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# MASSACHUSETTS INSTITUTE OF TECHNOLOGY PRESENTATION

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An adaptive system is one that adapts itself to a changing environment, a changing character of input signals, or a changing system or component characteristic in such a manner that a desired performance will be maintained.

The development research program that has been completed by the M.I.T. Instrumentation Laboratory has investigated the characteristics of one class of adaptive control systems and their application to aircraft, missile, and spacecraft control systems. In later presentations, Dr. Li will consider the overall classification of the various kinds of adaptive systems. The type of system which I would like to discuss at this time is that which Dr. Li would call a dynamic performance adaptive system with closed-loop adjustment of system parameters. Such a system controls the dynamic performance of a control system with respect to a reference system, or specification, by adjustment of the system parameters either through a closed-loop process of nulling a performance index or through a self-optimalizing* process of seeking an optimum operating point. This type of system eliminates the uncertainties and design compromises that accompany the commonly used, open-loop, gain programs and the need for accurate estimation of the airplane performance functions prior to system design.

We have further suggested the name " model-reference adaptive system" for the type of system under consideration. A model-reference system is characterized by the fact that the dynamic specifications for a desired system output are embodied in a unit which is called the model-reference for the system, and which forms part of the equipment installation. The command signal input to the control system is also fed to the model. The difference between the output signal of the model and the corresponding output quantity of the system is then the response error. The design objective of the adaptive portion of this type of system is to minimize this response error under all operational conditions of the system.

*Definition of Optimum Response - It is obvious that criteria are needed for specifying an " optimum" response. In this regard the following definitions are proposed.

Optimum control of the aircraft is said to result if the control system provides close control of the transient and steady-state responses of the aircraft so as to utilize the capabilities of the aircraft most effectively in fulfilling the specifications of its flight mission. These specifications of course vary with the type of aircraft and are different for separate portions of the flight mission of any one aircraft (for example, the landing and the

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terminal interception phases). They may or may not require the maximum capabilities of the aircraft, but in almost all cases they will specify such characteristics as response time, damping, dynamic and static errors, and control of interference effects. This definition of optimum lays greatest emphasis upon meeting the mission specifications of the vehicle.

Figure 1 is a functional block diagram of a model-reference system. The characteristic feature of the model-reference type of system is the model, which is the physical embodiment of the design specifications of the system. A change in the model is exactly equivalent to a change in the system specifications. The first consideration, then, is to decide upon the system specifications, which of course must be compatible with the performance capabilities of the aircraft. When this is done, the model performance will also be compatible with the aircraft capabilities. Further, if different specifications exist for each mode of system operation, these differences can be incorporated into the model. The output of the model is the desired response of the system and is physically available as a reference signal. The command input to the system is also sent as an input to the model, and thus all of the information required for making the system adapt is obtained from the normal operational inputs to the system. If the performance function of the system were exactly the same as that of the model, the outputs of the system would be identical to those of the model. The system would thus meet its performance specifications, and its response would meet our definition of optimum. In general, the performance functions will not be identical, and the difference between the system response and the model response can then be a measure of response error which can in turn be used to generate error functions which are measurable criteria of system performance. These error functions (or quantities) then serve to generate command signals to change either the controllable parameters of the control loops or the characteristics of the input signal so that the desired response of the flight control system will result.

Note also that the adaptive control equipment is making adjustments to a control system whose feedback control loops are closed independently of the adaptive controls rather than being closed through the adaptive equipment. If the latter equipment fails, the control system still remains as a closed-loop system.

The adaptive control features can be added to any existing control system without major alteration of the control signal paths. In a multi-loop system the adaptive features can often readjust the remaining parameters to result in satisfactory flight characteristics even though complete failure of the adaptive controls for one parameter occurs. (We discovered this when it happened to us in flight.)

For these reasons it appeared that greater flexibility could be obtained with a model-reference system. When this was considered together with the relative ease with which the required equipment could be built and installed

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in the aircraft currently bailed to the Instrumentation Laboratory, it was decided to investigate this type of adaptive system.

To evaluate the techniques developed during this program, they were applied to an all-maneuvering flight control system developed earlier at M.I.T. and flight tested in an F-94A airplane. They are not restricted to use only with this system, however. In the complete system, seven parameters were varied. Three of these were in the pitch sub-system, one in the rudder coordination sub-system, and three in the yaw sub-system. Only limited flight test time was available for the program, and as a result it was not possible to flight test the complete system at one time. On two flights it was possible, however, to have six of the seven parameters controlled automatically by the adaptive system.

There is insufficient time available this morning to cover the details of the entire system. They are presented in the final report of this program, and this report is available here today. To illustrate the design procedures, let us consider the yaw sub-system in detail, and if time permits briefly outline the main features of the pitch and rudder coordination sub-systems. All of the slides to be presented are taken from figures found in the final report, and you can study them in more detail by referring to the report later.

The design procedure consists of the following steps:

1. Design of a model to meet the system pspecifications
2. Selection of the control system loop configuration
3. Determination of which parameters should be varied and how they affect the system response
4. Determination of error criteria which will adjust the parameters
5. And finally, analysis and simulation to determine the convergence times and dynamic operating performance of the system.

Since no mission specifications had been set up for the system of this development program, an arbitrary dynamic performance specification was chosen. This was expressed as the requirement that the system generate an aircraft yaw angular velocity in response to a command input, and that for a step function input a response time of approximately 3 seconds with no overshoot would result. The loop configuration in this case was chosen to be that of figure 2.

This figure presents a functional block diagram of the adaptive yaw system. This is an orientational control system which stabilizes the aircraft

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to the yaw reference orientation established by the yaw integrating gyro. This yaw system produces yaw angular velocity with respect to inertial space proportional to a yaw command signal input. The yaw angular velocity is generated by rolling the aircraft to establish a roll angle while minimizing aerodynamic sideslip. Two degrees of freedom are thus involved, and the yaw system is accordingly more complicated than the pitch system. It has been found that the rudder coordination system required to control sideslip can be analyzed separately from the outer loops which control roll angle and yaw angular velocity. The rudder coordination system was also adaptive and is described in the report. In the discussion that follows, it will be assumed that the rudder system is operating correctly, and if time permits we will return to it later.

For the present application, the dominant modes of the system can be represented by a third order performance function exhibiting one real pole and a pair of complex conjugate poles. Therefore, a third order model-reference was chosen, and in order to meet the system specifications the real pole exhibited a characteristic time of 1.4 seconds, and the second order poles were characterized by an undamped natural frequency equal to 1.65 radians/second and a damping ratio of 0.8.

An additional design feature which increases the flexibility available to the designer was also investigated during this program. It was recognized that meeting the same system specifications at low dynamic pressure flight conditions would require a very high open-loop sensitivity for the yaw orientational control loop. Such gains may be undesirable from fail-safe considerations. Further, since parallel control servos were used in the test airplane, past experience had indicated that the high loop sensitivities would result in control stick deflections due to random turbulence to which the pilots would object. If the loop sensitivity were arbitrarily limited at some maximum value, however, the error criterion used to control that sensitivity could no longer be satisfied at those flight conditions that require higher values. The remaining control loops would readjust to produce the best system possible under the circumstances, but the system would cease to operate about its optimum point, and all the error quantity signal levels could be expected to increase.

There are several solutions to this problem. The one that was investigated here was chosen for its apparent reasonableness and simplicity. It was recognized that one might indeed desire a different system specification at the lower dynamic pressure conditions. In particular it may be desirable to have a slower responding system when the aircraft is near its stalling speed. This can be accomplished very simply by making the first order term in the model performance function vary once the limited value of the orientation loop is reached. In operation, whenever high sensitivities were called for, the model slowed down until the maximum available sensitivity was sufficient to permit the error criterion to be satisfied. In this sense, the model itself was adaptive, and the sampling criteria which were derived from the model were also adaptive.

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With the performance specifications established in the design of the model, there remained the task of selecting error criteria and assigning the various loop parameter controls to minimize them. In our approach to date, various functions of the response error have served to define error quantities. The criteria of performance are the specified optimum values of the error quantities usually taken to be either minimum or null values. In general, the error quantities are examined over some interval of time called the sampling time. In this approach, the sampling time has been controlled by the input and output signals of the system model. The sampling begins with the initiation of a normal operating input to the system and is terminated at a time that is controlled by the magnitude of the output of the model in relation to the input. This enables one to tie the length of the sampling interval to such quantities as the rise time or the solution time of the dynamic model.

