MODEL REFERENCE ADAPTIVE SYSTEMS TO IMPROVE RELIABILITY

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ABSTRACT

One means for improving the reliability of an automatic control system is proposed whereby the system is given the capability for reorganizing or readjusting itself to repair the effects of failure of the components of the system. This paper shows how a model reference adaptive control system can be used to realize that capability, and shows by simulation of the performance of an aircraft flight control system how the rapid convergence times of these systems can accomplish the necessary readjustments fast enough to prevent dangerous flight disturbances due to the failures. Extension to other flight vehicles can be readily made.

INTRODUCTION

The purpose of this paper is to describe the use of a model reference adaptive control system not only to achieve a specified dynamic performance but also to increase control system reliability. It is an extension of the work reported in Refs. 1 and 2 to the consideration of providing a capability for self-reorganization after partial failure occurs.

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Adaptive control systems have been developed so that a specified dynamic performance can be achieved, even though the characteristics that affect that performance vary during the operating times of the system due to either changes in environment or wholly unanticipated reasons. The mission of a high performance aircraft provides examples of the former, and this paper considers various failures of typical components in a system as examples of the latter. By using an adaptive system combined with redundant control channels, acceptable performance can result even though certain multiple failures occur. The model reference adaptive system is attractive for this application because of its rapid convergence to the optimum operating condition from an arbitrary initial state. The parameters can be readjusted fast enough to prevent dangerous flight attitudes even in the event that a failure occurs which would cause instability if no adaptation took place.

Since the emphasis of this paper is on the use of an adaptive system, it is not the authors' purpose to present an exhaustive treatment of the hardware considerations in the design of redundant channels for reliability. An automatic control system for aircraft will be used as an example to illustrate the techniques, but other control applications can of course be suggested.

MODEL REFERENCE ADAPTIVE SYSTEMS

The model reference adaptive control concept (1-4),[3] as originally proposed and investigated at the M. I. T. Instrumentation Laboratory, was evolved to make it possible to design a control system that could adjust its own controllable parameters so that its dynamic performance would satisfy the system specifications in the presence of changing operating characteristics. To do this, a reference model is provided which stores the system specifications and permits closed loop control of the parameters through the use of response error functions measured during the normal operating responses of the system. Optimum, or fully adapted, performance is achieved when the measured error functions have values corresponding to a specified performance index. Use of the model permits design flexibility, since the model can change with the operating modes of the vehicle and can exhibit nonlinear characteristics if the system specifications require these features.

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[3] Numbers in parentheses indicate References at end of paper.

Fig. 1 is a simplified functional diagram of the adaptive system. The dotted box encloses the components that are contained in a complete closed loop control system capable of performing its assigned function provided its parameters can be adjusted to proper values. The input to the system is also fed to a reference model, the output of which is proportional to the desired response. This output is compared with the indicated system output to form the response error. The need for parameter adjustments is determined by generating functions of the error, and command signals calling for time rates of change of the controllable parameters are sent to the parameter adjustment devices in the control system. Any needed parameter adjustment takes place whenever any typical operating input signal or disturbances exist, and the adaptive features can be operated continuously. No special test inputs (step function, impulses, sinusoids, etc.) are needed.

The model reference adaptive control concept can readily be applied to make any control system adaptive by using the design techniques described in Ref. 2 and in the Appendix. The dynamic performance of the control system will then approximate that of the reference model, whose output is proportional to a system output that meets the system specifications. The controllable loop parameters are adjusted automatically so that the integral squared error between the system and model outputs is minimized, which is accomplished by nulling an integral error quantity for each parameter, as shown in the Appendix. As a result, convergence times on the order of the dominant characteristic time of the system can be obtained, and the adaptive features can be mechanized with simple equipment. The concept has been successfully applied to higher order systems with several controllable parameters and to cases with nonlinear or variable models.

USE OF REDUNDANT CHANNELS

The possibilities for improving the overall probability of mission success through duplicating or triplicating a flight control system with independent control channels have been extensively discussed in the literature (5, 6). Redundancy techniques rely on the fact that the probability of complete failure of the system to perform satisfactorily can be made less than the probability of failure of a single channel. This paper uses as an example an aircraft multiloop control system that is triplicated to provide a threefold independent redundancy. By proper selection of the design output capability of each channel, one entire channel can fail completely, and the original dynamic performance can still be achieved. One channel overcomes the effects of the failed channel, and the third channel remains to provide the required control capability. A triplicated system also makes it possible to determine which channel has failed so that it can be deactivated. If, in addition, the failure causes a change in dynamic characteristics, an adaptive capability can restore the original dynamic response.

In an aircraft that must use a fully powered hydraulic actuator to deflect a control surface, the pilot mechanically controls the position of the servo valve, and reliability is achieved by duplicating the hydraulic systems and providing emergency sources of power. To provide automatic control, smaller servo actuators are used to add inputs to the main hydraulic actuators either in parallel with or in series to those of the pilot, as shown in Fig. 2. If redundant automatic control channels are provided, the outputs of the several servo actuators must be summed mechanically in some manner and then fed into the main actuator. Two methods are generally considered. In one, the output member shafts of the servo actuators are tied in parallel to a common linkage member, which in effect sums the force outputs of the actuators to cause a resultant movement of the linkage member. In the other method, a series mechanical summing linkage is used to obtain a mechanical displacement of some point proportional to the sum of the individual displacements of the actuator output shafts. In a multiloop system that is adaptive, the series summation design can also compensate for certain secondary failures in addition to one servo actuator failure without any reduction in system performance, and certain tertiary failures can occur with only a resulting reduced output operation. There is an analogy here with the case of a loss of an engine on a multi-engine aircraft for which the remaining power permits safe operation although with a reduced maximum performance. One disadvantage of the series method is that a loss of one of the channels results in a reduction of loop gain with a corresponding change in dynamic performance, but the adaptive system removes this limitation in the same manner that it handles loop gain changes due to changes in environment. To illustrate these adaptive features, the series summation method was selected as an example for this paper. There are other advantages of each method, but these need not be considered here.

