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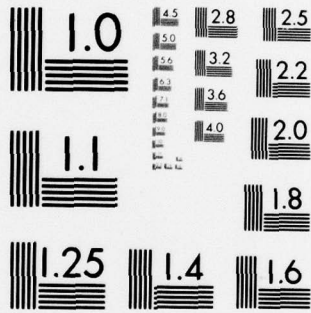
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THESIS

AN APPLICATION OF OPTIMAL CONTROL THEORY
TO THE FFG-7 GAS TURBINE PROPULSION SYSTEM

by

Richard A. Kalyn
June 1979

Thesis Advisor:

T. M. Houlihan

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An Application of Optimal Control Theory
to the FFG-7 Gas Turbine Propulsion System

by

Richard A. Kalyn
Lieutenant Commander, United States Navy
B.S.E., Princeton University, 1964

Submitted in partial fulfillment of the
requirements for the degree of

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from the

NAVAL POSTGRADUATE SCHOOL
June 1979

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Author

RA Kalyn

Approved by:

Thomas Houlihan

Thesis Advisor

Alex Gerba Jr.

Second Reader

J. J. Marto

Chairman, Department of Mechanical Engineering

William M. Tolles

Dean of Science and Engineering

ABSTRACT

An optimal integral control design program was applied to a linearized state variable model of the FFG-7 ship class gas turbine and Controllable Reversible Pitch (CRP) propeller main propulsion system. Various combinations of output parameters were investigated in an attempt to produce a feasible control design. Only one acceptable design was achieved which did not violate any physical constraints.

TABLE OF CONTENTS

I.	INTRODUCTION-----	8
	A. OBJECTIVE-----	8
	B. COMPUTER FACILITIES AND SOFTWARE UTILIZED-----	8
II.	PROPULSION PLANT MODEL-----	10
III.	CONTROL SYSTEM DESIGN WITH CONSYN-----	13
	A. BASIC PHILOSOPHY-----	13
	B. PROGRAM FLOW LOGIC-----	15
	C. MODIFICATIONS TO THE ORIGINAL PROGRAM-----	16
IV.	RESULTS-----	20
	A. GENERAL-----	20
	B. SPECIFIC-----	25
V.	CONCLUSIONS AND RECOMMENDATIONS-----	38
	A. CONCLUSIONS-----	38
	B. RECOMMENDATIONS-----	39
APPENDIX A List of CONSYN Subprograms-----		40
APPENDIX B Propulsion Plant Data-----		41
	1. State Variable Representation at 70%, 75%, 80%, and 85% of Maximum Gas Generator Speed-----	41
	2. A, B, C, D Matrix Elements for 75% of Maximum Gas Generator Speed-----	42
	3. A, B, C, D Matrix Elements for 85% of Maximum Gas Generator Speed-----	43
	4. Scaled A, B, C, D Matrix Elements for 85% of Maximum Gas Generator Speed, Constant Bleed-----	44
	5. Physical Constraints-----	45

APPENDIX C	Derivation of Equations Required for System Simulation with CSMP-----	46
APPENDIX D	Rationale for Design Form Selection-----	48
APPENDIX E	Derivation of Scaled State Variable Data with Constant Bleed-----	50
APPENDIX F	Computer Output of Optimization Run for Design 6-2F-----	53
LIST OF REFERENCES	-----	85
INITIAL DISTRIBUTION LIST	-----	86

LIST OF TABLES

I.	Design Forms Evaluated-----	22
II.	Design Form Variations Evaluated-----	23
III.	Optimal Controller Data, Design 6-2F-----	26
IV.	Performance Data Summary for Various Designs-----	27
V.	Comparison of Initial Condition Actual Outputs with Those Predicted by the Linear Model-----	29

LIST OF FIGURES

1. Integral Control Synthesis----- 18

 a. Original Plant----- 18

 b. Open Loop Integral Control----- 18

 c. Closed Loop Optimal Integral Control----- 19

 d. Closed Loop Optimal Output Integral Control----- 19

2. Optimum Closed Loop Response----- 30

 a. Gas Generator Speed and Power Turbine Speed----- 30

 b. Ship Speed and Propeller Pitch to Diameter Ratio--- 31

 c. Fuel Flow Rate and Stator Guide Vane Angle----- 32

 d. Combustor Outlet Temperature and Power Turbine
 Inlet Temperature----- 33

 e. Compressor Surge Margin and Total Discharge
 Pressure----- 34

 f. Power Turbine Torque and Power----- 35

3. Open Loop Response----- 36

 a. Gas Generator Speed and Power Turbine Speed----- 36

 b. Ship Speed----- 37

I. INTRODUCTION

A. OBJECTIVE

Advanced technology propulsion systems require a control system design that is able to achieve the desired performance at the greatest possible efficiency. One particular scheme that shows great promise in this regard is the optimum integral control design program, CONSYN, developed in Ref. 1.

This study was undertaken to examine the validity and effectiveness of applying CONSYN to the FFG-7 ship class gas turbine propulsion system model obtained from Ref. 2.

B. COMPUTER FACILITIES AND SOFTWARE UTILIZED

The above objective was implemented by simulation on the IBM 360/67 computer of the W. R. Church Computer Center at the Naval Postgraduate School. The following programming software was required:

- Various routines in the International Mathematical and Statistical Library (IMSL)
- The IBM developed Continuous System Modeling Program (CSMP)
- The Control Program for Engineering Synthesis with Constrained Function Minimization (COPES/CONMIN) developed by Garret N. Vanderplaats of the NASA Ames Research Center

· The routines developed for CONSYN in Ref. 1 as modified by Ref. 3 and this study, are listed in Appendix A.

II. PROPULSION PLANT MODEL

The propulsion system for the OLIVER HAZARD PERRY (FFG-7) class patrol frigates consists of two General Electric Corporation LM2500 Marine Gas Turbines, coupled through a reduction gear to a controllable reversible pitch (CRP) propeller manufactured by the Bird-Johnson Company. Since the gas turbine is a highly non-linear device, the linearized state variable model developed in Ref. 2 is valid only for small changes from a specified steady state operating point. This model was obtained from a coupled ship and propulsion plant dynamic non-linear model consisting of the following features:

- A non-linear model of the LM2500 engine developed by General Electric.
- A non-linear model of the ship, propeller and propulsion train provided by the Bath Iron Works Company.
- Secondary flow losses considered.
- Bleed flow for extraction and turbine cooling considered.
- Inlet and exhaust losses incorporated.
- Pressure and temperature dynamics neglected.
- Nested loop balancing utilized to obtain various steady state operating points.

In matrix equation form, this linearized state variable model of the various engine and ship parameters is expressed as:

$$\dot{X} = AX + BU$$

$$Y = CX + DU$$

where

X is the system state vector, and consists of three components:

$$x_1 = NG - NG_{ss} \quad ; \quad NG = \text{Gas Generator Speed (rpm)}$$

$$x_2 = NPT - NPT_{ss} \quad ; \quad NPT = \text{Power Turbine Speed (rpm)}$$

$$x_3 = V - V_{ss} \quad ; \quad V = \text{Ship Speed (knots)}$$

U is the system input vector, and consists of four components:

$$u_1 = WF - WF_{ss} \quad ; \quad WF = \text{Fuel Flow (lbm/hr)}$$

$$u_2 = \beta - \beta_{ss} \quad ; \quad \beta = \text{Stator Guide Vane Angle (deg)}$$

$$u_3 = WB - WB_{ss} \quad ; \quad WB = \text{Compressor Bleed Flow (lbm/s)}$$

$$u_4 = P/D - P/D_{ss} \quad ; \quad P/D = \text{Propeller Pitch/Diam Ratio (``'')}$$

Y is the system output vector, and consists of six components:

$$Y_1 = SMC = SMC_{ss} \quad ; \quad SMC = \text{Compressor Surge Margin (\%)}$$

$$Y_2 = T4 - T4_{ss} \quad ; \quad T4 = \text{Combustor Outlet Temp (}^\circ\text{R)}$$

$$Y_3 = QPT - QPT_{ss} \quad ; \quad QPT = \text{Power Turbine Torque (ft-lbf)}$$

$$Y_4 = P3 - P3_{ss} \quad ; \quad P3 = \text{Compressor Total Disch Press (psia)}$$

$$Y_5 = HPPT - HPPT_{ss} \quad ; \quad HPPT = \text{Power Turbine Power (hp)}$$

$$Y_6 = T5 - T5_{ss} \quad ; \quad T5 = \text{Power Turbine Inlet Temp (}^\circ\text{R)}$$

and the ss subscripts indicate values at a specific steady state operating point, the same point used for determination of the constant A, B, C, D matrix elements.

This study considered single engine up-power transients of 70% to 75%, and 80% to 85% of maximum gas generator speed. In both cases, the steady state operating point selected was that

for the higher power, or final condition. The necessary state variable data to accomplish this study was obtained from computer printouts generated in conjunction with Ref. 2, and is contained in Appendix B. Physical constraints on inputs and input rates are also contained in Appendix B.

III. CONTROL SYSTEM DESIGN WITH CONSYN

A. BASIC PHILOSOPHY

The CONSYN (Control Synthesis) design program presented in Ref. 1 is a further refinement of linear regulator theory developed in Ref. 4. It is based on the initial assumption that the plant dynamics can be represented by the linearized state variable matrix equations

$$\dot{X} = AX + BU$$

$$Y = CX + DU$$

where, as previously discussed, all states are perturbed from their steady state operating points. This is illustrated in block diagram form in Fig. 1a. This original plant is then augmented with integrators to achieve open loop integral control as shown in Fig. 1b. Application of linear quadratic regulator theory to this augmented system leads to the minimization of a performance or cost index, J , defined by the matrix equation

$$J = \int_0^{t_f} (Y^T Q Y + \dot{U}^T R \dot{U}) dt$$

where Q is a constant, diagonal, positive semi-definite matrix used to weight output deviation from final values, and R is a constant, diagonal, positive definite matrix used to weight input rate deviations from final values.

The linear regulator problem solution yields an optimal state feedback regulator which follows the matrix equation control law

$$\dot{U} = Z - G_1 X - G_2 U$$

and is illustrated in Fig. 1c, where Z is the demand vector. Finally, in order to achieve integral control commands generated by the error between demand and output, the system shown in Fig. 1c is converted to that shown in Fig. 1d. This final system configuration has the same time response as that shown in Fig. 1c but has the added advantage of assuring zero steady state error even if system degradation alters the elements of coefficient matrices.

Since that choice of Q and R matrix elements for the solution of the linear regulator problem is arbitrary, COPES/CONMIN logic is then utilized to find the optimum Q and R which minimizes the cost index J without violating any of the imposed physical constraints.

In summary then, the CONSYN design program applies a linear regulator design form to the given output control problem using the augmented state vector

$$X_* = \begin{bmatrix} X \\ -U \end{bmatrix} .$$

Block diagram methods along with suitably partitioned matrices are utilized to arrive at the desired structure of the optimal control system.

B. PROGRAM FLOW LOGIC

The CONSYN design program operates in three distinct segments: Initial Design, Optimization, and Final Design Output. A summary of the significant logic and operations within each of these segments follows.

1. Initial Design

a. Input the following:

- (1) A, B, C, D matrices
- (2) Initial guess for appropriate Q and R matrices
- (3) Initial condition X and U vectors, which are then combined to form the augmented state vector $X_* = \begin{bmatrix} -X \\ U \end{bmatrix}$

(4) System constraints

b. Calculate system open loop characteristics

c. Calculate P, the solution to the steady state matrix Riccati equation¹

$$A_*^T P + P A_* - P B_* R^{-1} B_*^T P + C_*^T Q C_* = 0$$

$$\text{where } A_* = \begin{bmatrix} A & B \\ 0 & 0 \end{bmatrix} \quad B_* = \begin{bmatrix} 0 \\ I \end{bmatrix} \quad C_* = \begin{bmatrix} C \\ D \end{bmatrix}$$

d. Calculate G the optimal state feedback gain matrix

$$G = R^{-1} B_*^T P = \begin{bmatrix} G_1 \\ G_2 \end{bmatrix}$$

¹The detailed development of this Riccati equation and the following G, H, and L gain relationships in the partitioned matrix form is found in Refs. 1 and 4.

e. Calculate H and L the integral control gain matrices

$$\begin{bmatrix} L \\ H \end{bmatrix} = G \begin{bmatrix} -A & B \\ EC & ED \end{bmatrix}^{-1}$$

where $E = \begin{bmatrix} I & 0 \end{bmatrix}$ and is required so that the number of outputs fed back for comparison with the demand vector is equal to the number of inputs.

f. Simulate time response of system.

g. Print results of all of the above.

2. Optimization

Vary Q and R matrix elements under the direction of COPES/CONMIN logic to achieve the smallest cost function value without violating any constraints.

3. Final Design Output

Print complete results of system characteristics associated with the optimum Q and R matrix elements.

Since the CONSYN program does not contain a plotting routine for system time response simulation, a separate program must be utilized. For this study, the IBM CSMP in conjunction with a VERSATEC plotter was employed. A derivation of the equations required for this simulation is contained in Appendix C.

C. MODIFICATIONS TO THE ORIGINAL PROGRAM

As discussed in Ref. 3, the following two significant modifications were made to the original CONSYN program:

- The Kleinman technique for the solution of the matrix Riccati equation in subroutine OPGAIN was replaced by an eigenvalue method.

• The fixed step integration solution in subroutine PEAK for system simulation was replaced by a variable step integration routine.

In using CONSYN with these changes for this study, difficulty was encountered with the variable step integration routine. Numerical underflows, overflows, and step size decimation were encountered to varying degrees in all attempts to use it. Consequently, the fixed step integration method was returned to subroutine PEAK, along with a logic modification to determine and print out the number of terms required for the matrix series convergence of $\text{PHI} = e^{\text{Ft}}$. Here, the matrix F is defined as

$$F = A_* - B_* G$$

where the matrices A_* , B_* and G are as previously defined.

