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SYSTEM DESIGN OF A RUDDER COORDINATION SYSTEM

BY

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I. Summary

This memorandum summarizes the application of the parameter optimization computer program to the design of a rudder coordination system for the F-8 airplane. The flight condition was Mach 0.56 at 20,000 feet altitude. The system configuration selected consisted of signal paths that fed yaw rate and aileron signals to the rudder. The two signal paths were summed and then modified by a high pass filter to eliminate any steady state bias signal. The input axis of the yaw gyro was perpendicular to the aircraft zero lift line and the trim angle of attack was 7.75 degrees. Since control of transient sideslip is achieved by moving the zeros of the aileron to roll angle transfer function, the poles of the model cannot be arbitrarily assigned. An iterative procedure of selecting the model poles permits one to use the technique to obtain the desired placement of the system zeros. The parameter optimization was used to design the complete system first, and then a root locus analysis of the individual component effects was made, and the results are presented here.

The yaw rate feedback can be used to control the damping ratio of the lateral oscillation independently of the sideslip coordination requirement if that is desired. The yaw rate loop static sensitivity can then be fixed and the rudder coordination path designed. Although one such value is 0.0, the optimization program showed that for using any yaw rate feedback, a value that resulted in $(w_\phi/w_d)^2$=0.37 gave the least excitation of the lateral

oscillation for aileron inputs.

The rudder coordination system can be designed considering the aileron as the input signal or alternatively using a roll angle feedback to the aileron and a roll angle command input. The same coordination path parameters are obtained in either case.

Finally, once the transient sideslip has been controlled, the control of steady-state sideslip can be achieved by feeding to the rudder a signal proportional to the integral of sideslip (or its equivalent). This does not change the system structure and design parameters previously obtained for the control of transient sideslip, but it produces an unstable spiral mode as would be expected.

II. Analysis of the Rudder Coordination System

The use of the parameter optimization program for determining the rudder coordination system for the F-8 has been explored. A flight condition of Mach 0.56 at 22,000 feet altitude had been suggested by the Flight Research Center.

The task the rudder coordination system performs is the minimization of sideslip, and it can be divided into two phases which are control of transient sideslip during aileron induced maneuvers and control of steady state sideslip. The latter can be achieved by a slow acting integral compensation which can be designed independently of the former. For control of transient sideslip, the important effect that the rudder coordination system causes is the movement of the complex zeros of the aileron to roll angle transfer function. Figure 2 summarizes the complex plane movement of the poles and zeros for several different system choices. The oscillatory mode poles and zeros for the basic airplane are shown as points numbered 1. The indicated separation of the poles and zeros results in a noticeable excitation of the lateral oscillation in the rool rate time response as shown in Figure 3. The effect of a crossfeed path from aileron to rudder changes the zeros but not the poles. The simplest such path modifies the signal only by a gain factor and a high pass filter. (no yaw rate feedback). Curve A on Figure 2 shows the movement of the zeros as the aileron to rudder static sensitivity increases. The optimization program selected a value of static sensitivity of

$$S_{cs[\delta_a \delta_r]} = 0.364$$

which places the zeros near the poles. The corresponding roll rate response is also shown in Figure 3.

Such a system does not change the damping ratio of the lateral oscillation. Although the aileron will then not excite the mode, gusts and rudder inputs will do so. Yaw rate feedback to the rudder can be used to increase the damping ratio of the mode. This feedback structure will change both the poles and zeros as shown by curves B and C of Figure 2.

If no crossfeed path is used, the parameter optimization program selects a static sensitivity

$$S_{cs[w_z, \delta_r]} = 0.45 \text{ sec.}$$

as the value that minimizes the excitiation of the lateral oscillation. The roll rate time response is presented in Figure 4, and it is probably unsatisfactory. Adding a pure gain aileron to rudder path would cause the zero movement shown as curve D in Figure 2. This does not result in satisfactory pole-zero cancellation for any gain value. By adding a lag to the crossfeed path, curve D can be made to bend to the right. The optimization selected a lag time constant of 0.263 sec. which produces the zero trajectory shown as curve E of Figure 2. For the yaw rate static sensitivity being used, near pole-zero cancellation occurs for a crossfeed static sensitivity of

$$S_{cs[\delta_a,\delta_r]} = 0.653$$

This point is marked by a small circle on curve E. The roll rate and sideslip response for the resultant system to a step aileron is shown in Figure 5.