Many failures in the various components may be classed as either "hard-over" failures or "open circuit" failures. The net result of the first type is that a servo actuator drives at its maximum speed in one direction, which may be caused by any failure that holds a valve wide open. In the second type there is an abrupt loss of signal in one channel with an attendant loss in the overall system loop gain. Other failures due to slow deterioration or intermittent operation may also occur, but these are not as critical from the flight safety viewpoint.

ILLUSTRATIVE EXAMPLE

Consider the yaw control system of Figs. 3a and 3b for controlling the lateral axes (roll and yaw) of a supersonic transport (7). This particular control system has been chosen so that the adaptive techniques could be illustrated using a system whose dominant linear dynamic characteristics were at least fifth order, and which required the adjustment of three controllable parameters to satisfy its performance index. The input command to the system applies a torque about the output axis of a single degree of freedom integrating gyro unit, and the resulting control action causes the aircraft to rotate so that there is a component of its angular velocity with respect to inertial space about the aircraft yaw axis proportional to the input command. With no command, the aircraft maintains a constant yaw orientation with zero roll angle. Roll rate and roll angle loops are also provided for stability. Further description of this type of system can be found in Ref. 3.

The systems and aircraft of Fig. 3 were simulated on a GPS repetitive, compressed time analog computer. Three redundant channels were provided, and the output displacements of the three autopilot servos were mechanically summed by an arrangement that can be drawn schematically as in Fig. 4, in which the three hydraulic autopilot servos are shown. Linkage members 1 and 2 were floating summing members. Each servo was loaded by preloaded springs so that a disengaged servo would provide a pivot point for its corresponding floating linkage member. In normal operations, however, the displacements of the three servos would be approximately equal, and the summing members would translate only. In case of failures that permitted release of hydraulic pressure in the failed channel, the spring restraints would recenter the servo. Floating member 3 added the servo outputs in series with those of the pilot, and the springs had to provide preloads greater than the value reaction forces so that this member would rotate when the servos were disengaged.

To make the system adaptive, three system parameters were controlled to obtain optimum performance throughout the flight profile of the aircraft. These were taken to be the open loop gains of the three feedback loops of Fig. 3. To achieve the same type of failure protection that was provided in the triplicated basic control system, the adaptive system was also triplicated. Since it is desired that the magnitudes of the input signal to the three servo actuators be equal to prevent spurious disengagements, any variation in gain called for by one adaptive system varied the gains of all three systems. This was equivalent to mounting three potentiometers on the same servo driven shaft, although in practice variable gain gates driven by an electronic counter would be used. Because the adaptive equipment was triplicated, there would be three sets of gates for each of the variable parameters.

For simplicity, in Fig. 3 only one of the redundant control system channels is shown. With the exception of the main actuator and the aircraft, the components would appear in triplicate. The three control servos and the tie-in to the main actuator would appear as shown in Fig. 4. Similarly, only one channel of adaptive equipment is shown to control the three variable gain gates, G_1, G_2, G_3. Each set of gates changes the corresponding gains of the three redundant channels, as shown schematically for gate G_1. Such an amount of equipment would be impractical in an aircraft installation a few years ago before the development of modern computer technology. Now, the packaging of this amount of capability can be relatively small and simple in comparison with many current systems. For purposes of notation, the three controllable system parameters were designated as follows: P_1, the open loop gain of the yaw integrating gyro loop; P_2, the ratio of the roll angle stabilization loop gain to P_1; and P_3, the ratio of the roll rate damping loop gain to P_1.

Provision was made for monitoring a failed channel so that it could be deactivated. When this took place, the disengaged servo was recentered by the centering springs with a longer characteristic time constant than that of the engaged servo. The monitor compared the output displacement of the three autopilot servos and disengaged one if its output was not the same as those of the other two within a given tolerance level. Since the system is nonlinear, a simulation scale factor must be specified when discussing the nonlinear elements. With the selected scale factor, the monitor level used corresponded to 66% of full travel of one series actuator. This is much higher than necessary for providing reasonable protection against nuisance disengagements. The logic for the monitor is summarized in the following equations:

A, B, C = command to disengage channel 1, 2, 3

$\delta_1, \delta_2, \delta_3$ = autopilot actuator displacements of channels 1, 2, 3

ϵ = tolerance level (positive)

$$A = (|\delta_1 - \delta_2| > \epsilon) \text{ and } (|\delta_1 - \delta_3| > \epsilon) = ab$$

$$B = (|\delta_1 - \delta_2| > \epsilon) \text{ and } (|\delta_2 - \delta_3| > \epsilon) = ac$$

$$C = (|\delta_1 - \delta_3| > \epsilon) \text{ and } (|\delta_2 - \delta_3| > \epsilon) = bc$$

A failure anywhere in a channel disengaged that channel if the outputs were sufficiently different. Upon disengaging one channel, no further automatic monitoring action took place, but an indication of the failure was presented to the pilot so that he would be aware of his reduced system capability and could take appropriate emergency procedures.

Typical results are shown in Figs. 5-7. Fig. 5 is presented to show the capability of the adaptive system to converge rapidly to its optimum state from an arbitrary set of the parameter values. At zero time, P_1 was 57% of its optimum value, P_2 was 70% and P_3 was 57%. Such a mismatch of parameter values would be extremely unlikely even at the time the control system is first activated, although a multiple failure can be visualized which would correspond to this case. The input to the system was a step function command applied at zero time, calling for a constant bank angle turn followed by a step function roll-out command applied after the roll-in had been completed. Fig. 5a shows the desired yaw angular velocity (or roll angle) response as represented by the output of the model. Superimposed on the model is the response of the system with the adaptive system operating to readjust the parameters. The response error was reduced to and remained less than 5% of the steady-state input command in a time that is roughly 40% greater than the model's response time. Fig. 5b shows that the major readjustment of the parameters took place using only the error information available during the first transient maneuver. Fig. 5c shows that had no adaptation taken place, the system would be only marginally stable and quite unusable. To experience this gain configuration through system failures, an approximately equivalent case results if one channel fails and is disengaged, if there has been an "open" in one of the remaining P_2 channels, and if there has been an "open" in one of the remaining P_3 channels.