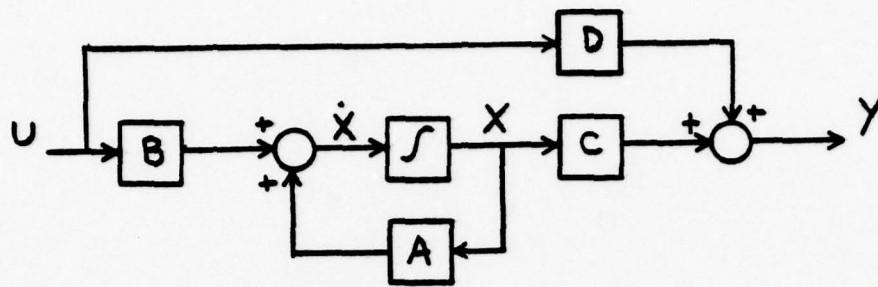


Fig. 1a. Original Plant

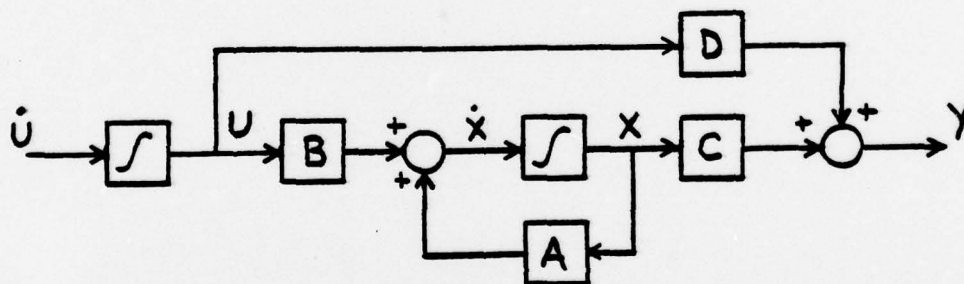


Fig. 1b. Open Loop Integral Control

Figure 1. Integral Control Synthesis

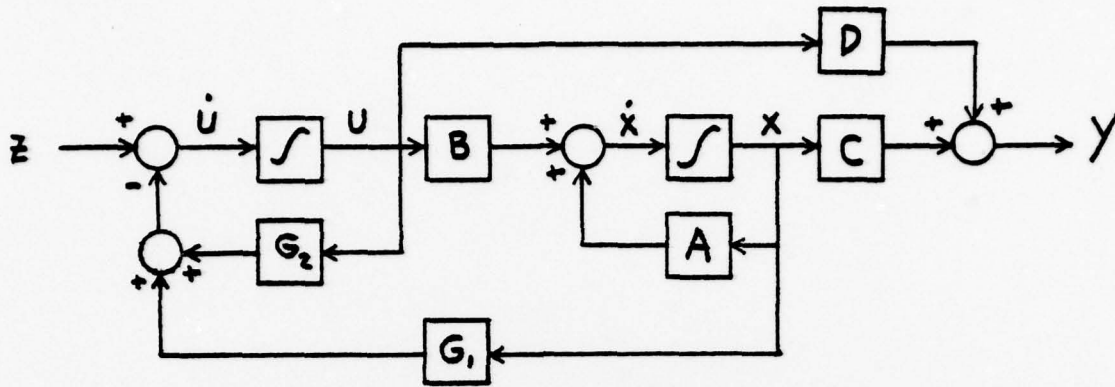


Fig. 1c. Closed Loop Optimal Integral Control

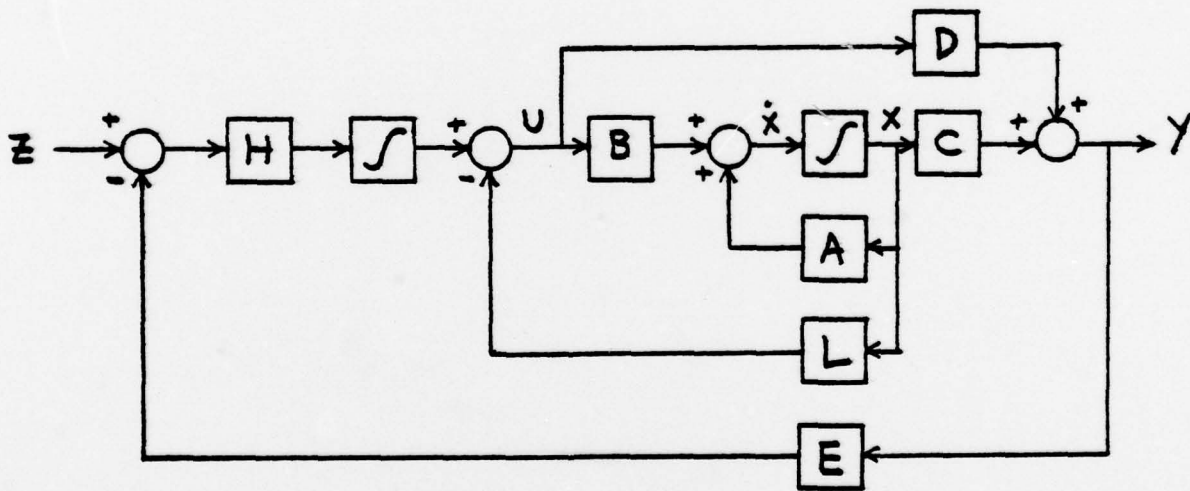


Fig. 1d. Closed Loop Optimal Output Integral Control

Figure 1. (Cont'd)

IV. RESULTS

A. GENERAL

The overall results were disappointing. Of all the basic design forms and variations evaluated, only one was found which did not violate one or more physical constraints. In addition, the study was hampered by the relatively long computer execution times required for the optimization of a single proposed design (approximately 20 minutes), and the excessively long computer turn-around times (approximately 10 hours). In all, at least 150 difference designs were attempted, with a total computer execution time expenditure of over 50 hours. A summary of the design forms and variations considered is given in Tables I and II.

Initial efforts to find an acceptable design were concentrated on design form numbers 2 and 4 in Table I. These forms were selected because they appeared to be the most analogous to the design evaluated in Ref. 5 for the F401 turbofan jet aircraft engine with respect to those outputs designated for feedback.¹ All proposed designs of these forms consisted of transients between 70% and 75% of maximum gas generator speed, variable bleed, and no state variable scaling. All variations considered resulted in violation

¹See Appendix D for a more detailed discussion.

of one or more physical constraints. Examples most often noted were:

- Maximum propeller pitch exceeded
- Maximum propeller pitch rate exceeded, either in the positive or negative direction
- Negative bleed

Design form number 4 was then exercised at various transients between 80% and 85% of maximum gas generator speed with similar types of physical constraint violations.

In an effort to determine why negative bleed was sometimes occurring, G. J. Michael, one of the authors of Refs. 4 and 5 was contacted. The following information and guidance was obtained from this communication:

- Although variable bleed was used as a control in Ref. 4, it also sometimes assumed negative values due to mathematical anomalies in the engine model that could not be eliminated. As a result, bleed was not used as a control input in Ref. 5.
- Although the primary motivation for state variable scaling in Refs. 4 and 5 was to avoid publishing proprietary information in the open literature, doing so in the case of this study might eliminate additional computational anomalies.

TABLE I
DESIGN FORMS EVALUATED

		Basic Form I.D. Number					
		2	4	5	6	7	8
U =		u_1	u_1	u_1	u_1	u_1	u_1
		u_2	u_2	u_2	u_2	u_2	u_2
		u_3	u_3	u_4	u_4	u_4	u_4
		u_4	u_4				
Y =		u_2	u_2	u_2	u_2	u_2	u_1
		u_4	x_3	x_3	Y_3	Y_5	u_4
		Y_3	Y_3	Y_6	Y_6	Y_6	x_3
		Y_6	Y_6	Y_3	x_3	x_3	Y_1
		Y_1	Y_1	Y_1	Y_1	Y_1	Y_2
		Y_2	Y_2	Y_2	Y_2	Y_2	Y_3
		Y_4	Y_4	Y_4	Y_4	Y_4	Y_5
		Y_5	Y_5	Y_5	Y_5	Y_3	Y_6

NOTE: The first n elements of the Y vector, where n is the number of inputs, are those that are to be fed back for comparison with the demand vector.

TABLE II
DESIGN FORM VARIATIONS EVALUATED

1. Initial to final Power Level, % of Maximum Gas Generator Speed:
 - a. 70 - 75%
 - b. 80 - 85%
2. Bleed:
 - a. Variable
 - b. Constant
3. Settling time - 20 to 200 seconds.
4. Ship speed constraint with respect to settling time:
 - a. Within $\pm 2\%$ of steady state value
 - b. Not constrained
5. State variable scaling or normalization with respect to the difference between initial and final steady state values:
 - a. Scaled
 - b. Unscaled
6. Elements of the Q and R performance index weighting matrices allowed to be changed by the optimization routine:
 - a. All Q and R elements
 - b. r_1 (the weight of fuel flow rate error) fixed at 1.0, all other Q and R elements allowed to change.

Design form numbers 5, 6, 7 and 8 were then exercised at various transients between 80% and 85% of maximum gas generator speed, constant bleed, and with state variable scaling.¹ The following results were noted:

- An acceptable design which did not violate any of the input or input rate constraints was achieved with design form number 6, with the performance index weight on fuel flow rate error fixed at 1.0.
- There was no significant difference in system response obtained from design form numbers 5, 6 and 7.
- For those designs which did not impose a specification on ship speed with respect to requested settling time, the optimization routine reduced the degree of initially violated constraints during the first several iterations. The remaining iterations produced no further changes in the degree of constraint violation or in the value of the objective function.
- For those designs which did impose a specification on ship speed with respect to requested settling time, the degree of initially violated constraints was reduced at the expense of violating another constraint that was not initially violated.

¹See Appendix E for the derivation of the scaled state variable data with constant bleed.

- The number of terms required for the series convergence of $\text{PHI} = e^{Ft}$ in subroutine PEAK was much less than before state variable scaling was utilized; usually fewer than ten terms were needed for convergence.
- Deviations from actual values were noted for the linearized model calculations for outputs at the initial condition. The worst occurred for power turbine power which assumed a negative value.

B. SPECIFIC

A summary of the design data associated with the one acceptable design achieved is presented in Table III. Plots of system time response simulation for this design are shown in Figures 2a through 2f. Plots of state open loop response to a step input corresponding to the final steady state input values are shown in Figures 3a and 3b. It is noted that with the optimum design, all engine parameters reached their final steady state values within 6 seconds, and the ship speed achieved 99% of its final steady state value after 100 seconds.

Summaries of performance data for various selected designs are presented in Table IV, with the degree of constraint violation indicated.

A comparison of actual output values with those predicted by the linearized model at the initial condition is given in Table V.

TABLE III

OPTIMAL CONTROLLER DATA, DESIGN 6-2F

Performance Index Weighting Factors

Output Error								Input Rate Error		
q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	r_1	r_2	r_3
(u_2)	(y_3)	(y_6)	(x_3)	(y_1)	(y_2)	(y_4)	(y_5)	(\dot{u}_1)	(\dot{u}_2)	(\dot{u}_4)
.66	.37	.26	7×10^{-7}	6×10^{-8}	.56	.72	.023	1.0	.32	.28

The H Matrix

.3032	.5066	.9441
1.533	.03452	-.02609
-.1797	.9716	-.8782

The L Matrix

-.3585	-.02830	-.0006817
.1184	-.03476	-.001542
.8133	-.3113	-.2850

NOTE: The complete computer output of the optimization run for this design is contained in Appendix F.

TABLE IV
PERFORMANCE DATA SUMMARY FOR VARIOUS DESIGNS

Constraint	Limit	Design Code									
		2-1A	4-1A	4-1B	4-2B	6-2C	6-2D	6-2E	6-2F	8-2E	8-2F
WF _{max}	7600	1640	1640	1850	3860	3870	4170	3860	3860	3950	3910
WF _{min}	900	1320	1320	1320	2360	2360	2360	2360	2360	2360	2360
β _{max}	40	33.3	33.3	33.3	23.4	23.4	23.4	23.4	23.4	23.4	23.4
β _{min}	0	29.0	27.5	29.4	13.0	13.3	15.0	13.2	13.2	11.9	13.1
WB _{max}		1.61	2.54	2.03	10.4	-----constant = .02-----					
WB _{min}	0	(-1.49)	(-2.15)	.02	(-.22)	-----constant = .02-----					
P/D _{max}	1.43	(2.05)	(2.15)	(2.30)	1.43	1.43	1.43	1.43	1.43	1.43	1.43
P/D _{min}	.01	1.29	1.29	.93	1.17	1.05	.80	1.15	1.17	1.15	1.12
WF	+3200	30.5	34.7	1090	1920	611	(4770)	(4650)	1880	(3810)	3180
β	+59	-45.8	-43.3	-10.2	-12.7	-12.7	-1.8	-17.2	-16.5	-3.7	-6.2
WB		11.0	19.1	2.58	246	-----constant = 0-----					
P/D	±.12	(2.59)	(1.02)	(2.80)	(-2.91)	(-.72)	(-.21)	(-.17)	-.12	(-.17)	(-.85)

NOTE: Circled items indicate constraint limit exceeded. The design code used above is explained as follows:

(1st Digit)	-	(2nd Digit)	(letter)
↑		↑	↑
Design form from Table I		Power Code 1 = 70-75% 2 = 80-85%	Variation Code from next page

TABLE IV (Cont'd)

		<u>Variation Code</u> (Also see Table II)					
		<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E</u>	<u>F</u>
<u>Bleed</u>	Variable	X	X				
	Constant			X	X	X	X
<u>State Variables</u>	Scaled				X	X	X
	Unscaled	X	X	X			
<u>Q and R Weights</u>	Variable	X	X	X	X	X	
	r_1 Fixed						X
<u>Ship Speed</u>	Constrained		X	X	X		
	Unconstrained	X				X	X

TABLE V

COMPARISON OF INITIAL CONDITION ACTUAL OUTPUTS WITH THOSE
COMPUTED BY THE LINEAR MODEL

<u>Output</u>	<u>Actual Value</u> ¹	<u>Computed Value</u>
SMC	32.39	30.00
T4	1776	1853
QPT	9706	8182
P3	98.53	91.09
HPPT	3219	-1795
T5	1316	1365

¹Obtained from data generated in conjunction with Ref. 2.

