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SUBJECT: On Certain Performance Characteristics of the E-1 CAM
State Variable Feedback Control System

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ENCLOSURE: (1) On Certain Performance Characteristics of the E-1 CAM
State Variable Feedback Control System

The purpose of this memorandum is to present certain performance characteristics of the E-1 CAM state variable feedback control system. Treatment is given to (1) dynamic response comparison between open loop and closed loop systems during thrust buildup, (2) sensitivity to deviations of open loop demands from their nominal trajectories, and (3) effect of single feedback signal loss on performance.

A preliminary thrust buildup controller design is used in the investigation and while this design does not perform to the extent that may be expected from the final design, it does indicate aspects of performance which will be characteristic of the final state variable feedback control system.

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ON CERTAIN PERFORMANCE CHARACTERISTICS OF THE
E-1 CAM STATE VARIABLE FEEDBACK CONTROL SYSTEM

PRELIMINARY THRUST BUILDUP DESIGN

A preliminary thrust buildup state variable feedback control system design is used in the present investigation. The design is consistent with the control system configuration given in Figure 1. A complete description of this configuration and the design procedure for determining its components are given in Reference (1). Determination of the feedback gains was made on the basis of a sixth order controls analysis model obtained at the low power point (1250/50) using the system simplification technique of (2). Quadratic optimization, described in Reference (3), was then used to find the state feedback gains and steady state trim controller gains which are given in Figure 2, along with the analysis model* and weighting factors. The control system with this particular set of feedback gains (identified as low 2) was found to satisfactorily control the E-1 CAM through the thrust buildup mode of operation. While this controller does not quite meet the transient performance requirements, it was considered adequate for indicating performance characteristics of the final design. It is expected that the final controller design will have more than one set of feedback gains and interpolation would be made as a function of operating map region.

OPEN LOOP VERSUS CLOSED LOOP DYNAMIC RESPONSE

To determine the effect of the state feedback on thrust buildup dynamic response, open loop and closed loop runs were made for comparison. The same open loop actuator input demands were used in both runs. For the closed loop run the inputs were augmented by differential input signals produced by the state feedback. So that, any differences in the responses can be attributed to the state feedback. Figure 3 shows the open loop thrust buildup response in chamber conditions with the

*Figure 2 gives the model as an augmented eighth order model where the two additional states are integral of temperature error and integral of pressure error. In this form the integral portion of the steady state trim controller is artificially made part of the plant while the gain portion is incorporated into the feedback gain matrix $\underline{H}$.

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open loop actuator input signals. In this run the T15M and P15M error signals saturated. Figure 4 is a repeat of this open loop run with scale changes. The maximum chamber temperature error reached approximately 1750°R while the peak chamber pressure error was 115 psi.

The closed loop thrust buildup response using the feedback gains of low 2 is given in Figure 5. The bottom four traces are the total actuator input signals--superimposed on the open loop input demands are dynamic input variations produced by the state variable feedback. As can be seen, the SSCV input does not have a dynamic component. The reason for this is that in the quadratic optimization design of the gains in low 2, use of SSCV was penalized because the highly nonlinear nature of the SSCV makes it an undesirable dynamic input. Simultaneous use of the other three actuators was, however, allowed in the design and these inputs are seen to have dynamic components. For this closed loop thrust buildup the maximum chamber temperature error was 250°R while maximum chamber pressure error was 20 psi.

SENSITIVITY TO OPEN LOOP DEMANDS

Since the present control scheme requires open loop demands for the actuators and state variables, it is of interest to determine the sensitivity of closed loop performance to deviations of the open loop demands from their nominal trajectories. Put another way, this is the sensitivity of closed loop performance to uncertainty or changes in the plant statics.

For the open loop demands, the control scheme uses simply a linear interpolation of the steady state values of the states and actuators between low power point and throttle point, and then between throttle point and design point. To perform this sensitivity study, the design point steady states used in the open loop demands were displaced from their nominal values. Chamber temperature and chamber pressure demands were, of course, exceptions to this since they are the given system demands.

Figure 6 shows a thrust buildup response (using low 2) where the nominal open loop demands for each of the states and each of the actuators were arbitrarily reduced by 20% at design point. So that, between throttle point and

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design point a ramped deviation is added to the nominal demands with a maximum deviation of 20% occurring at design point. As can be seen, the thrust buildup response is essentially the same as that for nominal open loop demands. Figure 7 gives a similar thrust buildup with a 50% reduction in the open loop demands at design point. A performance degradation is apparent in this run with the error signals taking on a different shape towards design.

EFFECT OF SINGLE FEEDBACK SIGNAL LOSS ON PERFORMANCE

Finally a set of runs was made to study the malfunction case of losing a single feedback variable. It was found that the low 2 closed loop system was unstable when any one of P195, T15M, or P15M was removed from the feedbacks. However, loss of any one of CI3, R9, or HC1 did not appreciably affect the nominal thrust buildup performance.* This implies that the state variables CI3, R9, and HC1 were not weighted properly in the design of the low 2 controller since they did not contribute to the closed loop dynamics. It is expected that the final controller design will fully utilize all feedback states and thus improve the closed loop dynamics. Figures 8, 9, and 10 show thrust buildups with each of CI3, R9, and HC1 removed respectively.

*Since CI3, R9, and HC1 were estimated from measurements of S_N , T_9 and P_9 , and ϕ_{c1} , respectively, loss of any one of the first set is synonymous with loss of its measured counterpart.

