limit condition then reached is of interest. Adaptive control is seen to institute corrective action very rapidly and avoids the large overshoot associated with no adaptive action.

**Changing Goals:** Intentional changes in the parameters  $q_i$ , should lead to new aircraft performance, since the reference model is now changed. The successful adaptation to these changing specifications is shown in Figure 11.

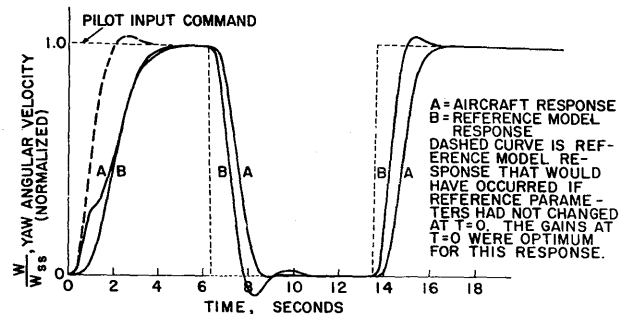


Figure 11: Aircraft Response to Pilot Inputs, Reference Model Changes During Manuevers

## CONCLUSIONS

Hybrid computation has advanced to the point where the feasibility of using fairly sophisticated adaptive control techniques can be easily and economically investigated. Extensions of this illustrative problem to others requiring multispeed operations with iterations of differential equations can easily be made. The effectiveness of the analog computer in the solution of such problems is greatly enhanced by a flexible logical computer, which permits greater utilization of analog time and equipment and which can be easily tailored to fit each application.

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