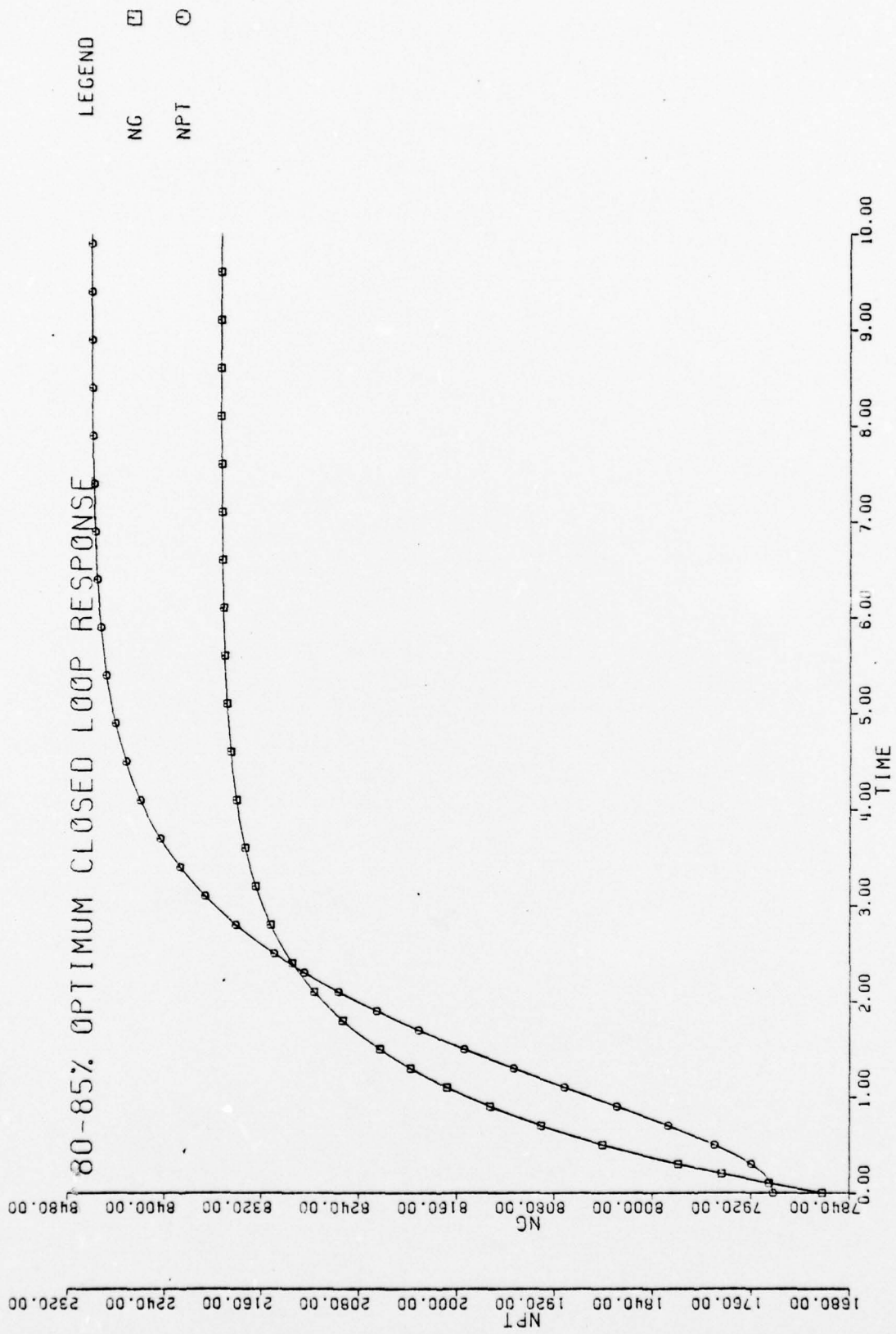


Figure 2a. Gas Generator Speed and Power Turbine Speed

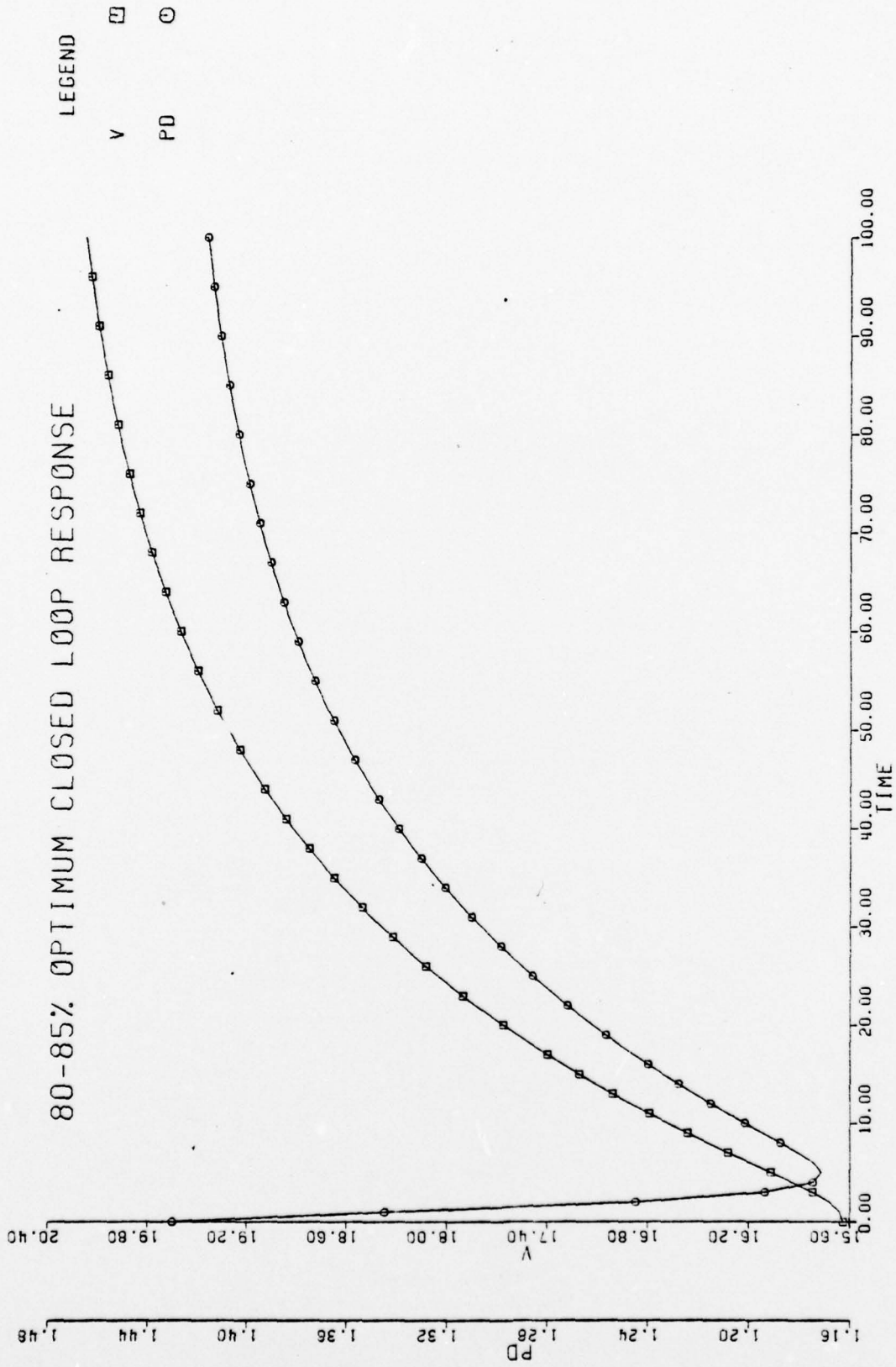


Figure 2b. Ship Speed and Propeller Pitch to Diameter Ratio

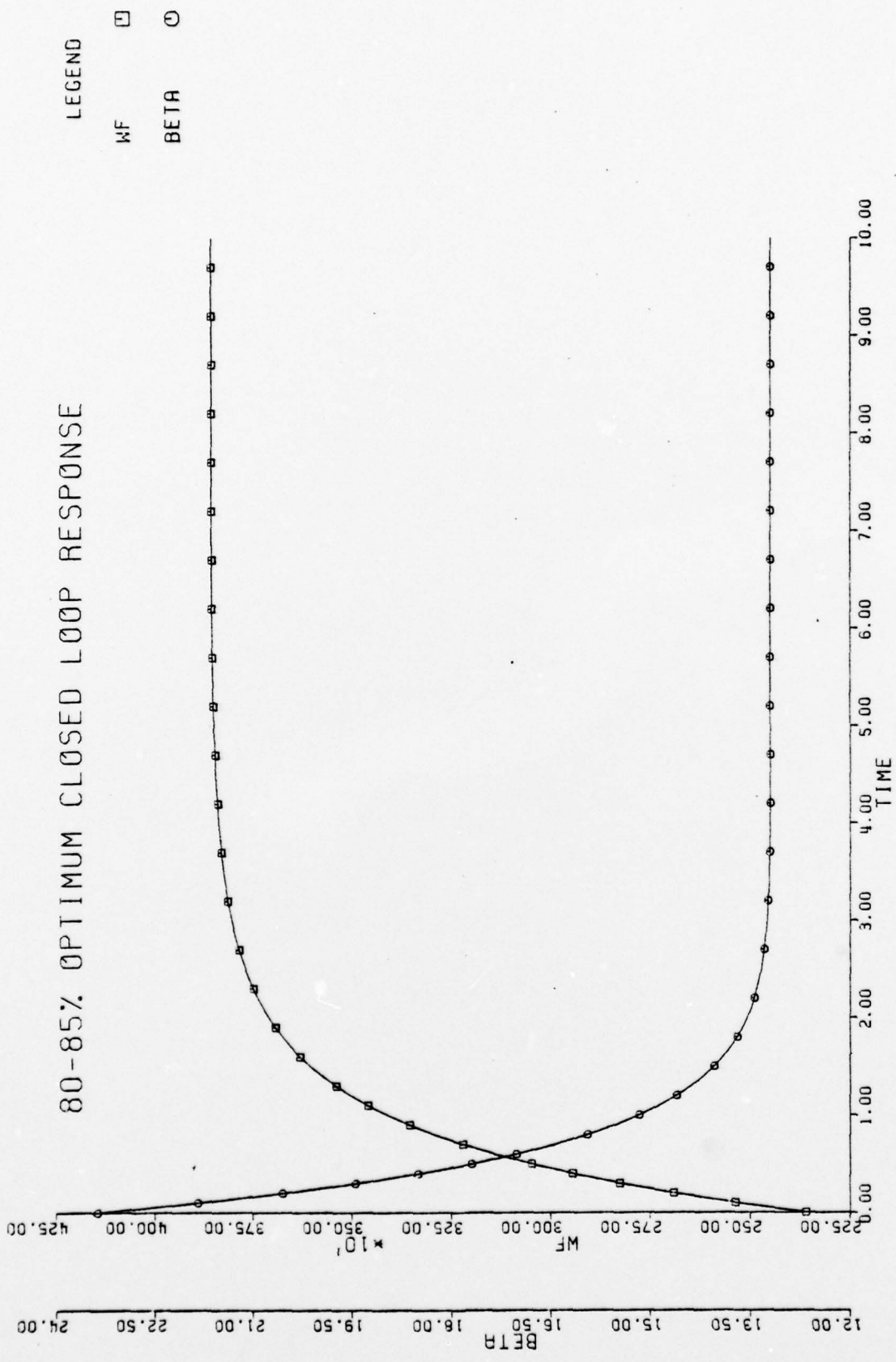


Figure 2c. Fuel Flow Rate and Stator Guide Vane Angle

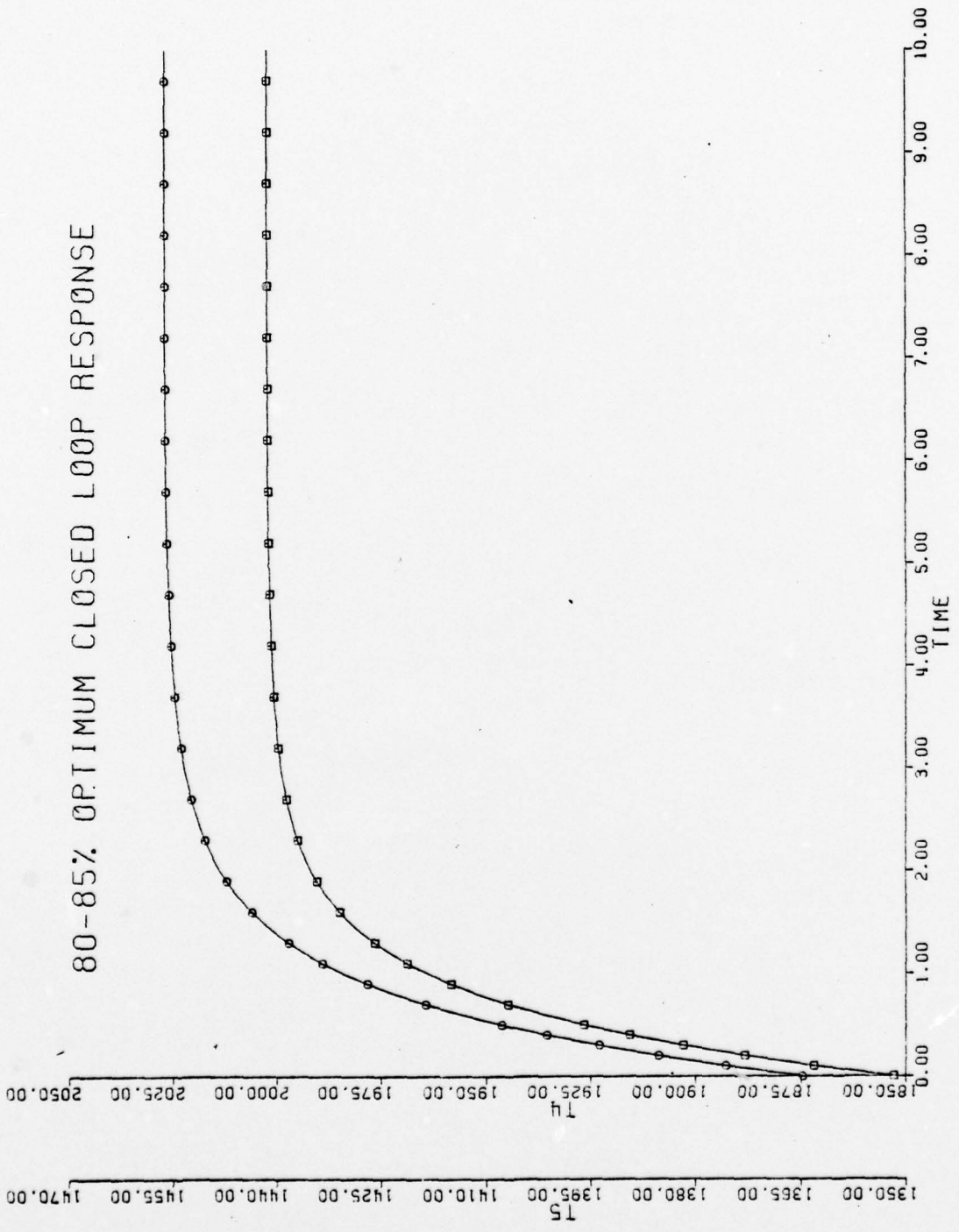


Figure 2d. Combustor Outlet Temperature and Power Turbine Inlet Temperature

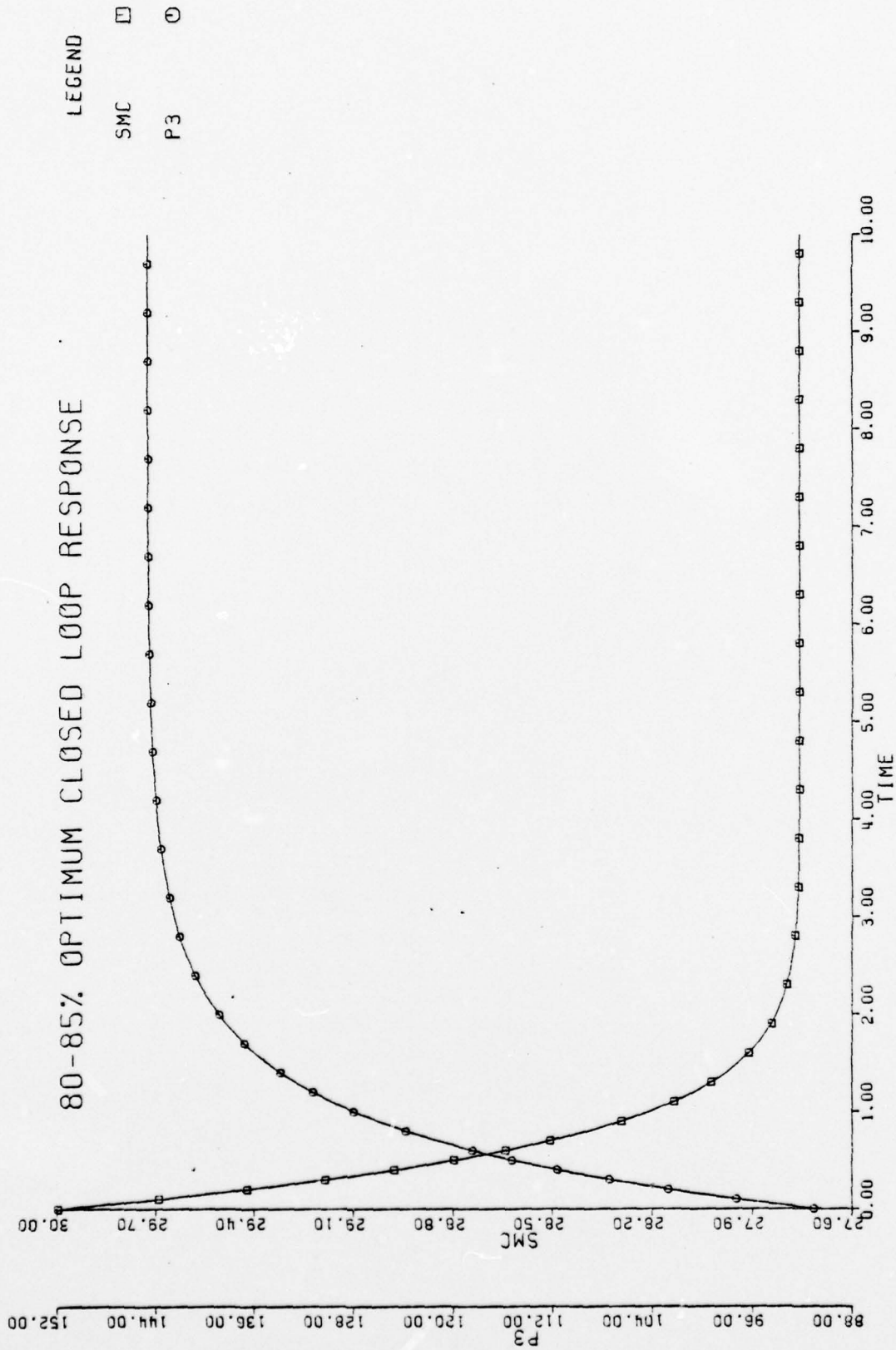


Figure 2e. Compressor Surge Margin and Total Discharge Pressure

80-85% OPTIMUM CLOSED LOOP RESPONSE

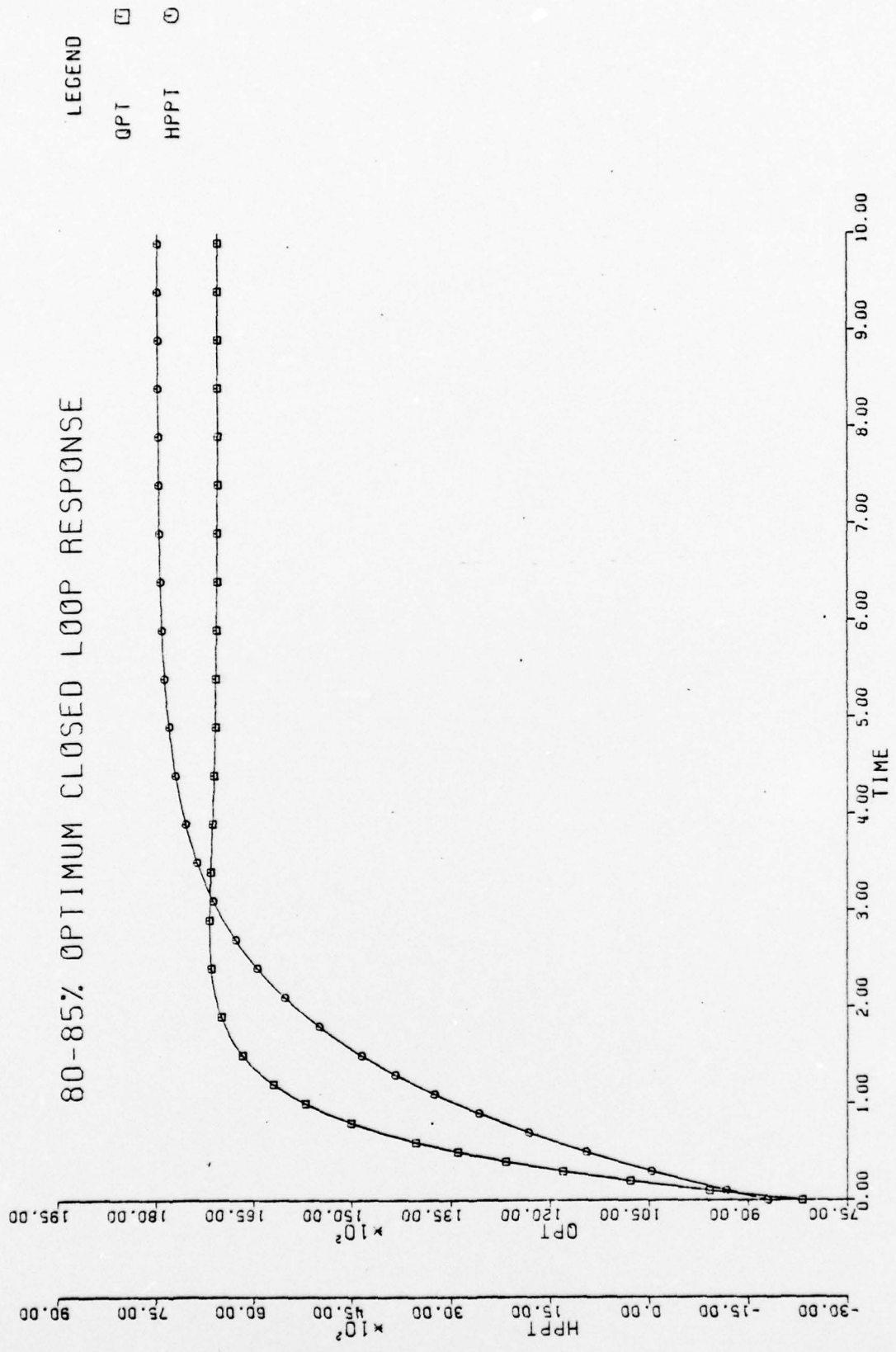


Figure 2f. Power Turbine Torque and Power

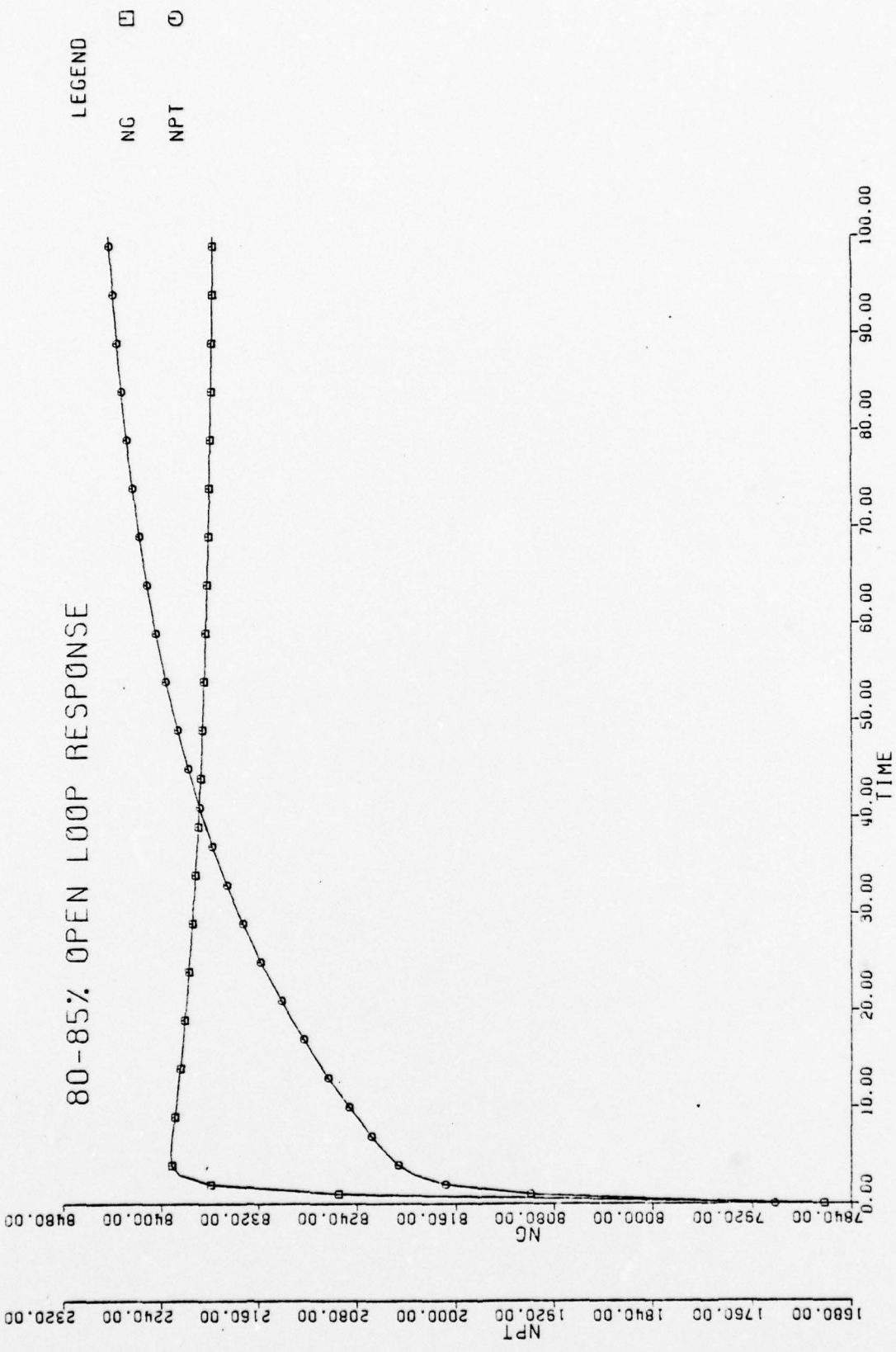


Figure 3a. Gas Generator Speed and Power Turbine Speed

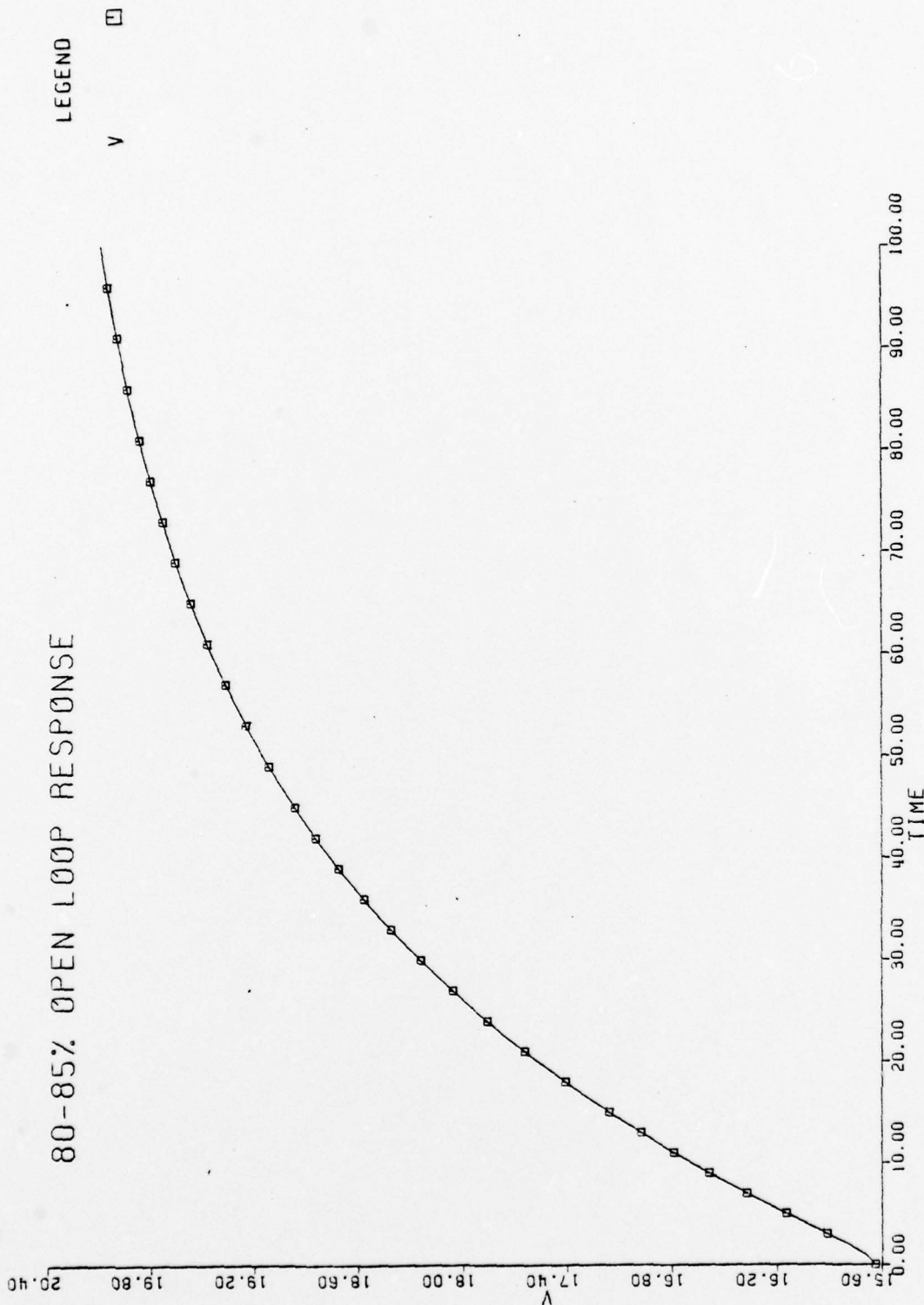


Figure 3b. Ship Speed

V. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1. Some form of state variable scaling is necessary to improve the efficiency of the numerical calculations. Scaling causes the A, B, C, D matrix elements to be much closer to the same order of magnitude.
2. If bleed is to be utilized as a control variable, the failure of the mathematical model to prevent it from assuming negative values must be corrected.
3. Although the system's non-linearity was in evidence at the initial condition state as shown in Table V, the mathematical model became a much more accurate representation of the actual system as the final steady state operating point was approached.
4. Optimal Controller design with the CONSYN program is by no means a completely automated (or cookbook) process. Much manual interaction with options and variable parameters must be employed in order to achieve a feasible design.
5. Input and input rate constraints were design limiting. As long as these constraints were not violated, there were no unreasonable excursions of any state or output variables.

B. RECOMMENDATIONS

1. The specific reason(s) why the optimization routine is so frequently unable to reduce violated constraints beyond a certain point must be investigated and corrected before any practical controller design by this method can be achieved.

APPENDIX A

LIST OF CONSYN SUBPROGRAMS

<u>Name</u>	<u>Purpose</u>
ANALIZ	Integral control design and analysis (previously named CYCLE in Ref. 1)
CONTL	Controllability Check
COST	Evaluation of Performance index and determination of maximum eigenvalue
DET	Matrix determinant
INVERT	Matrix inverse
LIAP	Solution to bilinear symmetric Lyapunov equations
MULT	Matrix multiplication
MULTV	Vector multiplication
MULTZ	Complex matrix multiplication
OBSERV	Observability check
OPGAIN	Solution to optimal linear regulator
PEAK	System simulation
PHIOFT	State transition matrix
POLY	Coefficients of characteristic polynomial
PRINTM	Matrix print, double precision
PRINTN	Matrix print, single precision
RANK	Matrix rank
ROOT	Polynomial roots

APPENDIX B

