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Report No. R-1494
21 January 1977

DESIGN STUDY OF A FEEDBACK CONTROL SYSTEM FOR THE MULTICYCLIC FLAP SYSTEM ROTOR (MFS)

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16. Abstract

Analytical studies were performed to determine the feasibility of automatically providing higher harmonic control to a deflectable control flap at the tip of a helicopter rotor blade through feedback of selected independent parameters.

Because the feedback study was based on the results of study work performed under Contract NAS2-7738, the rotor configuration data was updated to the configuration tested in the wind tunnel, which involved shortening the servoflap to half-size spanwise, and altering its balance and stiffness characteristics

Following the updating of the analysis, control parameters were selected for input to the feedback system. The study work was then extended to arrive at a preliminary circuit design that would condition the selected parameters, weigh limiting factors and, ultimately, provide a proper output signal to the multicyclic control actuators.

Since the first model of a feedback system would be tested on the wind tunnel multicyclic model, the preliminary design takes into consideration interfacing with existing multicyclic controls and uses existing test sensors.

Study results indicate that feedback control for the higher harmonics is feasible; however, design for a flight system would require an extension of the present analysis. The present analysis was done for one flight condition - 120 kts, 11,500 lbs gross weight and level flight - since a data base for other conditions was not available.

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1.0 INTRODUCTION

Work performed under and in support of the Reference 1 Contract demonstrated that introducing a mixture of proper amplitude and phase of multiple harmonics (steady through 4Ω) as a control command to a deflectable servoflap, located near the tip of a torsionally-elastic rotor blade, could improve the airload distribution over the rotor disk. The results of this improved distribution are a delay in stall and compressibility effects, reduced hub vibratory shear loads, and reduced blade vibratory bending moments. Computer programs were developed by both the Contractor and by Ames Research Center that are effective in predicting efficient control input settings for favorable tradeoffs in the important response parameters, given computer-calculated responses to an array of possible control combinations at a particular flight condition. At these efficient control settings, significant improvement over conventional rotor control was shown.

Based on the results of the work discussed above, an existing experimental Controllable Twist Rotor (CTR), developed and wind tunnel-tested for USAAMRDL, Eustis Directorate, was modified to incorporate control modifications permitting the mixing of up to four harmonics of flap deflection, with independent control of the magnitude and phase of each. The control modifications and subsequent testing in the NASA Ames Research Center 40 x 80 wind tunnel were performed under Contract NAS 2-8726. Data from the wind tunnel tests are presently being analyzed for comparison to previous predictions.

The next logical extension of the work performed on the manually-operated system, developed and tested under Contract NAS 2-8726, was to conduct a preliminary design study to define and analyze a closed-loop self-optimization function. The purpose of the work, which is the subject of this report, was to study the feasibility of automatically providing higher harmonic control through feedback of selected independent parameters.

Because the feasibility study was to be based solely on the results of the initial study work performed under Contract NAS 2-7738, it was felt that the rotor configuration used in the study should be updated to the configuration tested which involved shortening the servoflap to half-size spanwise, and altering the mass balance and stiffness characteristics. The updated analysis is described herein.

Following the updating of the analysis, control parameters were selected for input to the feedback system. The study work was then extended to arrive at a preliminary circuit design that would condition the selected parameters, weight limiting factors, and ultimately provide a proper output signal to the multicyclic control actuators. Because the early study work was restricted to one flight condition (120 knot level flight), certain assumptions have been made concerning varying flight conditions and these assumptions are explained in the appropriate sections of this report.

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2.0 MULTICYCLIC FLAP SYSTEM (MFS) - ANALYSIS UPDATE

2.1 Range of Study

The primary purpose of the multicyclic servoflap system is to reduce helicopter vibration levels by reducing rotor-generated vibratory loads that are transmitted to the fuselage. Although vibration problems are more severe at extreme operating conditions, the accurate prediction of rotor loads and performance at those conditions is difficult. Therefore, the prime thrust of this investigation is in an area where retreating blade stall and high advancing blade Mach number effects are not significant. Rotor blade and disk loadings correspond to contemporary practice, and the propulsive force is representative of utility-type helicopters.

The following flight condition and loading condition was investigated for the CTR with multicyclic controls:

Advance Ratio	.333
Disk Loading	4.67 psf
C_z/σ	.092
C_x/σ	.0071

The preceding parameters correspond to a rotor that has a diameter of 56 feet, a tip speed of 613 fps, and a solidity of 0.062. The ranges of disk loading, blade loading, and propulsive force loading correspond to the sea level flight conditions of a utility helicopter with a gross weight of 11,500 pounds and a flat plate drag area of 20 square feet. The study was conducted at an advance ratio of 0.333 (120 knots).

Figures 1a and 1b show the planform, inertia and stiffness of the rotor used in this study.

2.2 Analytical Procedure

The baseline rotor chosen for this study was the CTR developed and tested under the Reference 2 contract. This configuration differs from that examined in the Reference 1 contract in that the servoflap is reduced to half-size, and both mass balance and stiffness are increased.

One disk loading was investigated with constant inflow across the disk ($\lambda = -.037$). The rotor drag, (C_x/σ was held constant at .0071, which is equivalent to twenty square feet of flat plate area at $\mu = .333$ (120 knots). Lateral force, $F_y = 0$.

This rotor was optimized using the method outlined in Reference 3 for dual control rotor optimization. The following rotor parameters and limits were used as a measure of the effectiveness and determination of secondary control optimization:

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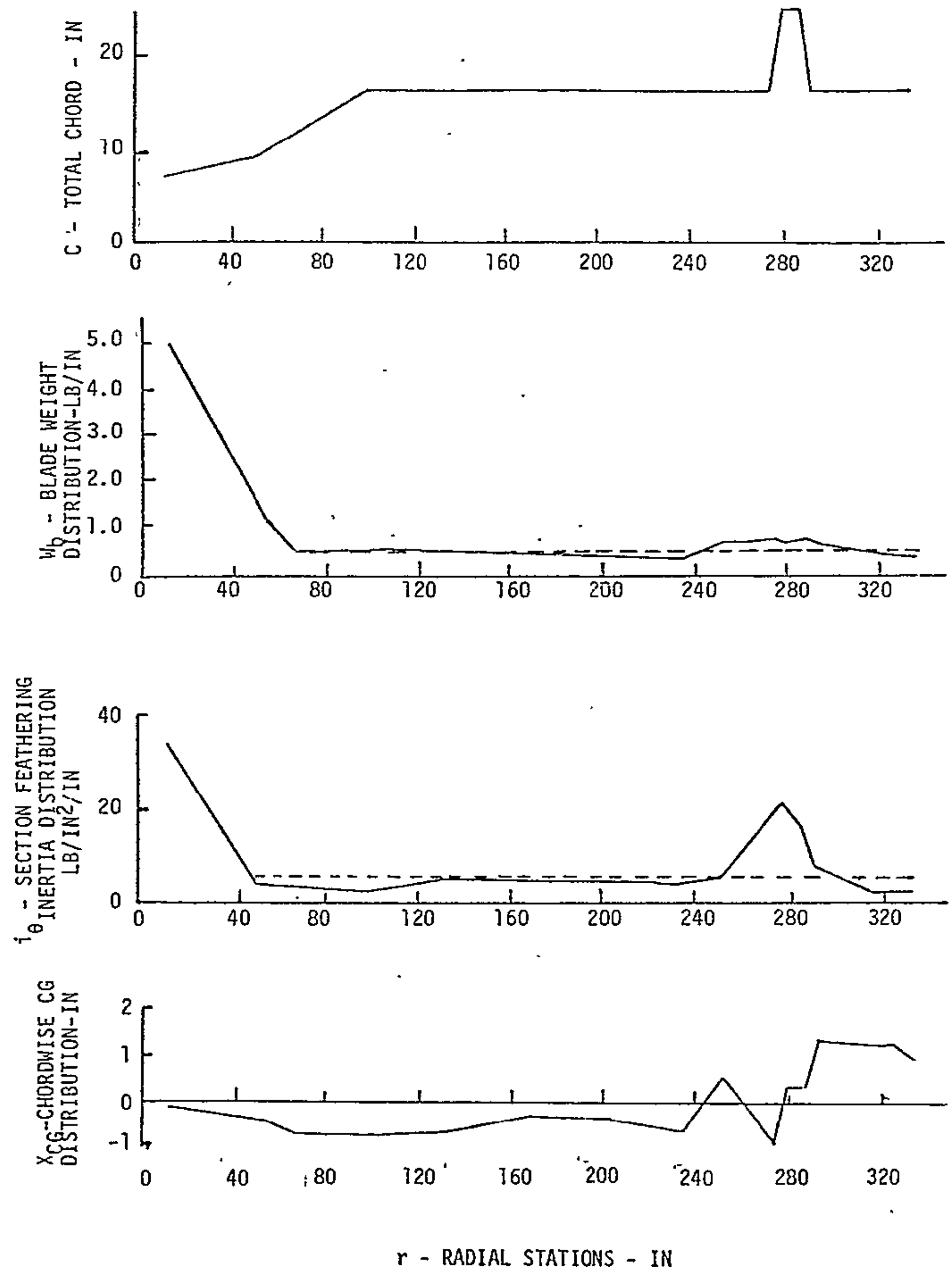


Figure 1a. CTR Physical Properties.

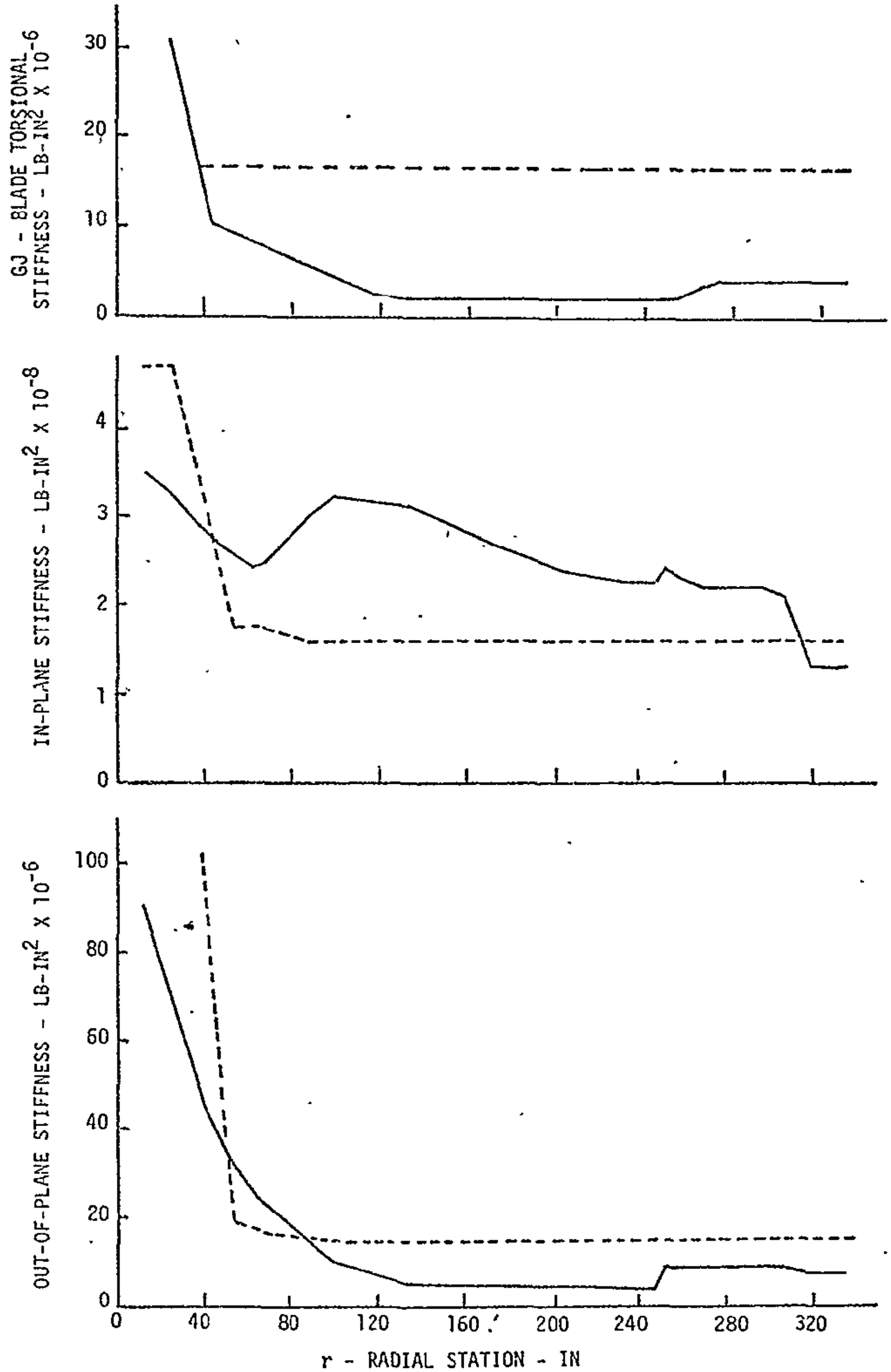


Figure 1b. CTR Physical Properties.

a. Rotor horsepower $\leq$ 750

b. Maximum local blade angle of attack $\leq$ 12 degrees

c. Maximum out-of-plane bending moment $\leq$ 9 in-kips

d. Vibratory hub shears $\leq$ 220 lb.

The angle of attack limit was chosen to provide a margin of maneuverability before local blade stall would be encountered. The 9000 in-lb peak-to-peak bending moment was selected on the basis of the calculated infinite blade life. The maximum out-of-plane moment occurs in the flap region of the blade where the endurance limit is $\pm$ 4500 in-lb.

Each of the four dependent variables outlined above can be expressed in quadratic form in terms of the independent control variables. These equations have linear coefficients and are developed for trim conditions only. Equation (1) is the typical form of the relationship between a dependent variable, i.e., horsepower, and the collective and first-harmonic flap inputs:

$$HP = a_0 + a_1 \delta_0 + a_2 \delta_{1s} + a_3 \delta_{1c} + a_4 \delta_0^2 + a_5 \delta_{1s}^2 + a_6 \delta_{1c}^2 + a_7 \delta_0 \delta_{1s} + a_8 \delta_0 \delta_{1c} + a_9 \delta_{1s} \delta_{1c} + a_{10} \delta_0 \delta_{1s} \delta_{1c} \quad (1)$$

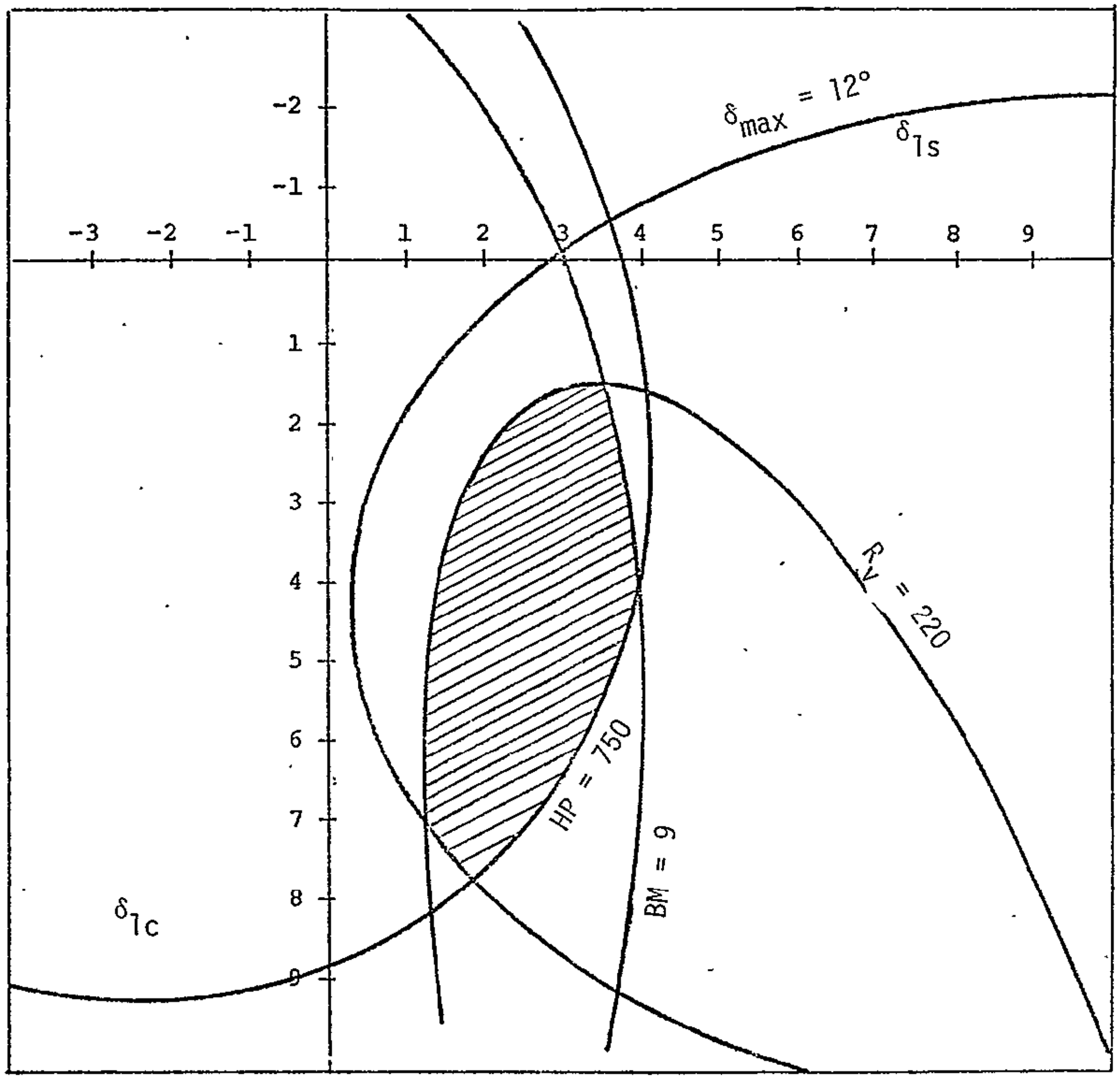
Similar equations were written for the remaining three parameters of interest. Appendix A is a listing of the regression analysis program SURGEN. The program uses a number of trim cases to calculate the rotor parameter equation coefficients for the disk loading desired. In addition, the multiple correlation coefficients, standard error of the estimate, and a table of residuals are listed by SURGEN. Analysis of residuals for sum, sum of squares, mean, variance and standard deviation, and a listing of the orders of the residuals from the most negative to most positive are also tabulated for convenience.

With the models, a tradeoff study was previously made to establish a region of flap control that would produce values of the four rotor parameters that meet the criteria established. Using a plot program on the Hewlett-Packard computer, representative contour plots, as in Figure 2, were generated.

2.3 Multicyclic Flap Input

Multicyclic control was investigated with the same rotor for one gross weight corresponding to C_z/σ of .092. For C_z/σ of .092, the constant inflow across the disk was - .037.