Fig. 6 shows the operation of the system when a "hard-over" failure occurs during level flight with no input command. Fig. 6a is with no monitoring action, and Fig. 6b is with monitoring action and recentering of the failed channel. In each case a 33% reduction in loop gain results. In the absence of an input command, the disturbance resulting from the failed servo appeared to the adaptive system as an output member disturbance, but even this provided some information for gain readjustment. The speed of adaptation is dependent on the gain of the adaptive loop and the magnitude of the error signal. For the conditions of this run P_1 achieved approximately 25% recovery during the transient caused by the "hard-over" failure. The primary adjustment required was that of P_1, although all gains adjusted themselves in an attempt to minimize the disturbance.

Fig. 7a shows the operation of the system for a compound failure occurring during the transient response to an input command. The sequence of events of this run was: 1) a command to the system at t = 0; 2) a "hard-over" failure at $t/t_{ref} = 0.18$; 3) detection of the failure and recentering of the failed channel; and 4) open in one of the two remaining rate damping paths at $t/t_{ref} = 0.45$. These failures caused a 33% reduction in P_1 followed by a 50% reduction in P_3. It can be seen from Fig. 7b that with no adaptation this compound failure resulted in an almost unstable system that rendered it unusable. With the adaptive system operating, the system not only retained good stability, but the adaptation restored the original dynamic performance in a time interval following the failures of approximately 1.3 times the response time of the model. Only the maximum output level has been reduced due to the loss in servo output capability.

SUMMARY

The results of the simulation study presented in this paper show that model reference adaptive control techniques further extend the improvements in system reliability which can be obtained by using redundant control channels. Because of rapid convergence to the optimum operating condition, the adaptive system can readjust system parameters to prevent instability, even though failures cause abrupt changes in system characteristics which could result in instability if no adaptation takes place. Although the system may momentarily be unstable after a failure or a series of failures, the parameters can be readjusted fast enough to prevent an excessive perturbation of the system output.

The example that was chosen to illustrate the basic principles is an aircraft flight control system, but the same techniques may be applied to many control problems. These techniques should be of particular interest in automatic landing of commercial aircraft where reliability must be extremely high and in the control of satellites and outer space probes where the extremely long times of flight indicate a fairly low probability of successful completion of a mission when using single channel systems.

The following considerations are pertinent to the design of model reference adaptive systems:

1) The concepts can be applied to any control system whose parameters must be varied during its operating time in order to achieve a specified dynamic performance.

2) Adaptation can take place continuously using the normal operating and disturbance inputs to the system.

3) No special test inputs are required.

4) Error quantities required for adjusting the parameters can be readily generated using signals available in the control system.

5) The model is designed by the system specifications and need only approximate the dynamic characteristics of the system over the frequency range of importance.

6) The filters required to generate error weighting functions are specified by the model design and the fixed compensation elements of the control system.

7) The system is sensitive to instability and will rapidly readjust parameters to avoid instability.

8) When used in conjunction with redundant channels, it permits safe operation even with multiple component failures.

APPENDIX

This appendix describes the analytical considerations for design of model reference adaptive control systems. A more complete discussion appears in Refs. 1 and 2.

For the purpose of definition of terms, Fig. 8 is a mathematical block diagram representation of the model reference adaptive system of Fig. 1, showing the generation of the response error quantity. The performance of each component block of the diagram is represented by its performance function (or transfer function) with subscripts that identify the component and its input and output quantities.

The criterion for successful adaptation is that the integral squared error be the minimum value obtainable with the parameter variation provided. The response error is the difference between the system output and the model output quantities. The performance index is thus given by

$$\int (E)^2\, dt = \int (q_{s_i} - q_m)^2\, dt = \text{minimum} \qquad [A-1]$$

Since $(E) = f(P_1, P_2, \ldots P_n, t)$, where the P_n are the controllable loop parameters, the desired operating state for the system is the one at which

$$\frac{\partial}{\partial P_n}\left(\int (E)^2\, dt\right) = 0 \qquad [A-2]$$

If the limits of integration are independent of P_n and if the integral of the derivative of the function exists, an error quantity can be defined by

$$(EQ)P_n = \int \frac{\partial (E)^2}{\partial P_n}\, dt = 2\int \left(\frac{\partial E}{\partial P_n}\right) E\, dt \qquad [A-3]$$

The performance index then requires that this error quantity be zero. Eq. A-3 states that if an error quantity signal could be generated proportional to the product (the rate of change of the error with the parameter multiplied by the error), the parameter should be adjusted until the integral of that signal is zero. In practice, the integration can be performed by the same device that adjusts the parameter, and it is required only to generate the product of the two signals and feed this quantity as an input signal to the parameter adjustment device. The net change in the parameter over some time interval is then proportional to the integral error function. That is

$$\Delta P_n = (EQ)P_n \qquad [A-4]$$

The net change in the parameter is zero when the error quantity is nulled.

The error quantity function of Eq. A-3 can be expressed in an alternative manner by interpreting $(\partial E/\partial P_n)$ as an error weighting function $W_E(t)$, or

$$(EQ)P_n = C\int W_E(t)\, E(t)\, dt \qquad [A-5]$$

where C is an arbitrary constant.

Ref. 2 shows that this weighting function can be readily generated in a model reference adaptive control system as follows. Because variations in the system parameters do not affect the model

$$W_E(t) = \left(\frac{\partial E}{\partial P_n}\right) = \left(\frac{\partial q_{s_i}}{\partial P_n}\right) \qquad [A-6]$$

Since q_{si} is the only indication of the system output quantity, no loss in generality occurs if the subscript i is dropped.