PROPULSION PLANT DATA

1. State Variable Representation at 70%, 75%,
80%, and 85% of Maximum Gas Generator Speed

	<u>70%</u>	<u>75%</u>	<u>80%</u>	<u>85%</u>
States				
NG (rpm)	6879.	7370.	7862.	8353.
NPT (rpm)	1058.	1313.	1742.	2300.
V (knots)	9.688	11.91	15.64	20.40
Inputs				
WF (lbm/hr)	1319.	1640.	2361.	3857.
β (deg)	33.29	30.58	23.37	13.20
WB (lbm/S)	.02	.02	.02	.02
P/D (°°°)	1.43	1.43	1.43	1.43
Outputs				
SMC (%)	32.63	33.21	32.39	27.76
T4 (°R)	1613.	1663.	1776.	2002.
QPT (ft-lbf)	3745.	5627.	9706.	17040.
P3 (PSIA)	54.02	69.24	98.53	144.6
HPPT (hp)	754.4	1407.	3219.	7461.
T5 (°R)	1284.	1277.	1316.	1456.

APPENDIX B (Cont'd)

2. A, B, C, D MATRIX ELEMENTS FOR 75%
OF MAXIMUM GAS GENERATOR SPEED

The A Matrix

-.2709	-.1186	0.0
.1295	-.9364	57.71
0.0	.0002429	-.02793

The B Matrix

.7287	37.74	-28.29	0.0
.08656	-8.978	-7.861	-526.6
0.0	0.0	0.0	.1114

The C Matrix

.01078	-.0003271	0.0
-.2160	.0008184	0.0
3.171	-2.473	0.0
.02112	.0001619	0.0
.7928	.4526	0.0
-.2289	.01866	0.0

The D Matrix

-.01811	-.5678	2.453	0.0
.4905	9.434	10.21	0.0
2.120	-219.9	-192.5	0.0
.008820	-1.405	-1.195	0.0
.5300	-54.97	-48.13	0.0
.3635	11.49	11.85	0.0

APPENDIX B (Cont'd)

3. A, B, C, D MATRIX ELEMENTS FOR 85%
OF MAXIMUM GAS GENERATOR SPEED

The A Matrix

-1.212	-.1923	0.0
.3466	-1.711	100.3
0.0	.0004290	-.05181

The B Matrix

.6284	68.15	-26.72	0.0
.1194	-14.23	-10.79	-1634.
0.0	0.0	0.0	.3445

The C Matrix

.01097	0.0	0.0
-.2715	0.0	0.0
8.489	-5.786	0.0
.04678	0.0	0.0
3.717	7.101	0.0
-.2484	.01736	0.0

The D Matrix

-.007521	-.3569	1.229	0.0
.2423	7.875	7.273	0.0
2.925	-348.4	-264.3	0.0
.008168	-1.802	-1.349	0.0
1.281	-152.6	-115.8	0.0
.1855	7.277	6.693	0.0

APPENDIX B (Cont'd)

4. SCALED A, B, C, D MATRIX ELEMENTS FOR 85%
MAXIMUM GAS GENERATOR SPEED, CONSTANT BLEED

The Scaled A Matrix

-1.212	-.2185	0.0
.305	-1.711	.8556
0.0	.05029	-.05181

The Scaled B Matrix

1.915	1.412	0.0
.3201	-.2594	-2.928
0.0	0.0	.07237

The Scaled C Matrix

1.163	0.0	0.0
-.5899	0.0	0.0
.5683	-.4402	0.0
.4986	0.0	0.0
.4302	.9341	0.0
-.8712	.06919	0.0

The Scaled D Matrix

-2.43	-.7839	0.0
1.604	.3544	0.0
.5966	-.4831	0.0
.2652	-.3978	0.0
.4518	-.3659	0.0
1.982	.5286	0.0

APPENDIX B (Cont'd)

5. PHYSICAL CONSTRAINTS

Inputs	<u>Note</u>
900 < WF < 7600 lbm/hr	(1)
0 < β < 40°	(1)
.01 < P/D < 1.43	(2)
 Input Rates	
-3200 < ḠF < 3200 lbm/hr/S	(3)
-59 < ḡ < 59 °/S	(3)
-.12 < Ḑ/D < .12 1/S	(4)

- NOTES: (1) Approx. range between idle and full power condition.
 (2) Model does not allow for negative pitch.
 (3) Obtained from G.E.
 (4) Computed from data provided by Bird Johnson Company as follows:

Propeller Diameter = 16.5 ft
 Maximum Ahead Pitch = 23.5 ft
 Maximum Reverse Pitch = 14.7 ft
 Minimum Time for Pitch Change from
 Full Reverse to Full Ahead = 20 sec

$$\dot{P}/D = \frac{\Delta P/D}{\Delta t} = \frac{23.5 - (-14.7)}{16.5 - (-16.5)} = \frac{38.2}{20 \text{ S}} = .12 \text{ 1/S}$$