For the multicyclic flap concept, the range of cyclic control was limited to $\pm$ 5 degrees for each harmonic, such that the resultant maximum deflection for the 2nd harmonic and higher controls was $\pm$ 8 degrees. The flap ranges were selected based on the CTR work that had been conducted in the past. The restriction of the resultant of the 2nd and higher harmonic inputs to a maximum



V = 120 kt

F_z = 11500 lb

F_x = 907 lb

ΩR = 613 fps

μ = .33

C_z/σ = .092

C_x/σ = .007

δ_0 = - 1

Figure 2. CTR Control Optimization, $\delta_0 = -1$.

of 8 degrees was to prevent excessive flap deflection from negating the benefits of higher harmonics. The following control range was established as a base:

Steady	$\delta_0 = -1°$	
First Harmonic Sine and Cosine	$\delta_{1s} = 3$, $\delta_{1c} = 5$	
Second Harmonic Sine and Cosine	+ 5 to - 5	Random Selection
Third Harmonic Sine and Cosine	+ 5 to - 5	Random Selection
Fourth Harmonic Sine and Cosine	+ 5 to - 5	Random Selection

The selection of a control matrix by a method similar to that for the CTR was considered impractical because of the large number of control combinations possible. For example: Involving only 2nd, 3rd and 4th harmonic controls, with seven control levels for each of six controls (i.e., δ_{2s}, δ_{2c}, δ_{3s}, δ_{3c}, δ_{4s}, δ_{4c}), a combined total of 117,649 cases are possible. A base of 140 cases with various combinations of 2nd, 3rd and 4th harmonics was selected by use of a random number table. This method avoids individual prejudices and statistically provides equal weight to the independent variables. Thus, a better chance is provided to account for the effects of each variable within the limited number of cases that were run.

In Reference 3, cases trimmed at a fixed value of collective and first harmonic controls, together with variation in higher harmonic controls, showed horsepower, bending moment and maximum blade angle of attack to have significantly smaller changes from the base case values having no higher harmonic controls as compared to changes in vibratory hub shears (see Reference 3, Cases A1, I9, J3, M6, N8). Since the study objective was to arrive at optimum controls that reduce vibratory hub shears while keeping bending moment, horsepower and maximum angle of attack with prescribed bounds, a single optimum set of collective and first harmonic controls was selected for the MFS study.

Aside from the smaller variations of bending moment, horsepower and maximum angle of attack with higher harmonic control input, another reason for using a single set of collective and first harmonic flap control inputs is the very large number of trim cases which need to be generated to be able to create a reasonably accurate model which includes variations of collective and 1/rev controls. The number of linear regression model coefficients for each rotor parameter for the latter situation would have to be expanded from 27 to 54. The program scope did not permit such an expanded analysis.

As previously stated, the set of collective and first harmonic controls chosen for case generation with higher harmonic controls was: $\delta_0 = -1$, $\delta_{1s} = 3$ and $\delta_{1c} = 5$ (see shaded region of Figure 2). Since variation of collective and first harmonic input was eliminated, the linear regression model of each dependent rotor parameter expands to only 27 coefficients for the independent control variables. Equation (2) is the form of the equation with hub shear being illustrated as one of the dependent variables:

$$R_v = a_0 + a_1 \delta_{2s} + a_2 \delta_{2c} + a_3 \delta_{3s} + a_4 \delta_{3c} + a_5 \delta_{4s} + a_6 \delta_{4c} + a_7 \delta_{2s}^2$$
$$+ a_8 \delta_{2s} \delta_{2c} + a_9 \delta_{2s} \delta_{3s} + a_{10} \delta_{2s} \delta_{3c} + a_{11} \delta_{2s} \delta_{4s}$$
$$+ a_{12} \delta_{2s} \delta_{4c} + a_{13} \delta_{2c}^2 + a_{14} \delta_{2c} \delta_{3s} + a_{15} \delta_{2c} \delta_{3c} + a_{16} \delta_{2c} \delta_{4s}$$
$$+ a_{17} \delta_{2c} \delta_{4c} + a_{18} \delta_{3s}^2 + a_{19} \delta_{3s} \delta_{3c} + a_{20} \delta_{3s} \delta_{4s} + a_{21} \delta_{3s} \delta_{4c}$$
$$+ a_{22} \delta_{3c}^2 + a_{23} \delta_{3c} \delta_{4s} + a_{24} \delta_{3c} \delta_{4c} + a_{25} \delta_{4s}^2 + a_{26} \delta_{4s} \delta_{4c}$$
$$+ a_{27} \delta_{4c}^2 \qquad (2)$$

where:

$$\delta = \delta_0 + \delta_{1s} \sin \psi + \delta_{1c} \cos \psi + \delta_{2s} \sin 2 \psi + \delta_{2c} \cos 2 \psi + \delta_{3s} \sin 3 \psi$$
$$+ \delta_{3c} \cos 3 \psi + \delta_{4s} \sin 4 \psi + \delta_{4c} \cos 4 \psi \qquad (3)$$

Due to the increased complexity of the higher harmonic flap inputs, it was not possible to use a graphic method to predict the best area of higher harmonic control inputs to minimize rotor parameters. Emphasis was placed on the use of successive models to predict trends. Since one purpose of this study was to determine the effect of higher harmonic control input on the reduction of 4/rev pylon excitation, the major effort was oriented toward this goal. Since reduction of vibratory hub shears is of primary interest, the model for hub shears was used to predict higher harmonic controls which achieve minimum in-plane and out-of-plane vibratory hub shears. The model was introduced into the BASIC language program, MCMOD1, Appendix B, which scanned all possible integer control combinations between - 4 degrees to + 4 degrees for each set of higher harmonic control (i.e., δ_{2s}, δ_{2c}, δ_{3s}, δ_{3c}, δ_{4s}, δ_{4c}) and resulting in an absolute resultant higher harmonic control setting of less than or equal to 8 degrees.

6F cases were then executed using selected model predicted controls that predicted minimum out-of-plane hub shears.

2.4 Analysis Results and Discussion

The following is a listing of the flight conditions examined for both the Multicyclic Controllable Twist Rotor (MCTR) and CTR:

$C_z/\sigma = .092$ $\quad$ $F_z = 11500$ lb rotor lift

$C_x/\sigma = .0071$ $\quad$ $F_y = 0$

$\mu = .333$ (120 kts)

The CTR regression model (Equation 1) was based on about 42 trimmed cases. The model coefficients are tabulated for the rotor parameters of interest in Table 1.

Figure 2, discussed previously and resulting from the above models, yielded good correlation between the models and actual trim.

The MFS study was concerned with determining whether flap inputs with greater than first harmonic frequency could be used to reduce vibratory pylon loading without severe detriment to the remaining rotor parameters.

Over 140 cases were trimmed at this rotor loading (11500 lb). This allows direct comparison with the CTR evaluated at this level. The fixed collective and first harmonic servoflap controls were chosen from the optimal CTR control region ($\delta_0 = -1$, $\delta_{1s} = 3$, $\delta_{1c} = 5$).

The regression model coefficients generated by SURGEN for in-plane hub shears, out-of-plane hub shears, out-of-plane bending moments, horsepower and maximum angle of attack are presented in Table 2.

Table 3 is a compilation of the multicyclic trim cases generated showing values of the above rotor parameters for the control inputs presented.

Table 4 presents the comparative values of in-plane hub shears, out-of-plane hub shears, bending moment, horsepower and maximum blade angle of attack for the multicyclic SURGEN model and the 6F trim program with only optimum collective and first harmonic control input.

These values are used for base comparison of cases having higher harmonic control input. It is seen from Table 4 that, for the hub shears, bending moment and maximum angle of attack, the SURGEN model predicts high as compared to the 6F program trim cases and, therefore, the SURGEN model appears conservative. Better agreement could be achieved by including more trim cases in the SURGEN model. However, for the purposes of this study, the model predictions are adequate.

Tables 5 through 7 present cases having minimum out-of-plane hub shears within the limited trim cases generated. The out-of-plane hub shears for these latter cases are found to have reductions up to and over 70% with higher harmonic control input. Bending moment and maximum angle of attack increased up to 27% and horsepower values increased by as much as 7% over the case values generated with no higher harmonic control input.

TABLE 1. CTR ROTOR PARAMETER MODEL COEFFICIENTS				
	HP	BM	α_{max}	R_v
a_0	737.5	7776	13.38	248.6
a_1	0	0	0	0
a_2	2.367	333	- .554	- 11.68
a_3	- .777	- 252	- .564	- 4.271
a_4	0	0	0	0
a_5	.265	28	.028	1.983
a_6	.253	18	.066	.453
a_7	0	0	0	0
a_8	0	0	0	0
a_9	- .123	13	0	- 1.125
a_{10}	0	0	0	0

TABLE 2. MULTICYCLIC ROTOR PARAMETER MODEL COEFFICIENTS

	R_v (Resultant)	R_{vop}	R_{vip}	BM	HP	α_{max}
a_0	297.0	287.32	79.29	4410.59	744.94	11.05
a_1	- 17.59	- 18.51	- 5.83	- 142.22	1.40	.20
a_2	9.34	12.59	- 6.13	- 206.07	- 1.25	.59
a_3	27.14	25.17	8.81	32.57	- 2.92	- .07
a_4	1.62	.07	- .35	52.89	- 1.25	- .01
a_5	48.99	48.86	3.72	- 10.43	- .27	- .03
a_6	- 15.76	- 14.47	- 13.51	53.99	.43	- .13
a_7	2.17	2.64	.59	37.94	1.60	.08
a_8	8.84	7.92	1.45	3.69	1.12	- .03
a_9	2.49	2.68	.02	- 20.54	.17	- .08
a_{10}	- 2.77	- 2.73	.40	- 12.94	.07	.03
a_{11}	.41	1.07	- .54	- 25.76	- .57	- .03
a_{12}	- 7.72	- 7.92	3.01	- 22.42	.18	- .01
a_{13}	12.58	12.38	2.70	29.91	1.50	.12
a_{14}	2.58	2.79	1.33	- 12.56	- .06	- .06
a_{15}	1.30	3.03	- 6.29	- 49.34	- .02	- .09
a_{16}	- 1.43	- .70	- 4.48	- 5.04	- .08	.02
a_{17}	- 14.41	- 13.82	- 2.56	35.07	- .57	- .06
a_{18}	6.08	6.39	1.90	60.62	.78	.04
a_{19}	3.68	4.25	- .46	16.38	.25	- .003
a_{20}	16.39	16.18	1.16	- 13.56	- .03	- .05
a_{21}	- 6.94	- 6.96	- .94	- 98.58	- .39	.06
a_{22}	11.06	11.08	3.79	16.27	.71	.05
a_{23}	13.11	10.83	8.50	55.97	- .05	- .09
a_{24}	24.10	21.44	9.09	- 12.51	.36	- .06
a_{25}	15.13	14.76	3.10	68.83	1.36	.07
a_{26}	5.66	6.12	- 1.52	30.84	- .03	- .006
a_{27}	19.60	19.20	3.15	87.33	1.19	.06

TABLE 3. COMPILATION OF MULTICYCLIC 6F AIRLOADS TRIM CASES

CASE NO	FLAP INPUTS-DEGREES D0	D1S	D1C	D2S	D2C	D3S	D3C	D4S	D4C	VIBRATORY HUB SHEARS +/- LBS TOTAL	OP	IP	BENDING MOMENT-OP +/- IN-LB	HORSE POWER	MAX ANGLE OF ATTACK-DEG
S9	-1.000	3.000	5.000	0.0	0.0	1.000	0.0	-2.121	2.121	232.0	228.0	75.0	5392.0	748.0	11.55
T2	-1.000	3.000	5.000	0.707	0.707	2.829	2.829	2.000	0.0	851.0	837.0	181.0	5500.0	744.0	10.64
T3	-1.000	3.000	5.000	-1.414	1.414	1.414	1.414	0.0	0.0	456.0	450.0	108.0	4640.0	742.0	12.00
T4	-1.000	3.000	5.000	0.0	0.0	-2.121	2.121	2.000	0.0	453.0	432.0	142.0	5531.0	760.0	11.67
T5	-1.000	3.000	5.000	2.000	0.0	-3.536	3.536	-0.707	0.707	382.0	366.0	122.0	5187.0	776.0	13.53
T6	-1.000	3.000	5.000	0.0	0.0	-2.121	2.121	4.000	0.0	654.0	622.0	208.0	6207.0	773.0	12.25
T7	-1.000	3.000	5.000	-0.707	0.707	0.0	0.0	3.000	0.0	666.0	656.0	119.0	5285.0	760.0	12.33
T8	-1.000	3.000	5.000	1.000	0.0	3.000	0.0	-2.121	2.121	186.0	167.0	93.0	5175.0	760.0	12.00
T9	-1.000	3.000	5.000	-0.707	0.707	-3.536	3.536	0.0	0.0	427.0	421.0	107.0	5177.0	764.0	12.36
Z1	-1.000	3.000	5.000	2.000	0.0	-2.121	2.121	0.707	0.707	346.0	334.0	100.0	4877.0	763.0	12.70
Z2	-1.000	3.000	5.000	0.0	0.0	4.000	0.0	-2.121	2.121	301.0	288.0	126.0	5167.0	755.0	12.92
Z3	-1.000	3.000	5.000	0.0	0.0	-0.707	0.707	1.414	1.414	452.0	445.0	78.0	5069.0	752.0	10.95
Z4	-1.000	3.000	5.000	0.0	0.0	-1.414	1.414	0.0	0.0	206.0	200.0	62.0	4563.0	752.0	11.45
Z5	-1.000	3.000	5.000	0.0	0.0	-1.414	1.414	4.000	0.0	682.0	656.0	184.0	6045.0	768.0	12.14
Z7	-1.000	3.000	5.000	-1.414	1.414	1.414	1.414	-2.121	2.121	386.0	380.0	93.0	5074.0	751.0	12.99
Z9	-1.000	3.000	5.000	1.414	1.414	4.000	0.0	-1.414	1.414	354.0	344.0	143.0	4572.0	764.0	12.85
Z0	-1.000	3.000	5.000	2.121	2.121	-1.414	1.414	0.0	0.0	298.0	297.0	30.0	4012.0	769.0	13.99
AA	-1.000	3.000	5.000	2.000	-1.000	-2.000	-3.000	-2.000	0.0	480.4	464.0	149.0	5322.0	782.0	11.75
AB	-1.000	3.000	5.000	2.000	-1.000	-1.000	-1.000	-3.000	3.000	420.0	389.0	159.0	5935.0	798.0	12.22
AC	-1.000	3.000	5.000	2.000	-1.000	1.000	1.000	-3.000	0.0	162.0	139.6	82.0	5139.0	770.0	12.86
AD	-1.000	3.000	5.000	2.000	0.0	0.0	-1.000	-3.000	0.0	358.5	336.0	126.0	5356.0	773.0	12.57
AE	-1.000	3.000	5.000	2.000	1.000	0.0	-1.000	-4.000	0.0	497.0	469.0	174.0	5681.0	790.0	13.35
AF	-1.000	3.000	5.000	2.000	1.000	0.0	0.0	-4.000	2.000	373.0	338.0	158.0	5754.0	791.0	13.63
AG	-1.000	3.000	5.000	3.000	-2.000	-2.000	0.0	-1.000	-1.000	237.0	236.0	57.5	5390.0	771.0	12.70
AH	-1.000	3.000	5.000	3.000	-1.000	0.0	1.000	-3.000	2.000	277.0	263.0	87.0	5391.0	791.0	13.57
AI	-1.000	3.000	5.000	3.000	0.0	1.000	-3.000	-3.000	1.000	238.0	216.0	101.0	5358.0	782.0	13.37
AJ	-1.000	3.000	5.000	3.000	1.000	-1.000	0.0	-3.000	1.000	299.0	274.0	135.0	5337.0	786.0	13.71
AK	-1.000	3.000	5.000	3.000	1.000	0.0	-1.000	-3.000	2.000	322.0	290.0	152.0	5598.0	789.0	13.56
AL	-1.000	3.000	5.000	4.000	-3.000	-1.000	-1.000	-1.000	0.0	206.0	204.0	83.0	5745.0	791.0	12.72
AM	-1.000	3.000	5.000	4.000	-3.000	-1.000	0.0	-1.000	0.0	137.0	136.0	62.0	5748.0	785.0	13.04
AN	-1.000	3.000	5.000	4.000	-1.000	-2.000	-1.000	-1.000	0.0	268.0	268.0	95.0	5273.0	786.0	13.31
AP	-1.000	3.000	5.000	2.121	2.121	-1.414	1.414	0.0	0.0	298.0	297.0	30.0	4012.0	769.0	13.99
AQ	-1.000	3.000	5.000	0.0	0.0	4.000	0.0	-2.121	2.121	301.0	289.0	126.0	5285.0	755.0	12.92
AR	-1.000	3.000	5.000	0.0	0.0	-0.707	0.707	1.414	1.414	458.0	445.0	78.0	5068.0	752.0	10.95
AS	-1.000	3.000	5.000	0.0	0.0	-1.414	1.414	0.0	0.0	206.0	200.0	62.0	4563.0	752.0	11.45
AT	-1.000	3.000	5.000	0.0	0.0	-1.414	1.414	4.000	0.0	682.0	656.0	184.0	6047.0	768.0	12.14
AU	-1.000	3.000	5.000	-1.414	1.414	1.414	1.414	-2.121	2.121	386.0	380.0	93.0	5094.0	751.0	12.99
AW	-1.000	3.000	5.000	1.414	1.414	4.000	0.0	-1.414	1.414	354.0	344.0	143.0	4616.0	764.0	12.85
AX	-1.000	3.000	5.000	0.707	0.707	2.000	0.0	-3.536	3.535	317.0	302.0	120.0	6077.0	779.0	13.16
AY	-1.000	3.000	5.000	1.414	1.414	0.0	0.0	-2.121	2.121	174.0	156.0	96.0	5215.0	770.0	12.63
AZ	-1.000	3.000	5.000	1.000	0.0	0.0	0.0	-1.414	1.414	141.0	140.0	43.0	4958.0	756.0	11.56
BA	-1.000	3.000	5.000	0.0	0.0	3.000	0.0	-2.829	2.829	257.0	239.0	98.0	5714.0	759.0	12.96
BC	-1.000	3.000	5.000	-0.707	0.707	1.414	1.414	1.414	1.414	640.0	637.0	100.0	5053.0	750.0	11.02
BD	-1.000	3.000	5.000	4.000	0.0	-0.707	0.707	0.0	0.0	173.0	172.0	29.0	4472.0	778.0	13.75
BE	-1.000	3.000	5.000	0.0	0.0	-2.121	2.121	-3.536	3.536	693.0	683.0	120.0	6317.0	795.0	12.21
BI	-1.000	3.000	5.000	2.000	0.0	-1.414	1.414	0.0	0.0	185.0	178.0	52.0	4267.0	760.0	12.68

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TABLE 3. COMPILATION OF MULTICYCLIC 6F AIRLOADS TRIM CASES (continued)