The determination of $W_E(t) = (\partial q_s/\partial P_n)$ can be accomplished in two ways. In one of these, a straightforward partial differentiation of the differential equation for q_s as a function of the input quantities can be made. An alternative method leads more directly to the system signals that are needed for generating the weighting function. If the system mechanization is considered, the controllable parameter can always be represented as a variable sensitivity S_p in some signal path of the system. This is true even if the effect of the change in the sensitivity is to change a compensation time constant rather than a control loop gain. The partial derivative $(\partial q_s/\partial P_n)$ is proportional to the change in the system output for a change in the sensitivity. The variable sensitivity for a typical case can be represented as shown in Fig. 9. Across the controllable sensitivity

$$e_S = S_p\, e_2 \qquad [A-7]$$

Also

$$\partial e_S = e_2\, \partial S_p;\; e_S + \partial e_S = S_p\, e_2 + e_2\, \partial S_p \qquad [A-8]$$

The effect of the change ∂S_p can be considered as a disturbance entering the system at a point following S_p.[2] Ref. 8 shows that the performance function relating the output of the system ∂q_s to a disturbance input is equal to the performance function of the system for the q_{in} input multiplied by the reciprocal of the performance function of the chain of components of the forward signal path from the input q_{in} to the disturbance summation point, or

$$\partial q_s = (PF)_{s[q_{in}, q_s]} \left(\frac{1}{(PF)_{1 \ldots}} \right) e_2 \, \partial S_p \qquad [A-9]$$

Hence

$$\left(\frac{\partial q_s}{\partial S_p} \right) = (PF)_{s[q_{in}, q_s]} \left(\frac{1}{(PF)_{1 \ldots}} \right) e_2 \qquad [A-10]$$

Eq. A-10 shows that the error weighting function is a quantity that could be generated by taking the signal that occurs at the input to the variable parameter and feeding it through a filter having the same performance function as the system, cascaded with a filter that is the reciprocal of some of the forward path components. However, the first filter cannot be used, because it is exactly this ignorance of the system that leads to the requirement for adaptation.

The model reference system provides a way out of this dilemma by the inherent requirement that the model is designed so that it provides a good approximation to the dynamic characteristics of the system when the P's are properly adjusted. Thus the approximation to Eq. A-10 is made by substituting the model performance function for that of the system. The Laplace transform of the error weighting function then is

$$W_E(\lambda) = (PF)_{m[q_{in}, q_m]} \left(\frac{1}{(PF)_{1 \ldots}} \right) e_2(\lambda) \qquad [A-11]$$

In practice, the controllable sensitivities can be located at points for which the cascaded forwarded loop performance functions are constant or at most simple known compensation functions.

[2] Other equivalents for different configurations are readily drawn.

NOMENCLATURE

A_X = roll angle

C = arbitrary constant

E, $(E)q$ = response error defined as difference between the model and the system output quantities

e = control path voltage signal

$(EQ)_P$ = error quantity for the parameter P; a function of the error which indicates the need for adjustment of P

G = variable gain gates for parameter adjustments

P = value of a controllable system parameter

ΔP = incremental adjustment to P

$(PF)_{n[q_{in}, q_{out}]}$ = performance function of component n relating the output q_{out} to the input q_{in}

q_{in} = system input quantity

q_m = model output quantity

q_s = system output quantity

q_{s_i} = indicated system output quantity

$S_{n[q_{in}, q_{out}]}$ = static sensitivity of component n relating the output q_{out} to the input q_{in} under steady conditions

t = time

t_{ref} = reference time to normalize time response records (t_{ref} = response time of the model to a step-input)

$W_E(t)$ = error weighting function

W_X = aircraft roll angular velocity with respect to inertial space

W_Z = aircraft yaw angular velocity with respect to inertial space

δ_a = aircraft aileron deflection

$\delta_{1,2,3}$ = autopilot actuator outputs of channels 1, 2, 3

ϵ = tolerance level of the monitor

λ = Laplace operator

τ_c = time constant of component identified by subscript

ζ = damping ratio (fraction of critical)

ω_n = natural frequency

Subscripts

A = aircraft

as = autopilot servo

ms = main servo

S = output of a variable sensitivity point

ss = steady state

s = system

i = indicated

m = model

1, 2, 3. . . = arbitrary components

c = command

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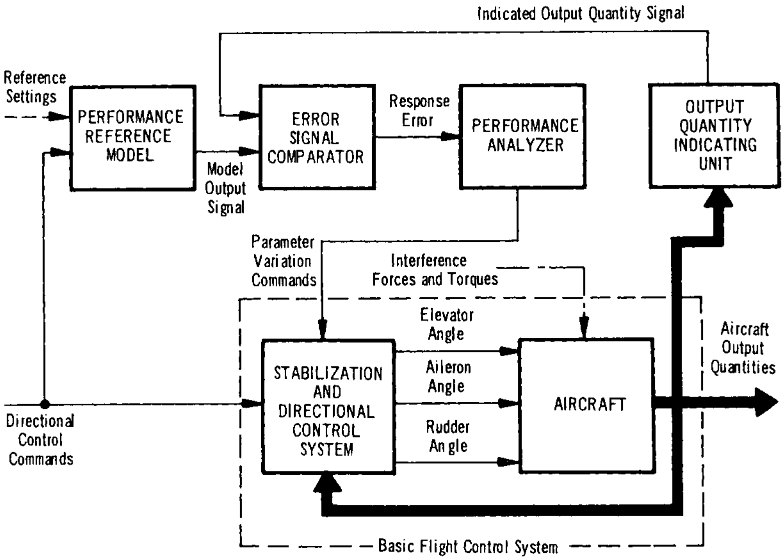


Fig. 1 Simplified functional diagram for a model reference adaptive flight control system