There are three parameters which can be varied to control the dynamic response of the system. These are the open-loop sensitivities of the three control loops. For convenience the three parameters chosen express these open-loop sensitivities in terms of the ratios of the aileron displacement to the three output quantities yaw angle, roll angle, and roll rate since these are the measurable ground calibration quantities. The three parameters are represented by the notation: $P_{yoc}$, the yaw orientational control loop parameter; $P_{rs}$, the roll stabilization loop parameter; and $P_{rd}$, the roll damping loop parameter.

In selecting an error quantity for the orientational loop parameter, it was observed that this sensitivity directly affects the magnitude of the torque applied to the airplane in response to an input command. It is thus effective in controlling the initial portion of the response, or the rise time of the system. Therefore, the error quantity chosen to control $P_{yoc}$ was the integral of the error sampled over the rise time of the model, arbitrarily taken to be the time at which the model output reached 70% of the input. The error criterion was that the integral be zero.

Of the three variables, the roll stabilization parameter exerted the greatest effect upon the system stability. An error quantity that afforded a simple mechanization was desired, and a nulling rather than a minimizing quantity was preferred to reduce convergence time. Thus the error criterion for this parameter specified that the integral of the error sampled over the response time of the model was to be zero.

The integral of the absolute value of the error was chosen as the error quantity for the roll rate damping loop, and the design criterion was that this integral be a minimum. Even when the error criteria for the previous two loops had been satisfied, oscillations could result due to insufficient damping. The absolute value operation adds an increment to the error quantity for each half cycle of an oscillation, and thus the integral becomes large when oscillations are present.

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The next step in the design procedure is the analysis and simulation of the system to determine its static and dynamic performance characteristics.

Figure 3 presents some of the general features of useful error quantities. Before examining these error quantities it is appropriate to consider some general features of the properties of useful error quantities discussed in Chapter 2. If one first considers the case of two variable parameters, the extension to more variables is straightforward. If the parameters are $P_1$ and $P_2$ and the corresponding error quantities are $(EQ)_1$ and $(EQ)_2$, one can plot families of curves of $(EQ)_1$ versus $P_2$ for constant values of $P_1$. A typical presentation for a nulling criterion would be similar to that of Figure 3a. In the vicinity of any operating point defined by the set $(P_1, P_2)$, the change in $(EQ)_1$ can be written

$$d(EQ)_1 = \frac{\partial (EQ)_1}{\partial P_1} dP_1 + \frac{\partial (EQ)_1}{\partial P_2} dP_2 \qquad (1)$$

where the derivatives are evaluated at the point $P_1$, $P_2$. The second partial can be evaluated by cross-plotting the data for the desired value of $P_1$. Similarly, we could evaluate the change in $(EQ)_2$ as

$$d(EQ)_2 = \frac{\partial (EQ)_2}{\partial P_2} dP_2 + \frac{\partial (EQ)_2}{\partial P_1} dP_1 \qquad (2)$$

If one then selects a value of $P_2$, the value of $P_1$ which $(EQ)_1$ would select is given by the intersection point on the $(EQ)_1 = 0$ axis, and these can be plotted as in Figure 3b. If the process is repeated for the second error quantity data, another curve is obtained as in Figure 3c. If the two curves intersect at only one point, both error criteria are satisfied only for the values of $P_1$ and $P_2$ corresponding to the point of intersection.

Ideally, the second terms on the right-hand sides of Equations (1) and (2) would be zero, in which case the error quantities would be functions only of their associated parameters. If this were true the corresponding data for Figure 3a would show only one curve rather than a family of curves, and the Figure 3c would appear as shown in Figure 3d. On the other hand the error quantities become useless if there is no intersection in the range of usable values of $P_1$ and $P_2$ as in Figure 3e.

As you will remember the error quantities used to set $P_{yoc}$ and $P_{rs}$

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were two different samples of the integral of the error. The data corresponding to part c of figure 3 is shown in figure 4.

The error quantity selected for the roll damping loop was the integral of the absolute value of the error, and the type of minimum this quantity exhibits is shown in figure 5 for the case for which $(EQ)_{yoc} = (EQ)_{rs} = 0$.

As might be surmised the use of three error criteria result in some redundant action. Actually the final operating point is defined by the minimum of the integral of the absolute value of the error and could probably be attained through some method of time sharing the error quantity among the three parameters. The other two criteria, however, perform the very important function of greatly reducing the convergence time of the system as will be shown subsequently.

One can obtain a geometrical representation of the optimalizing action of the system by looking at a three-dimensional space defined by three orthogonal axes the coordinates of which are the values of $P_{yoc}$, $P_{rs}$, and the error quantity for the third parameter. All possible combinations of these three quantities define a surface resembling a bowl-like shell, the bottom of which is the minimum value of the integral of the absolute value of the error. There is a similar shell for each value of the roll damping loop parameter as shown in figure 6.

The intersections of the shell and planes parallel to the $P_{yoc} - P_{rs}$ plane define contours of constant value of the integral as shown in figure 7. Two dashed lines are plotted on the figure. One of these corresponds to points at which the error criterion for $P_{yoc}$ is satisfied, and the other for points at which the error quantity for $P_{rs}$ is satisfied. These curves actually are projections of two curves on the surface of the shell. These two curves intersect at the minimum value of $(EQ)_{rd}$ due to the previous choice for $P_{rd}$.

To show the effect upon the system damping, the poles of the dominant second order mode were obtained for the data of figure 7. These are shown in figure 8. It is desirable that convergence take place in such a manner that regions of instability are avoided. Figure 9 shows that if any two of the error criteria can be satisfied, the system will be stable.

A movie was shown showing the simulation of the system on a high-speed, suppressed, time-scale analogue computer. The type of test that was simulated was one in which the system parameters had been deliberately set at initial values far from their optimum settings. The response of the system was shown as the parameters were changed by the adaptive process.

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Flight test results of the system are presented in figures 10, 11, 12, and 13. These show the results of flight tests in which the initial conditions chosen for the loop parameters represent errors that are far greater than those which would be encountered in practice. In particular, figure 11 shows that the system will recover from an unstable initial condition using only one sample of error information.

In summary, we have presented the results of an adaptive control system research program which has investigated the characteristics of the model-reference type of adaptive system. Briefly, these characteristics are as follows:

1. The system provides closed-loop control of the system parameters so that a specified dynamic performance will result.

2. The system specifications are embodied in a model-reference which forms a portion of the equipment installation.

3. The design techniques can be applied to any existing system without major alteration of the system configuration.

4. All information required for performing the adaptive operations is obtained from the model and system responses under normal operating inputs.

5. Sampling is controlled entirely by the interrelationship between the input and output of the model.

6. Convergence times of the order of 10 seconds of sampling time for large errors in parameter initial conditions has been experienced in flight tests. The use of nulling criteria for some of the parameters greatly reduces convergence time.

We do not claim that the full potentiality of these systems has been reached. Rather, we think a door has been opened, and what lies beyond warrants a further research effort.

Finally, it should be acknowledged that the impetus for the model-reference system evolved from some of the early work performed by Capt R. R. Rath of Wright Air Development Center who deserves much of the credit for keeping interest in the entire area of adaptive control systems alive.