FIGURE 1
CONTROL SYSTEM CONFIGURATION
FOR DIGITAL CONTROL OF E-1 CAM (5A)
USING STATE VARIABLE FEEDBACK

QUADRATIC OPTIMIZATION PROGRAM, CASE NO. 1

THE A MATRIX IS								SIMPLIFIED MODEL
-0.1317100-01	-0.8651100 01	0.5073400 01	0.2729500 04	0.0	0.0	0.0	0.0	
0.1119700-01	-0.7573400 00	0.1459900 00	0.1748100 01	0.0	0.0	0.0	0.0	
0.7411600 00	-0.5453100 01	-0.1449400 02	0.3916500 04	0.0	0.0	0.0	0.0	
-0.3728200-03	0.1917800-02	0.4744800-02	-0.1776400 02	0.0	0.0	0.0	0.0	
0.3478000-01	-0.1847000 00	0.4010000 00	0.6898100 02	-0.1000000 00	0.0	0.0	0.0	
0.9100000-02	-0.5720000-01	0.2155000 00	0.1802100 03	0.0	-0.1000000 01	0.0	0.0	
0.0	0.0	0.0	0.0	0.1000000 01	0.0	0.0	0.0	
0.0	0.0	0.0	0.0	0.0	0.1000000 01	0.0	0.0	
THE B MATRIX IS								
0.4600000 00	0.2804000 02	-0.5776000 00	0.2634000 01					
-0.4750000-02	0.9600000 00	-0.8240000-02	0.4910000-01					
-0.771500 02	0.6244000 02	0.2864000 03	0.1762400 02					
-0.3730000-01	-0.3140000-01	-0.2260000-01	0.8476000-01					
0.2100000-01	0.3014000 01	-0.2300000-02	0.6830000-01					
0.2400000-01	0.7630000 00	-0.4770000-01	0.1870000 00					
0.0	0.0	0.0	0.0					
0.0	0.0	0.0	0.0					
THE Q MATRIX IS								
0.7300000-05	0.0	0.0	0.0	0.0	0.0	0.0	0.0	
0.0	0.2500000-03	0.0	0.0	0.0	0.0	0.0	0.0	
0.0	0.0	0.4100000-04	0.0	0.0	0.0	0.0	0.0	
0.0	0.0	0.0	0.3270000 02	0.0	0.0	0.0	0.0	
0.0	0.0	0.0	0.0	0.6400000-07	0.0	0.0	0.0	
0.0	0.0	0.0	0.0	0.0	0.4000000-04	0.0	0.0	
0.0	0.0	0.0	0.0	0.0	0.0	0.2000000-04	0.0	
0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4940000-03	
THE R MATRIX IS								STATE AND INPUT WEIGHTING COEFFICIENTS
0.1000000 10	0.0	0.0	0.0					
0.0	0.1000000 00	0.0	0.0					
0.0	0.0	0.1000000 10	0.0					
0.0	0.0	0.0	0.1000000 00					
THE FEEDBACK GAIN MATRIX								
-0.1215240-02	0.1273540-01	-0.2157420-02	-0.1808840 01	-0.1098230-01	-0.2716430-01	-0.3903960-02	-0.2965850-01	FEEDBACK GAIN
0.2377360-02	-0.2794620-01	0.2861370-02	0.1293440 01	0.5772120-01	-0.2852300-01	0.1300350-01	-0.2653860-01	MATRIX
0.5250240-02	-0.5715830-01	0.9899390-02	0.5918110-09	0.7348730-01	0.5796190-01	0.2068910-01	0.6656900-01	
0.1603430-02	-0.1584310-01	0.2775520-02	0.2990080 01	0.6377020-02	0.5393850-01	0.3958280-02	0.5793160-01	

FIGURE 2

RESULTS OF LOW POWER POINT
QUADRATIC OPTIMIZATION DESIGN OF LOW 2

FIGURE 3

OPEN LOOP E-1 CAM (6.1) THRUST BUILDUP

FIGURE 4
REPEAT OF OPEN LOOP E-1 CAM (6.1)
THRUST BUILDUP WITH SCALES CHANGED

FIGURE 5

CLOSED LOOP E-1 CAM (6.1) THRUST BUILDUP
WITH LOW 2 STATE VARIABLE FEEDBACK CONTROLLER

FIGURE 6

E-1 CAM (6.1) THRUST BUILDUP USING LOW 2 WITH OPEN LOOP
DEMANDS RAMPED TO 20% BELOW NOMINAL AT DESIGN POINT

FIGURE 7 - E-1 CAM (6.1) THRUST BUILDUP USING
LOW 2 WITH OPEN LOOP DEMANDS RAMPED
TO 50% BELOW NOMINAL AT DESIGN POINT

FIGURE 8 - E-1 CAM (6.1) THRUST BUILDUP USING
LOW 2 WITH CI3 FEEDBACK REMOVED
(S_N REMOVED)

FIGURE 9 - E-1 CAM (6.1) THRUST BUILDUP USING
LOW 2 WITH R9 FEEDBACK REMOVED
(T9 FEEDBACK REMOVED)

FIGURE 10 - E-1 CAM (6.1) THRUST BUILDUP
USING LOW 2 WITH HCL FEEDBACK
REMOVED (ϕ_{c1} REMOVED)

FIGURE V-1
BASIC CIRCUIT ARRANGEMENT

REFERENCES

1. Parziale, E. A., Schenz, R. F.: "Design and Simulation Results for the E-1 CAM Revision 5A Throttle Control Using State Variable Feedback," NIICO 5055M, Dated January 19, 1971.
2. Parziale, E. A., Dowling, E. F.: "A System Simplification Technique to Obtain a Controls Analysis Model of the NERVA Engine," NIICO 5051M, dated January 18, 1971.
3. Gray, D. L.: "Quadratic Optimal Control Digital Computer Program, QUAD OP," NIICO 5068M, dated February 26, 1971.