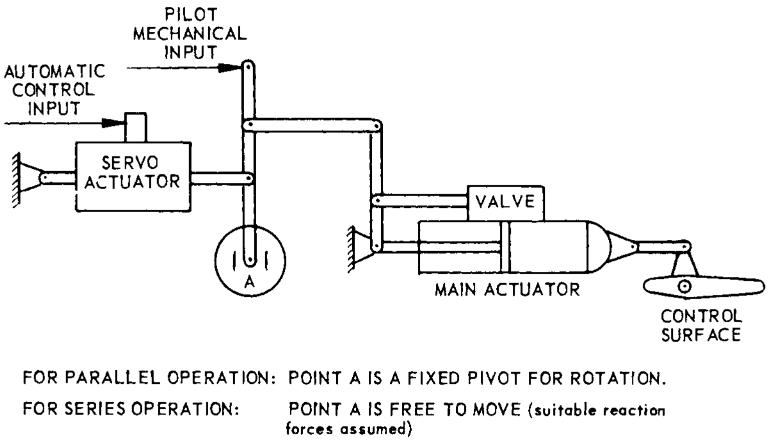


Fig. 2 Schematic diagram for providing automatic control deflection of an aircraft control surface

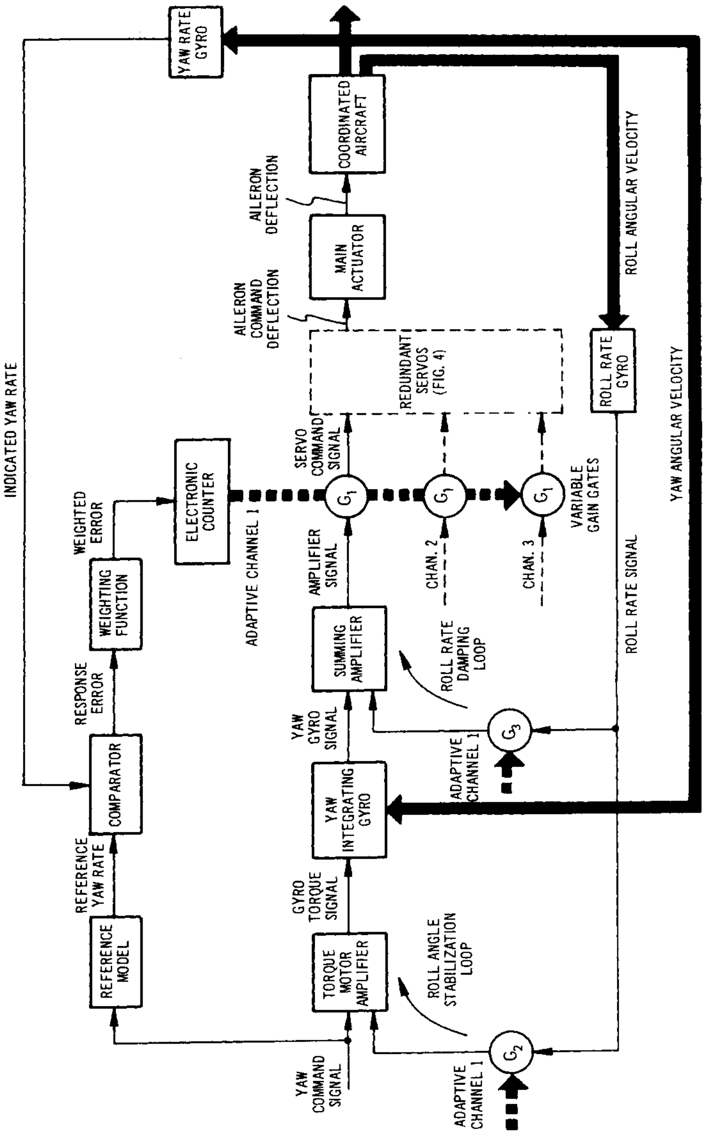
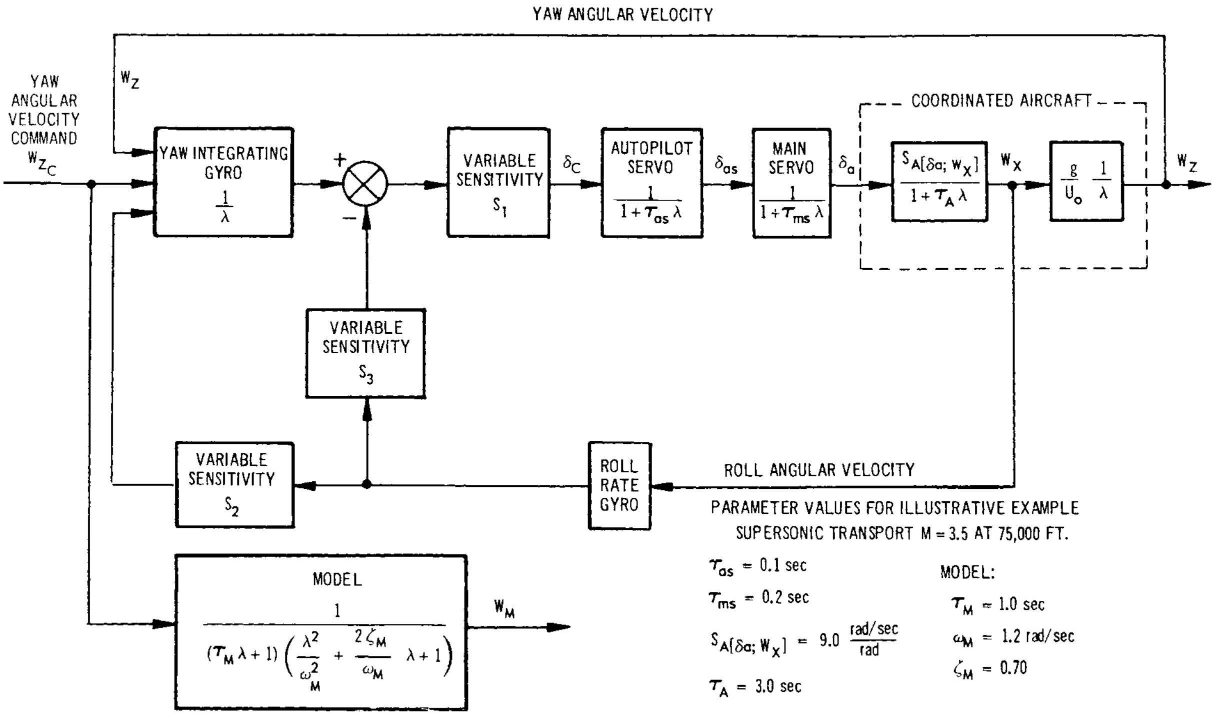