CASE NO	FLAP INPUTS-DEGREES D0	D1S	D1C	D2S	D2C	D3S	D3C	D4S	D4C	VIBRATORY HUB SHEARS +/- LBS TOTAL	OP	IP	BENDING MOMENT-OP +/- IN-LB	HORSE POWER	MAX ANGLE OF ATTACK-DEG
L7	-1.000	3.000	5.000	2.829	2.829	0.0	0.0	3.000	0.0	734.0	730.9	71.4	4370.0	788.0	15.00
L8	-1.000	3.000	5.000	0.0	0.0	1.414	-1.414	4.000	0.0	824.0	813.5	129.5	5252.0	764.0	12.36
L9	-1.000	3.000	5.000	0.0	0.0	1.414	-1.414	0.0	0.0	327.0	320.5	92.2	4208.0	750.0	10.88
M1	-1.000	3.000	5.000	0.0	0.0	0.707	-0.707	1.414	1.414	423.0	421.4	35.5	4496.0	748.0	11.25
M4	-1.000	3.000	5.000	0.0	0.0	4.000	0.0	2.121	-2.121	940.0	916.0	229.8	6602.0	760.0	11.07
M7	-1.000	3.000	5.000	2.829	2.829	0.707	0.707	1.000	0.0	605.0	604.2	77.0	3811.0	776.0	14.32
M8	-1.000	3.000	5.000	0.707	-0.707	3.536	-3.536	0.0	0.0	558.0	548.1	180.9	5335.0	761.0	11.56
M9	-1.000	3.000	5.000	1.000	0.0	3.000	0.0	2.121	-2.121	861.0	840.0	199.4	6007.0	758.0	11.35
O1	-1.000	3.000	5.000	2.829	2.829	2.000	0.0	0.0	0.0	597.0	592.0	119.3	4189.0	775.0	13.73
O2	-1.000	3.000	5.000	0.707	-0.707	0.0	0.0	3.000	0.0	585.0	572.5	121.9	5244.0	759.0	11.30
O3	-1.000	3.000	5.000	0.0	0.0	2.000	0.0	4.000	0.0	913.0	900.3	163.2	5605.0	765.0	11.69
O4	-1.000	3.000	5.000	0.0	0.0	2.121	-2.121	4.000	0.0	864.0	855.4	131.3	5041.0	768.0	12.59
O5	-1.000	3.000	5.000	2.000	0.0	3.536	-3.536	0.707	-0.707	703.0	684.0	190.2	5193.0	769.0	11.71
O6	-1.000	3.000	5.000	1.000	0.0	1.000	0.0	1.414	1.414	481.0	478.0	50.3	4424.0	751.0	10.98
O7	-1.000	3.000	5.000	0.0	0.0	0.0	0.0	4.000	0.0	761.0	746.5	146.6	5700.0	764.0	12.10
O8	-1.000	3.000	5.000	0.0	0.0	3.536	3.536	0.707	0.707	787.0	775.0	160.9	5807.0	754.0	11.37
O9	-1.000	3.000	5.000	0.0	0.0	2.121	-2.121	2.000	0.0	606.0	600.0	115.4	4391.0	744.0	11.69
P1	-1.000	3.000	5.000	1.414	-1.414	1.414	1.414	0.0	0.0	346.0	334.0	108.2	4913.0	750.0	11.41
P2	-1.000	3.000	5.000	0.707	-0.707	1.000	0.0	4.000	0.0	801.0	784.8	159.6	5651.0	766.0	11.30
P3	-1.000	3.000	5.000	4.000	0.0	0.0	0.0	2.829	-2.829	788.0	772.0	158.6	5329.0	765.0	14.14
P4	-1.000	3.000	5.000	2.121	2.121	3.000	0.0	1.414	1.414	678.0	676.0	116.8	4183.0	762.0	12.82
P5	-1.000	3.000	5.000	0.707	-0.707	2.829	2.829	2.000	0.0	803.0	778.4	208.0	5980.0	756.0	11.16
P6	-1.000	3.000	5.000	0.0	0.0	1.000	0.0	2.121	-2.121	708.0	688.0	170.3	5147.0	751.0	11.80
P7	-1.000	3.000	5.000	1.000	0.0	2.121	-2.121	1.000	0.0	492.0	488.0	112.0	4393.0	749.0	11.24
P8	-1.000	3.000	5.000	0.0	0.0	3.536	3.536	0.707	0.707	787.0	775.0	180.9	5807.0	754.0	11.37
P9	-1.000	3.000	5.000	0.707	0.707	1.414	1.414	0.707	0.707	511.0	506.3	90.9	4333.0	746.0	11.23
N1	-1.000	3.000	5.000	0.707	0.707	1.414	1.414	0.0	0.0	410.0	403.4	95.6	4413.0	744.0	11.52
N2	-1.000	3.000	5.000	2.121	2.121	0.707	-0.707	0.707	-0.707	554.0	552.0	99.0	3707.0	763.0	13.56
N3	-1.000	3.000	5.000	0.707	0.707	3.536	-3.536	2.000	0.0	757.0	752.0	164.0	4679.0	762.0	12.89
N5	-1.000	3.000	5.000	4.000	0.0	0.0	0.0	3.000	0.0	590.0	580.7	111.1	4976.0	775.0	13.29
N6	-1.000	3.000	5.000	0.0	0.0	2.000	0.0	2.121	-2.121	785.0	764.0	188.6	5638.0	751.0	11.55
N7	-1.000	3.000	5.000	0.707	0.707	0.0	0.0	5.000	0.0	938.0	927.6	170.7	5800.0	778.0	13.13
N8	-1.000	3.000	5.000	2.000	0.0	0.0	0.0	4.000	0.0	754.0	739.8	147.3	5221.0	758.0	12.68
Q1	-1.000	3.000	5.000	2.121	-2.121	0.707	0.707	1.000	0.0	372.0	357.8	105.0	4846.0	759.0	11.43
Q4	-1.000	3.000	5.000	0.707	-0.707	2.121	-2.121	0.0	0.0	383.0	376.7	115.1	4638.0	750.0	10.57
Q7	-1.000	3.000	5.000	3.000	0.0	1.414	-1.414	0.0	0.0	349.0	348.9	87.5	4175.0	763.0	12.04
Q8	-1.000	3.000	5.000	0.707	-0.707	3.536	3.536	0.0	0.0	647.0	635.6	192.5	6217.0	755.0	11.85
Q9	-1.000	3.000	5.000	0.0	0.0	1.000	0.0	2.121	2.121	596.0	592.2	67.0	5092.0	755.0	11.32
S0	-1.000	3.000	5.000	-0.707	0.707	3.536	3.536	0.0	0.0	689.0	678.0	172.0	5103.0	751.0	12.30
S1	-1.000	3.000	5.000	3.000	0.0	-1.414	1.414	0.0	0.0	150.0	147.0	44.0	4433.0	768.0	13.34
S2	-1.000	3.000	5.000	-0.707	0.707	-2.121	0.0	0.0	0.0	292.0	288.0	70.0	4722.0	752.0	11.77
S4	-1.000	3.000	5.000	-2.121	2.121	0.707	0.707	1.000	0.0	569.0	566.0	116.0	4773.0	748.0	12.57
S5	-1.000	3.000	5.000	0.0	0.0	2.000	0.0	-2.121	2.121	221.0	208.0	76.0	5256.0	750.0	11.98
S6	-1.000	3.000	5.000	0.707	-0.707	-3.536	3.536	2.000	0.0	530.0	504.0	171.0	5590.0	772.0	13.00
S7	-1.000	3.000	5.000	2.121	2.121	-0.707	0.707	-0.707	0.707	203.0	193.0	62.0	4344.0	771.0	13.58
S8	-1.000	3.000	5.000	1.000	0.0	-2.121	2.121	1.000	0.0	340.0	322.0	109.0	4895.0	759.0	12.30

KAMAN AEROSPACE CORPORATION
OLD WINDSOR ROAD, BLOOMFIELD, CONNECTICUT 06002

TABLE 3. COMPILATION OF MULTICYCLIC 6F AIRLOADS TRIM CASES (continued)

CASE NO	FLAP INPUTS-DEGREES D0	D1S	D1C	D2S	D2C	D3S	D3C	D4S	D4C	VIBRATORY HUB SHEARS +/- LBS TOTAL	3P	1P	BENDING MOMENT-OP +/- IN-LB	HORSE POWER	MAX ANGLE OF ATTACK-DEG
B7	-1.000	3.000	5.000	0.0	0.0	2.121	2.121	0.0	0.0	474.0	463.8	134.0	5053.0	736.0	10.56
B8	-1.000	3.000	5.000	0.0	0.0	0.0	4.242	0.0	0.0	513.0	504.3	145.9	5170.0	756.0	11.69
C7	-1.000	3.000	5.000	0.0	0.0	0.0	0.0	2.121	2.121	550.0	544.8	73.6	5253.0	756.0	11.49
D2	-1.000	3.000	5.000	2.121	2.121	2.121	2.121	0.0	0.0	577.0	570.3	102.4	4451.0	760.0	13.32
D3	-1.000	3.000	5.000	4.000	0.0	2.829	2.829	0.0	0.0	502.0	493.0	163.8	4538.0	783.0	12.20
D5	-1.000	3.000	5.000	0.0	0.0	1.414	1.414	0.707	0.707	490.0	483.7	101.5	4656.0	747.0	10.52
D8	-1.000	3.000	5.000	0.0	0.0	2.000	0.0	4.000	0.0	913.0	900.0	163.2	5605.0	765.0	11.69
E1	-1.000	3.000	5.000	1.414	1.414	3.000	0.0	1.000	0.0	657.0	649.5	133.6	4843.0	750.0	11.73
E2	-1.000	3.000	5.000	2.000	0.0	0.0	0.0	2.829	-2.829	783.0	764.0	170.1	5057.0	781.0	13.02
E5	-1.000	3.000	5.000	0.707	-0.707	4.000	0.0	1.414	1.414	736.0	700.1	135.0	5185.0	746.0	11.09
E6	-1.000	3.000	5.000	0.0	0.0	3.536	3.536	0.0	0.0	671.0	659.0	182.5	6072.0	753.0	11.60
E7	-1.000	3.000	5.000	2.000	0.0	1.000	0.0	2.829	2.829	716.0	710.1	100.1	5484.0	768.0	11.79
E9	-1.000	3.000	5.000	0.707	0.707	5.000	0.0	1.414	-1.414	911.0	892.0	208.0	6418.0	759.0	11.41
F1	-1.000	3.000	5.000	0.0	0.0	4.000	0.0	1.414	-1.414	814.0	792.0	208.6	6334.0	753.0	11.03
F2	-1.000	3.000	5.000	1.000	0.0	2.829	2.829	2.000	0.0	831.0	811.0	192.2	5824.0	756.0	11.31
F3	-1.000	3.000	5.000	2.829	-2.829	2.121	2.121	0.0	0.0	407.0	390.3	141.7	5871.0	768.0	12.71
F5	-1.000	3.000	5.000	1.414	1.414	0.0	0.0	0.707	0.707	375.0	365.3	100.7	4017.0	752.0	12.45
F8	-1.000	3.000	5.000	0.0	0.0	3.536	3.536	0.0	0.0	671.0	659.0	182.5	6072.0	753.0	11.60
F9	-1.000	3.000	5.000	2.121	-2.121	1.000	0.0	1.414	-1.414	489.0	468.0	142.0	5146.0	758.0	11.17
G1	-1.000	3.000	5.000	5.000	0.0	0.0	0.0	0.0	0.0	254.0	252.8	50.1	4722.0	798.0	14.20
G4	-1.000	3.000	5.000	0.0	0.0	2.121	2.121	2.121	-2.121	806.0	779.7	218.8	5997.0	757.0	11.55
G6	-1.000	3.000	5.000	0.707	-0.707	0.707	-0.707	2.000	0.0	480.0	472.8	81.2	4589.0	755.0	10.90
G7	-1.000	3.000	5.000	3.000	0.0	0.707	0.707	2.829	2.829	702.0	690.1	132.8	5552.0	760.0	12.13
G8	-1.000	3.000	5.000	0.0	0.0	3.536	-3.536	0.707	0.707	556.0	555.8	163.4	5021.0	754.0	12.60
G9	-1.000	3.000	5.000	2.829	-2.829	1.000	0.0	3.000	0.0	639.0	638.6	152.9	5433.0	776.0	11.50
H2	-1.000	3.000	5.000	0.0	0.0	1.000	0.0	5.000	0.0	966.0	948.3	181.7	6060.0	776.0	12.41
H3	-1.000	3.000	5.000	2.121	2.121	2.121	-2.121	4.000	0.0	957.0	951.3	123.2	4257.0	782.0	14.67
H4	-1.000	3.000	5.000	2.000	0.0	2.829	-2.829	0.707	0.707	466.0	464.0	133.6	4398.0	762.0	11.84
H5	-1.000	3.000	5.000	2.000	0.0	0.707	0.707	2.829	2.829	740.0	730.8	122.7	5535.0	770.0	11.54
H7	-1.000	3.000	5.000	2.829	2.829	2.121	-2.121	1.000	0.0	678.0	672.9	154.6	4480.0	780.0	14.34
I1	-1.000	3.000	5.000	2.000	0.0	0.0	0.0	1.414	1.414	399.0	396.0	57.3	4549.0	758.0	11.53
I2	-1.000	3.000	5.000	2.000	0.0	1.414	-1.414	0.0	0.0	343.0	336.5	83.8	4087.0	753.0	11.34
I7	-1.000	3.000	5.000	2.829	2.829	1.414	1.414	0.707	0.707	603.0	601.5	78.4	3985.0	777.0	13.74
[illegible]	-1.000	3.000	5.000	0.707	-0.707	1.414	1.414	1.414	1.414	757.0	577.3	493.3	5080.0	753.0	11.00
K1	-1.000	3.000	5.000	1.000	0.0	5.000	0.0	1.000	0.0	766.0	754.7	186.6	6102.0	755.0	11.31
K2	-1.000	3.000	5.000	2.000	0.0	3.536	3.536	0.0	0.0	631.0	612.3	172.1	5852.0	760.0	12.63
K4	-1.000	3.000	5.000	0.0	0.0	3.000	0.0	2.829	-2.829	1001.0	976.0	235.0	6417.0	761.0	11.75
K6	-1.000	3.000	5.000	2.829	-2.829	4.000	0.0	0.0	0.0	493.0	478.7	164.0	6311.0	770.0	12.39
K7	-1.000	3.000	5.000	2.000	0.0	1.414	-1.414	1.000	0.0	439.0	432.0	75.6	4049.0	753.0	11.44
K9	-1.000	3.000	5.000	0.0	0.0	5.000	0.0	2.000	0.0	896.0	881.5	195.3	6139.0	758.0	11.46
L1	-1.000	3.000	5.000	2.829	-2.829	1.000	0.0	2.000	0.0	501.0	485.6	122.8	5118.0	770.0	11.64
L2	-1.000	3.000	5.000	0.707	0.707	2.000	0.0	3.536	-3.536	1119.0	1096.0	237.4	6247.0	770.0	13.07
L3	-1.000	3.000	5.000	1.414	1.414	4.000	0.0	1.414	-1.414	879.0	864.0	180.3	5845.0	762.0	12.03
L4	-1.000	3.000	5.000	3.536	-3.536	0.707	-0.707	1.414	-1.414	473.0	452.0	140.2	5474.0	775.0	11.76
L5	-1.000	3.000	5.000	1.414	-1.414	1.414	1.414	2.121	-2.121	676.0	640.0	217.7	5874.0	759.0	11.19
BK	-1.000	3.000	5.000	-1.414	1.414	0.0	0.0	0.0	0.0	284.0	280.0	70.0	4288.0	747.0	11.85
BL	-1.000	3.000	5.000	2.000	0.0	-2.829	2.829	0.707	0.707	407.0	384.0	136.0	5124.0	770.0	13.02
BM	-1.000	3.000	5.000	2.121	2.121	-2.121	2.121	4.000	0.0	818.0	803.0	153.0	5425.0	791.0	14.88

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KAMAN CORPORATION

TABLE 4. SURGEN AND 6F TRIM ROTOR PARAMETER COMPARISON

Case: 3315 Multicyclic CTR Without Higher Harmonic Control Inputs (MCTR w/o HH)

Controls: $\delta_0 = -1$, $\delta_{1s} = 3$, $\delta_{1c} = 5$

ROTOR PARAMETERS	SURGEN PREDICTION	6F PROGRAM TRIM VALUES
R_v (Resultant)	297	212
R_{vop}	287.3	210.3
R_{vip}	79.29	44.8
BM	4410.6	4175
HP	745	748
α_{max}	11.05	10.83

TABLE 5. SURGEN AND 6F TRIM ROTOR PARAMETER COMPARISON

Case: 3301X4 Multicyclic CTR, Model-Predicted Controls for Minimum Out-of-Plane Hub Shears

Controls: $\delta_0 = 1$, $\delta_{1s} = 3$, $\delta_{2s} = 4$, $\delta_{3s} = 0$, $\delta_{4s} = -2$,
$\delta_{1c} = 5$, $\delta_{2c} = -2$, $\delta_{3c} = 1$, $\delta_{4c} = 1$

ROTOR PARAMETER	SURGEN PREDICTION	% VARIATION FROM MCTR W/O HH	6F PROGRAM TRIM VALUES	% VARIATION FROM MCTR W/O HH
R_v (Resultant)	163.2	- 45%	118.7	- 44%
R_{vop}	148.9	- 48%	113.7	- 48%
R_{vip}	87.7	10%	36.3	- 19%
BM	5344.6	21%	5340	28%
HP	789.6	6%	791.7	6%
α_{max}	13.74	24%	13.78	27%

TABLE 6. SURGEN AND 6F TRIM ROTOR PARAMETER COMPARISON

Case: 330112 Multicyclic CTR, Model-Predicted Controls for Minimum Out-of-Plane Hub Shears

Controls: $\delta_0 = -1$, $\delta_{1s} = 3$, $\delta_{2s} = 4$, $\delta_{3s} = 0$, $\delta_{4s} = -2$,
$\delta_{1c} = 5$, $\delta_{2c} = -2$, $\delta_{3c} = 1$, $\delta_{4c} = 0$

ROTOR PARAMETER	SURGEN PREDICTION	% VARIATION FROM MCTR W/O HH	6F PROGRAM TRIM VALUES	% VARIATION FROM MCTR W/O HH
R_v (Resultant)	143.6	- 50%	141.7	- 33%
R_{vop}	139	- 52%	140.0	- 33%
R_{vip}	68.7	- 13%	22.5	- 50%
BM	5437.3	21%	5317	27%
HP	785.7	5%	786.2	5%
α_{max}	13.8	25%	13.82	27%

TABLE 7. SURGEN AND 6F TRIM ROTOR PARAMETER COMPARISON

Case: 3301X5 Multicyclic CTR, Model-Predicted Controls for Minimum Out-of-Plane Hub Shears

Controls: $\delta_0 = -1$, $\delta_{1s} = 3$, $\delta_{2s} = 4$, $\delta_{3s} = -1$, $\delta_{4s} = -1$,
$\delta_{1c} = 5$, $\delta_{2c} = -2$, $\delta_{3c} = 1$, $\delta_{4c} = 0$

ROTOR PARAMETER	SURGEN PREDICTION	% VARIATION FROM MCTR W/O HH	6F PROGRAM TRIM VALUES	% VARIATION FROM MCTR W/O HH
R_v (Resultant)	156.7	- 47%	70.0	- 67%
R_{vop}	148	- 48%	62	- 71%
R_{vip}	75.8	- 4%	30.2	- 33%
BM	5238.6	19%	5268.5	26%
HP	781.8	5%	780.9	4%
α_{max}	13.58	23%	13.58	25%

In comparing the results of the SURGEN model predictions with the 6F trim cases, it is seen, as in Table 4, the SURGEN model is conservative. The SURGEN model predicts bending moments, horsepower and blade maximum angle of attack quite adequately. The hub shears are usually higher using the SURGEN model. However, the trends with higher harmonic control input are the same.

It is also seen in Tables 5 through 7 that the controls that minimized the out-of-plane hub shears, in most cases, reduced the in-plane hub shears. When the in-plane hub shear SURGEN model was used to obtain minimum in-plane hub shears and these controls were then used in the out-of-plane hub shear SURGEN model, the out-of-plane hub shear increased 33%. Thus, it appears that the out-of-plane hub shear model is predominant, in that the out-of-plane hub shears are of the greatest magnitude and the controls that minimize the out-of-plane hub shears also reduce the in-plane hub shears.