APPENDIX C

DERIVATION OF EQUATIONS USED FOR SYSTEM SIMULATION WITH CSMP

The following matrix equations may be obtained from inspection of the system block diagram in Fig. 1d:

$$\dot{X} = AX + BU$$

$$Y = CX + DU$$

$$U = \int [H(Z-EY)] dt - LX$$

or, upon differentiating,

$$\dot{U} = H(Z-EY) - L\dot{X}$$

However, the demand vector Z is equal to zero since all desired output deviations are zero at the final steady state operating point which has been defined as the origin. Thus,

$$\dot{U} = -(HEY + L\dot{X})$$

Recalling that the matrix E was defined as

$$E = [I \mid 0],$$

the above matrix equations can, therefore, be expanded into the following form for the 3-state, 3-input, and 8-output system considered:

$$\dot{x}_1 = a_{11} x_1 + a_{12} x_2 + a_{13} x_3 + b_{11} u_1 + b_{12} u_2 + b_{13} u_3$$

$$\dot{x}_3 = a_{31} x_1 + a_{32} x_2 + a_{33} x_3 + b_{31} u_1 + b_{32} u_2 + b_{33} u_3$$

$$y_1 = c_{11} x_1 + c_{12} x_2 + c_{13} x_3 + d_{11} u_1 + d_{12} u_2 + d_{13} u_3$$

$$y_8 = c_{81} x_1 + c_{82} x_2 + c_{83} x_3 + d_{81} u_1 + d_{82} u_2 + d_{83} u_3$$

APPENDIX C (Cont'd)

$$\begin{aligned}\dot{u}_1 &= -(h_{11} y_1 + h_{12} y_2 + h_{13} y_3 + l_{11} \dot{x}_1 + l_{12} \dot{x}_2 + l_{13} \dot{x}_3) \\ \dot{u}_3 &= -(h_{31} y_1 + h_{32} y_2 + h_{33} y_3 + l_{31} \dot{x}_1 + l_{32} \dot{x}_2 + l_{33} \dot{x}_3)\end{aligned}$$

APPENDIX D

RATIONALE FOR DESIGN FORM SELECTION

In Ref. 5, the following outputs were selected for feedback in the case of the F401 turbofan jet engine controller design:

1. Fan inlet guide vane angle (FIGV)
2. Rear compressor variable vane angle (RCVV)
3. Thrust
4. High turbine inlet temperature (HTIT)

Those outputs selected for feedback in design form number 2 of this study were:

1. Propeller pitch to diameter ratio (P/D)
2. Compressor stator guide vane angle (β)
3. Power turbine torque (QPT)
4. Power turbine inlet temperature (T5)

A comparison of these designs follows:

1. The marine propulsion gas turbine engine, of course, has no turbofan. However, the P/D was considered analogous to the FIGV since both directly relate to the loading of the output turbine. In the aircraft case, the output turbine drives the fan; in the marine case, the output turbine drives the propeller.
2. β is completely analogous to RCVV since this is the compressor vane control in both cases.

APPENDIX D (Cont'd)

3. The thrust in the aircraft case is a measure of the total power produced. In the marine case, either ship speed, power turbine power, or power turbine torque is analogous. Torque was selected since it was considered the easiest of the three to measure accurately.
4. HTIT is equivalent to combustor outlet temperature. However, the high temperature involved shortens transducer lifetime, and is variable around the perimeter of the combustor. To eliminate these difficulties, power turbine inlet temperature, instead, was chosen for feedback.

APPENDIX E

DERIVATION OF SCALED STATE VARIABLE DATA WITH CONSTANT BLEED

From the matrix equation,

$$\dot{\mathbf{x}} = \mathbf{A}\mathbf{x} + \mathbf{B}\mathbf{u}$$

consider one of the scalar equations

$$\begin{aligned} \dot{x}_1 = a_{11} x_1 + a_{12} x_2 + a_{13} x_3 + b_{11} u_1 + b_{12} u_2 \\ + b_{13} u_3 + b_{14} u_4 \end{aligned}$$

Since the x 's and u 's are deviations from the steady state operating point, and bleed is constant, then $u_3 = 0$.

Now define the following scaled variables:

$$\hat{x}_i = \frac{x_i}{\Delta x_i}, \quad \hat{u}_i = \frac{u_i}{\Delta u_i}, \quad \hat{u}_4 = u_4$$

where the Δ 's refer to the difference between initial and final conditions, and u_4 will not be scaled since its initial and final values are equal.

Then

$$\begin{aligned} \Delta x_1 \dot{\hat{x}}_1 = a_{11} \Delta x_1 \hat{x}_1 + a_{12} \Delta x_2 \hat{x}_2 + a_{13} \Delta x_3 \hat{x}_3 \\ + b_{11} \Delta u_1 \hat{u}_1 + b_{12} \Delta u_2 \hat{u}_2 + b_{14} \hat{u}_4 \end{aligned}$$

Dividing through by Δx_1 results in

$$\begin{aligned} \dot{\hat{x}}_1 = a_{11} \hat{x}_1 + a_{12} \frac{\Delta x_2}{\Delta x_1} \hat{x}_2 + a_{13} \frac{\Delta x_3}{\Delta x_1} \hat{x}_3 + b_{11} \frac{\Delta u_1}{\Delta x_1} \hat{u}_1 \\ + b_{12} \frac{\Delta u_2}{\Delta x_1} \hat{u}_2 + \frac{b_{14}}{\Delta x_1} \hat{u}_4 \end{aligned}$$

APPENDIX E (Cont'd)

Carrying this procedure out with the other state and output equations results in the scaled matrix equations:

$$\hat{\dot{X}} = \hat{A}\hat{X} + \hat{B}\hat{U}$$

$$\hat{Y} = \hat{C}\hat{X} + \hat{D}\hat{U}$$

where

$$\hat{A} = \begin{bmatrix} a_{11} & a_{12} \frac{\Delta x_2}{\Delta x_1} & a_{13} \frac{\Delta x_3}{\Delta x_1} \\ a_{21} \frac{\Delta x_1}{\Delta x_2} & a_{22} & a_{23} \frac{\Delta x_3}{\Delta x_2} \\ a_{31} \frac{\Delta x_1}{\Delta x_3} & a_{32} \frac{\Delta x_2}{\Delta x_3} & a_{33} \end{bmatrix}$$

$$\hat{B} = \begin{bmatrix} b_{11} \frac{\Delta u_1}{\Delta x_1} & b_{12} \frac{\Delta u_2}{\Delta x_1} & b_{14} \frac{1}{\Delta x_1} \\ b_{21} \frac{\Delta u_1}{\Delta x_2} & b_{22} \frac{\Delta u_2}{\Delta x_2} & b_{24} \frac{1}{\Delta x_2} \\ b_{31} \frac{\Delta u_1}{\Delta x_3} & b_{32} \frac{\Delta u_2}{\Delta x_3} & b_{34} \frac{1}{\Delta x_3} \end{bmatrix}$$

APPENDIX E (Cont'd)

$$\hat{C} = \begin{bmatrix} c_{11} \frac{\Delta x_1}{\Delta Y_1} & c_{12} \frac{\Delta x_2}{\Delta Y_1} & c_{13} \frac{\Delta x_3}{\Delta Y_1} \\ c_{21} \frac{\Delta x_1}{\Delta Y_2} & c_{22} \frac{\Delta x_2}{\Delta Y_2} & c_{23} \frac{\Delta x_3}{\Delta Y_2} \\ \vdots & \vdots & \vdots \\ c_{61} \frac{\Delta x_1}{\Delta Y_6} & c_{62} \frac{\Delta x_2}{\Delta Y_6} & c_{63} \frac{\Delta x_3}{\Delta Y_6} \end{bmatrix}$$

$$\hat{D} = \begin{bmatrix} d_{11} \frac{\Delta u_1}{\Delta Y_1} & d_{12} \frac{\Delta u_2}{\Delta Y_1} & d_{14} \frac{1}{\Delta Y_1} \\ d_{21} \frac{\Delta u_1}{\Delta Y_2} & d_{22} \frac{\Delta u_2}{\Delta Y_2} & d_{24} \frac{1}{\Delta Y_2} \\ \vdots & \vdots & \vdots \\ d_{61} \frac{\Delta u_1}{\Delta Y_6} & d_{62} \frac{\Delta u_2}{\Delta Y_6} & d_{64} \frac{1}{\Delta Y_6} \end{bmatrix}$$

CARD IMAGES OF CONTROL DATA

CARD

IMAGE

FFG-7 80-85% POWER TRANSIENT, CONSTRAINED OPTIMUM INTEGRAL CONTROL DESIGN #6-2F
 11

11

10

5

671

-1.0

1	0.0	100.	1	12	2.502
2	0.0	100.	2	23	2.502
3	0.0	100.	3	34	2.635
4	0.0	100.	4	45	2.635
5	0.0	100.	5	56	0.0
6	0.0	100.	6	67	0.0
7	0.0	100.	7	78	2.139
8	0.01	100.	8	89	5.801
9	0.01	100.	9	100	.12
10			10	111	
11			11	122	
12			12	133	
13			13	144	
14			14	155	
15			15	166	
16			16	177	
17			17	188	
18			18	199	
19			19	210	
20			20	221	
21			21	232	
22			22	243	
23			23	254	
24			24	265	
25			25	276	
26			26	287	
27			27	298	
28			28	309	
29			29	320	
30			30	331	
31			31	342	
32			32	353	
33			33	364	
34			34	375	
35			35	386	
36			36	397	
37			37	408	
38			38	419	
39			39	430	
40			40	441	
41			41	452	
42			42	463	
43			43	474	
44			44	485	
45			45	496	
46			46	507	
47			47	518	
48			48	529	
49			49	540	
50			50	551	
51			51	562	
52			52	573	
53			53	584	
54			54	595	
55			55	606	
56			56	617	
57			57	628	
58			58	639	
59			59	650	
60			60	661	
61			61	672	
62			62	683	
63			63	694	
64			64	705	
65			65	716	
66			66	727	
67			67	738	
68			68	749	
69			69	760	
70			70	771	
71			71	782	
72			72	793	
73			73	804	
74			74	815	
75			75	826	
76			76	837	
77			77	848	
78			78	859	
79			79	870	
80			80	881	
81			81	892	
82			82	903	
83			83	914	
84			84	925	
85			85	936	
86			86	947	
87			87	958	
88			88	969	
89			89	980	
90			90	991	
91			91	1002	
92			92	1013	
93			93	1024	
94			94	1035	
95			95	1046	
96			96	1057	
97			97	1068	
98			98	1079	
99			99	1090	
100			100	1101	
101			101	1112	
102			102	1123	
103			103	1134	
104			104	1145	
105			105	1156	
106			106	1167	
107			107	1178	
108			108	1189	
109			109	1200	
110			110	1211	
111			111	1222	
112			112	1233	
113			113	1244	
114			114	1255	
115			115	1266	
116			116	1277	
117			117	1288	
118			118	1299	
119			119	1310	
120			120	1321	
121			121	1332	
122			122	1343	
123			123	1354	
124			124	1365	
125			125	1376	
126			126	1387	
127			127	1398	
128			128	1409	
129			129	1420	
130			130	1431	
131			131	1442	
132			132	1453	
133			133	1464	
134			134	1475	
135			135	1486	
136			136	1497	
137			137	1508	
138			138	1519	
139			139	1530	
140			140	1541	
141			141	1552	
142			142	1563	
143			143	1574	
144			144	1585	
145			145	1596	
146			146	1607	
147			147	1618	
148			148	1629	
149			149	1640	
150			150	1651	
151			151	1662	
152			152	1673	
153			153	1684	
154			154	1695	
155			155	1706	
156			156	1717	
157			157	1728	
158			158	1739	
159			159	1750	
160			160	1761	
161			161	1772	
162			162	1783	
163			163	1794	
164			164	1805	
165			165	1816	
166			166	1827	
167			167	1838	
168			168	1849	
169			169	1860	
170			170	1871	
171			171	1882	
172			172	1893	
173			173	1904	
174			174	1915	
175			175	1926	
176			176	1937	
177			177	1948	
178			178	1959	
179			179	1970	
180			180	1981	
181			181	1992	
182			182	2003	
183			183	2014	
184			184	2025	
185			185	2036	
186			186	2047	
187			187	2058	
188			188	2069	
189			189	2080	
190			190	2091	
191			191	2102	
192			192	2113	
193			193	2124	
194			194	2135	
195			195	2146	
196			196	2157	
197			197	2168	
198			198	2179	
199			199	2190	
200			200	2201	
201			201	2212	
202			202	2223	
203			203	2234	
204			204	2245	
205			205	2256	
206			206	2267	
207			207	2278	
208			208	2289	
209			209	2300	
210			210	2311	
211			211	2322	
212			212	2333	
213			213	2344	
214			214	2355	
215			215	2366	
216			216	2377	
217			217	2388	
218			218	2399	
219			219	2410	
220			220	2421	
221			221	2432	
222			222	2443	
223			223	2454	
224			224	2465	
225			225	2476	
226			226	2487	
227			227	2498	
228			228	2509	
229			229	2520	
230			230	2531	
231			231	2542	
232			232	2553	
233			233	2564	
234			234	2575	
235			235	2586	
236			236	2597	
237			237	2608	
238			238	2619	
239			239	2630	
240			240	2641	
241			241	2652	
242			242	2663	
243			243	2674	
244			244	2685	
245			245	2696	
246			246	2707	
247			247	2718	
248			248	2729	
249			249	2740	
250			250	2751	
251			251	2762	
252			252	2773	
253			253	2784	
254			254	2795	
255			255	2806	
256			256	2817	
257			257	2828	
258			258	2839	
259			259	2850	
260			260	2861	
261			261	2872	
262			262	2883	
263			263	2894	
264			264	2905	
265			265	2916	
266			266	2927	
267			267	2938	
268			268	2949	
269			269	2960	
270			270	2971	
271			271	2982	
272			272	2993	
273			273	3004	
274			274	3015	
275			275	3026	
276			276	3037	
277			277	3048	
278			278	3059	
279			279	3070	
280			280	3081	
281			281	3092	
282			282	3103	
283			283	3114	
284			284	3125	
285			285	3136	
286			286	3147	
287			287	3158	
288			288	3169	
289			289	3180	
290					

TABLE 7 8C-828 POWER TRANSIENT, CCNSTRAINED OPTIMUM INTEGRAL CONTROL DESIGN #6-2F

CONTROL PARAMETERS:
 NUMBER OF GLOBAL DESIGN VARIABLES, NCALC = 16
 NUMBER OF LOCAL DESIGN VARIABLES, NSV = 0
 NUMBER OF CONSTRAINTS IN TWO-SPACE, NZVAR = 0
 NUMBER OF CONSTRAINTS IN ONE-SPACE, NZVAR = 0
 INPUT INFORMATION PRINT CODE, IPNS = 0
 SENSITIVITY PRINT CODE, IPSENS = 0
 TWO-SPACE PRINT CODE, IP2VAR = 0
 DEBUG PRINT CODE, IPDBG = 0

CALCULATION CONTROL, NCALC
 VALUE MEANS ANALYSIS
 1 SINGLE ANALYSIS
 2 ITERATION
 3 DESIGN VARIABLE FUNCTION SPACE
 4 OPTIMUM SENSITIVITY

GLOBAL VARIABLE NUMBER OF OBJECTIVE
 MULTIPLIER (NEGATIVE INDICATES MINIMIZATION) = -3.1000E 01

CONMIN PARAMETERS (IF ZERO, CONMIN DEFAULT WILL OVER-RIDE)

IPRINT ITMAX ICNDR NSCAL ITRM LINOBJ NACMX1 NFDG
 5 0 0 11 0 12 0 0

F0CH F0CHM CT CTAIN
 0.0 0.0 0.0 0.0
 CTA CTAHIN THETA PHI
 0.0 0.0 0.0 0.0
 DELFUN DAFUN ALPHAX ABOBJ1
 0.0 0.0 0.0 0.0

DESIGN VARIABLE INFORMATION OVER-RIDE MODULE INPUT
 NON-ZERO INITIAL VALUE WILL UPPER INITIAL VALUE SCALE
 D. V. LOWER BOUND ROUND SCALE
 NO. 1 0.0 0.0 0.10000E 03 0.0 0.0
 2 0.0 0.0 0.10000E 03 0.0 0.0
 3 0.0 0.0 0.10000E 03 0.0 0.0
 4 0.0 0.0 0.10000E 03 0.0 0.0
 5 0.0 0.0 0.10000E 03 0.0 0.0
 6 0.0 0.0 0.10000E 03 0.0 0.0
 7 0.0 0.0 0.10000E 03 0.0 0.0
 8 0.0 0.0 0.10000E 03 0.0 0.0
 9 0.10000E-01 0.10000E-01 0.10000E 03 0.0 0.0
 10 0.0 0.0 0.10000E 03 0.0 0.0