Fig. 3a Functional block diagram of the yaw control system showing only one of the redundant control channels and one adaptive channel



PARAMETER VALUES FOR ILLUSTRATIVE EXAMPLE
SUPERSONIC TRANSPORT M = 3.5 AT 75,000 FT.

τ_{as} = 0.1 sec

τ_{ms} = 0.2 sec

$S_{A[\delta a;\, W_X]} = 9.0 \ \frac{\text{rad/sec}}{\text{rad}}$

τ_A = 3.0 sec

$\frac{g}{U_o} = 0.0095\ \text{sec}^{-1}$

MODEL:

τ_M = 1.0 sec

ω_M = 1.2 rad/sec

ζ_M = 0.70

REFERENCE TIME USED TO NORMALIZE RECORDS t_{ref} = 3.0 sec

Fig. 3b Mathematical block diagram of the basic yaw orientation control system

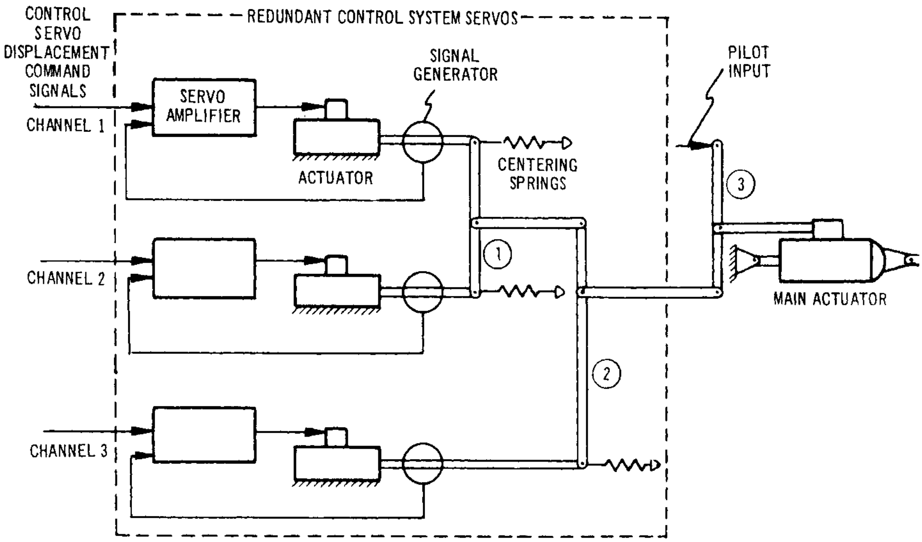


Fig. 4 Schematic diagram of three redundant servos whose output displacements are added mechanically