The SURGEN model's limitations are possibly due to the relatively small number of trim data available (141 cases) upon which they are based.

Variation in phasing of higher harmonic controls also shows pronounced effects on all rotor parameters. Tables 8, 9 and 10 present trim cases with variation in phasing of the 2nd, 3rd and 4th harmonic flap control inputs, respectively, while amplitudes are held fixed. Limited phasing variations were used in the trim cases to generate the SURGEN models; therefore, optimum controls may not be obtained with the present models.

Variation in optimum collective and first harmonic control input was not investigated.

2.5 Concluding Remarks

The following observations were made regarding the updated multicyclic analysis:

- With the addition of 2/rev, 3/rev and 4/rev higher harmonic flap control input, reduction of the 4/rev pylon excitation loads by at least 71% compared to the same rotor without higher harmonic control input was shown possible.

  Whereas the previous MFS study, cited in Reference 1, showed only 2/rev control input to be beneficial to reducing vibratory hub shears, the present study shows all higher harmonic controls together aid in reducing the vibratory hub shear.

- Vibratory hub shears, bending moment, blade angle of attack and horsepower are significantly variant with both higher harmonic control amplitudes and higher harmonic control phasing.

TABLE 8. EFFECTS OF HIGHER HARMONIC CONTROL INPUT PHASING

Case: P1 and T3 6F Trim, 2/Rev Phasing Effect

Controls: $\delta_0 = -1$, $\delta_{1s} = 3$, $\delta_{3s} = 1.414$, $\delta_{4s} = 0$

$\delta_{1c} = 5$, $\delta_{3c} = 1.414$, $\delta_{4c} = 0$

ROTOR PARAMETER	P1 $\delta_2 = 2\angle 135°$	T3 $\delta_2 = 2\angle -45°$
R_v (Resultant)	346	456
R_{vop}	334	450
R_{vip}	108.2	108
BM	4913	4640
HP	750	742
α_{max}	11.41	12.0

TABLE 9. EFFECTS OF HIGHER HARMONIC CONTROL INPUT PHASING

Case: Q7 and S1 6F Trim, 3/Rev Phasing Effect

Controls: $\delta_0 = -1,\ \delta_{1s} = 3,\ \delta_{2s} = 3,\ \delta_{4s} = 0$

$\delta_{1c} = 5,\ \delta_{2c} = 0,\ \delta_{4c} = 0$

ROTOR PARAMETER	Q7 $\delta_3 = 2\angle 135°$	S1 $\delta_3 = 2\angle -45°$
R_v (Resultant)	349	150
R_{vop}	348.9	147
R_{vip}	875	44
BM	4175	4433
HP	763	768
α_{max}	12.04	13.34

TABLE 10. EFFECTS OF HIGHER HARMONIC CONTROL INPUT PHASING

Case: AW and L3 6F Trim, 4/Rev Phasing Effect

Controls: $\delta_0 = -1,\ \delta_{1s} = 3,\ \delta_{2s} = 4,\ \delta_{3s} = -2$

$\delta_{1c} = 5,\ \delta_{2c} = -1,\ \delta_{3c} = -1$

ROTOR PARAMETER	AW $\delta_4 = 2\underline{/-45°}$	L3 $\delta_4 = 2\underline{/135°}$
R_v (Resultant)	354	879
R_{vop}	344	864
R_{vip}	143	180
BM	4616	5845
HP	764	762
α_{max}	12.85	12.03

- Minimization of 4/rev out-of-plane vibratory hub shears show the most pronounced effect on overall reduction of vibratory hub shears.

- In view of the pronounced effect of phasing higher harmonic controls on rotor parameters, more comprehensive investigation of phasing is required, together with amplitude variation in higher harmonic flap controls for trim case generation and subsequent rotor parameter SURGEN model development.

- Incorporation of flap collective and first harmonic variation, at least within the optimum control region of the basic CTR, is anticipated to give a better understanding of the interrelationship of all flap control inputs on rotor parameters of interest.

3.0 CONCEPTS OF MULTICYCLIC ADAPTIVE-CONTROL

3.1 Control Function

The purpose of the multicyclic control is to minimize certain parameters to the greatest extent possible while keeping others within acceptable limits. To accomplish this with feedback control, the definition of an "optimization" parameter as a function of the various controlled parameters is required. Feedback is then used to vary certain controlling, or independent, variables in such a way as to minimize the optimization parameter. The controlled parameters that have been selected for this feasibility study are as follows:

Bending Moment

Horsepower

Maximum Angle of Attack

Hub Shear

One of the criteria for selecting controlled parameters for the feasibility study was the ease with which they could be represented analytically on the basis of data from the 6F Aeroelastic Loads Program. When it comes time to implement this concept, a more important criterion will be the ease and repeatability with which the parameters can be measured on an operating rotor system. In this case, the control parameters are more likely to be:

Control load related to bending moment

Engine pressure

Pitch link load

Fuselage vibration levels

The controlling parameters, or independent variables, have been taken to be the sine and cosine components of the 2, 3 and 4/revolution servoflap control.

The function of the feedback control system is to determine the effect of each independent variable (x's) on the controlled parameters (y's) and, thus, on the optimization parameter (P). The system then manipulates the x's to minimize P. Mathematically, the general case is:

Optimization Function

$$P = f(y_1, y_2, y_3, y_4)$$

Change in P

$$\Delta P = \sum_{k=1}^{4} \frac{\partial P}{\partial y_k} \Delta y_k$$

where:

$$y_k = g_k(x_1, x_2, x_3, x_4, x_5, x_6)$$

$$\Delta y_k = \sum_{i=1}^{6} \frac{\partial y_k}{\partial x_i} \Delta x_i$$

$$\Delta P = \sum_{k=1}^{4} \left(\frac{\partial P}{\partial y_k} \cdot \sum_{i=1}^{6} \frac{\partial y_k}{\partial x_i} \Delta x_i \right)$$

The change in P caused by changes in a particular x_i is:

$$\Delta P_i = \sum_{k=1}^{4} \frac{\partial P}{\partial y_k} \cdot \frac{\partial y_k}{\partial x_i} \cdot \Delta x_i$$

and the sensitivity of P to changes in a particular x_i is:

$$S_i = \frac{\Delta P_i}{\Delta x_i} = \sum_{k=1}^{4} \frac{\partial P}{\partial y_k} \cdot \frac{\partial y_k}{\partial x_i}$$

From this, it can be seen that the feedback control system requires two kinds of information. The first is the relative importance of each of the controlled variables. The second is the sensitivity of each of the controlled variables to changes in each of the independent variables. The first is determined by the characteristics of the defined optimization function; and the second is determined by the rotor characteristics.

3.2 Optimization Parameter

The optimization parameter provides an integrated measure of the "goodness" of the rotor operation as described by measurements of each of the controlled parameters. In effect, it provides a measure of the relative value of changes in each of the controlled parameters. An optimization parameter of the following form has been used in the feasibility study:

$$P = f_1(BM) + f_2(HP) + f_3(AM) + f_4(RV)$$

The individual functions associated with each of the controlled parameters have been established on the basis of the operation of the feasibility study rotor with no multicyclic control and considerations of the consequences of each of these parameters in the operation of a helicopter. Figure 3 provides plots of the magnitudes and normalized slopes of each of these individual functions. The function for maximum angle of attack considers that the parameter is of no consequence as long as it is below the threshold value (12°). Operation above this threshold becomes undesirable at a very rapid rate. Bending moment and horsepower are similar to angle of attack, except that it is considered advantageous to reduce these parameters below their thresholds of 7000 in-lb and 750 HP. In practice, it may be desirable to have the horsepower threshold be a function of some helicopter parameter such as forward speed; however, this feasibility study is only concerned with a single operating point of the rotor and, therefore, the threshold is fixed. Hub shear, and thus induced body vibrations, is considered to be of increasing concern from 0 on upwards. A decrease at a high level of hub shear is considered more valuable than the same decrease at a lower value of hub shear. The mathematical functions used are as follows:

Bending Moment:

$BM < 7000$ $$f_1(BM) = 37 + 100\left(\frac{BM}{7000} - 1\right)$$

$BM \geq 7000$ $$f_1(BM) = 37 + 100\left(\frac{BM}{7000} - 1\right) + 10\left(\frac{BM - 7000}{1000}\right)^4$$

Horsepower:

$HP < 750$ $$f_2(HP) = 20\left(\frac{HP}{750} - 1\right)$$

$HP \geq 750$ $$f_2(HP) = 20\left(\frac{HP}{750} - 1\right) + 10\left(\frac{HP - 750}{25}\right)^4$$

Maximum Angle of Attack:

$\alpha_{max} < 12°$ $$f_3(\alpha_{max}) = 0$$

$\alpha_{max} \geq 12°$ $$f_3(\alpha_{max}) = 10\,(AM - 12)^4$$

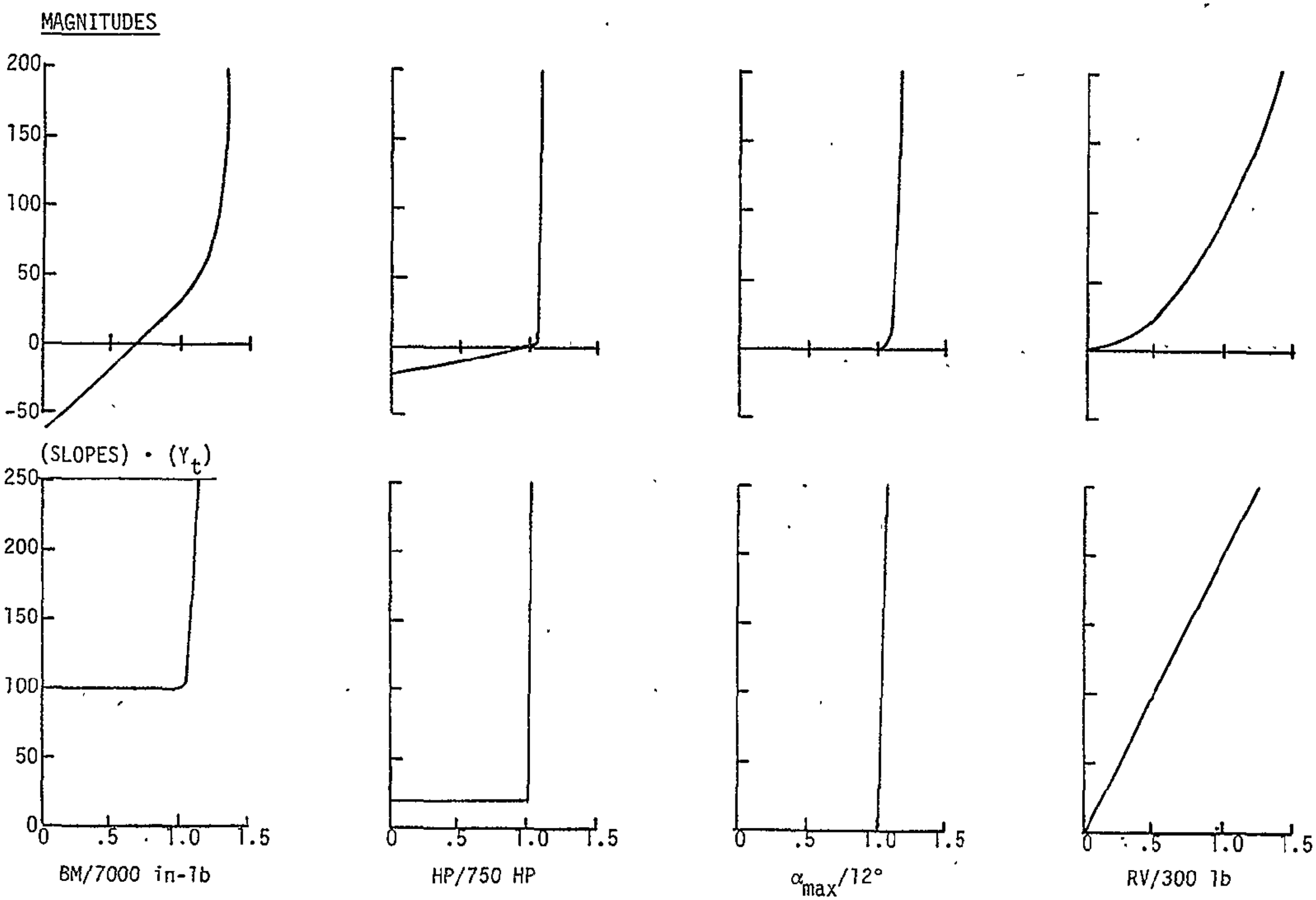

Figure 3. Optimization Functions.

Hub Shear:

$$f_4(RV) = 100 \cdot \left(\frac{RV}{300}\right)^2$$

Parameters such as horsepower and angle of attack could have been defined with discontinuities at the threshold points; however, operation of the feedback control system is better if the functions are continuous at all points. The scaling chosen in the functions above provides a value of the optimization parameter of about 100 at the rotor operating point corresponding to no multicyclic control. The measure of the improvement in rotor operation is provided by the decrease in this parameter from its initial value of 100.

The use of this particular optimization function in this feasibility study is not a limitation on the applicability of the results. In fact, it was chosen because it represents a variety of subfunctions. The effect of some other optimization functions are discussed in paragraph 4.1.

3.3 Rotor Characteristics

The rotor used for the feasibility study was analyzed under a variety of multicyclic control conditions with the 6F Aeroelastic Loads Program, as described in Section 2 of this report. The data developed from this analysis were then used to fit a 7-dimensional quadratic surface for each of the controlled variables. The coefficients for each of the four surfaces are shown on Table 11. The equation for each surface consists of a constant, six first order terms and twenty-one second order terms. The indices on the two dimensions of the matrix of coefficients represents the sine and cosine components of the second, third and fourth harmonic of the multicyclic control. For example, one term in the equation of the surface for bending moment is:

$$- 12.94 \cdot x_{2s} \cdot x_{3c}$$

The dimension used for the x's is degrees.

The real interest is in the slopes of these surfaces as represented by the derivatives of each of the controlled parameters with respect to each of the independent parameters. The coefficients of the derivative equations are given on Table 12. The equation for the derivative of a controlled variable with respect to an independent variable contains one first order term and six second order terms. The coefficients for the first order term and the off-diagonal second order terms are the same as the coefficients for the surfaces; however, the coefficients for the second order terms on the diagonal are double the value for the surface since they correspond to an x^2 term.

An inspection of these coefficients gives little, if any, indication of one independent variable being dominant with respect to any controlled variable. For instance, while the second harmonic would dominate bending moment when there is little or no multicyclic control (all second order terms at or near 0), 3s, 4s or 4c components with magnitudes in excess of 2° would have a greater effect, as would 3s in combination with 2° of 4c, or vice versa.

TABLE 11. SURFACE COEFFICIENTS

	FIRST ORDER	SECOND ORDER 2S	2C	3S	3C	4S	4C
COEFFICIENTS FOR BM: CONSTANT= 4410.59							
2S	-142.220	37.940	3.690	-20.540	-12.940	-25.760	-22.420
2C	-206.070		29.910	-12.560	-49.340	-5.040	35.070
3S	32.570			60.620	16.380	-13.560	-98.580
3C	52.890				16.270	55.970	-12.510
4S	-10.430					68.830	30.940
4C	53.990						87.330
COEFFICIENTS FOR HP: CONSTANT= 744.94							
2S	1.400	1.600	1.120	0.170	0.071	-0.570	0.180
2C	-1.250		1.500	-0.059	-0.019	-0.082	-0.570
3S	-2.920			0.780	0.250	-0.033	-0.390
3C	-1.250				0.710	-0.050	0.360
4S	-0.270					1.360	-0.030
4C	0.430						1.190
COEFFICIENTS FOR AM: CONSTANT= 11.053							
2S	0.196	0.079	-0.027	-0.082	0.030	-0.030	-0.015
2C	0.594		0.125	-0.061	-0.087	0.019	-0.057
3S	-0.068			0.041	-0.003	-0.054	0.063
3C	-0.009				0.047	-0.086	-0.059
4S	-0.032					0.071	-0.006
4C	-0.130						0.059
COEFFICIENTS FOR RV: CONSTANT= 297.							
2S	-17.590	2.170	8.840	2.490	-2.770	0.410	-7.720
2C	9.340		12.580	2.580	1.300	-1.430	-14.410
3S	27.140			6.080	3.680	16.390	-6.940
3C	1.620				11.060	13.110	24.100
4S	48.990					15.130	5.660
4C	-15.760						19.600

DONE

TABLE 12. DERIVATIVE COEFFICIENTS

	FIRST ORDER	SECOND ORDER 2S	2C	3S	3C	4S	4C
COEFFICIENTS FOR DERIVATIVES OF BM:							
2S	-142.220	75.880	3.690	-20.540	-12.940	-25.760	-22.420
2C	-206.070	3.690	59.820	-12.560	-49.340	-5.040	35.070
3S	32.570	-20.540	-12.560	121.240	16.380	-13.560	-98.580
3C	52.890	12.940	-49.340	16.380	32.540	55.970	-12.510
4S	-10.430	-25.760	-5.040	-13.560	55.970	137.660	30.940
4C	53.990	-22.420	35.070	-98.580	-12.510	30.940	174.660
COEFFICIENTS FOR DERIVATIVES OF HP:							
2S	1.400	3.200	1.120	0.170	0.071	-0.570	0.180
2C	-1.250	1.120	3.000	-0.059	-0.019	-0.082	-0.570
3S	-2.920	0.170	-0.059	1.560	0.250	-0.033	-0.390
3C	-1.250	0.071	-0.019	0.250	1.420	-0.050	0.360
4S	-0.270	-0.570	-0.082	-0.033	0.050	2.720	-0.030
4C	0.430	0.180	-0.570	-0.390	0.360	-0.030	2.380
COEFFICIENTS FOR DERIVATIVES OF AM:							
2S	0.196	0.158	-0.027	-0.082	0.030	-0.030	-0.015
2C	0.594	-0.027	0.250	-0.061	-0.087	0.019	-0.057
3S	-0.068	-0.082	-0.061	0.082	-0.003	-0.054	0.063
3C	-0.009	0.030	-0.087	-0.003	0.094	-0.086	-0.059
4S	-0.032	-0.030	0.019	-0.054	-0.086	0.142	-0.006
4C	-0.130	-0.015	-0.057	0.063	-0.059	-0.006	0.117
COEFFICIENTS FOR DERIVATIVES OF RV:							
2S	-17.590	4.340	8.840	2.490	-2.770	0.410	-7.720
2C	9.340	8.840	25.160	2.580	1.300	-1.430	-14.410
3S	27.140	2.490	2.580	12.160	3.680	16.390	-6.940
3C	1.620	-2.770	1.300	3.680	22.120	13.110	24.100
4S	48.990	0.410	-1.430	16.390	13.110	30.260	5.660
4C	-15.760	-7.720	-14.410	-6.940	24.100	5.660	39.200

DONE

Another view of these coefficients is provided on Table 13. In this case, the coefficients have been reordered to bring together all of the derivatives with respect to a particular independent variable. In addition, the coefficients have been normalized to 1% of the threshold value used in the optimization function for the corresponding controlled variable. The arrangement of this table provides a view of the effect of each independent variable on the optimization parameter; however, for the picture to be complete, each of the coefficients should be multiplied by the slope of the corresponding optimization function for a particular operating point as given in Figure 3. This indicates that each of the independent variables has significant impact on the optimization function, even the 3c component which has small first order coefficients, has second order coefficients associated with 3c, 4s and 4c which are sizeable.