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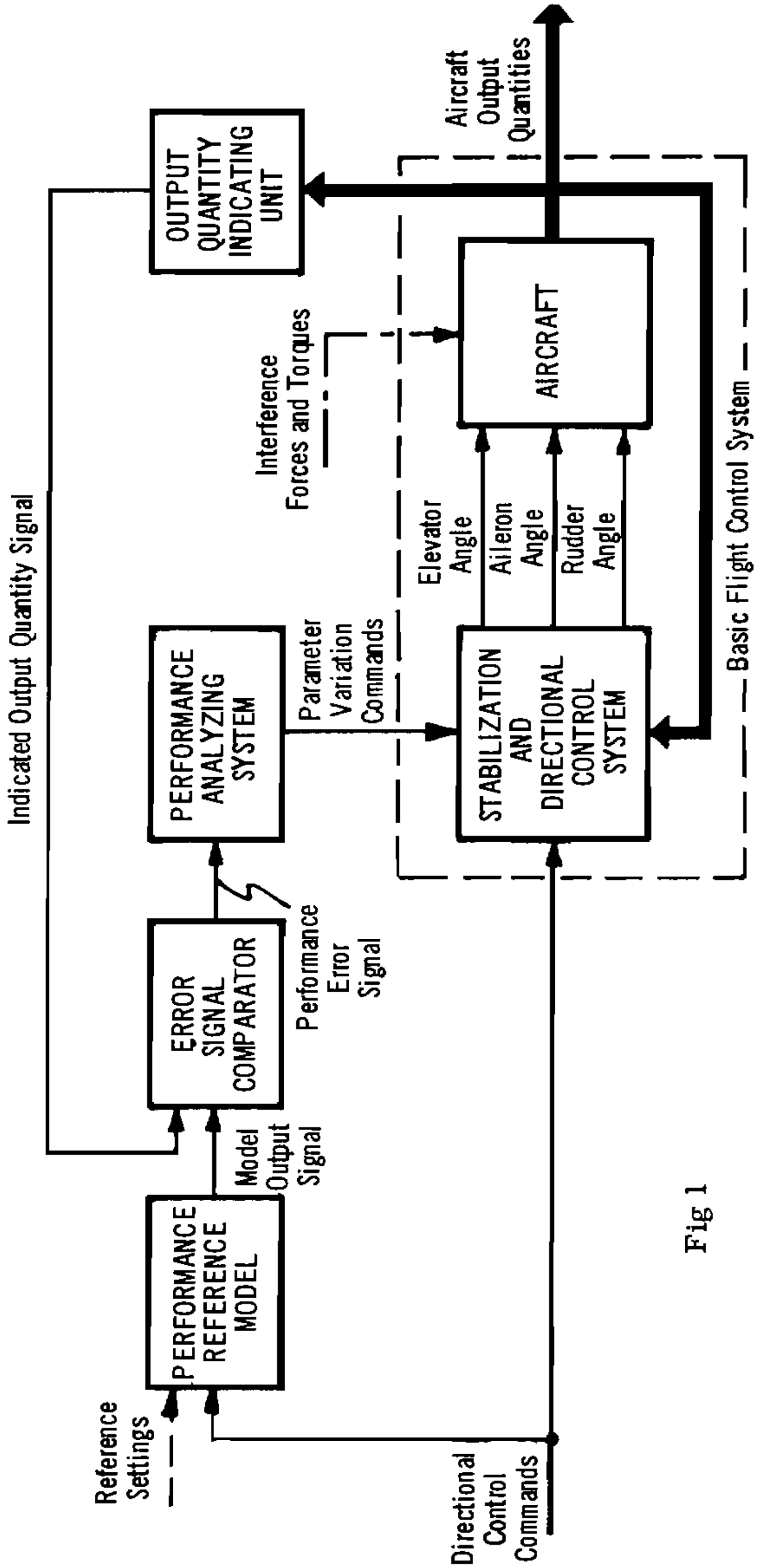

Fig 1

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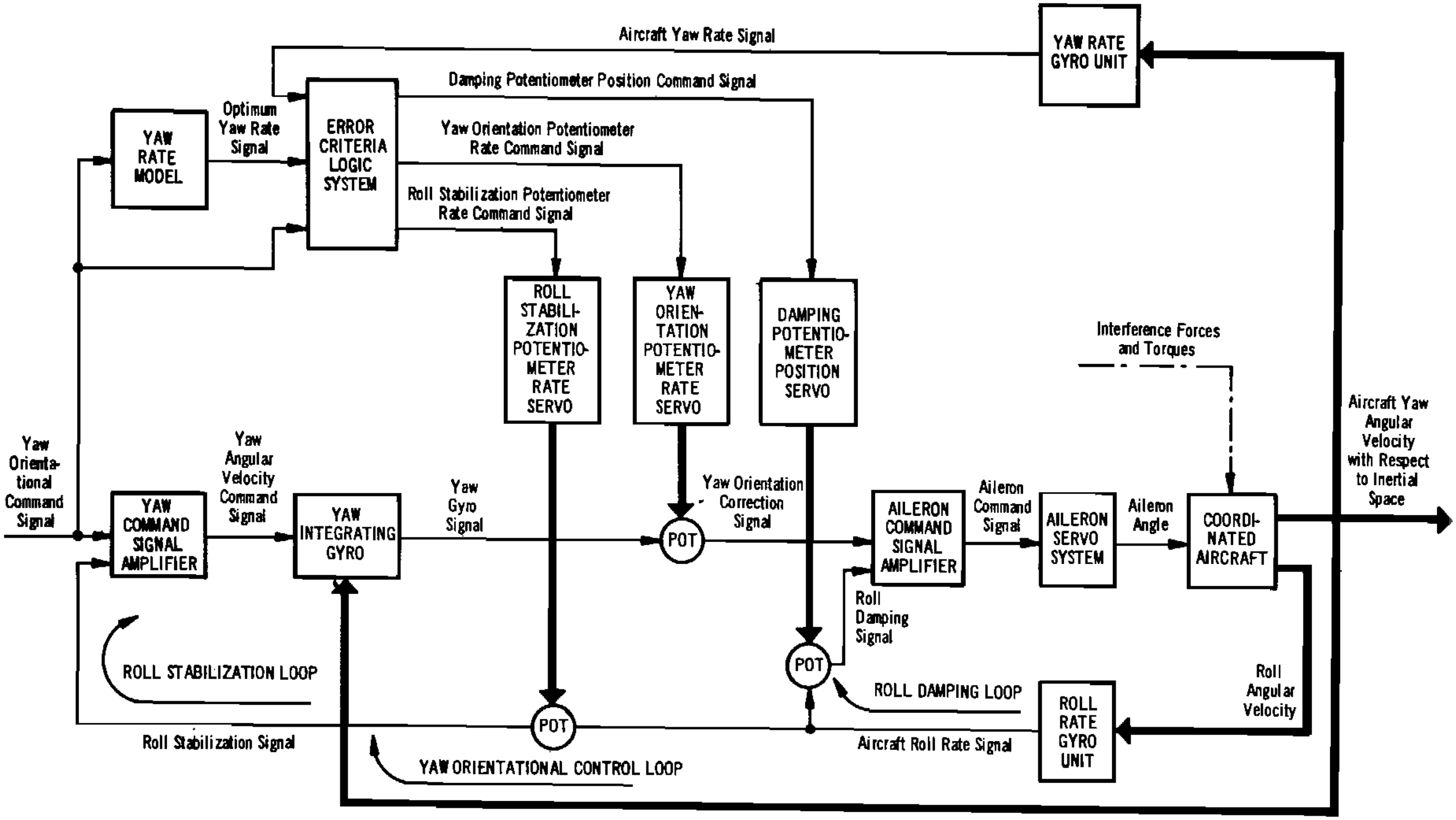

Fig 2 Functional block diagram of the adaptive yaw orientational control system.