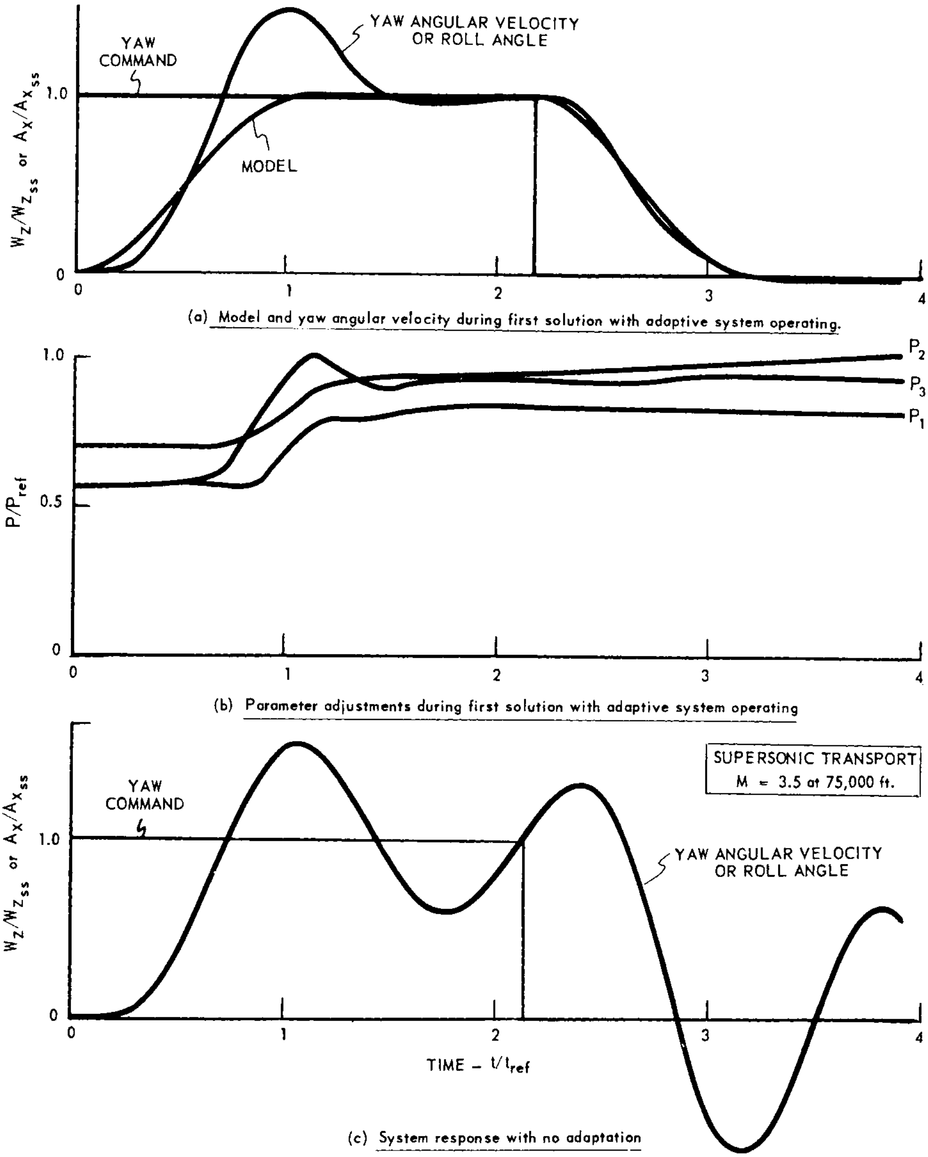


Fig. 5 Typical operation of the adaptive yaw orientation control system with the loop gains offset from optimum

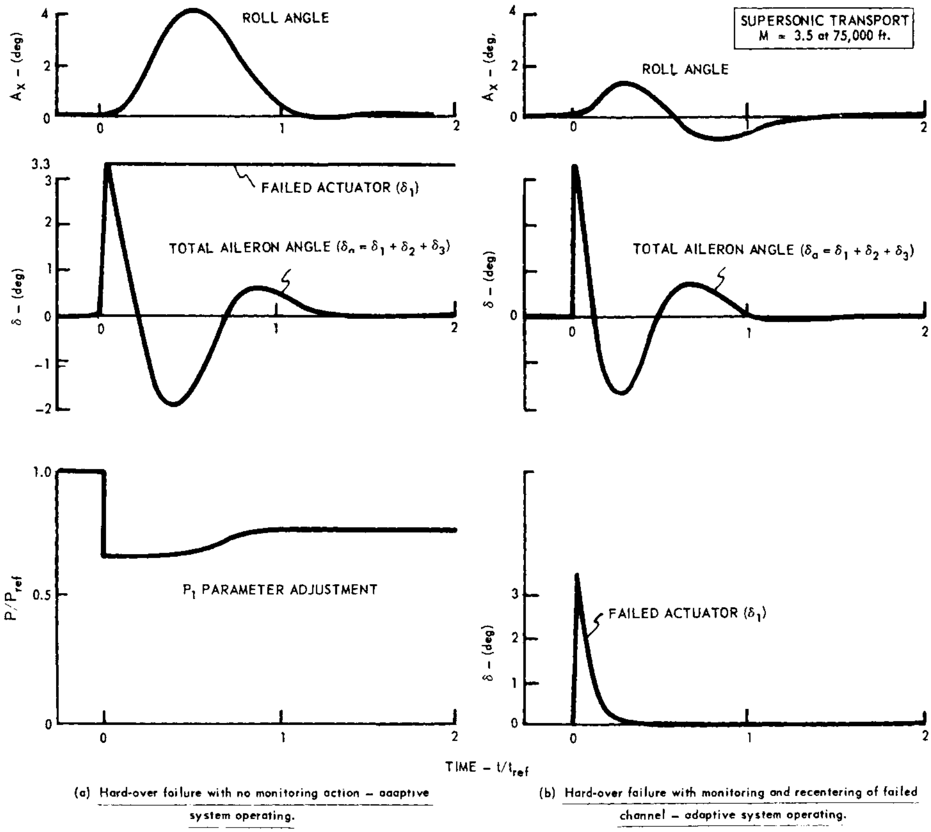


Fig. 6 Operation of the adaptive yaw orientation system in the event of a hard over failure and no input command