While it is dangerous to make sweeping conclusions based on rotor performance data at a single operating point, there are two conclusions that can be drawn that are important to the remainder of this feasibility study. First, the second order coefficients of the derivatives can be dominant under a variety of operating conditions. This tends to confirm the necessity for determining the derivatives during actual operation of the rotor, rather than incorporating them as part of the pre-programmed control function. The second conclusion is that each of the six independent variables has significant effect on at least bending moment and shear and, therefore, must be incorporated as part of the feedback control function.

3.4 Effects on Rotor Thrust Vector

In general, the changes in multicyclic control introduced at the tip end of the blade to minimize the controlled parameters also change the lift and horizontal thrust vector developed by the rotor. Therefore, to maintain rotor trim, it would be necessary to introduce changes to the 1/rev cyclic pitch at the root end of the rotor. If this were not done and if the effects of the multicyclic control were large, the changes to multicyclic control would cause changes in helicopter operation which would, in turn, require a constant pilot attention in order to maintain the required operating condition. However, work with the 6F Aeroelastic Loads Program has indicated that the effects of multicyclic control on rotor trim are, in fact, small at the operating point investigated. Therefore, for the purposes of this feasibility study, the effects of multicyclic control on rotor trim are taken as not large in comparison to other effects for which the pilot must continuously compensate. This assumption would probably not be valid if the rotor tip end pitch changes at 1/rev were made subject to feedback control.

3.5 Search Strategies

The feedback control system requires a strategy to direct its search to find the path from the current operating point to the "best" operating point as defined by the optimization parameter. This strategy is contained in the logic that is used to analyze the measurements from the operating rotor in conjunction with the characteristics of the optimization function to determine which of the independent variables to increment next.

TABLE 13. NORMALIZED DERIVATIVE COEFFICIENTS (REORDERED)

	FIRST ORDER	SECOND ORDER 2S	2C	3S	3C	4S	4C
DERIVATIVES WITH RESPECT TO 2S							
BM	-2.032	1.084	0.053	-0.293	-0.185	-0.368	-0.320
HP	0.187	0.427	0.149	0.023	0.009	-0.076	0.024
AM	1.635	1.320	-0.228	-0.683	0.252	-0.250	-0.124
RV	-5.863	1.447	2.947	0.830	-0.923	0.137	-2.573
DERIVATIVES WITH RESPECT TO 2C							
BM	-2.944	0.053	0.855	-0.179	-0.705	-0.072	0.501
HP	-0.167	0.149	0.400	-0.008	-0.003	-0.011	-0.076
AM	4.953	-0.228	2.082	-0.511	-0.726	0.158	-0.474
RV	3.113	2.947	8.387	0.860	0.433	-0.477	-4.803
DERIVATIVES WITH RESPECT TO 3S							
BM	0.465	-0.293	-0.179	1.732	0.234	-0.194	-1.408
HP	-0.389	0.023	-0.008	0.208	0.033	-0.004	-0.052
AM	-0.565	-0.683	-0.511	0.687	-0.026	-0.447	0.524
RV	9.047	0.830	0.860	4.053	1.227	5.463	-2.313
DERIVATIVES WITH RESPECT TO 3C							
BM	0.756	-0.185	-0.705	0.234	0.465	0.800	-0.179
HP	-0.167	0.009	-0.003	0.033	0.189	-0.007	0.048
AM	-0.077	0.252	-0.726	-0.026	0.787	-0.718	-0.495
RV	0.540	-0.923	0.433	1.227	7.373	4.370	8.033
DERIVATIVES WITH RESPECT TO 4S							
BM	-0.149	-0.368	-0.072	-0.194	0.800	1.967	0.442
HP	-0.036	-0.076	-0.011	-0.004	-0.007	0.363	-0.004
AM	-0.263	-0.250	0.158	-0.447	-0.718	1.180	-0.051
RV	16.330	0.137	-0.477	5.463	4.370	10.087	1.887
DERIVATIVES WITH RESPECT TO 4C							
BM	0.771	-0.320	0.501	-1.408	-0.179	0.442	2.495
HP	0.057	0.024	-0.076	-0.052	0.048	-0.004	0.317
AM	-1.085	-0.124	-0.474	0.524	-0.495	-0.051	0.978
RV	-5.253	-2.573	-4.803	-2.313	8.033	1.887	13.067

DONE

3.5.1 Maximum Slope. Theoretically, the shortest path from a given operating point to the "best" operating point is found by moving at all times in the direction of maximum slope on the seven-dimensional surface relating the six independent variables to the optimization parameter. Movement continues until the slopes in all directions become zero. In a practical system where movement takes place with a finite increment, the point where all slopes equal zero is not found. Instead, the slope changes sign as the minimum point is passed. The ability to get closer to the minimum point is inversely proportional to the size of the increment used. On the other hand, the time required to move from one operating point to another is also inversely proportional to the size of the increment. Therefore, a tradeoff or provision of a variable increment size is required. However, in a practical system, the noise associated with the measurements of the operation of the rotor also limits the degree to which the minimum point can be approached.

To implement this search strategy, the control system must first determine the derivative of the optimization parameter with respect to each of the independent variables. These derivatives are then inspected to select the one with the maximum magnitude. The independent variable corresponding to that derivative is then incremented in a direction corresponding to the sign of the derivative.

3.5.2 Determination of Derivatives. As indicated in paragraph 3.1, the control system must be responsive to the derivative of the optimization function with respect to each of the independent variables. This may be expressed as the sum of the products of the derivative of the optimization function with respect to the controlled variable and the derivative of the controlled variables with respect to the independent variable. Knowledge of the first derivative comes from the optimization function specified. Knowledge of the other derivatives must come from measurements on the operating rotor. However, there is no method for measuring the latter derivative directly. Rather, each of the independent variables must be perturbed and the corresponding changes in the controlled variables noted. Furthermore, the independent variable must be perturbed in such a way that the changes in the controlled variable caused by these perturbations can be distinguished from other normally occuring changes in the controlled variable. This can be accomplished by using a perturbation of sufficient amplitude or by accomplishing the perturbation with a recognizable modulation. In either case, a sufficient time must be provided for the dynamics of the rotor system to respond to the perturbation.

The sensitivity of the optimization function to changes in the independent variable can be found in one of two ways:

$$\frac{\Delta P}{\Delta x_i} = \frac{1}{x_{i2} - x_{i1}} \sum_{k=1}^{4} \frac{\partial P}{\partial y_k} (y_{k2} - y_{k1})$$

where:

$\frac{\partial P}{\partial y_k}$ is the derivative of the optimization function with respect to y_k, evaluated at the current operating point (1) or:

$$\frac{\Delta P}{\Delta x_i} = \frac{1}{x_{i2} - x_{i1}} \left[f(y_{12}, y_{22}, y_{32}, y_{42}) - f(y_{11}, y_{21}, y_{31}, y_{41}) \right]$$

where:

$f(y_k's)$ is the optimization function evaluated at the current operating point (1) and the perturbation point (2).

Theoretically, both methods are the same; however, there are some practical differences. For instance, the accuracy and resolution requirements on the calculation of the second are more stringent than on the first because the second involves the difference of two large numbers. However, depending on the nature of the optimization function, the storage of coefficients and the method of calculation may be simpler for the second than for the first. With either method, the resolution and accuracy requirements on the measurements of the controlled variables are the same.

One method of perturbing the independent variables is to modulate them with a frequency, low with respect to the rotor dynamics, and then observe the controlled variables for a sufficient number of modulation cycles to separate the changes caused by the perturbation from the other changes. In general, the number of cycles required is inversely proportional to the amplitude of the perturbation. (The limiting case is 1/2 cycle; i.e., the independent variable is deflected from its value at the operating point for a sufficient time for the rotor dynamics to respond.) Since the rotor dynamics are fixed, the time to make a measurement is, in effect, inversely proportional to the amplitude of the perturbation. If some form of modulation is used, it would be possible to perturb several of the independent variables simultaneously and then separate the responses of the controlled variables into the proper components corresponding to each of the perturbed independent variables. However, if several are perturbed simultaneously, the amplitudes will combine and, therefore, the maximum perturbation amplitude allowed on each independent variable is inversely proportional to the number of variables that are perturbed simultaneously. Therefore, simultaneous perturbations will not decrease the time required to accomplish the measurements.

The discussion above indicates that several rotor time constants are required to acquire the full set of derivatives. In addition, time must be allowed for the effect of the increment of the selected independent variable to take place. Therefore, because of its requirement to have all six derivatives, the maximum slope search described above may not be the minimum time search.

3.5.3 Sequential Step Search. The maximum slope search spends six time intervals determining derivatives before incrementing an independent variable towards the optimum point. During some of those six intervals, the system would have been incremented in such a way as to move closer to the "best" point. Therefore, the search time can be reduced if this possibility is recognized. This can be accomplished by noting whether the optimization function decreases or increases as a result of each increment of an independent variable. The increment is retained if the optimization function decreases and removed if it increases. The derivatives can also be determined when these increments are made. There are a variety of search techniques using this concept. They differ in the basic sequence used to increment the independent variables and in the logic used to modify that sequence in response to the results obtained from the increments. Possible criteria for establishing a basic sequence are:

a. Increment each independent variable in turn, i.e., all with the same frequency

b. Increment the most important independent variables more frequently

c. Increment the independent variable with the largest derivative most frequently

Inspection of the coefficients in Table 13 indicates that there is no apparent basis for establishing certain independent variables as being more important than others. Therefore, b. has not been considered. An approach based on c. cannot be accomplished without knowledge of the derivatives. These are constantly changing as the operating point moves and, therefore, must be determined at some minimum interval. This can be accomplished with a method based on a. The method chosen for the purposes of this feasibility study uses a combination of a and c. A basic 12-interval cycle is established. During the odd numbered intervals, each of the six independent variables is incremented in turn. The direction of the increment is determined on the basis of the last slope determined for that independent variable. The even numbered intervals are used to increment the independent variable with the largest derivative. A derivative is determined in each interval and stored for future decisions.

Variations of this strategy are also categorized by the action taken when it is determined whether or not the increment of an independent variable increases or decreases the optimization function. Some of the possibilities are:

a. Remove the increment if the optimization function increases

b. Retain 1/2 the increment if the optimization function increases and if the slope changes sign, the assumption being that the increment caused the operation to move past the minimum point

c. Try an increment of the opposite sign if the optimization function increases and the slope has changed sign.

The effects of these variations and others have been studied in the simulation studies described in Section 4.

3.5.4 <u>Magnitude of the Increment</u>. There are two considerations that call for a large increment of the independent variables. These are better immunity to noise and other random variations in the controlled parameters, and more rapid response of the system to changes in operating condition of the helicopter. The considerations for a smaller increment are a closer approach to the minimum point and less likelihood that the effect of the perturbations become objectionable to the operation of the helicopter. Some of each of these considerations can be accommodated by making the increment variable. The advantage of this complexity is dependent upon the noise levels that will be encountered, rate of change required of the multicyclic control components to accommodate changes in helicopter operation, and the sensitivity of the search to the size of the increment. Some of these effects are investigated in the simulation studies described in paragraph 4.2. However, the determination of the magnitude of the increment will be largely dependent upon experience with an operating rotor.

3.5.5 Choice of Independent Variables. While it was stated in paragraph 3.1 that the independent variables would be the sine and cosine components of the 2, 3 and 4/revolution pitch angle, consideration should also be given to using the magnitude and phase angle of the 2, 3 and 4/revolution pitch angle as the independent variables. The latter approach might reduce the search time in response to changing operating conditions. This would be true if the best phase angles of the multicyclic control angles are a function of the direction of the rotor thrust vector and if the best magnitude of the multicyclic control angles are a function of the magnitude of the rotor thrust vector. In order to determine the advantages of this approach, rotor characteristics would be required describing a variety of operating conditions.

There are also disadvantages to using magnitude and phase angle as the independent variables. For instance, when the magnitude of one harmonic is near zero, changes in the phase of that harmonic will have little or no effect. Furthermore, at a given phase angle, the best magnitude may be near zero. These two conditions can cause a suboptimum "depression" in the optimization function surface. The magnitude of this problem is dependent upon the rotor characteristics for various operating conditions and the characteristics of the optimization function.

In view of the potential problems and the lack of any clear indication of a specific advantage to using magnitude and phase angle as independent variables, the sine and cosine components are used as the independent variables in this feasibility study.

4.0 SIMULATION STUDIES

Many of the factors that must be investigated in the course of developing a preliminary design for the feedback control system cannot readily be treated analytically. Therefore, two computer models have been developed to allow these effects to be investigated. The first of these is based on the maximum slope method for selecting the operating point. Since this represents the most effective search procedure (without regard to the determination of the derivatives of the rotor characteristics), it is used to investigate those effects that are not associated with a particular search method. It is also used as the standard against which to compare the results of other search methods. The model is described in Appendix C. The other model allows the investigation of particular search strategies and the way in which they are affected by various system parameters. This model is discussed in Appendix D. The results, using each of these models, are discussed below. Unless noted otherwise, each model used the optimization function of Figure 3 and an increment of 0.5°.

4.1 Effect of Various Optimization Functions

The relative value of the various controlled parameters, as reflected by the optimization function, determines the operating point selected by the control system action. The effect of the optimization function on this selection process is dependent upon the rotor characteristics. The interaction of various optimization functions with the given set of rotor characteristics has been investigated using the maximum slope model. This model was chosen so that the results will be the least dependent on the particular search strategy used.

Two basic optimization functions were used in this investigation. The first places equal value on each of the controlled parameters. This is represented by the following equation:

$$P = 100\left(\frac{BM}{7000} + \frac{HP}{750} + \frac{\alpha_{max}}{12} + \frac{RV}{300}\right)$$

The second is the optimization function presented in paragraph 3.2 and described in Figure 3. The variations investigated include various combinations of the terms from these two functions, as well as changes in the constants used in the second. The results are judged in terms of the operating point selected by each function as described by the values of the four controlled variables. The results are summarized on Table 14. The operating point with no multicyclic control has been included as a basis for comparison with the operating point selected by the various optimization functions.

The first case is the linear optimization function where each of the controlled variables, normalized to a particular value, has equal weight. This shows that a significant reduction in the hub shear (RV) can be achieved with only a small increase in the other three controlled variables.

Cases 2, 3 and 4 show the cummulative effect of successive changes of the terms associated with hub shear, maximum angle of attack and horsepower, from those of Case 1 to the optimization function described in paragraph 3.1. The change in the hub shear term places a greater importance on hub shear with the result that it is decreased at the expense of increases in the other three parameters. The change in the angle of attack term eliminates the penalty of angles near 12° so that the angle of attack is further increased, providing an additional reduction in hub shear. The change of the horsepower term increases the penalty of 771 HP. Therefore, horsepower is decreased and hub shear increases. The change in maximum angle of attack is just the consequence of the different selected operating point. The change in the bending

TABLE 14. EFFECT OF VARIOUS OPTIMIZATION FUNCTIONS

OPTIMIZATION FUNCTION	SELECTED OPERATING POINT: INDEPENDENT VARIABLES						SELECTED OPERATING POINT: CONTROLLED VARIABLES			
	2S	2C	3S	3C	4S	4C	BM	HP	α_m	RV
Base Line: No Multicyclic Pitch	0	0	0	0	0	0	4411	745	11.1	297
1. $P = \frac{BM}{7000} + \frac{HP}{750} + \frac{\alpha_m}{12} + \frac{RV}{300}$	2	-.5	-.5	0	-1	.5	4549	759	11.7	211
2. Change RV term to that of Figure 3	2.5	-.5	.5	0	-1.5	1	4653	765	12.0	197
3. Also change α_m term to that of Figure 3	3	-.5	.5	0	-1.5	1	4723	771	12.4	186
4 Also change HP term to that of Figure 3	2.5	-.5	0	0	-1.5	1	4653	765	12.0	197
5. Optimization Function of Figure 3 (i.e., also change BM to that of Figure 3)	2.5	-.5	.5	0	-1.5	1	4653	765	12.0	197
6. #5 without linear BM term	2.5	-.5	0	0	-1.5	1	4683	766	12.1	195
7. #5 with HP threshold increased from 750 to 800	3	-.5	0	0	-1.5	1	4723	771	12.4	186
8. #5 with α_m threshold increased from 12 to 13	3	-.5	.5	0	-1.5	1	4688	770	12.3	188
9. #5 with HP_t = 800, α_{mt} = 13	4.5	-1	0	0	-1.5	1	5054	792	13.6	156
10. #5 without linear BM term, HP_t = 800	3.5	-1	0	0	-1.5	1	4880	777	12.7	173
11. #5 without linear BM term, α_{mt} = 13	3	-1	0	.5	-1.5	1	4794	770	12.4	180
12. #5 without linear BM term, HP_t = 800, α_{mt} = 13	4.5	-1.5	0	0	-1.5	1	5165	792	13.5	153

moment term results, in Case 5, in the full optimization function of Figure 3. Since this new term has essentially the same value as the original term at a bending moment of 4653 in-lb, the operating point is unchanged.

Cases 6, 7 and 8 show the effects of making changes in the bending moment, horsepower and maximum angle of attack terms. In Case 6, the linear portion of the bending moment term is removed. The operating point then selected indicates that, with these rotor characteristics, allowing greater bending moments does not significantly decrease the hub shear that can be obtained. However, Cases 7 and 8 indicate that increasing the threshold for either horsepower or maximum angle of attack does allow a decrease in hub shear to be obtained. The fact that the horsepower and maximum angle of attack are essentially the same in Cases 7 and 8 is caused by the particular rotor characteristics being used and not the optimization function. The optimization function is assigning an essentially equal penalty in either case whether the penalty is caused by horsepower being above its threshold or angle of attack being above its threshold.

Cases 9, 10 and 11 show these three changes being applied in pairs. In Case 9, the thresholds for both horsepower and angle of attack have been increased and, as would be expected, another significant decrease in hub shear is achieved. Cases 10 and 11 again show that bending moment does not represent a serious constraint with these rotor characteristics. Although the elimination of that term does allow a greater decrease in hub shear than the increase of the two thresholds by themselves.

Case 12 incorporates all three of the changes described above and, in effect, represents the addition of the bending moment deletion to Case 9. As indicated, this does not provide much further reduction in hub shear.

In conclusion, it can be seen that with these rotor characteristics, significant decreases in hub shear, and the resulting body accelerations, can only be achieved at the price of increases in horsepower, maximum angle of attack and, to some extent, bending moment. Therefore, the optimization function selected must accurately reflect the relative value of these parameters for the multicyclic control system to be effective.

4.2 Magnitude of the Increment

The factors to be considered in chosing the amplitude with which to increment the various independent variables were discussed in paragraph 3.5.4. The effects of various increment magnitudes have been investigated with the maximum slope model in the absence of other factors, such as noise and the peculiarities of particular search strategies. Some of the results are shown on Figure 4. The optimization function of Figure 3 was used and the model was started at the operating point corresponding to no multicyclic control. The increment was first set at 1° and the model allowed to run until it reached its best operating point. The increment was then changed to .5° and the model was allowed to continue until it again reached its best operating point. Two additional cycles were taken with the increment at .2° and .1°, respectively.