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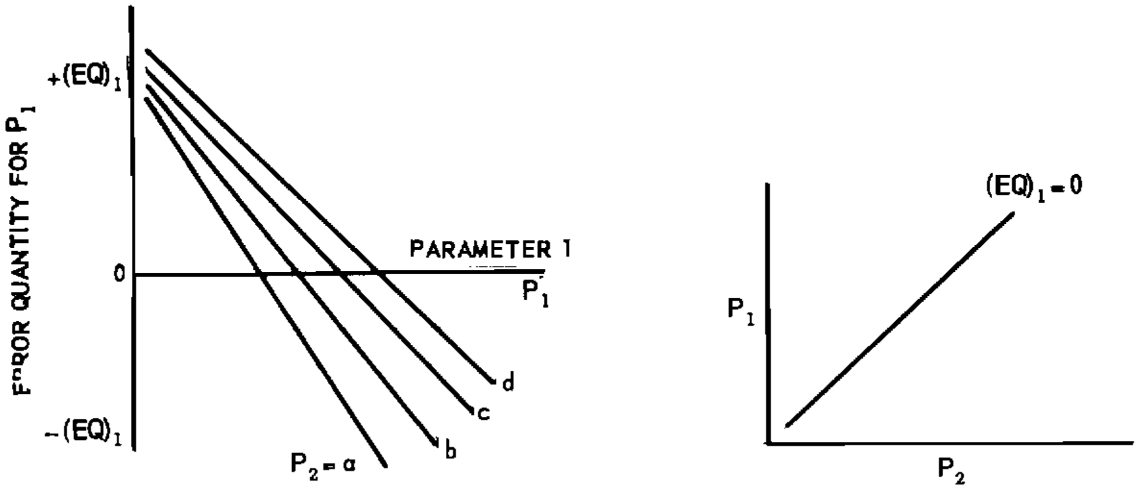
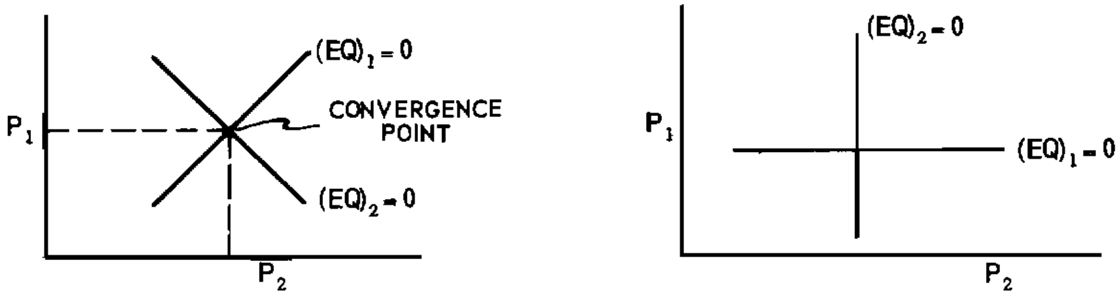


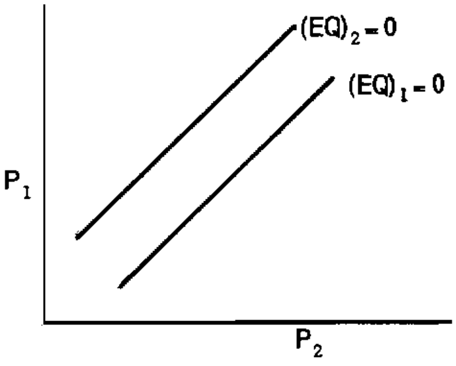
*a) Typical variation of $(EQ)_1$ versus $P_1$ for constant values of $P_2$*

*b) Typical variation of $P_1$ versus $P_2$ for $(EQ)_1 = 0$*



*c) Typical curves showing the existence of a convergence point*

*d) Variation of $P_1$ and $P_2$ when the error quantities are independent*



*e) Variation of $P_1$ and $P_2$ for which no convergence point exists*

**Fig. 3** Properties of error quantities.

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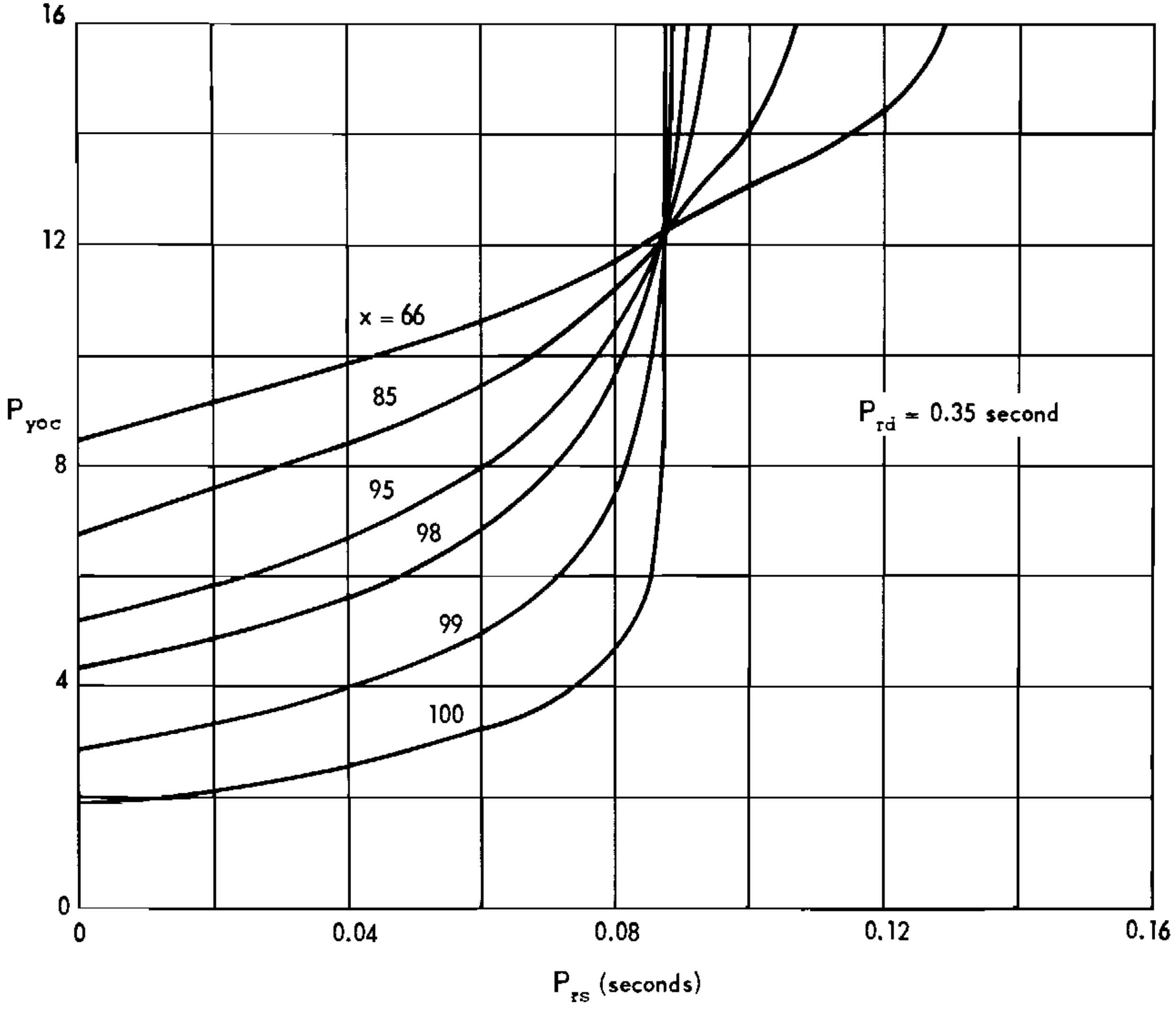

(c)

Fig 4 Combinations of the values of the system parameters for which $\int_0^{t_{s(x)}} (E)W_{(M-A)Z_A}\, dt = 0$ for several values of the sampling interval for the system of Fig. 2