DESIGN VARIABLES	D.V. NO.	GLOBAL VAR. NO.	MULTIPLYING FACTOR
1	1	1	0.10000E 01
2	2	2	0.10000E 01
3	3	3	0.10000E 01
4	4	4	0.10000E 01
5	5	5	0.10000E 01
6	6	6	0.10000E 01
7	7	7	0.10000E 01
8	8	8	0.10000E 01
9	9	9	0.10000E 01
10	10	10	0.10000E 01

CONSTRAINT INFORMATION

THERE ARE 9 CONSTRAINT SETS

ID	GLOBAL VAR. 1	GLOBAL VAR. 2	GLOBAL LINEAR ID
1	0	0	0
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0

TOTAL NUMBER OF CONSTRAINED PARAMETERS = 9

DATA STORAGE REQUIREMENTS

INPUT EXECUTION	REAL AVAILABLE	INTEGER EXECUTION	AVAILABLE
95	533	68	1000

LOWER BOUND	NORMALIZATION FACTOR	UPPER BOUND	NORMALIZATION FACTOR
-0.19770E 01	0.19770E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.12200E 01	0.12200E 01	0.25020E 01	0.25020E 01
-0.14200E 01	0.14200E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01
-0.11390E 01	0.11390E 01	0.25020E 01	0.25020E 01

LINEAR INTEGRAL OPTIMAL CONTROL DESIGN PROGRAM
 PROBLEM IDENTIFICATION- FFG7 80-85z

JCALC= 1

THE A MATRIX

	1	2	3
1	-1.21200000	00	-2.18500000-01 0.0
2	3.65000000-01	-1.71100000	00 8.55600000-01
3	0.0	5.02500000-02	-5.18100000-02

THE B MATRIX

	1	2	3
1	1.91500000	00	1.41200000 00 0.0
2	3.20100000-01	-2.59400000-01	-2.92800000 00
3	0.0	0.0	7.23700000-02

THE C MATRIX

	1	2	3
1	0.0	0.0	0.0
2	5.68300000-01	-4.40200000-01	0.0
3	-6.71200000-01	6.91500000-02	0.0
4	0.0	0.0	1.00000000 00
5	1.16300000	00	0.0
6	-5.85900000-01	0.0	0.0
7	4.98600000-01	0.0	0.0
8	4.36200000-01	9.34100000-01	0.0

THE D MATRIX

	1	2	3
1	0.0	1.00000000	00 0.0
2	5.96600000-01	-4.83100000-01	0.0
3	1.98200000	00	5.28600000-01 0.0
4	0.0	0.0	0.0
5	-2.43000000	00	-7.83900000-01 0.0
6	1.64000000	00	3.54400000-01 0.0
7	2.65200000-01	-3.57600000-01	0.0
8	4.51800000-01	-3.65900000-01	0.0

THE H MATRIX

```
1 2 3
1 9.61629490-01 5.77020220-01 2.65880300 00
2 1.30488000 00 1.60840910-01 5.75368380-02
3 -1.18511900 00 1.00346140 00 -2.23069300 00
```

THE L MATRIX

```
1 2 3
1 -1.20315240 00 -6.69447700-02 -4.14727990 00
2 1.14449800-01 -6.97858060-02 -1.65131150 00
3 2.00656620 00 -3.87785220-01 1.71938150 00
```

FINAL SYSTEM CHARACTERISTICS

THE CHARACTERISTIC POLYNOMIAL - IN ASCENDING POWERS OF S

```
3.79267530-01 1.30024350 01 4.07131000 01 5.01047330 01 3.01787050 01 8.96051260 00
1.00000000 00
```

THE EIGENVALUES OF THE STATE MATRIX

```
REAL PART IMAGINARY PART
-3.23103120-02 0.0
-1.53239440 00 -5.17157650-01
-1.53239440 00 9.17157650-01
-1.55402770-01 0.0
-1.26215380 00 0.0
-3.83886000 00 0.0
```

REQUESTED SETTLING TIME IS 60.000 SECONDS

SIMULATION RUN TIME = 72.000

THE INITIAL CONDITION VECTOR

X(1)	-1.000
X(2)	-1.000
X(3)	-1.000
U(1)	-1.000
U(2)	1.000
U(3)	0.0

STEADY STATE VALUES OF THE OUTPUTS AT 60.000 SECONDS

Y(1)	0.005
Y(2)	0.006
Y(3)	0.004
Y(4)	-0.151
Y(5)	-0.003
Y(6)	0.004
Y(7)	0.008
Y(8)	0.019

PEAK VALUES TIME OF OCCURRENCE

X(1)	0.110	3.10
X(2)	0.095	2.70
X(3)	-0.102	71.95
Y(1)	1.000	*****
Y(2)	0.039	5.15
Y(3)	0.087	0.70
Y(4)	-0.102	71.95
Y(5)	0.483	*****
Y(6)	0.043	0.70
Y(7)	0.050	4.15
Y(8)	0.135	3.00
U DOT(1)	2.587	
U DOT(2)	-1.179	
U DOT(3)	-0.931	
U(1)	0.045	
U(2)	1.000	
U(3)	0.0	

MINIMUM INPUT VALUES

U(1)	-1.000
U(2)	0.004
U(3)	-0.396

MINIMUM STATE VALUES

X(1)	-1.000
X(2)	-1.000
X(3)	-1.003

MINIMUM OUTPUT VALUES

Y(1)	0.004
Y(2)	-1.208
Y(3)	-0.651
Y(4)	-1.003
Y(5)	-0.253
Y(6)	-0.660
Y(7)	-1.162
Y(8)	-2.182

 C O N M I N
 FORTRAN PROGRAM FOR
 CONSTRAINED FUNCTION MINIMIZATION

CONSTRAINED FUNCTION MINIMIZATION

CONTROL PARAMETERS

IPRINT	NDY	ITMAX	MCON	NSIDE	ICNDR	MSCAL	MFGO
5	10	20	18	1	11	11	0
LINOBJ	ITRY	N1	N2	N3	N4	N5	
0	3	12	38	12	12	24	
CT		CTMIN		CTL		CTLMIN	
		0.10000E 00	0.40000E-02	-0.10000E-01		0.10000E-02	
THETA		PHI		DELFUN		SABFUN	
0.10000E 01		0.50000E 01		0.10000E-03		0.23559E-01	
FUCH		FUCHM		ALPHAX		ABOBJ	
0.10000E-01		0.10000E-01		0.10000E 00		0.10000E 00	
LOWER BOUNDS ON DECISION VARIABLES (VLR)							
1)	0.0	0.0		0.0		0.0	0.0
7)	0.0	0.0		0.10000E-01		0.10000E-01	0.0
UPPER BOUNDS ON DECISION VARIABLES (VUR)							
1)	0.10000E 03	0.10000E 03		0.10000E 03		0.10000E 03	0.10000E 03
7)	0.10000E 03	0.10000E 03		0.10000E 03		0.10000E 03	0.10000E 03

ALL CONSTRAINTS ARE HCN-LINEAR

INITIAL FUNCTION INFORMATION

OBJ = 0.235590E 02

DECISION VARIABLES (X-VECTOR)

1)	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01
7)	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01	0.10000E 01

CONSTRAINT VALUES (G-VECTOR)

1)	-0.10230E 01	-0.98183E 00	-0.49418E 00	-0.13997E 01	-0.17774E 01	-0.62049E 00
7)	-0.10028E 01	-0.99862E 00	-0.10000E 01	0.0	-0.72147E 00	-0.39551E 01
13)	-0.22097E 01	0.20967E 00	-0.79679E 00	-0.12032E 01	0.67578E 01	-0.87578E 01

```

BEGIN ITERATION NUMBER 1
CT = -0.10000E 00 CTL = -0.10000E-01 PHI = 0.50000E 01
NEW SCALING VECTOR (SCALE)
0.10000E 01 0.10000E 01 0.10000E 01 0.10000E 01 0.10000E 01 0.10000E 01 0.10000E 01 0.10000E 01
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
PEAK CALLED; NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
THERE ARE 1 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
10
THERE ARE 2 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE
14
17
THERE ARE 0 ACTIVE SIDE CONSTRAINTS
GRADIENT OF OBJ
1) 0.38910E 00 0.64528E 00 0.72632E 00 0.15636E 02 0.11658E 01 0.42725E 00
7) 0.30975E 00 0.10956E 01 0.70180E 00 0.84991E 00
GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER 10 0.0 0.0 0.0 0.0 0.0 0.0
1) 0.0 0.0
CONSTRAINT NUMBER 14 0.95987E-01 0.55194E-01 0.60636E-01 0.25141E-01 0.52071E-01
7) 0.13816E-01 0.21186E 00 -0.20957E-01 0.96738E-02
CONSTRAINT NUMBER 17 -0.17347E 00 -0.10566E 01 -0.39005E-01 0.52137E 00 -0.42534E-01 -0.12970E-01
1) -0.16460E 00 0.48577E 01 0.27046E 00 -0.45976E 01
PUSH-OFF FACTORS (THE TAIL) I=1,NAC
1) 0.20000E-01 0.19180E 00 0.10000E 01
CONSTRAINT PARAMETER, BETA = 0.0
SEARCH DIRECTION (S-VECTOR)
1) 0.52889E 01 0.42549E-01 -0.46463E-01 -0.10000E 01 -0.74558E-01 -0.27325E-01
7) -0.19811E-01 -0.70069E-01 -0.44891E-01 -0.44891E-01 -0.54357E-01
ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.1597E 02 PROPOSED ALPHA = 0.1000E 01

```

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.10000E 01
 X-VECTOR
 C0 0.9575E 00 0.9535E 00 0.6557E-06 0.9254E 00 0.9727E 00 0.9802E 00 0.9299E 00
 C1 0.9751E 00 0.9456E 00
 C2 0.9551E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 8 TERMS

OBJ = 0.72552E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.9997E 00 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 -0.1000E 01 0.0 -0.7450E 00 -0.3621E 01 -0.2120E 01 0.1193E 00 -0.7870E 00 -0.1213E 01
 C. 6133E 01 -0.8133E 01

PROPOSED DESIGN
 ALPHA = 0.10000E 01
 X-VECTOR
 C0 0.9149E 00 0.9071E 00 0.6557E-06 0.8509E 00 0.9453E 00 0.9604E 00 0.8559E 00
 C1 0.9502E 00 0.8913E 00
 C2 0.9102E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 8 TERMS

OBJ = 0.69385E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.9997E 00 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 -0.1000E 01 0.0 -0.7460E 00 -0.3608E 01 -0.2091E 01 0.9060E-01 -0.7861E 00 -0.1214E 01
 C. 2033E 01 -0.8033E 01

TWC-PCINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.50000E 01
 X-VECTOR
 C0 0.8507E 00 0.7213E 00 0.6557E-06 0.5527E 00 0.8360E 00 0.8811E 00 0.5796E 00
 C1 0.7307E 00 0.6739E 00
 C2 0.7307E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 8 TERMS

OBJ = 0.56344E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.9999E 00 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 -0.1000E 01 0.0 -0.7532E 00 -0.3505E 01 -0.1965E 01 -0.3532E-01 -0.7811E 00 -0.1219E 01
 C. 5420E 01 -0.7420E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.60000E 01
 OBJ = 0.563443E 01

DECISION VARIABLES (X-VECTOR)
 1) 0.85069E 00 0.74471E 00 0.72129E 00 0.65565E-06 0.55265E 00 0.83605E 00
 2) 0.88114E 00 0.57959E 00 0.73065E 00 0.67386E 00

CONSTRAINT VALUES (G-VECTOR)
 1) -0.10000E 01 -0.99990E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.62049E 00
 2) -0.10000E 01 -0.99990E 01 -0.50000E 01 -0.00000E 00 -0.78110E 00 -0.73065E 00
 13) -0.19647E 01 -0.35318E-01 -0.78110E 00 -0.12189E 01 0.54199E 01 -0.74199E 01

BEGIN ITERATION NUMBER 2

CT = -0.10000E+00
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS
 PEAK CALLED: NORM OF A = 0.6379D 01; SERIES FOR PHI CONTAINED 8 TERMS

THERE ARE 2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE 10 14

THERE ARE 1 VIOLATED CONSTRAINTS
 CONSTRAINT NUMBERS ARE 11

THERE ARE 1 ACTIVE SIDE CONSTRAINTS
 DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)

GRADIENT OF OBJ
 1) 0.36192E 00 0.62790E 00 0.81024E 00 0.16359E 02 0.12558E 01 0.47817E 00
 7) 0.21380E 00 0.98553E 00 0.71764E 00 0.81511E 00

GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
 CONSTRAINT NUMBER 10 0.0 0.0 0.0 0.0 0.0 0.0
 7) 0.0 0.0 0.0 0.0 0.0 0.0

CONSTRAINT NUMBER 14
 1) 0.13286E-01 0.11730E 00 0.75126E-01 0.77177E-01 0.44585E-01 0.69062E-01
 7) 0.68234E-01 0.26849E 00 -0.22561E-01 0.60637E-02

CONSTRAINT NUMBER 17
 1) -0.18549E 00 -0.18422E 01 0.46444E 01 0.94223E 00 -0.46635E-01 -0.12398E-02
 7) -0.29001E 00 0.84336E 01 0.33321E 00 -0.54813E 01

SIDE CONSTRAINT ON VARIABLE 4
 1) 0.0 0.0 -0.10000E 01 0.0 0.0
 7) 0.0 0.0 0.0 0.0 0.0

PUSH-CFF FACTORS (THETA(I), I=1,NAC)
 1) 0.20000E-01 0.63676E-02 0.10000E 01 0.0
 CONSTRAINT PARAMETER, BETA = -0.19454E-03

SEARCH DIRECTION (S-VECTOR)
 1) -0.27931E 00 -0.48458E 00 -0.62530E 00 0.0 -0.10000E 01 -0.36903E 00
 7) -0.21130E 00 -0.76058E 00 -0.55384E 00 -0.62908E 00

CNF-DIMENSIONAL SEARCH
 INITIAL SLOPE = -0.4102E 01 PROPOSED ALPHA = 0.2513E 01

** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ** *

PROPOSED DESIGN
 ALPHA = 0.55265E 00
 X-VECTOR
 0.6593E 00 0.4769E 00 0.3757E 00 0.6557E-06 0.5960E-07 0.6321E 00 0.7644E 00 0.1593E 00
 0.4246E 00 0.3262E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.31798E 01

CONSTRAINT VALUES
 1) 0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 2) 0.1000E 01 -0.7914E 00 -0.2962E 01 -0.1701E 01 -0.2989E 00 -0.1492E 00 -0.1251E 01
 3) 0.2933E 01 -0.4483E 01

PROPOSED DESIGN
 ALPHA = 0.20938E 00
 X-VECTOR
 0.6378E 00 0.3754E 00 0.2448E 00 0.6557E-06 0.5960E-07 0.5548E 00 0.7201E 00 0.1192E-06
 0.3086E 00 0.1945E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.24299E 01

CONSTRAINT VALUES
 1) 0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9957E 00 -0.1000E 01
 2) 0.1000E 01 -0.7914E 00 -0.2962E 01 -0.1566E 01 -0.4337E 00 -0.7177E 00 -0.1282E 01
 3) 0.2933E 01 0.3002E 00

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.56582E-01
 X-VECTOR
 0.6574E 00 0.4301E 00 0.3153E 00 0.6537E-06 0.5960E-07 0.5965E 00 0.7440E 00 0.8579E-01
 0.3711E 00 0.2652E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.28548E 01

CONSTRAINT VALUES
 1) 0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 2) 0.1000E 01 0.0 0 -0.8059E 00 -0.2757E 01 -0.1647E 01 -0.3331E 00 -0.7350E 00 -0.1261E 01
 3) 0.8568E 00 -0.2897E 01

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.56582E-01
 X-VECTOR
 0.6574E 00 0.4301E 00 0.3153E 00 0.6557E-06 0.5960E-07 0.5965E 00 0.7440E 00 0.8579E-01
 0.3711E 00 0.2652E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.28548E 01

CONSTRAINT VALUES (G-VECTOR)
 1) 0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 2) 0.1000E 01 0.0 0 -0.8059E 00 -0.2757E 01 -0.1647E 01 -0.3331E 00 -0.7390E 00 -0.1261E 01
 3) 0.8568E 00 -0.2897E 01