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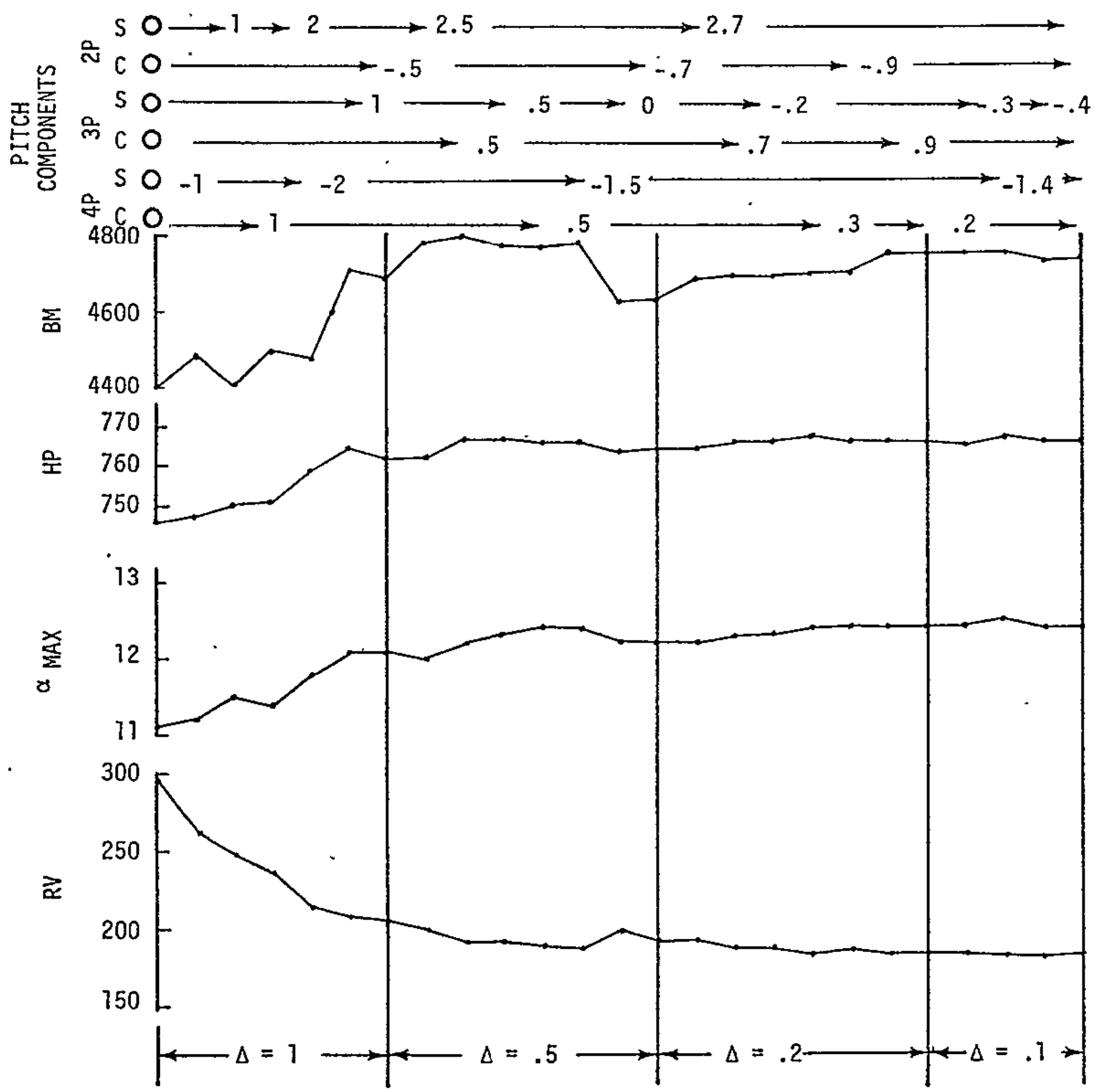

Figure 4. Effect of Increment Size.

These results indicate that, with the optimization function and rotor characteristic used and without considering noise in measurement of the rotor characteristics, there is little benefit in decreasing the increment below .5°.

4.3 Effect of Search Strategies

The general considerations for search strategies were discussed in paragraph 3.5, with particular emphasis on sequential step searches in paragraph 3.5.3. The simulation model described in Appendix D was set up to investigate the characteristics of the various alternatives for sequential step searches. Two sequences were investigated: one with a basic cycle of six intervals, wherein each of the independent variables was incremented, in turn; and the other with a basic cycle of twelve intervals, wherein the six independent variables were incremented in the odd numbered intervals and the independent variable having the maximum slope was incremented in the even numbered intervals. Within each of these sequences, four alternatives on the action to be taken if the optimization parameter increases as a result of an increment were investigated. These four alternatives are:

A. Retain the increment and move to the next interval in the cycle

B. Remove the increment and redetermine the operating point without the increment

C. Remove one-half the increment and take the new value of the optimization parameter to be the average of the values with and without the full increment

D. Try an increment of the opposite sign. If the optimization parameter still increases, remove the increment and redetermine the operating point without the increment.

In each case, the slope ($\Delta P/\Delta X$) is determined in each interval and stored for use in determining the direction of the increment the next time the corresponding independent variable is to be incremented. In addition, in method D, if the increments with opposite signs both cause the optimization parameter to increase, the slope is set equal to zero, with the sign equal to that of the smaller of the two slopes.

In methods B and D, the redetermination of the operating point with the increment removed is necessary in order to allow the system to follow changes in rotor trim conditions. It is also necessary to account for the effects of noise and other random variations.

The results are summarized on Table 15. This shows, for each of the cases, the number of iterations for the optimization parameter, P, to reach 60, 50 and its minimum. The minimum value of P is also given. The remaining four values in the table are the average values and the standard deviation of the optimization parameter, P, and the hub shear, R_v, after steady state has been reached. The particular value of R_v is, of course, a function of the

TABLE 15. EFFECTS OF SEARCH STRATEGIES

SEQUENCE ACTION IF P INCREASES	ITERATIONS TO P = 60	50	MIN	P_{min}	STEADY STATE $\overline{P}$	σ_P	$\overline{R_v}$	σ_{Rv}
Each X in Sequence								
1A Continue	25	45	48	46	58	8	198	12
1B Remove Δ; restart	26	47	48	48	49	1	193	4
1C Remove 1/2 Δ; P = average	25	40	44	46	54	6	198	12
1D Try - Δ; if $P_2 < P_1$, restart	38	49	65	47	48	1	197	5
Each X in Sequence, Alternate X with Maximum Slope								
2A Continue	30	41	44	46	52	4	196	9
2B Remove Δ; restart	27	41	62	46	47	1	187	5
2C Remove 1/2 Δ; P = average	19	32	56	46	49	2	191	8
2D Try - Δ; if P still increases, restart	25	33	52	46	48	1	193	5
2D' Same as 2D, except Δ = 1°	22	35	55	48	59	20	188	12

optimization parameter. However, the value of the standard deviation of R_V is an indication of the stability of the operating point achieved. A plot of the operation of method 2D is shown on Figure 5.

Comparison of the four methods, wherein each independent variable is incremented in sequence, shows that method A has the largest average optimization parameter and the largest standard deviations. This is caused by the increments that drive the system away from the "best" operating point remaining in existence for the six intervals of the basic cycle. In case B, where the increment is removed if P increases, the steady state operation is improved without any significant change in the time to reach the steady state condition. Removing one-half the increment, as in method C, provides a slight reduction in the time to reach steady state. However, the steady state condition is more like that of method A. Method D was an attempt to reduce the time to reach steady state while retaining the steady state characteristics of method B. However, the improvement in time was not achieved.

The sequence wherein the sequential incrementing of the independent variables is alternated with the independent variable providing the maximum slope, generally reduces the number of iterations necessary to reach the steady state condition. Method D showed the greatest reduction and does provide a significant decrease in the number of iterations to achieve steady state while retaining the steady state characteristics of method B. The improvement in the steady state conditions for methods 2A and 2C over 1A and 1C, respectively, is probably due to removing the bad excursions from the "best" operating point sooner through the provisions for incrementing the independent variable providing the maximum slope.

The effect of increment size is shown by case 2D', which is the same as 2D, except that the increment is 1 degree (the increment is 1/2 degree for all other cases). While it might have been expected that the time to reach steady state would have been reduced, such was not the case. Undoubtedly the results would have been different if a greater amount of multicyclic control were required to reach the "best" operating point. Whether or not this would ever be an advantage is dependent on how fast the operating point must be changed in response to rotor trim changes. The deterioration of the steady state condition is caused by the larger excursions from the "best" operating point caused by the larger increments.

Methods 2C and 2D appear best, with 2C providing somewhat faster initial movement towards the "best" operating point, but 2D providing slightly better steady state conditions.

The final choice of a search strategy is dependent upon the requirements for the system to follow changes in rotor trim conditions. This is, in turn, dependent upon the rotor characteristics under a variety of trim conditions and the characteristics of the final optimization function.

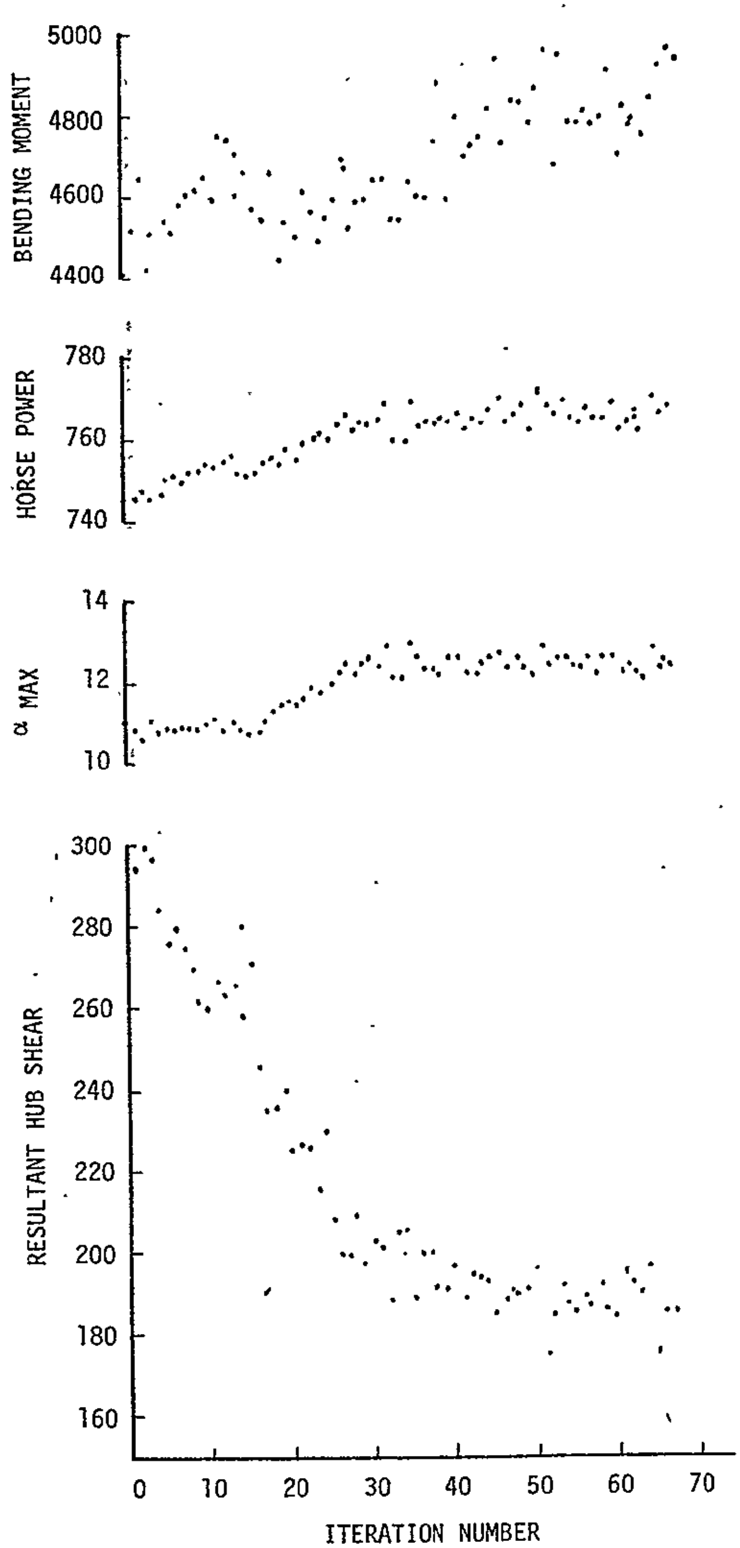

Figure 5. Response to Search Strategy 2D.

4.4 Noise Investigation

The control system must make measurements of the dependent variables to provide feedback to the control process. In addition, the measurements of these dependent variables also provide the basis for determining the derivatives of the optimization function with respect to each of the independent variables. However, the instrumentation used to measure these dependent variables is subjected to various external effects. In addition, the dependent variables themselves are perturbed by sources not related to the increments of the independent variables. Both of these effects constitute noise which can mislead the control system.

To investigate these effects, a noise generator was included in the simulation model described in Appendix D. A random process is used to generate noise with an amplitude that is normally distributed about zero. These noise amplitudes are then added to the calculated values of the dependent variables. The noise generator has been arranged so that the RMS amplitude of the noise added to a particular dependent variable is equal to a given percentage of the threshold value used in the optimization function for that variable.

Runs of the simulation model were made with RMS noise amplitudes of .2%, .5%, 1%, 2% and 5% applied to all of the dependent variables. The results are shown on Table 16. No results are shown for the 5% case, since the system did not show signs of reaching a stable operating condition during the first 175 iterations. P was calculated before and after the noise was added to the dependent variables, and information about both is provided on Table 16. The R_V information is also given without noise, since that represents the actual R_V.

Since the noise generation is a random process, many runs at each of the operating conditions would be necessary in order to draw definitive conclusions. Such has not been done within the scope of this feasibility study. However, from Table 16, it would appear that noise begins to have an effect at 1% RMS. The 2% case was interesting in that the system seemed to find one operating point after approximately 65 iterations. This point was held for 30 or 40 iterations and then the system moved to a different operating point, as indicated on Table 16. The run was terminated after 200 iterations, and at that point there was an indication that the operating point was again shifting.

A detailed investigation of some of the data produced by the simulation model indicates that the noise added to the horsepower is a major contributor to the instability evidenced by the model. A review of the derivatives of all of the dependent variables with respect to the independent variables also indicates that horsepower is most likely to be a problem. These derivatives are given on Table 17 for the initial point, that is the operating point with no multicyclic control, and the "best" point. These derivatives are calculated from the data given in Table 13. This data shows that, except for the sine component of the 2/rev at the "best" point, the derivatives of horsepower are very small. Changes of the multicyclic components of one-half degree provide only a very few tenths percent change in horsepower. Thus, with noise of 1% RMS and "signal" of only a few tenths of a percent, the signal to noise ratio is very

TABLE 16. EFFECTS OF NOISE

RMS NOISE %	ITERATIONS TO STEADY STATE	BEFORE NOISE $\overline{P}$	BEFORE NOISE σ_P	WITH NOISE $\overline{P}$	WITH NOISE σ_P	BEFORE NOISE R_v	BEFORE NOISE σ_{Rv}
0	40	48	1.8	48	1.8	189	6
.2	50	49	2.0	49	2.4	188	6
.5	50	49	1.5	49	1.7	198	5
1.0	55	51	3.3	55	9.6	204	7
2.0	65	66	4.3	69	7.4	241	9
	135	52	3.5	55	9.2	204	9
5.0	Unstable						

TABLE 17. VALUES OF DERIVATIVES

INDEPENDENT VARIABLES		DERIVATIVES OF DEPENDENT VARIABLES WITH RESPECT TO INDEPENDENT VARIABLES (% OF THRESHOLD/DEGREE)			
COMPONENT	VALUE	BM	HP	α_{max}	R_V
Initial Point					
2s	0°	- 2.0	0.2	1.6	- 5.9
2c	0°	- 2.9	- 0.2	5.0	3.1
3s	0°	0.5	- 0.4	- 0.6	9.0
3c	0°	0.8	- 0.2	- 0.1	0.5
4s	0°	- 0.1	0.0	- 0.3	16.3
4c	0°	0.8	0.1	- 1.1	- 5.3
"Best" Point					
2s	3.0°	1.4	1.4	6.5	2.5
2c	- 1.0°	- 3.6	- 0.1	1.7	- 0.6
3s	- 0.5°	- 1.5	- 0.4	- 1.8	- 1.0
3c	0.5°	0.1	0.0	2.3	2.4
4s	- 1.0°	- 2.4	- 0.6	- 2.5	2.0
4c	0.5°	- 0.7	0.4	- 0.1	1.8

low. This is aggravated by the fact that at the "best" operating point the derivative of the optimization function with respect to horsepower is very large. Therefore, the system sees large changes in the optimization parameter and attributes these to the incremental changes being made to the independent variables when, in fact, the large changes in optimization parameter are a result of the noise on the horsepower signal. That the system functions at all in the face of 1% noise can be attributed to the fact that the system continuously makes many, many measurements of the dependent variables and so the effects of noise tend to average out, at least to some extent.

The results above indicate that noise must be given special consideration during the detail design. The effects of noise will be influenced by the rotor characteristics and the characteristics of the optimization function finally chosen. These characteristics and the characteristics of the noise anticipated in the measurement of each of the dependent variables will determine what type of signal processing will be necessary to reduce noise to acceptable levels.

4.5 Dynamic Considerations

In feedback control systems, action is taken on the basis of response to the previous action. Therefore, the total system characteristics are dependent upon the dynamics of the response of the controlled element to variations in the independent variables. Generally, the dynamic response of the controlled element is given and cannot be considered a design variable to the designer of the control system. In this multicyclic control system, the major design variable that influences the total system dynamics is the rate at which the independent variables are incremented, or the iteration interval.

In order to investigate the effects of the iteration interval, a way is needed to characterize the dynamic response of the rotor system and the instrumentation and signal processing used in the measurement of the dependent variables. For the purposes of this feasibility study, this response has been characterized as a first order time lag. This is adequate for establishing the gross effects of various iteration intervals. It certainly would not be adequate for an investigation as to how the dynamic characteristics of the control system might be adjusted to compensate for the dynamics of the rotor.

The effects of dynamic response have been incorporated in the simulation model by adjusting the calculated values of the dependent variables in accordance with the conventional equation for the response of the first order system as shown below:

$$y(t) = y_c - (y_c - y_o)\, e^{-t/\tau}$$

where:

y_c = calculated value of y

y_0 = value of y at beginning of interval

τ = time constant equivalent of the dynamic response

t = length of iteration interval

This adjustment provides the value of the dependent variables at the end of the iteration cycle and it is these values that are used to calculate the optimization function which, in turn, is used to determine the slopes and the subsequent control action. While the model has the capability of incorporating a different time constant for each of the dependent variables, the work in this feasibility study has been confined to the use of a single time constant. It will be noted that the response of the system can be characterized by the ratio of the iteration interval to the rotor time constant.

Runs were made with the simulation model of Appendix D under conditions ranging from an iteration interval very long with respect to the rotor time constant to one which was 10% of the rotor time constant. The results are summarized on Table 18. The important parameters are the time to reach a more or less steady state and the conditions that exist during that steady state. The time parameter on Table 18 is expressed in terms of the rotor time constant and is obtained from the product of the number of iterations and the ratio of the iteration interval to the rotor time constant. Conditions during steady state are characterized by the mean and standard deviation of the optimization parameter, P, and the hub shear, R_V. Time, the mean value of P, and the ratio of the standard deviation to the mean of hub shear are also plotted on Figure 6 as a function of the ratio of iteration interval to rotor time constant.