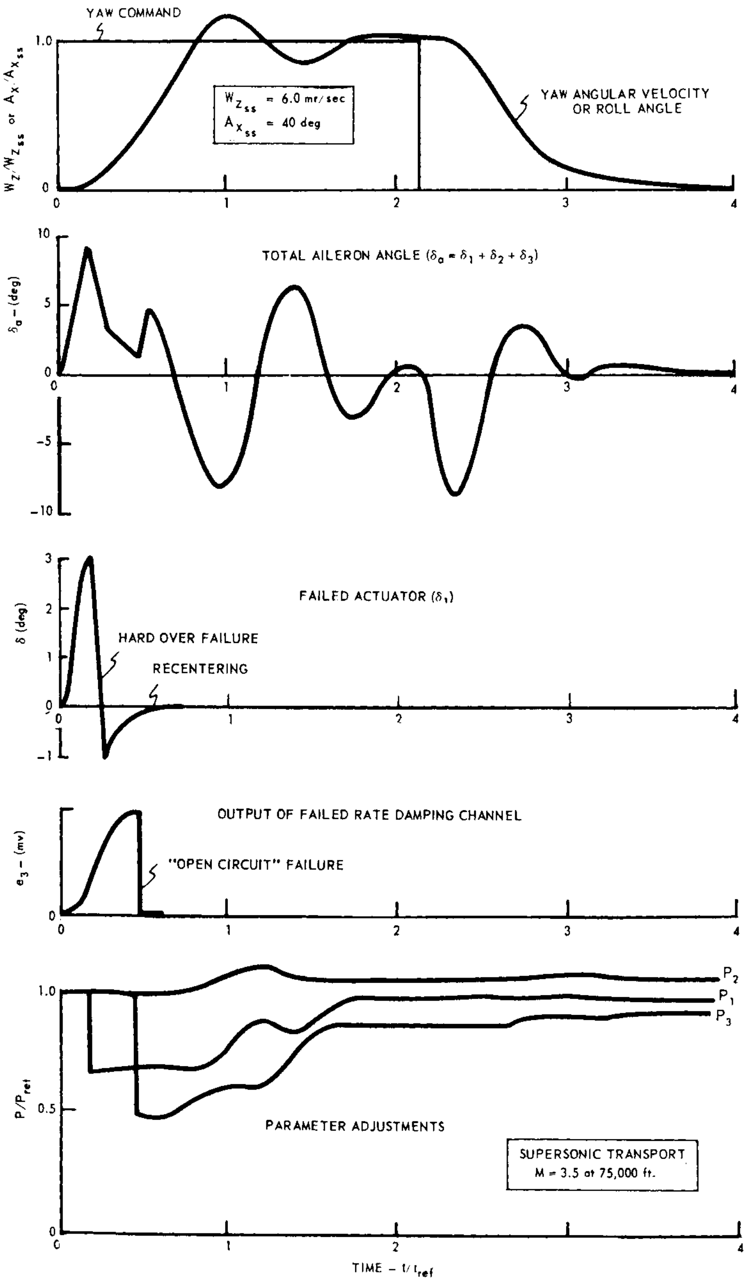


Fig. 7a Operation of the adaptive yaw orientation control system in the event of a compound failure during the response to an input command; adaptive system operating

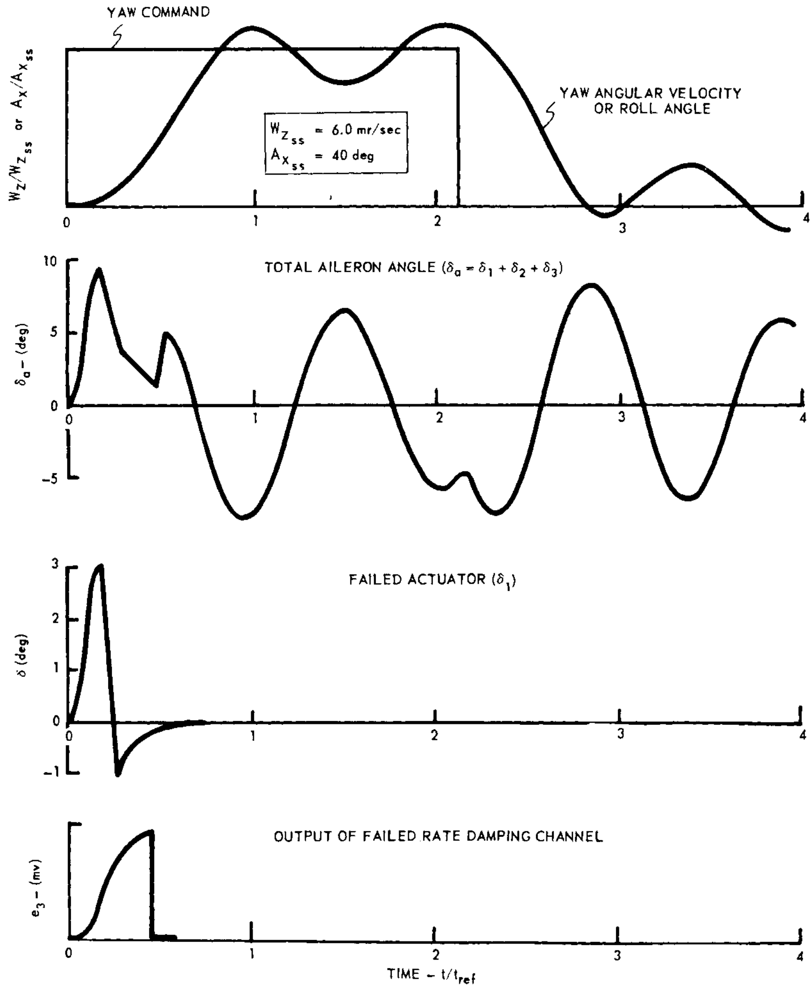


Fig. 7b Response of the yaw orientation control system in the event of a compound failure during the response to an input command; no adaptation

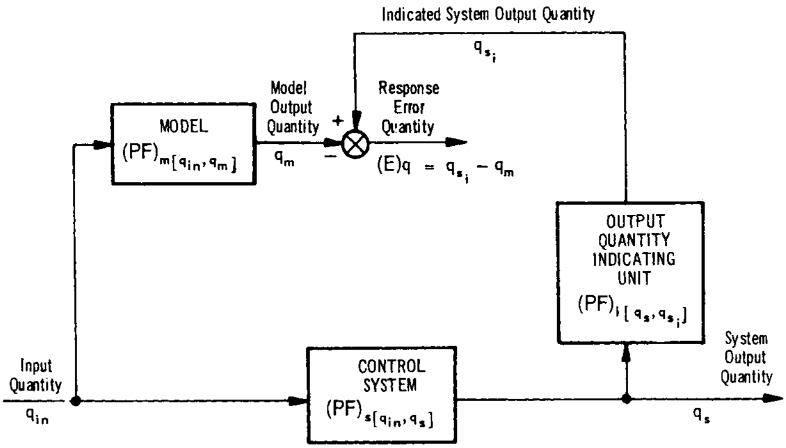


Fig. 8 Mathematical block diagram representation of a model reference adaptive control system

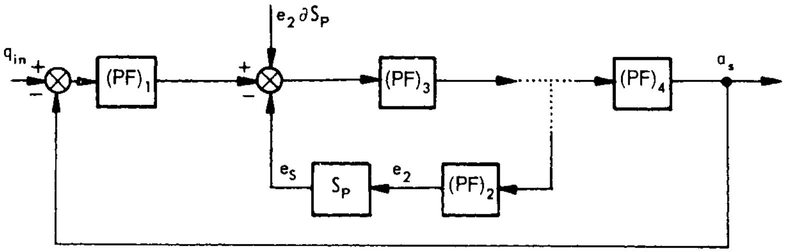


Fig. 9 Generalized control system block diagram