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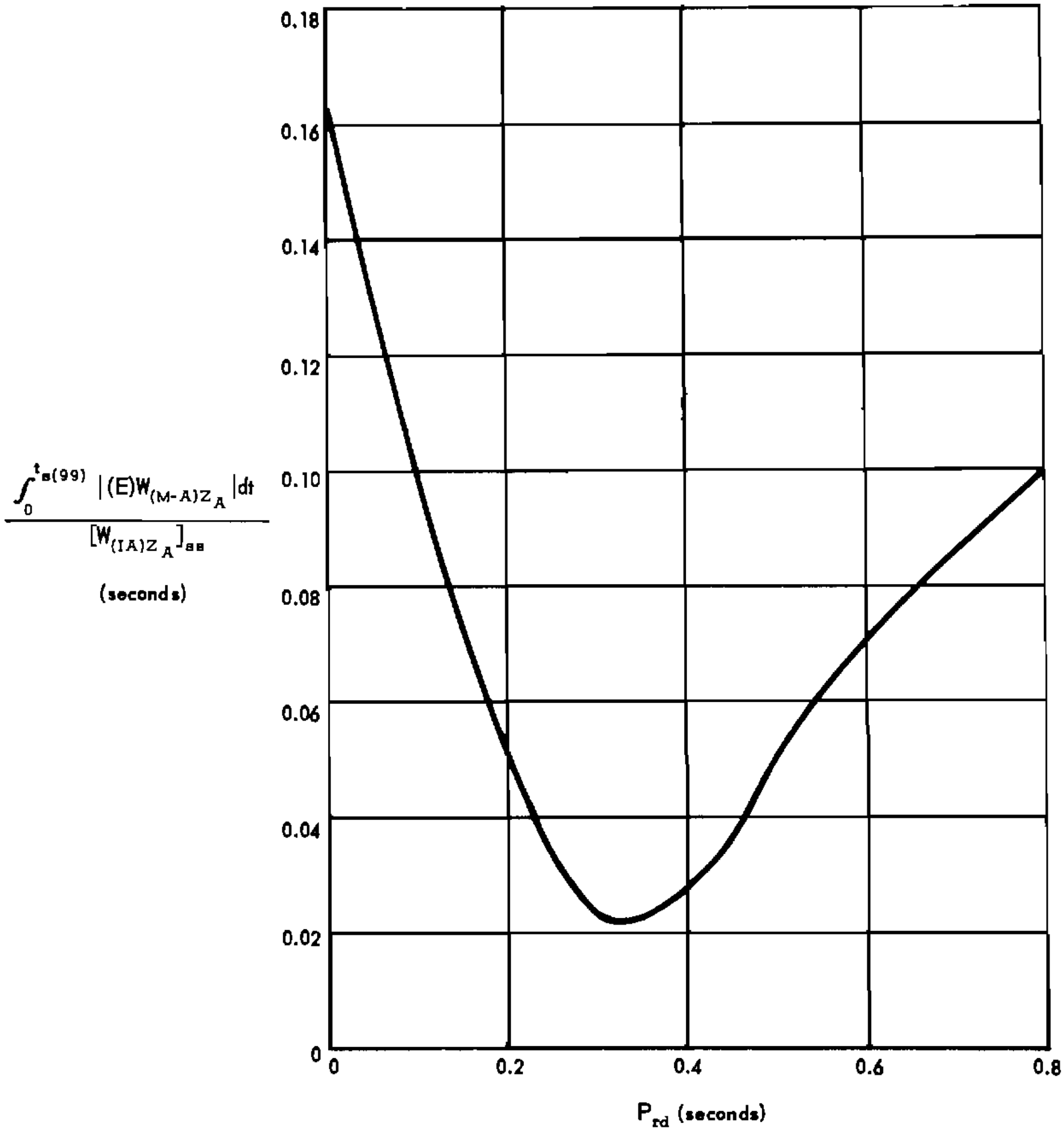

Fig 5 The variation in the normalized value of $(EQ)_{rd}$ as a function of $P_{rd}$ for various types of system operation for the system of Fig. 2

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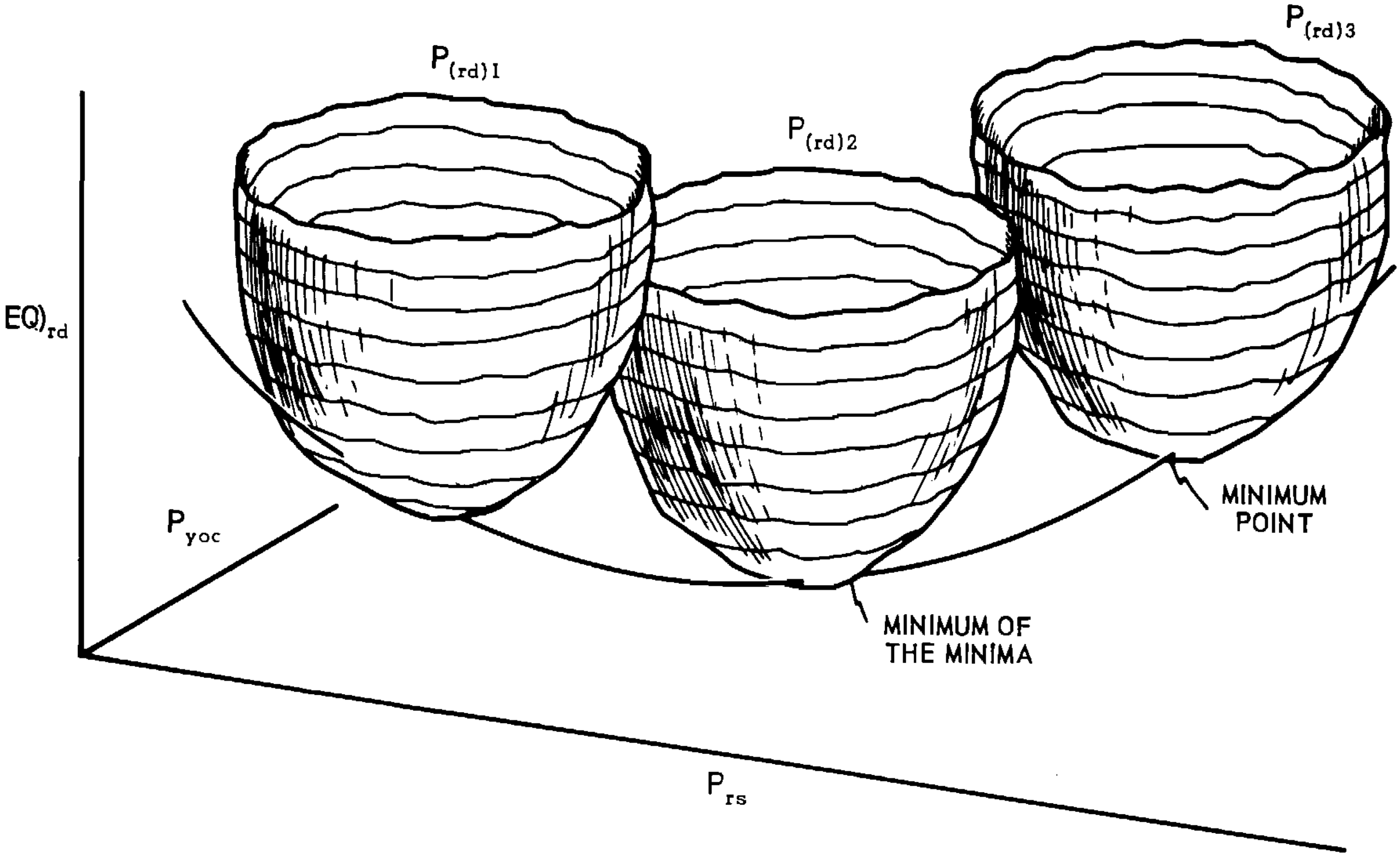

Fig 6 Geometrical representation of the optimalizing action of the yaw system.