It will be noted that the time to reach steady state continues to decrease as the iteration interval is decreased, until the interval becomes less than 15% of the rotor time constant. Below that point, the system did not arrive at a steady state condition within 300 iterations, or 30 rotor time constants. The scatter of the points on Figure 6 is exactly reproducible for identical conditions and is, undoubtedly, caused by the particular sequence of events that take place as a result of a particular set of conditions. More consistent results would probably be obtained on the basis of averages derived from using a variety of operating points. An example of the action that can take place in response to a particular set of circumstances occurred when the ratio of the iteration interval to the rotor time constant was .24. In this case, the operation settled down to the conditions shown on Table 18 after approximately 126 iterations. After an additional 325 iterations, a new operating point was found, wherein the mean value of the optimization parameter was 52, and its standard deviation 1.

Figure 6 indicates that the performance of the system begins to degrade as the iteration interval becomes about one-half the rotor time constant. However, the final determination of this threshold must await further definition of the rotor operation under other rotor trim conditions, and determination of the dynamic response associated with each of the measured variables.

TABLE 18. EFFECTS OF ITERATION INTERVAL, t

t/τ	$1 - e^{-t/\tau}$	P_{min}	ITERATIONS TO P_{min}	TO REACH STEADY STATE: ITERATIONS	TO REACH STEADY STATE: TIME*	CONDITIONS DURING STEADY STATE: $\overline{P}$	CONDITIONS DURING STEADY STATE: σ_P	CONDITIONS DURING STEADY STATE: $\overline{R_V}$	CONDITIONS DURING STEADY STATE: σ_{Rv}
	1	46	52	54	---	48	1	193	5
3	.95	46	43	45	135	48	1	193	5
2	.86	46	44	54	108	47	1	188	5
1.5	.78	47	45	54	81	48	2	193	5
1.2	.70	46	54	72	86	48	2	185	7
1.0	.63	48	48	80	80	50	2	188	6
.8	.55	49	40	90	72	48	1	188	6
.6	.45	47	41	90	54	48	2	190	8
.4	.34	48	39	108	43	54	2	193	12
.3	.26	52	56	162	47	67	2	204	20
.24	.21	56	42	126	30	61	3	211	9
.2	.18	59	96	117	23	65	2	212	20
.15	.14	60	44	126	19	71	5	216	13
.1	.095	60	118	-------Did not settle out within 300 iterations-------					

*In units of rotor time constants.

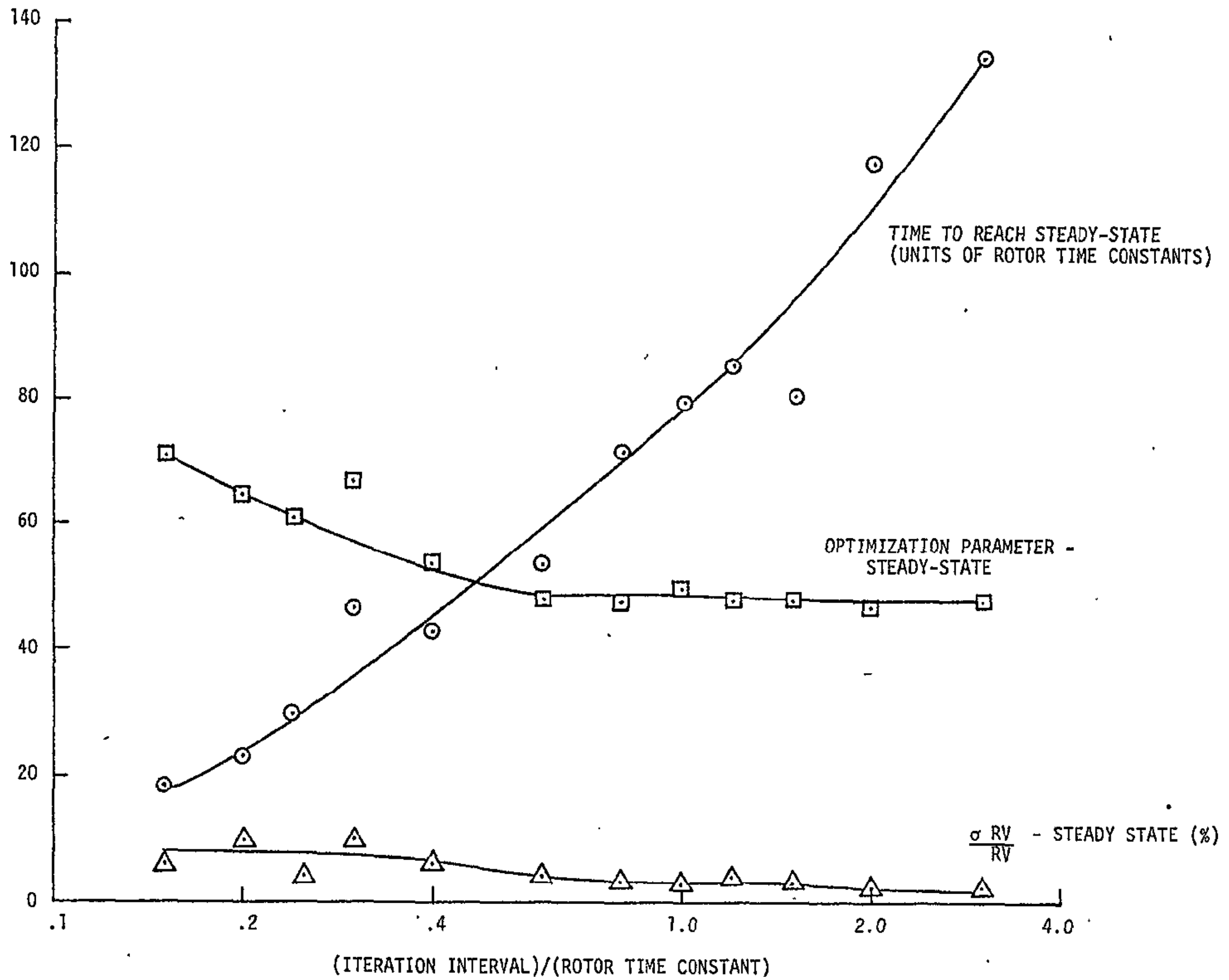

Figure 6. Effects of Iteration Interval.

4.6 Combined Noise and Dynamic Effects

In paragraphs 4.4 and 4.5, it was indicated that either noise or dynamic effects can influence the stability of the feedback control system and the quality of the operating point. These effects became noticeable with an RMS noise of 1%, or an iteration interval of about 1/2 of the effective system time constant. Therefore, these two effects have been tried in combination to determine the extent to which they interact.

The simulation model of Appendix D was run with an RMS noise of 1% and an iteration interval of 1/2 the equivalent rotor time constant. While the system did move towards the previous operating point for 60 to 80 iterations, it then began to move rapidly away from that operating point. Reducing the noise by a factor of 2 had very little effect. Doubling the iteration interval did provide an improvement in that the system did come close to the previous operating point and remained close to it for several hundred iterations. However, it then began moving away rapidly.

Several other combinations of noise and iteration interval were tested, and the results are summarized on Table 19. This shows that there is considerable reinforcement of the effects of noise and iteration interval with, perhaps, the system being somewhat more sensitive to the iteration interval. It also indicates that there must be a significant increase in the iteration interval or decrease in the noise level over their respective "threshold values", as determined independently, for acceptable performance. A combined factor of at least 4, and more likely 8 or 16, appears necessary.

5.0 PRELIMINARY DESIGN

5.1 Implementation Concepts

The basic algorithm for multicyclic control and its performance in conjunction with the rotor characteristics of Table 11 and the optimization function of Figure 3 has been described in the previous sections. This section is concerned with the implementation of this control algorithm and its interface with the existing MFS/HPR Module System.

The calculations and decision points involved in the control algorithm strongly suggest the use of digital concepts in its implementation. Furthermore, since flexibility will be an important attribute for the test configuration, programmable digital concepts should be used. This can be accomplished with either a mini- or a microprocessor, depending upon availability and the degree of flexibility determined necessary. A teletype or CRT terminal in conjunction with the processor can provide the necessary operator interface, although other methods can also be considered. This provides flexibility in the displays and controls available to the operator through changes in the processor program.

There is an analog control system in existence with provisions for generation of the second, third and fourth harmonics of the rotor azimuth angle, provision for modulating, or changing the amplitude and phase angle, of these harmonics with manual inputs, and provisions for summing the modulated harmonics to

TABLE 19. COMBINED NOISE AND DYNAMIC EFFECT

RMS NOISE	(ITERATION INTERVAL) / (EFFECTIVE TIME CONSTANT) .5	1	2
1 %	Unstable	Divergent	Fair
1/2 %	Unstable	Marginal	Fair
1/4 %	Marginal	Fair	Good

Categories:

Unstable	Does not reach or does not hold a stable operating point.
Divergent	Reaches and holds a stable operating point for a few hundred iterations and then diverges.
Marginal	Reaches and holds a stable operating point, but wanders away from it for short periods
Fair	Reaches and holds a stable operating point, such that the optimization parameter stays within 20% of the "value" without noise and dynamics.
Good	Operation essentially uneffected by noise and dynamics.

generate the specific control signals for each of the four blades. These control signals, in turn, drive the blade servos associated with each blade. This system has shown itself to be more than adequate for the puposes of the test configuration. Therefore, the feedback control system should interface the existing system at the modulation step. The control processor can provide modulation signals for each of the harmonics that replace the function of the existing manual inputs. However, it is more convenient to provide the modulation signals and implement the modulation process in terms of the sine and cosine components of each harmonic, rather than the amplitude and phase, as is done with manual control.

A block diagram of the preliminary design concept is shown in Figure 7. Signals from each of the sensors are conditioned by analog circuitry for input to the control processor through an analog to digital converter. (When the total signal processing task has been established on the basis of more complete knowledge of the characteristics of each of the measured signals, a determination will be made as to which parts can better be done in the analog signal conditioning circuits and which parts might better be done digitally within the control processor.) The signal conditioning for the body acceleration signals is the most complex, in that the requirement is to extract the amplitude of the fourth harmonic of a weighted average of these signals. The fourth harmonic can be extracted by a synchronous detector using the sine and cosine components of the fourth harmonic as generated by the existing harmonic generator. It may also be desirable to extract a particular harmonic from the control load signal which is representative of bending moment. The average of the horsepower signal and the peak of the pitch link load signal is determined.

The processor senses each of the measured inputs and implements the control algorithm to generate the amplitude of the sine and cosine components of each of the three harmonics. These six signals are then used to modulate the harmonics of rotor azimuth as developed by the existing harmonic generator and, thus provide signals that replace those generated by the present, manually controlled modulator. These signals are then summed in the existing amplifiers to provide the specific control signal for each of the four blades.

The processor also provides the interface with the operator through a teletype or CRT terminal. Other methods may also be considered when the complete requirement for operator interface is established. Among requirements to be considered are display of the measured variables and the calculated independent variables, initiation and termination of feedback control, change of control parameters such as iteration interval and increment size, and override of feedback control with manual control.

Other degrees of flexibility which should be provided, but not through the operator interface, include changes in the signal processing characteristics and the control algorithm.

5.2 System Test Sensors

As stated in paragraph 3.1, the parameters selected for control in the feedback system are Bending Moment, Horsepower, Maximum Angle of Attack and Hub

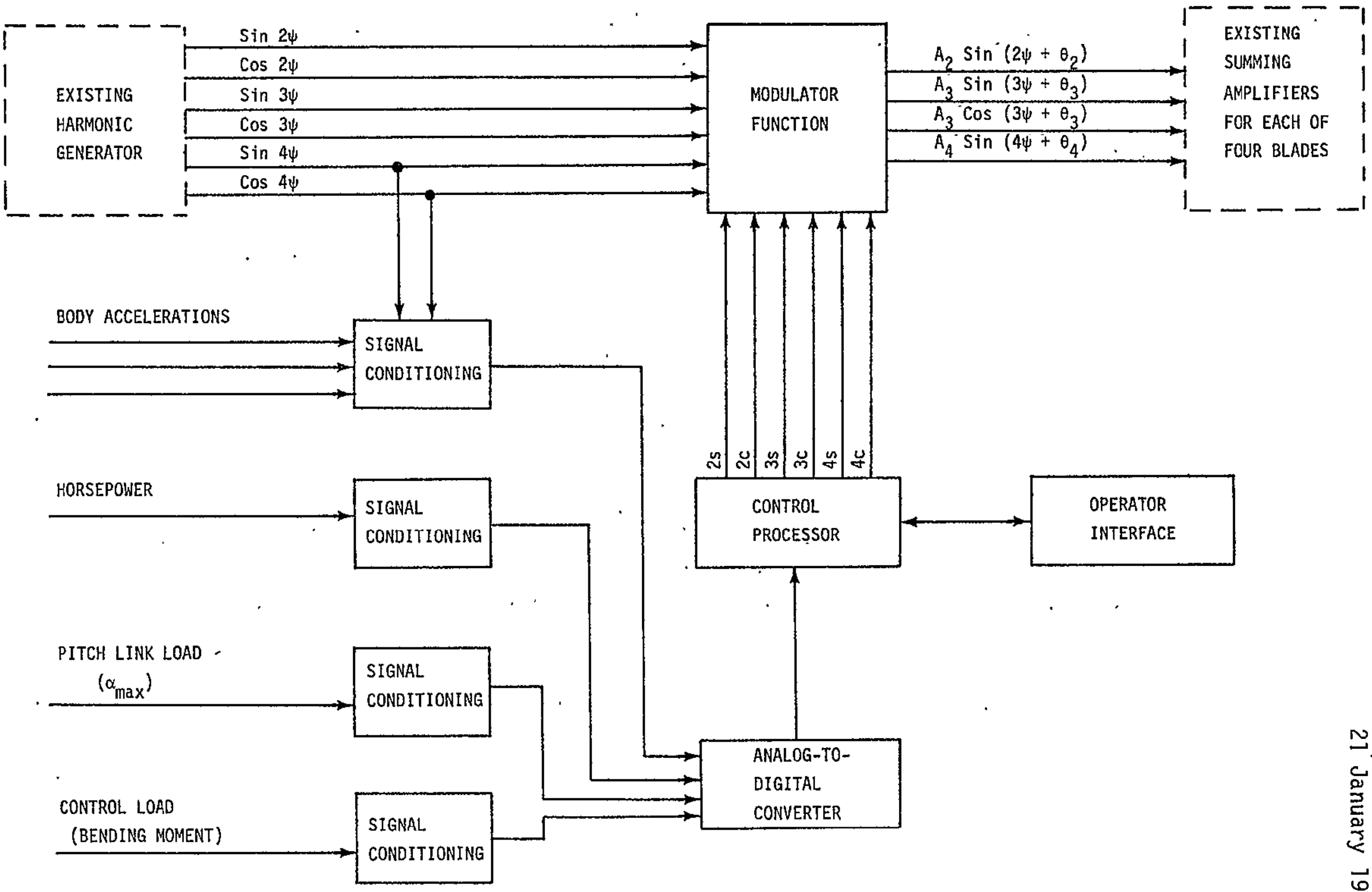

Figure 7. Preliminary Design Concept.

Shear. All studies to date have indicated that these parameters should be the primary controlling factors indicating satisfactory multicyclic performance. It is possible that data from wind tunnel tests may indicate that additional parameters may be sensed to limit the harmonic inputs to maintain all systems within acceptable load levels. The feedback system, which is the subject of this study, does not consider these additional limiting parameters; however, they could be added when necessary.

Direct measurement of the parameters listed above presents some problems. Ultimately, a flight version of the feedback system must be considered which makes the measurement of bending moment impractical from a reliability standpoint. Horsepower, angle of attack and hub shear cannot be measured directly in either an aircraft or the wind tunnel model. It is necessary, for all of the above parameters, to select control parameters that are either directly or indirectly related to the desired parameters.

Blade bending moment can only be measured directly by strain gage bridges. While this would be acceptable for a wind tunnel model, the installation of strain gage bridges on flight blades that may be exposed to varying weather conditions is not satisfactory for a reliable control system. There is a high probability that blade bending moments are related to control loads. The relationship must be verified and defined through analysis of wind tunnel data. If there is, in fact, a relationship, reliable load cells can be installed in the fixed control system. For wind tunnel test, it is more practical for cast considerations to use existing instrumentation that measures pitch link load.

Horsepower is a more straightforward parameter with which to work. In the wind tunnel model, rotor shaft torque can be used, whereas in a helicopter transmission, torque pressure, for which standard sensors are available, would be used.

Blade angle of attack cannot be directly measured, but there is a relationship between angle of attack and pitch link load. Again, in a flight helicopter, it would be more desirable to work with load cells in the non-rotating control system.

Hub shear has always presented a measurement problem. In the case of multicyclic control, the interest in vibratory hub shear reduction is due to the resultant reduction in fuselage vibration. Vibration measurement by accelerometers will provide the initial control measurement. It is uncertain, due to data availability, whether or not the accelerometer signals can be fed directly to the feedback circuitry or if the vibration levels must be first related to hub shear through methods of Force Determination. The number and location of the accelerometers is also uncertain until more data becomes available. For the purpose of this study, the accelerometer signals are fed directly to the feedback system.

5.3 Processor Functions

A flow diagram of the processor functions associated with the control algorithm is shown on Figure 8. (The other major function of the processor, which is not

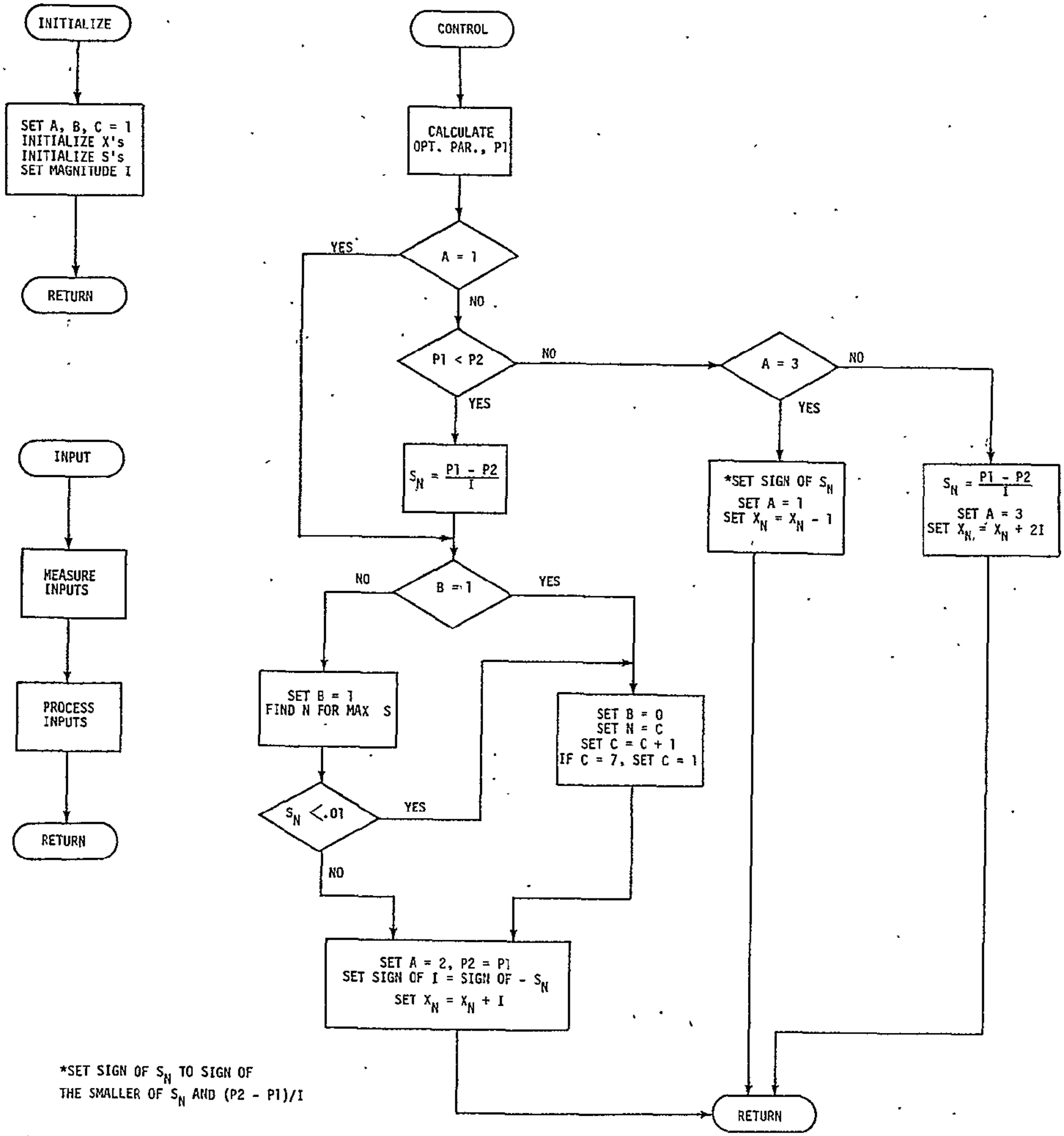

Figure 8. Processor Control Functions.

shown, is the servicing of the operator interface.) Three branches are shown. The "Initiate" branch is entered each time the feedback control function is initiated. Its purpose is to provide the initial values of the six components of multicyclic control (X's) and the initial values of the slopes of the optimization function with respect to each of these components (S's). The latter will usually be initialized at zero. Two flags, A and B, and a counter, C, that are used to control the operation of the control algorithm are initialized to the 1 state. The magnitude of the increment to be used in conjunction with the independent variables must also be set.