III. Parameter Optimization

The analysis summarized in Figure 2 was performed after the parameter optimizationprogram had been used. Previous experience had indicated that the system configuration of Figure 1 was a reasonable one to investigate. Two approaches were explored which differed in the aileron motion used to produce the roll and sideslip responses. Since the spiral mode of the airplane is stable, one can use a model of the airplane roll response to an aileron step input and determine the signal path structure to be fed to the rudder in order to minimize side slip. An alternative procedure, which is applicable even with an unstable spiral mode, is to use a roll angle control system by feeding roll angle back to the aileron. The model is then that of a roll control system.

In both cases, the evidence of desirable rudder coordination is the minimization of the excitation of the lateral oscillatory mode of the airplane when aileron inputs are applied. This is equivalent to locating the complex zeros of the aileron to roll angle transfer function near the poles of the oscillatory mode. The optimization program can be used to achieve this by selecting a roll model that does not contain the lateral oscillation, which is equivalent to assuming perfect pole-zero cancellation of the mode.

If an arbitrary model were to be used, the parameter optimization would attempt to achieve the best compromise between matching the model and eliminating the excitation of the lateral oscillation. One can concentrate upon the rudder coordination task by selecting a model which matches the dominant response modes of the system but eliminates the oscillatory mode. A reasonable first approximation for such a model can be selected for the first computer run. The results of the first parameter optimization run provides a refinement in the choice of model modes since the feedback structure may change the poles and zeros. The new model is used on the next computer run. This process is repeated until satisfactory rudder coordination is achieved.

Both of the alternative modelling procedures were investigated, and the same final parameter set was obtained in each case. Hence only the first case will be summarized here.

A block diagram of the configuration is shown in Figure 1. Both of the signal paths to the rudder were summed together and passed through a high-pass filter to eliminate steady-state inputs to the rudder. The filter time constant was selected to be 1.0 second.

Table 1 illustrates the convergence of the process using the first technique, i.e., no feedback path to the aileron. The first two iterations are for a configuration that used only yaw rate feedback to the rudder. The initial model assumed that the high pass filter mode would appear in the roll angle transfer function as almost a dipole. Actually, the zero moves appreciably away from the pole, and hence on iteration 2 the filter mode was taken as one of the model modes. Including in addition to that mode the airplane mode near -2.0 would have improved the value of the performance index obtained, but inasmuch as it had been anticipated that aileron to rudder cross feed would be investigated, such a model refinement was not used at this point with the yaw rate loop alone. (This alternative was further checked subsequently and a value of yaw rate loop feedback of 0.453 was found to give the best rudder coordination using only yaw rate feedback.) Table 1 shows that the yaw rate loop static sensitivity, P_1, did not vary appreciably during the later iterations in any event.

Adding the aileron to rudder path beginning with iteration 3 showed that the roll angle zero then does move back closer to the filter pole, and on iteration 4 that zero and the airplane pole were added to the model.

The final system resulted in the transfer function from aileron input to roll angle having the following poles and zeros:

Zeros: -0.7281, -3.643, -23.85, (-1.164 $\pm$ 2.268j)

Poles: -0.8775, -3.8051. -23.22, (-1.180 $\pm$ 2.186j), -0.03029, -2.781

Static Sensitivity: $S_{cs[\delta_a,\phi]} = 275.3$

These show that the lateral oscillation has been effectively cancelled by the aileron-rudder cross feed path. The dominant roll modes are then the modified spiral and roll subsidence modes. The roll rate time response to a step aileron deflection is presented in Figure 5 for the coordinated aircraft. Also shown are the responses with no coordination and with only yaw rate feedback.

It is interesting to note that the optimization program selected the value of 0.453 for the yaw loop even with no cross feed path. The time responses shown in Figure 6 indicated that this indeed is probably the best value for minimizing the effects of sideslip on the rolling response even though the rolling behavior still would not be acceptable. The transfer function has an $(\omega_\phi/\omega_d)^2$ ratio of 0.37 which is well below what the handling qualities criterion of 0.5 would specify, and this indicates that the higher value would give a poorer response. It may be worthwhile to pursue this further from a handling qualities standpoint.