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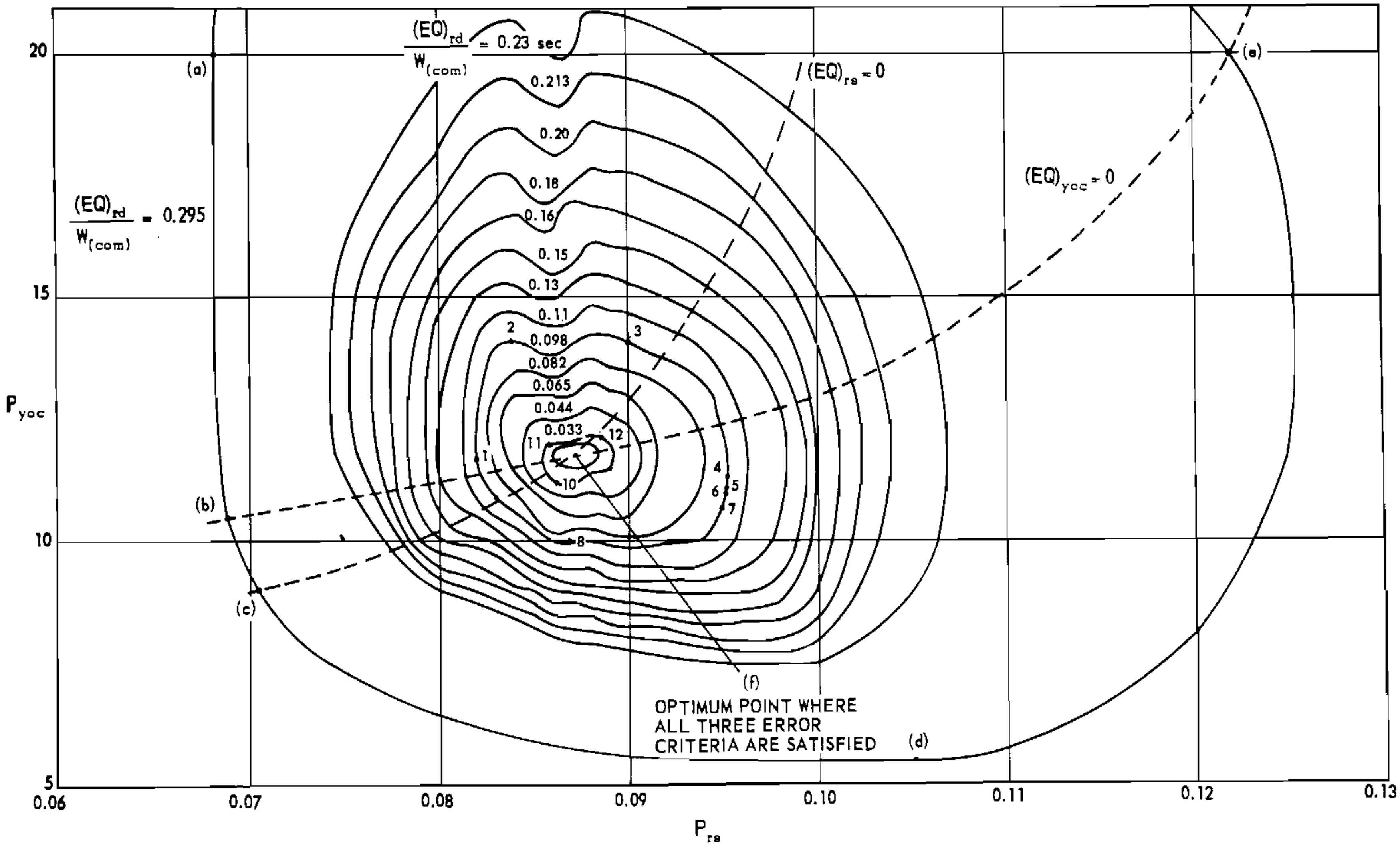

Fig 7 Contours of constant $(EQ)_{rd}/W_{(com)}$ for $P_{yoc}$ as a function of $P_{rs}$ with $P_{rd} = 0.35$.

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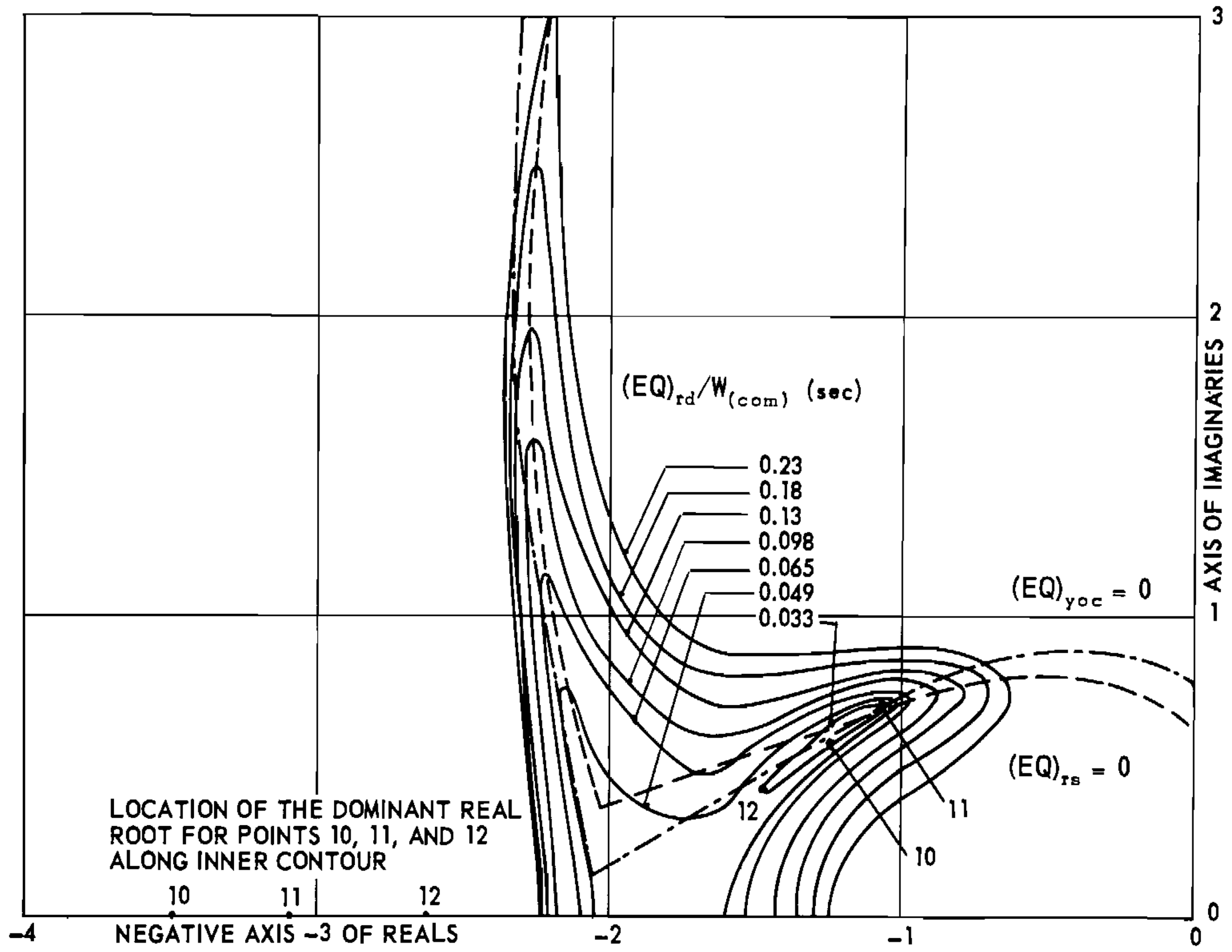

Fig 8 Complex plane location of the dominant second order poles of the system of Fig. 2 for the parameter values corresponding to the contour plot of Fig. 7

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NOTE: NUMBERS ALONG THE CURVES ARE VALUES OF $P_{rd}$.

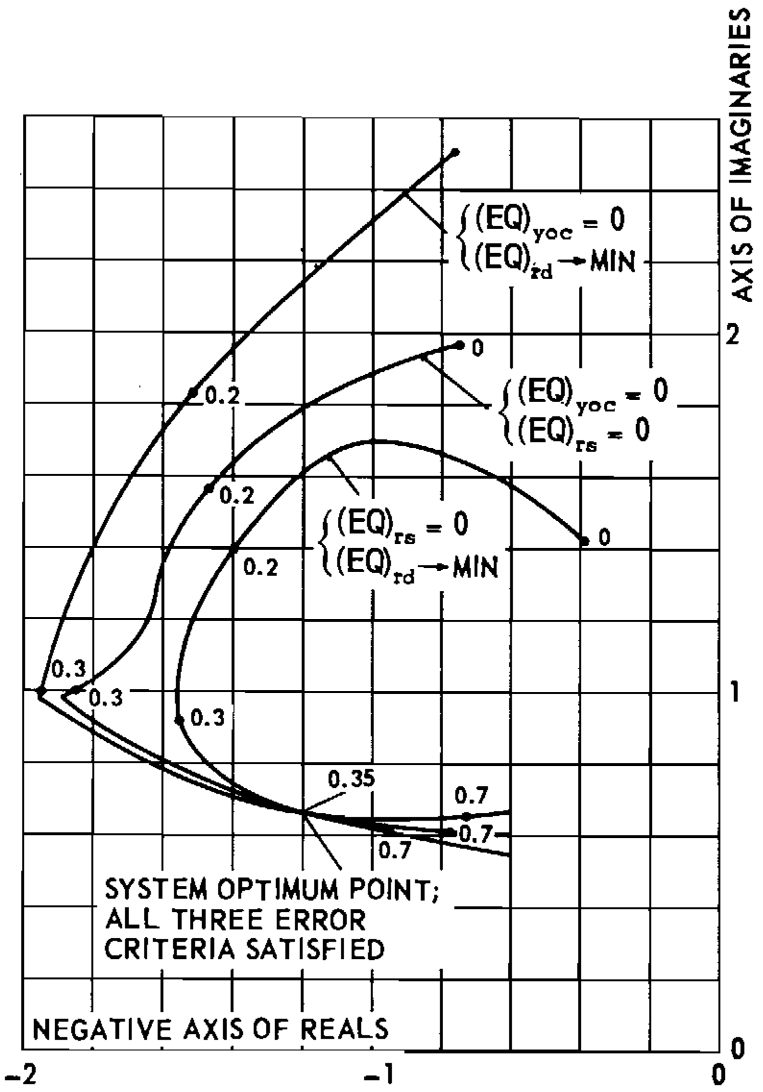

Fig 9 Complex plane loci of the poles of the dominant second order mode of the system of Fig. 2 for values of the loop parameters which satisfy the error criteria.