** * END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.64923E 00

OBJ = 0.285476E 01

DESIGN VARIABLES (X-VECTOR)
 1) 0.55265E 00 0.4769E 00 0.3153E 00 0.65565E-06 0.59605E-07 0.59646E 00
 2) 0.74335E 00 0.85792E-01 0.37108E 00 0.28545E 00

CONSTRAINT VALUES (G-VECTOR)
 1) 0.1000E 01 -0.49418E 00 -0.13997E 01 -0.17764E 01 -0.62045E 00
 2) -0.55996E 00 -0.10000E 01 0.0 -0.80587E 00 -0.27556E 01
 3) -0.16469E 01 -0.35309E 00 -0.12610E 01 0.89683E 00 -0.28668E 01

```

BEGIN ITERATION NUMBER 3
CT = -0.10000E 00 CTL = -0.10000E-01 PHI = 0.50000E 02
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.63790 01, SERIES FOR PHI CONTAINED 7 TERMS

```

```

THERE ARE 1 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
10

```

```

THERE ARE 1 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE
17

```

```

THERE ARE 2 ACTIVE SIDE CONSTRAINTS
DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
-4

```

```

GRADIENT OF OBJ 17 0.32701E 00 0.62103E 00 0.11005E 01 0.16372E 02 0.17644E 01 0.67778E 00
7) 0.31261E 00 0.15320E 01 0.71076E 00 0.73725E 00

```

```

GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER 10 0.0 0.0 0.0 0.0 0.0 0.0
7) 0.0 0.0 0.0 0.0 0.0 0.0

```

```

CONSTRAINT NUMBER 17 0.34364E 01 0.80034E 00 0.34773E 01 0.21535E 00 0.37317E 00
7) -0.23117E 00 -0.34364E 01 0.28662E 02 0.52578E 00 -0.19370E 01

```

```

SIDE CONSTRAINT ON VARIABLE 4 0.0 0.0 -0.10000E 01 0.0 0.0
7) 0.0 0.0 0.0 0.0 0.0

```

```

SIDE CONSTRAINT ON VARIABLE 5 0.0 0.0 0.0 0.0 -0.10000E 01 0.0
7) 0.0 0.0 0.0 0.0 0.0

```

```

PUSH-CFF FACTORS, (THERMAL), I=1,NAC 0.0
7) 0.20000E-01 0.10000E 01 0.0

```

```

CONSTRAINT PARAMETER, BETA = 0.0

```

```

SEARCH DIRECTION (S-VECTOR)
7) -0.21546E 00 -0.49538E 00 -0.71838E 00 0.0 0.0 -0.44242E 00
7) -0.20406E 00 -0.10003E 01 -0.50311E 00 -0.48126E 00 0.0

```

```

ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.375CE 01 PROPOSED ALPHA = 0.3294E-01

```

** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ** *

PROPOSED DESIGN
 ALPHA = 0.52436E-01
 X-VECTOR
 0.6623E 00 0.5167E 00 0.2917E 00 0.6557E-06 0.5960E-07 0.5919E 00 0.7372E 00 0.5286E-01
 0.3545E 00 0.2495E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.27267E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.1000E 01 -0.1000E 01
 -0.1000E 01 -0.8142E 00 -0.2638E 01 -0.1606E 01 -0.3940E 00 -0.7311E 00 -0.1269E 01
 -0.3167E 00 -0.2317E 01

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.50923E-01
 X-VECTOR
 0.6585E 00 0.4095E 00 0.2787E 00 0.6557E-06 0.5960E-07 0.5739E 00 0.7336E 00 0.3487E-01
 0.3455E 00 0.2409E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.26531E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9999E 00 -0.1000E 01
 -0.1000E 01 -0.8142E 00 -0.2638E 01 -0.1606E 01 -0.3940E 00 -0.7311E 00 -0.1269E 01
 -0.1625E 00 -0.2163E 01

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.85792E-01
 X-VECTOR
 0.9510E 00 0.3923E 00 0.2537E 00 0.6557E-06 0.5960E-07 0.5585E 00 0.7264E 00 0.1863E-07
 0.5279E 00 0.2747E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.24986E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9558E 00 -0.1000E 01
 -0.1022E 01 -0.8202E 00 -0.2553E 01 -0.1572E 01 -0.4278E 00 -0.7231E 00 -0.1277E 01
 -0.2673E 01 0.6730E 00

** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.50920E-01

OBJ = 0.26531E 01
 DECISION VARIABLES (X-VECTOR)
 1) 0.5092E 00 0.2787E 00 0.6556E-06 0.5960E-07 0.5739E 00 0.5739E 00
 2) 0.7335E 00 0.3487E-01 0.3455E 00 0.2409E 00 0.2409E 00 0.2409E 00

CONSTRAINT VALUES (G-VECTOR)
 1) -0.1000E 01 -0.9999E 00 -0.4941E 00 -0.1399E 01 -0.1770E 01 -0.6204E 00
 2) -0.5995E 00 -0.1000E 01 -0.1000E 01 0.0 -0.8141E 00 -0.2638E 01
 3) -0.1606E 01 -0.3939E 00 -0.7311E 00 -0.1268E 01 0.1628E 00 -0.2162E 01

```

BEGIN ITERATION NUMBER 4
CT = -0.10000E 00 CIL = -0.10000E-01 PHI = 0.50000E C3
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
THERE ARE 1 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
10
THERE ARE 1 VIOLATED CONSTRAINTS
CONSTRAINT NUMBERS ARE
17
THERE ARE 2 ACTIVE SIDE CONSTRAINTS
DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
-4
-5
GRADIENT OF OBJ 1 0.3271E 00 0.62017E 00 0.11280E 01 0.16376E 02 0.17310E 01 0.69838E 00
7) 0.3271E 00 0.10815E 01 0.77991E 00 0.7081E 00
GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER 10 0.0 0.0 0.0 0.0 0.0 0.0
7) 0.0 0.0
CONSTRAINT NUMBER 17 0.5066E 00 0.25531E 00 0.25094E 01 0.12721E 00 0.18150E 00
7) 0.12651E 00 0.72623E 01 0.75579E 00 -0.13719E 01
SIDE CONSTRAINT ON VARIABLE 4 0.0 0.0 -0.10000E 01 0.0 0.0
7) 0.0 0.0
SIDE CONSTRAINT ONE VARIABLE 5 0.0 0.0 -0.10000E 01 0.0
7) 0.0 0.0
PUSH-OFF FACTORS, (THETA(I), I=1,MAC) 0.0
1) 0.14473E 00 0.10000E 01 0.0
CONSTRAINT PARAMETER, BETA = 0.43284E-02
SEARCH DIRECTION (S-VECTOR)
1) -0.17163E 00 -0.32962E 00 -0.59952E 00 0.0 -0.37118E 00
7) -0.17386E 00 -0.10000E 01 -0.41452E 00 -0.37630E 00
ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.3723E 01 PROPOSED ALPHA = 0.2196E-01

```

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.21599E-01
 X-VECTOR
 0.6547E 00 0.5022E 00 0.2656E 00 0.6557E-06 0.5960E-07 0.5658E 00 0.7257E 00 0.1251E-01
 0.3364E 00 0.2327E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.2567E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1700E 01 -0.6205E 00 -0.9999E 00 -0.1000E 01
 -0.1000E 01 -0.1132E 00 -0.8177E 00 -0.2588E 01 -0.1586E 01 -0.4135E 00 -0.7270E 00 -0.1273E 01
 0.8402E-01 -0.2034E 01

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.34872E-01
 X-VECTOR
 0.6525E 00 0.3980E 00 0.2578E 00 0.6557E-06 0.5960E-07 0.5610E 00 0.7275E 00 0.7451E-08
 0.3310E 00 0.2278E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.25127E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1700E 01 -0.6205E 00 -0.9998E 00 -0.1000E 01
 -0.1000E 01 -0.3076E 00 -0.8201E 00 -0.2555E 01 -0.1514E 01 -0.4263E 00 -0.7241E 00 -0.1276E 01
 -0.2639E 01 0.6391E 00

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.22735E-02
 X-VECTOR
 0.6681E 00 0.4037E 00 0.2774E 00 0.6557E-06 0.5960E-07 0.5731E 00 0.7332E 00 0.3260E-01
 0.3445E 00 0.2601E 00
 *** I N S L (UBERTS) ***
 *** I N S L (UBERTS) ***
 *** I N S L (UBERTS) ***
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = -0.13440E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1700E 01 -0.6205E 00 -0.9998E 00 -0.1000E 01
 -0.1000E 01 -0.3076E 00 -0.8201E 00 -0.2555E 01 -0.1514E 01 -0.4263E 00 -0.7241E 00 -0.1276E 01
 -0.2639E 01 0.6391E 00

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.22735E-02
 X-VECTOR
 0.6681E 00 0.4037E 00 0.2774E 00 0.6557E-06 0.5960E-07 0.5731E 00 0.7332E 00 0.3260E-01
 0.3445E 00 0.2601E 00
 *** I N S L (UBERTS) ***
 *** I N S L (UBERTS) ***
 *** I N S L (UBERTS) ***
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = -0.13440E 01
 CONSTRAINT VALUES
 -0.9825E 21 0.7763E 24 0.4227E 22 -0.1760E 23 -0.4648E 21 0.2290E 21 0.3906E 22 -0.1924E 22
 -0.7512E 22 0.1067E 24 0.9469E 21 -0.1344E 23 0.4140E 22 -0.4140E 22 -0.4140E 22 -0.1133E 22 0.1133E 22
 -0.6053E 23 0.6053E 23

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.21959E-01
 X-VECTOR
 0.6547E 00 0.5022E 00 0.2656E 00 0.6557E-06 0.5960E-07 0.5658E 00 0.7257E 00 0.1251E-01
 0.3364E 00 0.2327E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.256700E 01
 CONSTRAINT VALUES (X-VECTOR)
 1) 0.9547E 00 0.4022E 00 0.26557E 00 0.65565E-06 0.59605E-07 0.56578E 00
 7) 3.72974E 00 0.12913E-01 0.35836E 00 0.23268E 00
 CONSTRAINT VALUES (G-VECTOR)
 1) -0.1000E 01 -0.9999E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.62049E 01
 7) -0.99992E 00 -0.10000E 01 -0.10080E 01 0.11317E 00 -0.81779E 00 -0.25588E 01
 13) -0.15865E 01 -0.41351E 00 -0.72764E 00 -0.12730E 01 0.84021E-01 -0.20340E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.21959E-01

OBJ = 0.256700E 01

DECISION VARIABLES (X-VECTOR)

1) 0.9547E 00 0.4022E 00 0.26557E 00 0.65565E-06 0.59605E-07 0.56578E 00

7) 3.72974E 00 0.12913E-01 0.35836E 00 0.23268E 00

CONSTRAINT VALUES (G-VECTOR)

1) -0.1000E 01 -0.9999E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.62049E 01

7) -0.99992E 00 -0.10000E 01 -0.10080E 01 0.11317E 00 -0.81779E 00 -0.25588E 01

13) -0.15865E 01 -0.41351E 00 -0.72764E 00 -0.12730E 01 0.84021E-01 -0.20340E 01

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PREPARED DECISION
 X VECTOR 0.49460E-01
 0.6605E 00 0.3716E 00 0.2668E 00 0.6842E-06 0.5960E-07 0.5651E 00 0.7251E 00 0.3338E-01
 0.3220E 00 0.2821E 00
 PEAK CALLED; NORM OF A= 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.26127E 01
 CONSTRAINT VALUES
 1) -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.4205E 00 -0.9958E 00 -0.1000E 01
 -0.1000E 01 0.0
 2) -0.8161E 00 -0.2611E 01 -0.1556E 01 -0.4043E 00 -0.7228E 00 -0.1277E 01
 3) 0.6306E-01 -0.2063E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.49460E-01

OBJ = 0.261274E 01

DECISION VARIABLES (X-VECTOR)
 1) 0.66017E 00 0.37163E 00 0.26681E 00 0.68416E-06 0.59605E-07 0.56507E 00
 2) 0.72511E 00 0.33379E-01 0.32198E 00 0.28214E 00

CONSTRAINT VALUES (G-VECTOR)
 1) -0.10000E 01 -0.99999E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.42049E 00
 2) -0.99983E 00 -0.10001E 01 -0.99999E 01 0.0 0.0 0.0 -0.99999E 01 -0.26113E 01
 3) -0.159937E 01 -0.40434E 00 -0.72282E 00 -0.12772E 01 0.63065E-01 -0.20631E 01

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.70588E-02
 X-VECTOR 0 0.3692E 00 0.2627E 00 0.6842E-06 0.5960E-07 0.5625E 00 0.7239E 00 0.2632E-01
 0.6595E 00 0.2799E 00
 0.3150E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.25856E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9988E 00 -0.1000E 01
 -0.1000E 01 0.0 0.8172E 00 -0.2595E 01 -0.1590E 01 -0.4104E 00 -0.7215E 00 -0.1278E 01
 0.1751E-01 -0.2018E 01

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.98718E-02
 X-VECTOR 0 0.3683E 00 0.2610E 00 0.6842E-06 0.5960E-07 0.5615E 00 0.7234E 00 0.2351E-01
 0.6586E 00 0.2789E 00
 0.3179E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS
 OBJ = 0.25746E 01

CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9988E 00 -0.1000E 01
 -0.1000E 01 0.0 0.8177E 00 -0.2588E 01 -0.1587E 01 -0.4129E 00 -0.7209E 00 -0.1279E 01
 0.3437E-02 -0.2003E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.98718E-02

OBJ = 0.257460E 01

DESIGN VARIABLES (X-VECTOR)
 1) 0.65859E 00 0.36825E 00 0.26100E 00 0.68416E-06 0.59605E-07 0.56148E 00
 7) 0.72342E 00 0.23507E-01 0.31787E 00 0.27854E 00

CONSTRAINT VALUES (C-VECTOR)
 1) -0.4000E 01 -0.57937E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.62049E 00
 7) -0.1000E 00 -0.1000E 01 0.81772E 00 0.81772E 00 -0.41292E 00 -0.72087E 01
 13) -0.15871E 01 -0.41288E 00 -0.72095E 00 -0.127791E 01 0.34367E-02 -0.20034E 01

```

BEGIN ITERATION NUMBER 7
CT = -0.10000E 00 C1L = -0.10000E-01 PHI = 0.10000E 04
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
10 17
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 2 ACTIVE SIDE CONSTRAINTS
DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
-4 -5
GRADIENT OF OBJ 1 0.3133E 00 0.6656E 00 0.1169E 01 0.1638E 02 0.17524E 01 0.71087E 00
1) 0.3356E 00 0.2050E 01 0.80567E 00 0.61998E 00
GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER 10 0.24702E 00 -0.95401E-01 -0.29731E 00 -0.43521E-01 -0.44155E-01
1) 0.18187E-01 -0.38487E 00 -0.41920E-01 -0.15561E 00
CONSTRAINT NUMBER 17 0.68133E 00 0.19312E 00 0.24556E 01 0.10515E 00 0.14732E 00
1) -0.2774E 00 0.57566E 01 0.69742E 00 -0.10935E 01
SIDE CONSTRAINT ON VARIABLE 4 0.0 -0.10000E 01 0.0 0.0
1) 0.0 0.0
SIDE CONSTRAINT ON VARIABLE 5 0.0 0.0 -0.10000E 01 0.0
1) 0.0 0.0
PUSH-OFF FACTORS, (THETA(I), I=1,NAC) 0.0
CONSTRAINT PARAMETER, BETA = 0.14108E 00
SEARCH DIRECTION (S-VECTOR)
1) -0.22238E 00 -0.10000E 01 -0.44026E 00 0.68576E-06 -0.13715E-05 -0.30889E 00
1) -0.24449E 00 -0.25638E 00 -0.37246E 00 0.19207E-01
ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.2358E 01 PROPOSED ALPHA = 0.5459E-01

```

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.5459E-01
 X-VECTOR
 0.5464E 00 0.3137E 00 0.2370E 00 0.7216E-06 0.5960E-07 0.5446E 00 0.7101E 00 0.9510E-02
 0.2975E 00 0.2800E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.24412E 01
 CONSTRAINT VALUES
 1) -0.1000E 01 -0.1000E 01 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9992E 00 -0.1000E 01
 2) -0.1000E 01 -0.5535E-01 -0.8212E 00 -0.2538E 01 -0.1561E 01 -0.4388E 00 -0.7154E 00 -0.1284E 01
 3) -0.1093E 00 -0.1891E 01