These results also suggest that the yaw rate feedback and the rudder sideslip coordination can be considered independently and hence that separate specifications could be used to design the system. Figure 2 shows that the value of yaw rate feedback which optimizes the sideslip coordination does not maximize the damping ratio of the lateral oscillation. Since the poles are not a function of the aileron to rudder path, a different aileron-rudder path compensation would cause the locus of zeros to intersect the root locus at a higher damping ratio. This was investigated by fixing the yaw rate gain at 0.75 sec. and re-optimizing the aileron-rudder path parameters. All that was required in this case was a different set of values for the gain and the lag time constant. The final system transfer function relating roll angle to aileron had the following poles and zeros:

Zeros: $-0.610, -3.72, -1.354 \pm 1.916j, -22.3$

Poles: $-1.10, -3.85, -1.390 \pm 1.905j, -21.8,$

$-0.262, -2.08$

$$S_{cs[\delta_a,\phi]} = 275.3$$

Adding the integral of sideslip as a feedback path to the rudder to these systems will control steady-state sideslip. It will however cause the spiral mode to become unstable as would be expected.

Iter.	Model Poles			Model Zero	P_1	P_2	P_3	Final (PI)	Data
1	-0.028	-2.0	---	---	0.5776	0	0	0.2196	B539
2	-0.0289	-0.8527	---	---	0.4279	0	0	1.777	F996
3	-0.03045	-0.8805	---	---	0.4292	0.4027	0.5254	1.256	F1051
4	-0.03043	-0.8802	-2.483	-0.757	0.4297	0.2709	0.6342	0.0028	F1119
5	-0.03043	-0.8801	-2.747	-0.7324	0.4426	0.2628	0.6532	0.0007	F1142

Notes:

1. $P_1 = S_{yd}$, $P_2 = \tau_{(lag)}$, $P_3 = S_{rc[\delta_a \delta_r]}$
2. Iterations 1 and 2 use no aileron to rudder cross feed signal path
3. Highpass filter time constant = 1.0 sec.; rudder servo time constant = 0.04 sec.
4. (PI) values listed are the values listed on the last iteration of a given computer run and have not been reduced to a time average error figure.
5. F-8 Airplane, Mach 0.56, Altitude 20,000 feet