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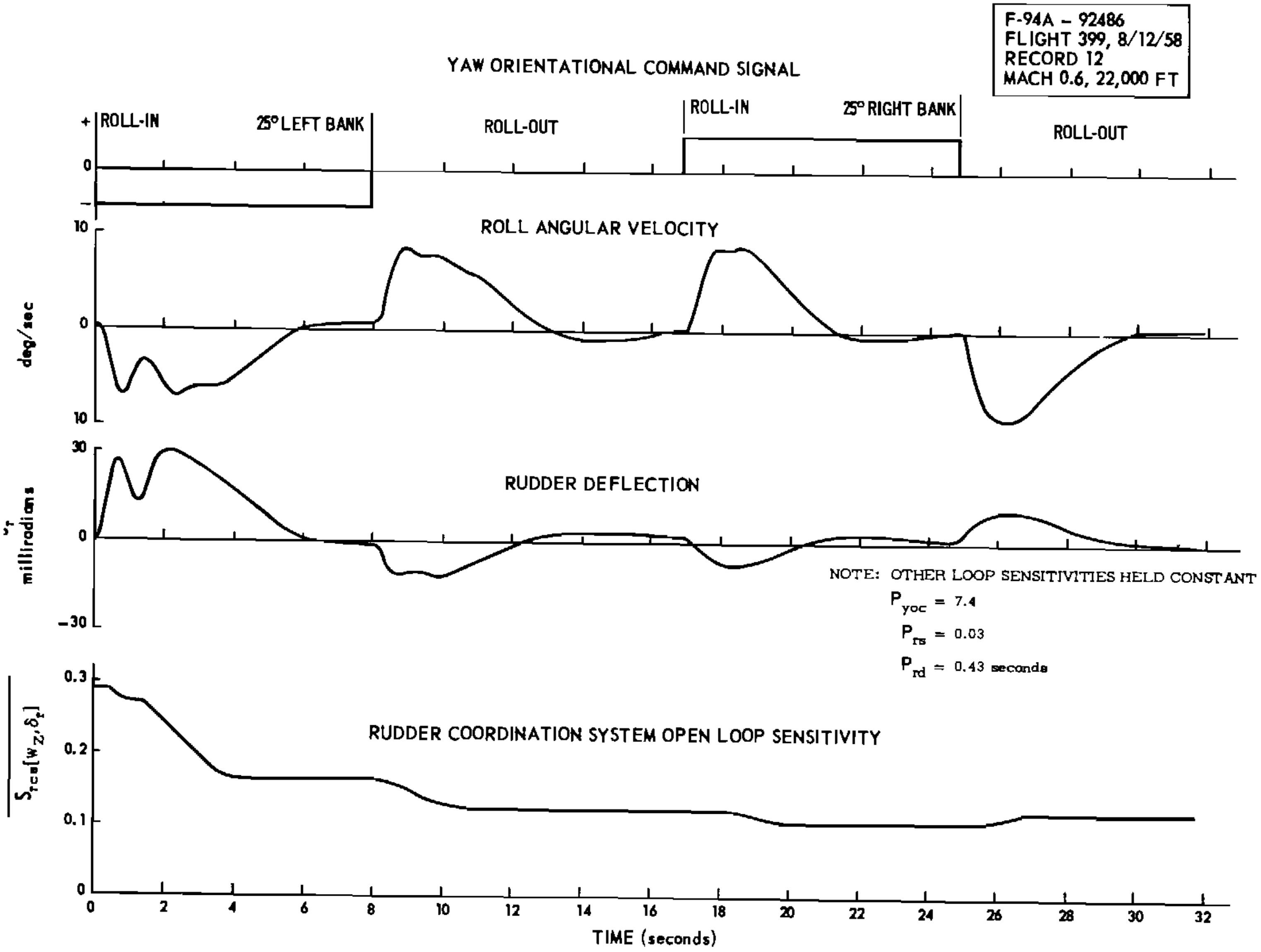

Fig. 10. Flight test results of the yaw optimalization system: effect of the operation of the automatic adjustment of the rudder coordination system loop sensitivity.

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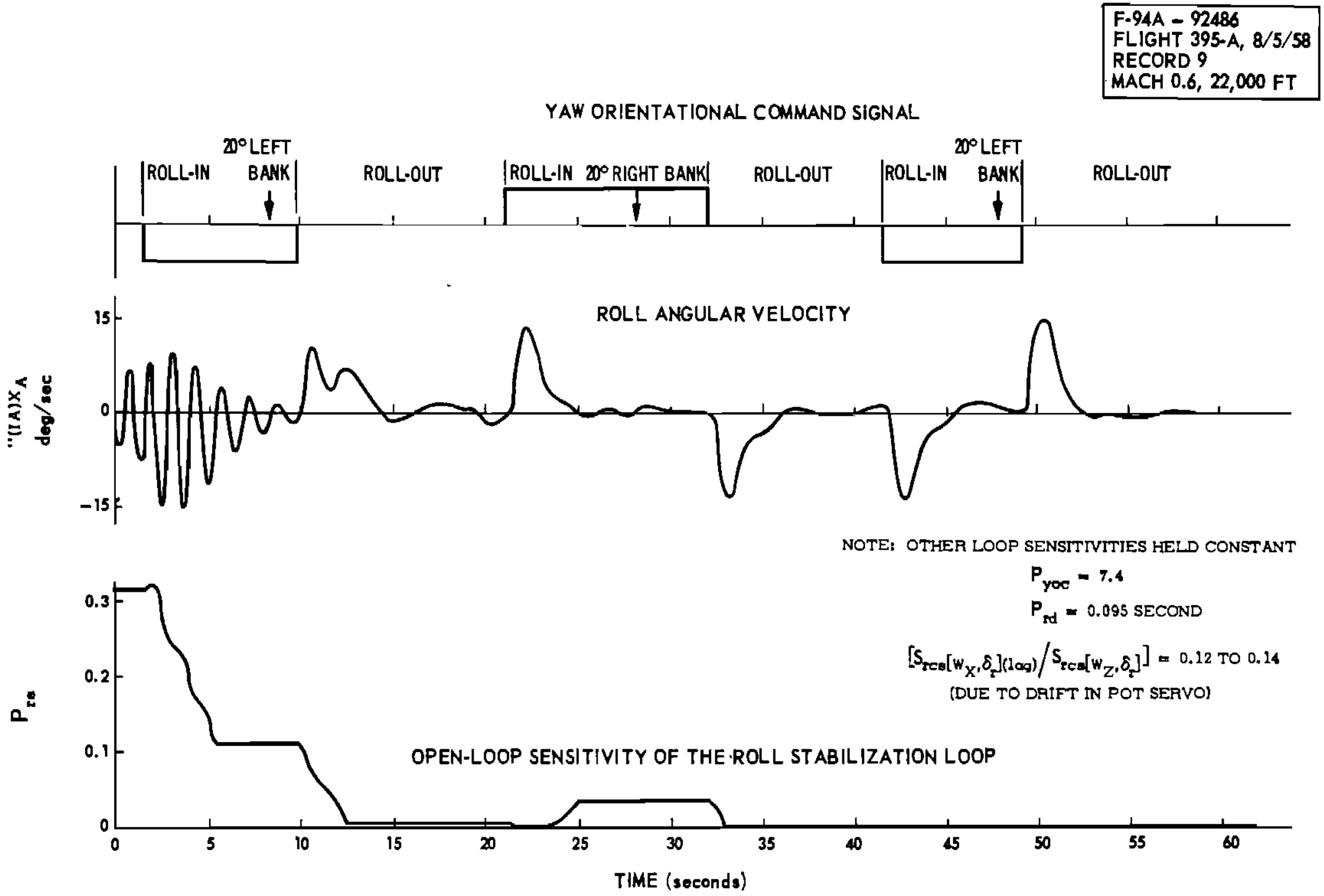

Fig 11 Flight test results of the yaw optimalization system: effect of the operation of the automatic adjustment of the roll stabilization loop sensitivity.