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.91688E-01
 X-VECTOR
 0.4384E 00 0.2769E 00 0.2206E 00 0.7470E-06 0.5960E-07 0.5332E 00 0.7010E 00 0.7451E-08
 0.2837E 00 0.2800E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.23457E 01
 CONSTRAINT VALUES
 1) -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9982E 00 -0.7110E 00 -0.1001E 01
 2) -0.1000E 01 -0.1450E 00 -0.8242E 00 -0.2497E 01 -0.1543E 01 -0.4574E 00 -0.7110E 00 -0.1284E 01
 3) -0.1883E 01 -0.1172E 00

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.50590E-01
 X-VECTOR
 0.4457E 00 0.3177E 00 0.2387E 00 0.7189E-06 0.5960E-07 0.5459E 00 0.7110E 00 0.1054E-01
 0.2975E 00 0.2769E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.24512E 01
 CONSTRAINT VALUES
 1) -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9992E 00 -0.7158E 00 -0.1000E 01
 2) -0.1000E 01 -0.4924E-01 -0.8210E 00 -0.2542E 01 -0.1563E 01 -0.4368E 00 -0.7158E 00 -0.1284E 01
 3) -0.1019E 00 -0.1898E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.0

OBJ = 0.257460E 01 NO CHANGE IN OBJ

DECISION VARIABLES (X-VECTOR)
 1) 0.65850E 00 0.56495E 00 0.24100E 00 0.68416E-06 0.59605E-07 0.56148E 00
 2) 0.92342E 00 0.23307E-01 0.31787E 00 0.27884E 00

CONSTRAINT VALUES (G-VECTOR)
 1) -0.10000E 01 -0.99999E 00 -0.49418E 00 -0.13997E 01 -0.17704E 01 -0.62049E 00
 2) -0.55974E 00 -0.10001E 01 -0.10003E 01 -0.38487E-02 -0.81772E 00 -0.25884E 01
 3) -0.15871E 01 -0.41288E 00 -0.72095E 00 -0.12751E 01 0.34367E-02 -0.20034E 01

```

BEGIN ITERATION NUMBER      8
CT = -0.34200E-01  CTL = -0.46416E-02  PHI = 0.10000E 04
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
  10  17
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 2 ACTIVE SIDE CONSTRAINTS
DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
  -4  -5
GRADIENT OF OBJ
  1) 0.31137E 00  0.66566E 00  0.11494E 01  0.16387E 02  0.17524E 01  C.71087E 00
  7) 0.33560E 00  0.20506E 01  0.80967E 00  0.61998E 00
GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER
  1) 0.31044E-01  0.42547E 00  0.16432E 00  -0.51208E 00  -0.74561E-01  -0.76053E-01
  7) 0.33047E-01  -0.66290E 00  -0.72204E-01  -0.26802E 00
CONSTRAINT NUMBER
  1) 0.39966E-01  0.10577E 00  0.29960E-01  0.38122E 00  0.16324E-01  0.22871E-01
  7) 0.21730E-01  0.89397E 00  0.10827E 00  -0.16976E 00
SIDE CONSTRAINT ON VARIABLE 4
  1) 0.0  0.0
  7) 0.0  0.0
SIDE CONSTRAINT ON VARIABLE 5
  1) 0.0  0.0
  7) 0.0  0.0
PUSH-OFF FACTORS, (THETA) I=1,MAC
  1) 0.12377E 01  0.12111E 01  0.0
CONSTRAINT PARAMETER, BETA = 0.13710E 00
SEARCH DIRECTION (S-VECTOR)
  1) -0.22062E 00  -0.10000E 01  -0.43101E 00  0.0
  7) -0.24263E 00  -0.23608E 00  -0.36639E 00  0.26039E-01
ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.2291E 01  PROPOSED ALPHA = 0.8201E-02
  -0.13666E-05  -0.30344E 00

```

*** CCNSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.82015E-02
 X-VECTOR
 0.6568E 00 0.3600E 00 0.2575E 00 0.6842E-06 0.5900E-07 0.5590E 00 0.7214E 00 0.2157E-01
 0.3149E 00 0.2179E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

CBJ = 0.25556E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9957E 00 -0.1000E 01
 -0.1000E 01 0.6808E-02 -0.8182E 00 -0.2582E 01 -0.1583E 01 -0.4165E 00 -0.7202E 00 -0.1280E 01
 -0.1438E-01 -0.1986E 01

TWO-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.41007E-01
 X-VECTOR
 0.6495E 00 0.3272E 00 0.2433E 00 0.6842E-06 0.5960E-07 0.5490E 00 0.7135E 00 0.1383E-01
 0.3028E 00 0.2800E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.24780E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9954E 00 -0.1000E 01
 -0.1000E 01 0.2954E-01 -0.8201E 00 -0.2554E 01 -0.1569E 01 -0.4315E 00 -0.7170E 00 -0.1283E 01
 -0.2070E-01 -0.1919E 01

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.89572E-01
 X-VECTOR
 0.6366E 00 0.2687E 00 0.2181E 00 0.6842E-06 0.5960E-07 0.5313E 00 0.6993E 00 0.1863E-07
 0.2814E 00 0.2815E 00
 PEAK CALLED; NORM OF A = 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.23327E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9981E 00 -0.1001E 01
 -0.1000E 01 0.1371E 00 -0.8244E 00 -0.2494E 01 -0.1540E 01 -0.4586E 00 -0.7105E 00 -0.1290E 01
 -0.1853E 01 -0.1474E 00

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.0

OBJ = 0.25740E 01 NO CHANGE ON OBJ

DECISION VARIABLES (X-VECTOR)
 1) 0.65659E 00 0.36825E 00 0.26100E 00 0.68416E-06 0.59605E-07 0.56148E 00
 7) 0.72342E 00 0.23507E-01 0.31787E 00 0.27854E 00

CONSTRAINT VALUES (G-VECTOR)
 1) -0.1000E 01 -0.99599E 00 -0.59418E 00 -0.13997E 01 -0.1770E 01 -0.62049E 00
 7) -0.59976E 00 -0.1000E 01 -0.1000E 01 -0.38487E-02 -0.81772E 00 -0.25884E 01
 13) -0.15871E 01 -0.41288E 00 -0.72095E 00 -0.12751E 01 0.34367E-02 -0.20034E 01

```

BEGIN ITERATION NUMBER 9
CT = -0.11696E-01 C1E = -0.21379D 01 0.5000E 01 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
PEAK CALLED: NORM OF A = 0.6379D 01 SERIES FOR PHI CONTAINED 7 TERMS
THERE ARE 2 ACTIVE CONSTRAINTS
CONSTRAINT NUMBERS ARE
10 17
THERE ARE 0 VIOLATED CONSTRAINTS
THERE ARE 2 ACTIVE SIDE CONSTRAINTS
DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
-4 -5
GRADIENT OF OBJ 0.31128E 00 0.66557E 00 0.11495E 01 0.16387E 02 0.17523E 01 C.71077E 00
1) 0.33550E 00 0.20505E 01 0.80957E 00 0.61985E 00
GRADIENTS OF ACTIVE AND VIOLATED CONSTRAINTS
CONSTRAINT NUMBER 10 0.34702E 00 -0.95401E-01 -0.29731E 00 -0.43521E-01 -0.44155E-01
1) 0.19187E-01 -0.38487E 00 -0.41920E-01 -0.13581E 00
CONSTRAINT NUMBER 17
1) -0.25744E 00 0.68132E 00 0.19307E 00 0.24556E 01 0.10515E 00 0.14732E 00
1) 0.13497E 00 0.57586E 01 0.69742E 00 -0.10938E 01
SIDE CONSTRAINT ON VARIABLE 4 0.0 -0.10000E 01 0.0 0.0
1) 0.0 0.0
SIDE CONSTRAINT ON VARIABLE 5 0.0 0.0 -0.10000E 01 0.0
1) 0.0 0.0
PUSH-OFF FACTORS (THETA(I), I=1,NCC)
1) 0.17664E 01 0.16740E 01 0.0 0.0
CONSTRAINT PARAMETER, BETA = 0.12536E 00
SEARCH DIRECTION (S-VECTOR)
1) -0.21438E 00 -0.10000E 01 -0.40374E 00 0.72196E-06 -0.14439E-05 -0.28733E 00
1) -0.23709E 00 -0.17624E 00 -0.34849E 00 0.46225E-01
ONE-DIMENSIONAL SEARCH
INITIAL SLOPE = -0.2095E 01 PROPOSED ALPHA = 0.1229E-03

```

*** CONSTRAINED ONE-DIMENSIONAL SEARCH INFORMATION ***

PROPOSED DESIGN
 ALPHA = 0.12288E-03
 X-VECTOR
 0.5526E 00 0.2610E 00 0.6842E-06 0.5960E-07 0.5614E 00 0.7234E 00 0.2349E-01
 0.3178E 00 0.2789E 00
 PEAK CALLED; NORM OF A= 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

CBJ = 0.25743E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9998E 00 -0.1000E 01
 -0.1000E 01 -0.8177E 00 -0.2588E 01 -0.1587E 01 -0.4129E 00 -0.7209E 00 -0.1279E 01
 0.3208E-02 -0.2003E 01

TWO-POINT INTERPOLATION

PROCESSED DESIGN
 ALPHA = 0.61440E-03
 X-VECTOR
 0.9595E 00 0.3676E 00 0.2608E 00 0.6846E-06 0.5960E-07 0.5613E 00 0.7233E 00 0.2340E-01
 0.3177E 00 0.2790E 00
 PEAK CALLED; NORM OF A= 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

OBJ = 0.25733E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9998E 00 -0.1000E 01
 -0.1000E 01 -0.8177E 00 -0.2588E 01 -0.1587E 01 -0.4131E 00 -0.7209E 00 -0.1279E 01
 0.2292E-02 -0.2002E 01

THREE-POINT INTERPOLATION

PROPOSED DESIGN
 ALPHA = 0.14951E-02
 X-VECTOR
 0.6583E 00 0.3668E 00 0.2604E 00 0.6852E-06 0.5960E-07 0.5610E 00 0.7231E 00 0.2324E-01
 0.3173E 00 0.2790E 00
 PEAK CALLED; NORM OF A= 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

CBJ = 0.25714E 01
 CONSTRAINT VALUES
 -0.1000E 01 -0.1000E 01 -0.4942E 00 -0.1400E 01 -0.1770E 01 -0.6205E 00 -0.9998E 00 -0.1000E 01
 -0.1000E 01 -0.4165E-02 -0.8178E 00 -0.2587E 01 -0.1587E 01 -0.4135E 00 -0.7208E 00 -0.1279E 01
 0.6477E-03 -0.2001E 01

*** END OF ONE-DIMENSIONAL SEARCH

CALCULATED ALPHA = 0.61440E-03

OBJ = 0.257330E 01

DESIGN VARIABLES (X-VECTOR)
 0.6583E 00 0.3676E 00 0.26076E 00 0.68460E-06 0.59605E-07 0.56130E 00
 0.3173E 00 0.27899E-01 0.31766E 00 0.27897E 00

CONSTRAINT VALUES (G-VECTOR)
 -0.10000E 01 -0.99999E 00 -0.49418E 00 -0.13957E 01 -0.17704E 01 -0.62049E 00
 -0.99976E 00 -0.10001E 01 -0.10003E 01 0.39784E-02 -0.81775E 00 -0.25680E 01
 131 -0.15869E 01 -0.41312E 00 -0.72090E 00 -0.12791E 01 0.22923E-02 -0.20023E 01

FINAL OPTIMIZATION INFORMATION
 OBJ = 0.457330E 01
 DECISION VARIABLES (X-VECTOR)
 1) 0.95845E 00 0.38764E 00 0.26076E 00 0.68460E-06 0.59405E-07 0.56130E 00
 2) 0.72327E 00 0.23399E-01 0.31766E 00 0.27897E 00
 CONSTRAINT VALUES (G-VECTOR)
 1) -0.10000E 01 -0.98999E 00 -0.49418E 00 -0.13987E 01 -0.17704E 01 -0.62046E 00
 2) -0.99999E 00 -0.10001E 01 -0.10003E 01 -0.39784E-02 -0.81775E 00 -0.25280E 01
 3) -0.15869E 01 -0.41312E 00 -0.72090E 00 -0.12791E 01 0.22523E-02 -0.20023E 01

THERE ARE 2 ACTIVE CONSTRAINTS
 CONSTRAINT NUMBERS ARE
 10 17
 THERE ARE 0 VIOLATED CONSTRAINTS
 THERE ARE 2 ACTIVE SIDE CONSTRAINTS
 DECISION VARIABLES AT LOWER OR UPPER BOUNDS (MINUS INDICATES LOWER BOUND)
 -4 -5

TERMINATION CRITERION
 ABS(OBJ(I)-OBJ(I-1)) LESS THAN DABFM FOR 3 ITERATIONS
 NUMBER OF ITERATIONS = 9
 OBJECTIVE FUNCTION WAS EVALUATED 106 TIMES
 CONSTRAINT FUNCTIONS WERE EVALUATED 106 TIMES
 PEAK CALLED; NORM OF A= 0.6379D 01, SERIES FOR PHI CONTAINED 7 TERMS

THE G1 GAIN MATRIX

	1	2	3
1	-1.0866400D-01	-3.0952129D-02	-2.4175647D-02
2	-1.1169897D-01	1.6544551D-02	-2.9664099D-02
3	2.3661280D-01	-1.4792147D-01	-2.5155605D-01

THE G2 GAIN MATRIX

	1	2	3
1	1.4776931D 00	5.8573780D-02	8.2804459D-02
2	1.8439331D-01	1.6786397D 00	1.0167706D-01
3	2.9682057D-01	1.1577675D-01	8.9076819D-01

THE L MATRIX

	1	2	3
1	3.02181850-01	5.06273390-01	9.44059090-01
2	1.53297570 00	5.45154100-02	-2.60921980-02
3	-1.75746620-01	9.71590650-01	-8.78248270-01

THE L MATRIX

	1	2	3
1	-3.58535660-01	-2.82570600-02	-6.81680680-04
2	1.18351990-01	-3.47638790-02	-1.54171070-03
3	8.13313040-01	-3.11267730-01	-2.84976280-01

FINAL SYSTEM CHARACTERISTICS

THE CHARACTERISTIC POLYNOMIAL - IN ASCENDING POWERS OF S

1.51572970-01	5.51483850 00	1.90491470 01	2.72210060 01	1.95679670 01	7.02191100 00
1.00000000 00					

THE EIGENVALUES OF THE STATE MATRIX

REAL PART	IMAGINARY PART
-3.06667060-02	0.0
-1.26617060 00	-4.24826580-01
-1.26617060 00	4.24826580-01
-9.11086910-01	0.0
-1.50182670 00	0.0
-2.07511000 00	0.0

REQUESTED SETTLING TIME IS 60.000 SECONDS

SIMULATION RUN TIME = 72.000

THE INITIAL CONDITION VECTOR

X(1)	-1.000
X(2)	-1.000
X(3)	-1.000
U(1)	-1.000
U(2)	1.000
U(3)	0.0

STEADY STATE VALUES OF THE OUTPUTS AT 60.000 SECONDS

Y(1)	0.000
Y(2)	-0.000
Y(3)	0.000
Y(4)	-0.168
Y(5)	-0.000
Y(6)	0.000
Y(7)	0.000
Y(8)	0.000

	PEAK VALUES	TIME OF OCCURRENCE
X(1)	0.000	15.65
X(2)	0.000	13.90
X(3)	-0.117	71.95
Y(1)	1.000	68.30
Y(2)	0.017	2.80
Y(3)	0.000	12.55
Y(4)	-0.117	71.95
Y(5)	0.483	71.95
Y(6)	0.000	12.60
Y(7)	0.000	16.25
Y(8)	0.000	14.10
UOOT(1)	1.255	
UOOT(2)	-1.419	
UOOT(3)	-0.120	
U(1)	0.000	
U(2)	1.000	
U(3)	0.000	
MINIMUM INPUT VALUES		
U(1)	-1.000	
U(2)	-0.000	
U(3)	-0.259	
MINIMUM STATE VALUES		
X(1)	-1.000	
X(2)	-1.000	
X(3)	-1.000	
MINIMUM OUTPUT VALUES		
Y(1)	-0.000	
Y(2)	-1.208	
Y(3)	-0.651	
Y(4)	-1.000	
Y(5)	-0.000	
Y(6)	-0.660	
Y(7)	-1.142	
Y(8)	-2.182	

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4. United Aircraft Research Laboratories Report M941338-2, An Analytical Method for the Synthesis of Nonlinear Multivariable Feedback Control, by G. J. Michael and F. A. Farrar, June 1973.
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