Table 1. Summary of Design Iterations

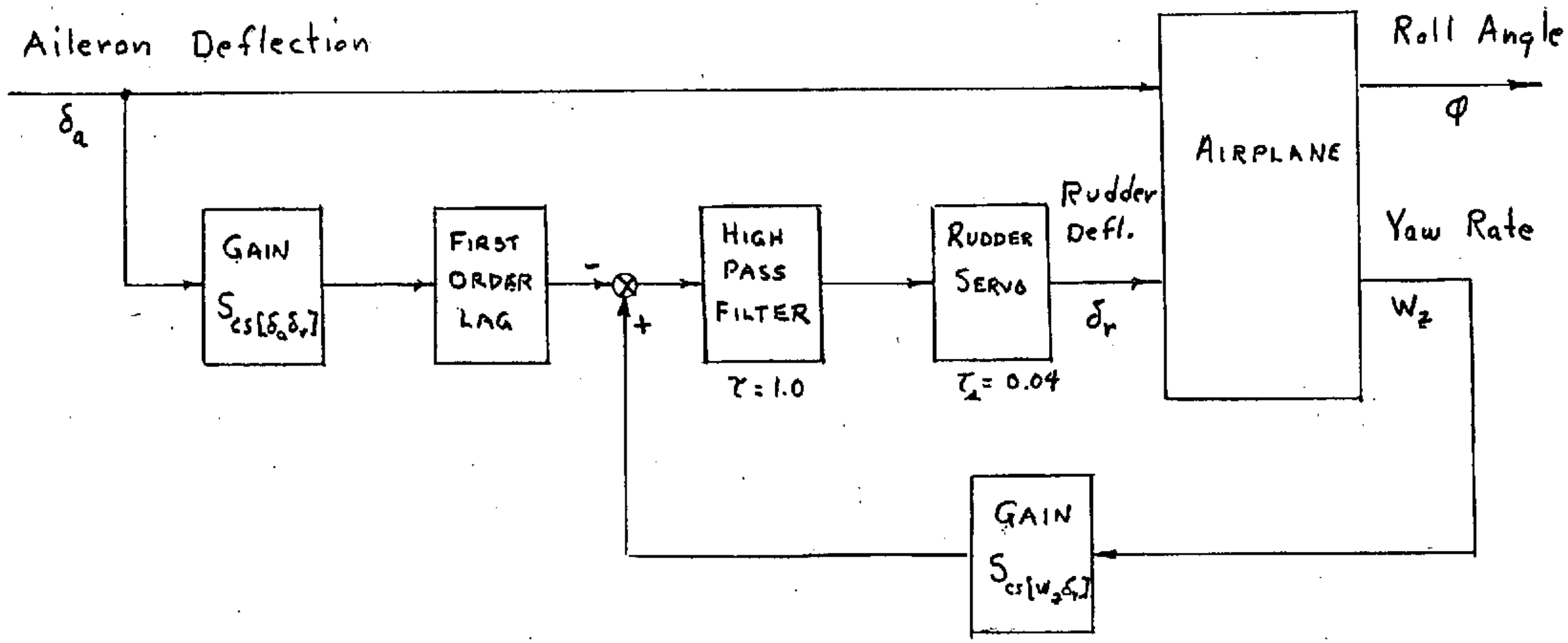

Figure 1. Functional Block Diagram: Rudder Coordination System

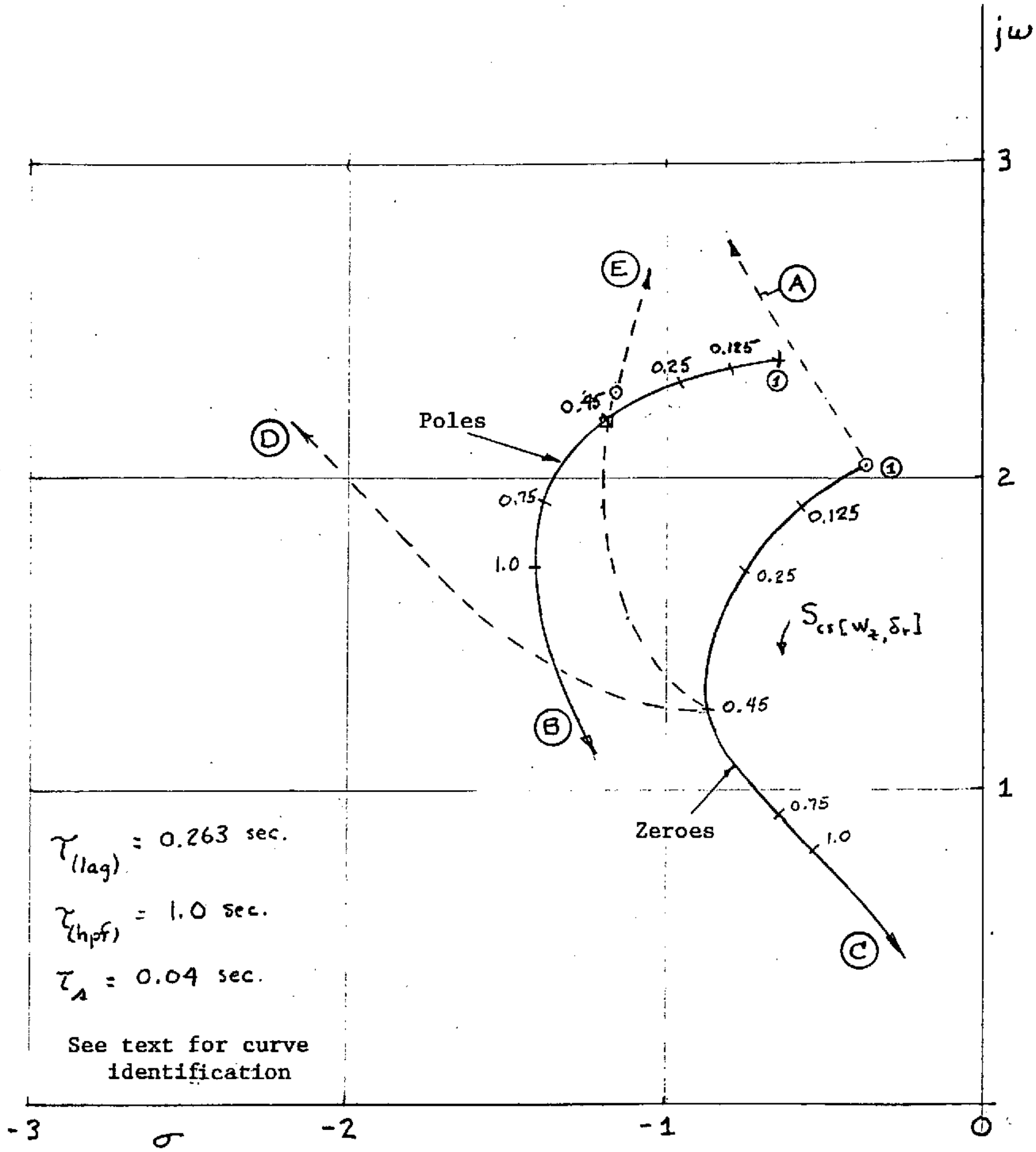

Figure 2. Complex Plane Movement of the Poles and Zeroes Associated with the Lateral Oscillatory Mode for the Aileron Angle Input to Roll Angle Output Transfer Function. F-8 Airplane Mach 0.56, 20,000 feet.