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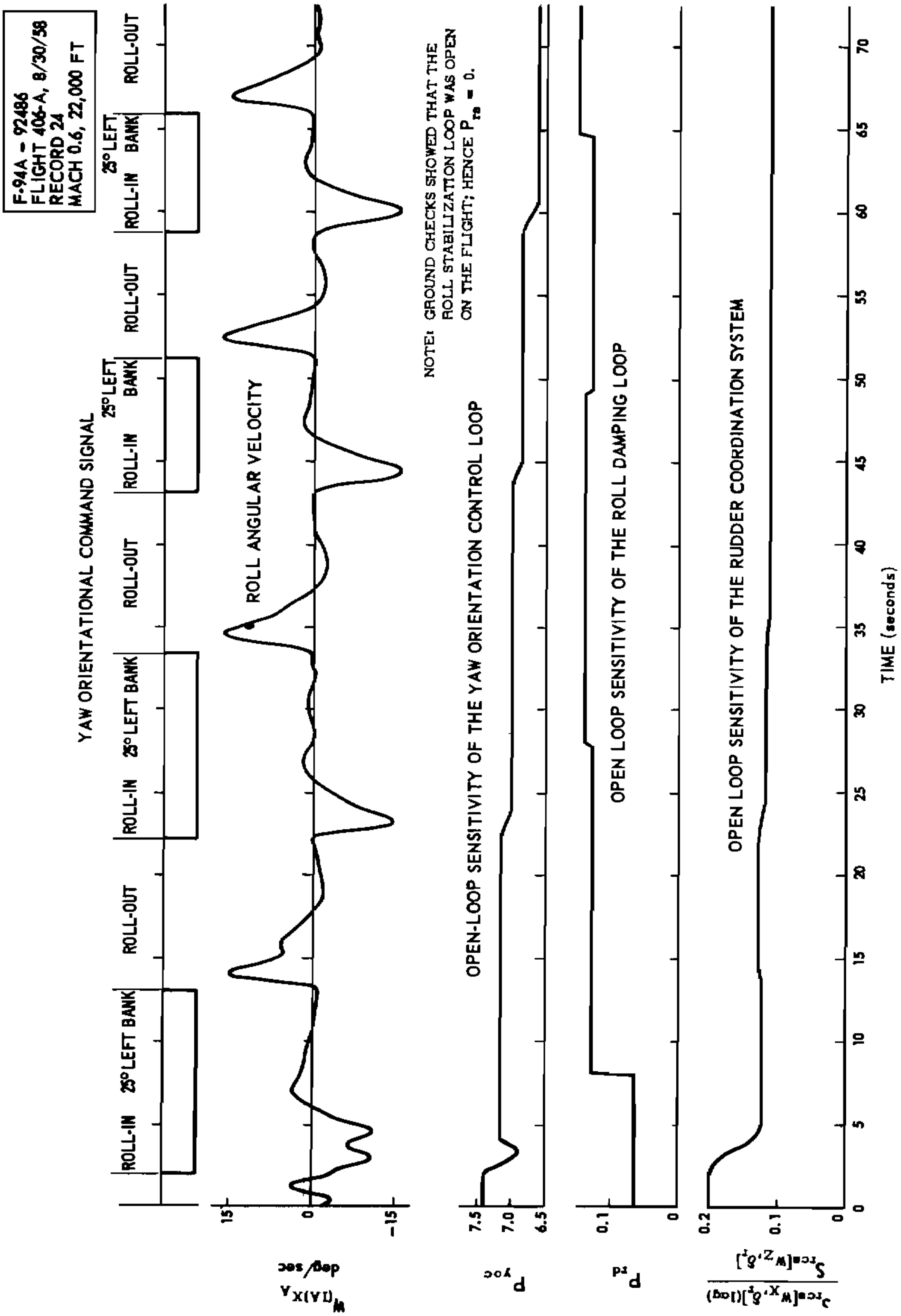

Fig 12 Flight test results of the yaw adaptive system: automatic adjustment of all loop sensitivities.

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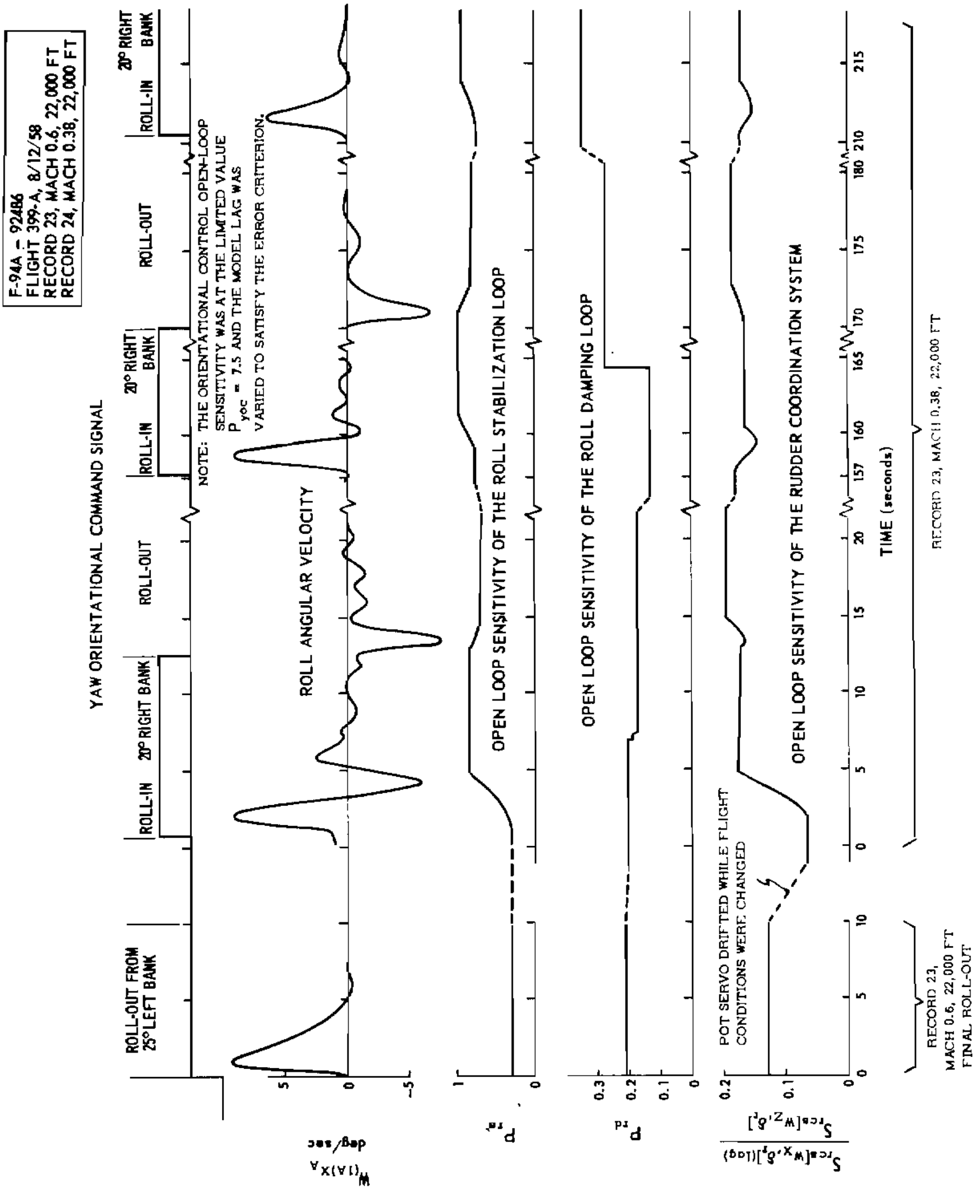

Fig 13 Flight test results of the yaw optimalization system: automatic adjustment of all loop sensitivities.

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