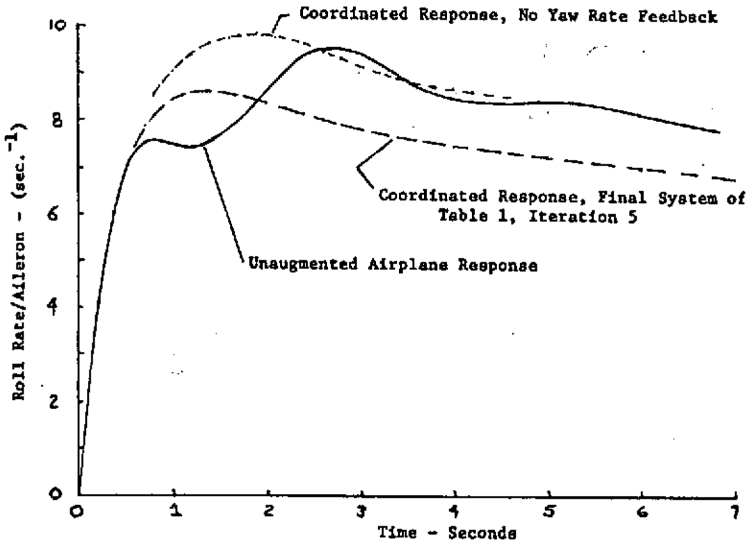

Figure 3. Roll Rate Response to a Step Function Aileron Input

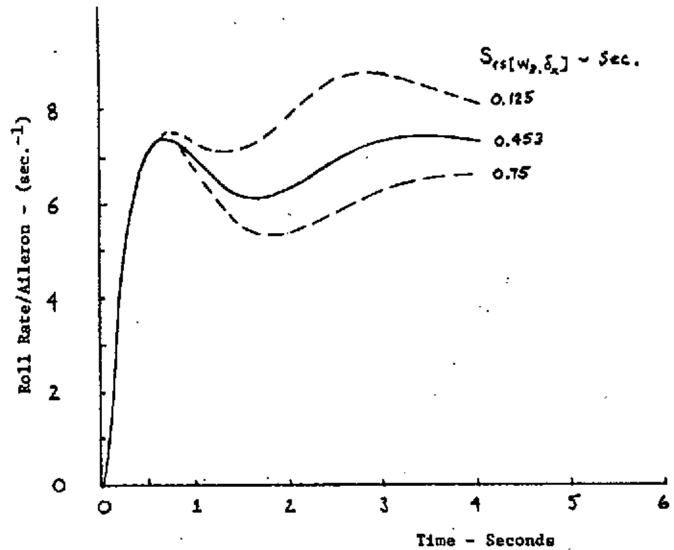

Figure 4. Roll Rate Response to a Step Function Aileron Input. Yaw Rate Feedback Loop Only; Effect of Yaw Rate Feedback Static Sensitivity.

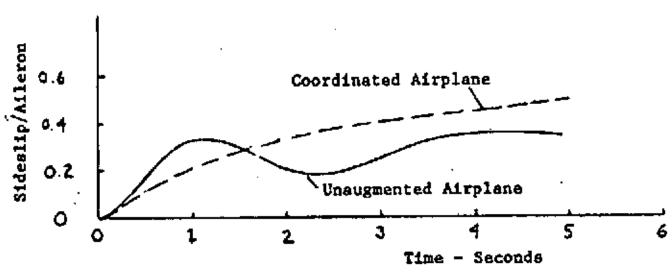

Figure 5. Sideslip Response for a Step Function Aileron Input