The "Input" branch is associated with measuring each of the inputs and accomplishing that portion of the signal processing that has been assigned to the control processor. Depending upon the nature of the signal processing to be accomplished within the control processor, this branch may be entered more frequently than the control branch.

The "Control" branch is concerned with the control function itself and is entered once each iteration interval. The first step is to calculate the optimization parameter from the measured and processed inputs. Next, flag A is checked to determine if there is a valid basis for determining whether the optimization parameter has increased or decreased as a result of the most recently incremented independent variable. If there is, and if the optimization parameter has decreased, the current and previous values of the optimization parameter and the increment, I, are used to calculate the slope to be associated with the most recently incremented independent variable, S_N. Flag B is then examined to determine whether the next independent variable to be incremented is to be selected on the basis of maximum slope or the numerical sequence. The counter, C, is used to keep track of the numerical sequence. The maximum slope criterion is not used if the maximum slope is less than .01. After setting the value of N (the independent variable to be incremented), the value of A and the baseline value of the optimization parameter, P_2, are set to the values appropriate for the next iteration cycle. The independent variable corresponding to N is then incremented in a direction dependent upon the sine of the slope associated with that independent variable.

If, back in the beginning of the "Control" branch, the optimization parameter were found to have increased, and if flag A is not in the 3 state, steps are taken to increment the most recently incremented independent variable in the opposite direction. If this had already been accomplished (i.e., flag A in the 3 state), the last increment is removed and flag A is set to 1 so that a new baseline value of the optimization parameter is determined on the next iteration cycle. In addition, the sign of the slope associated with the most recently incremented independent variable is set equal to the sign of the smaller of the slopes determined from the positive and negative increments. The magnitude of the slope is set near zero so that it is not considered in the determination of the independent variable with the maximum slope.

5.4 Modulator Function

A schematic of one implementation of the modulator function is shown in Figure 9. One set of inputs is the sine and cosine components of the second, third and fourth harmonics of the rotor azimuth angle generated by the existing harmonic generator. The second set of inputs is the required amplitudes of these components as determined by the control processor. The eight blocks marked M generate the product of their respective inputs. Pairs of these products are then summed to provide the signals required by the existing summing amplifiers for each of the four blades. The M blocks may be implemented in either of two ways. The first uses digital to analog converters on each of the six control processor outputs and eight, four-quadrant, analog multipliers. The second uses eight ladder networks, each being switched by the appropriate digital output of the control processor.

6.0 CONCLUDING REMARKS

During this feasibility study, several of the concepts associated with multicyclic adaptive control have been investigated and a preliminary design for their implementation has also been generated. In the course of the investigation, some questions have been uncovered which require further resolution; however, no fundamental problems were discovered. The preliminary design also indicates that the concepts can be implemented with available technology. There are certain areas where further work is required to support the development of a detailed design. These areas may be grouped in four categories: the characteristics of the optimization function; the characteristics of the measured variables; control system stability; and rotor characteristics.

6.1 Optimization Function Characteristics

The simulation studies have shown that the optimization function not only affects the selected operating point, but also affects certain system operating characteristics. It is important to know the nature of the criteria (i.e., the tradeoffs among the controlled, or measured, variables) for describing the "best" rotor operation and the nature and numbers of controlled variables. Consideration should also be given to the necessity for changing these criteria as a function of the rotor trim conditions.

6.2 Characteristics of Measured Variables

The characteristics of the optimization function will identify the kinds of variables that must be measured to provide the necessary feedback. Knowledge is required of the nature of the dynamic response of each of these measured variables to changes in the independent variables, as well as the amplitude and frequency characteristics of the noise to be associated with each of these measured variables. The latter is particularly important in establishing the nature of the signal conditioning necessary to reduce the noise to acceptable levels. Since these characteristics are not peculiar to multicyclic control, they may be developed on the basis of experience with other helicopter rotors and their instrumentation.

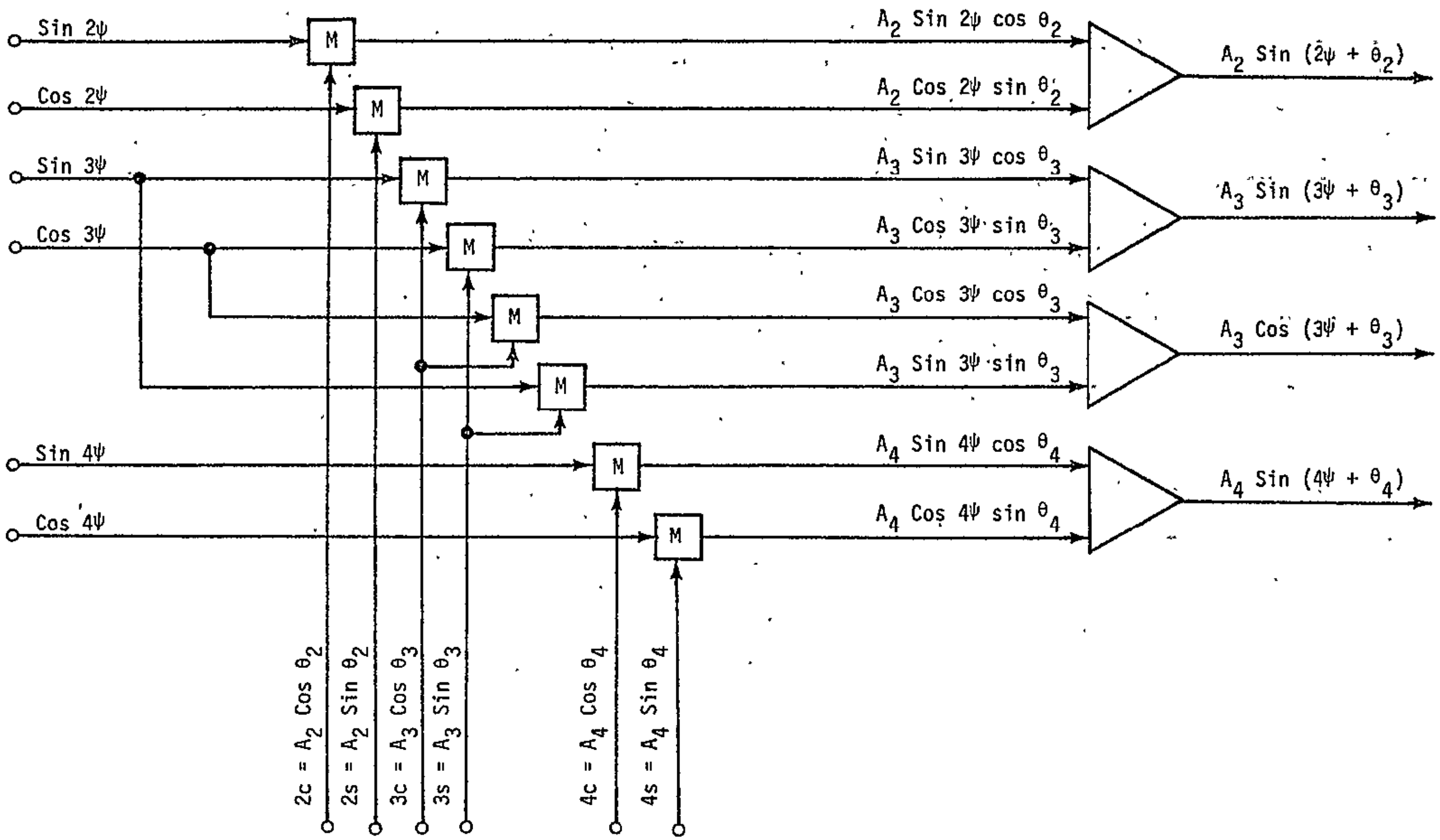

Figure 9. Modulator Function.

6.3 Control System Stability

Further study is required of the interaction among noise, rotor dynamics and characteristics of the optimization function as it applies to the control system stability and the total system performance. Consideration should also be given to implementing the optimization function in ways that minimize its effect on control system stability. Such studies will also indicate the benefits that can be obtained from signal conditioning and other forms of compensation for rotor and instrumentation effects that would otherwise degrade the performance of the control system. These studies will involve the use of simulation models such as those developed for the feasibility study. Their objective will be to develop the specific design criteria required for the development of a detail design.

6.4 Rotor Characteristics

The analysis of the control system performance requires a method of representing the characteristics of the rotor. This was achieved in the feasibility study by the surface coefficients of Table 13. The derivatives based on these coefficients should be verified to indicate that they represent the rotor to be used in the test configuration. Changes of these derivatives should be determined for the rotor with changes in rotor test conditions. This can most realistically be accomplished by comparing the characteristics as derived from the coefficients with characteristics derived from wind tunnel test data. Some test data have already been collected and are currently being analyzed, and additional wind tunnel testing is anticipated. The plans for this additional testing should also consider the need to develop data appropriate to the analysis of the operation of the multicyclic control system.

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2. Contract DAAJ02-72-C-0092, WIND TUNNEL INVESTIGATION OF THE CONTROLLABLE TWIST ROTOR PERFORMANCE AND DYNAMIC BEHAVIOR.

3. Lemnios, A. Z. and Dunn, F. K., THEORETICAL STUDY OF MULTICYCLIC CONTROL OF A CONTROLLABLE TWIST ROTOR, Kaman Report No. R-1393, April 1976.

APPENDIX A

SURGEN PROGRAM

```
      REAL MI
      DIMENSION Z(200,16),              X(56),Y(56),Q(56,56),P(56,56),
     2G(56),B(56),ANS1(56)
     3,HEAD(20),TITLES(15,5)
      COMMON /MODATA/ KMODEL
      COMMON/TWO/N
      COMMON/MODELS/F(200,56),ZORIG(200,16)
    5 FORMAT(1H1,////,10X,'SURGEN**** GENERATES A RESPONSE MATRIX TO FIT
     1 A SET OF DATA POINTS'//)
C
      READ(1,505) HEAD
  505 FORMAT(20A4)
C
C
C     NDATPT = NO OF DATA POINTS (CASES)
C       NO OF COLUMNS TO BE READ
C
C
C
C     NMOD = 1
C       MODEL1 = MULTICYCLIC CONTROL THRU THIRD HARMONIC
C         NMOD = 2
C     MODEL2 = CTR D0,D1S,D1C
C         NMOD = 3
C           MODEL 3 = MULTICYCLIC 4 HARMONICS
C
      READ(1,10) NDATPT,NCOLS,NMOD,IDBUG
      NCTL=7
      IF( NMOD .EQ. 2) NCTL=3
      IF(NMOD.EQ.3) NCTL = 6
      IF(NMOD.EQ.4) NCTL=9
      ILEFT=NCOLS-NCTL
      READ(1,510)((TITLES(I,J),J=1,5),I=1,ILEFT)
  510 FORMAT(8(5A2))
      NVAR=43
      IF(NMOD .EQ. 2)NVAR=14
      IF(NMOD .EQ. 3)NVAR=27
      IF(NMOD.EQ.4)NVAR=30
   10 FORMAT(8I10)
      INDEX=1
      KOUNT=0
      DO 20 I=1,NDATPT
      IF(NMOD .NE.3) GO TO 22
C
C     FOR MODEL 3 WANT TO SKIP FIRST THREE WORD ON CARD D0,D1S,D1C
      READ(1,33) (Z(I,J),J=1,NCOLS)
      GO TO 20
   22 READ(1,30) (Z(I,J),J=1,NCOLS)
   20 CONTINUE
   30 FORMAT(8F10.2)
   33 FORMAT(30X,5F10.2/8F10.2)
      DO 25 I=1,NDATPT
      DO 25 J=1,NCOLS
   25 ZORIG(I,J)=Z(I,J)
      Z1=NDATPT
      Z2=NCOLS
```

```
      .=..
      N1=NVAR+1
      N2=NVAR+2
 35   GO TO (5001,5002,5003,5004),NMOD
5001  CALL OPSYS('LOAD','SURGMOD1')
      GO TO 5005
5002  CALL OPSYS('LOAD','SURGMOD2')
      GO TO 5005
5003  CALL OPSYS('LOAD','SURGMOD3')
      GO TO 5005
5004  CALL OPSYS('LOAD','SURGMOD4')
5005  CONTINUE
      DO 31 I=1,NDATPT
      DO 31 J=1,N2
 31   F(I,J)=1.0
       WRITE(3,5)
      WRITE(3,516)
 516  FORMAT(//)
      WRITE(3,505) HEAD
      GO TO (40,45,42,48),NMOD
 40   CALL MODEL1(NDATPT,INDEX)
      GO TO 46
 42   CALL MODEL3(NDATPT,INDEX)
      GO TO 46
 45   CALL MODEL2(NDATPT,INDEX)
      GO TO 46
 48   CALL MODEL4(NDATPT,INDEX)
 46   KOUNT=KOUNT+1
      IF(NMOD.EQ.2.AND.N.EQ.8) GO TO 412
      DO 32 I=1,N1
      DO 32 J=1,N1
      Q(I,J)=0.0
 32   P(I,J)=0.0
      DO 34 I=1,N1
      Y(I)=0.0
 34   B(I)=0.0
       DO 36 I=1,N2
 36   X(I)=1.0
       DO 55 I=1,NDATPT
       DO 55 J=1,NCOLS
 55   Z(I,J)=ZORIG(I,J)
      S5=0.0
      S6=0.0
      S7=0.0
      DO 60 L=1,NDATPT
      DO 70 I=2,N2
 70   X(I)=F(L,I)
      DO 80 I=1,N1
      DO 90 J=1,N1
 90   P(I,J)=P(I,J)+X(I)*X(J)
 80   Y(I)=Y(I)+X(I)*X(N2)
      S7=S7+X(N2)
 60   S5=S5+X(N2)*X(N2)
      MI=P(1,1)
      S2=Y(1)
      DO 100 I=2,N1
```


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```
      II=I-1
      S1=P(1,I)
      S3=Y(I)
      S4=P(I,I)
      A=MI*S3-S1*S2
      BB=(MI*S4-S1*S1)*(MI*S5-S2*S2)
      RATIO=0.0
      IF((A .EQ. 0.0) .AND. (BB .EQ. 0.0)) GO TO 61
      RATIO=A/SQRT(BB)
   61 ROUND=((RATIO*1000.+.5)/1000.)
      WRITE(3,110) II,ROUND
  110 FORMAT(5X,'FACTOR',I3,5X,'CORRELATION=',F6.3)
  100 G(II)=A
      CALL OPSYS( 'LOAD','SURGMATX')
      CALL MATINV(P,Q,  NG,N1)
      IF( NG .NE. 9) GO TO 105
      WRITE(3,101)
  101 FORMAT(5X,10('*'),'ERROR IN MATRIX INVERSE   ',10('*'))
      GO TO 412
  105 IF ( IDBJG .NE. 0)WRITE(3,102)((P(NN,MM),NN=1,N1),MM=1,N1)
      IF ( IDBJG .NE. 0)WRITE(3,102)((Q(NN,MM),NN=1,N1),MM=1,N1)
  102 FORMAT('  MATRIX INVERSE'/6(10F12.4)//)
      CALL MTRXMP(N1,N1,1,Q,Y,B,0)
      WRITE(3,120)
  120 FORMAT(/,20X,'COEFFICIENTS OF BEST LINEAR FIT'/)
      DO 130 I=2,N1
  130 ANS1(I)=    ((B(I)*1000.+.5)/1000.)
      WRITE(3,140) (ANS1(I),I=2,N1)
  140 FORMAT(4(9F14.4/))
      CONST1=    ((B(1)*1000.+.5)/1000.)
  145 WRITE(3,150) CONST1
  150 FORMAT(10X,'CONSTANT TERM=',F10.4//)
      WRITE(3,160) (TITLES(KOUNT,J),J=1,5)
  160 FORMAT(20X,'TABLE OF RESIDUALS'/,5X,'POINT NO',7X,5A2)
      GO TO (181,170,193,194),NMOD
  170 WRITE(3,175)
  175 FORMAT(1H+,37X,'EST VALUE',4X,'DIFFERENCE',4X,'PERCENT',4X,'D0',
     14X,'D1S',3X,'D1C'/)
      GO TO 187
  181 WRITE(3,185)
      GO TO 187
  185 FORMAT(1H+,37X,'EST VALUE',4X,'DIFFERENCE',4X,'PERCENT',4X,'D0',
     14X,'D1S',3X,'D1C',3X,'D2S',3X,'D2C',3X,'D3S',3X,'D3C'
     2,3X,'CQ ',3X,'CLR/S'/)
  193 WRITE(3,192)
  192 FORMAT(1H+,37X,'EST VALUE',4X,'DIFFERENCE',4X,'PERCENT',4X,
     1                        'D2S',3X,'D2C',3X,'D3S',3X,'D3C'
     2,3X,'D4S',3X,'D4C'/)
      GO TO 187
  194 WRITE(3,198)
  198   FORMAT(1H+,37X,'EST VALUE',4X,'DIFFERENCE',4X,'PERCENT',4X,'D0',
     14X,'D1S',3X,'D1C',3X,'D2S',3X,'D2C',3X,'D3S',3X,'D3C'
     2,3X,'D4S',3X,'D4C'/)
  187 T2=0.0
      DO 180 J=1,NDATPT
       S3=0.0
```

```
      DO 190 I=1,N1
  190 S8=S8+F(J,I)*B(I)
      T2=T2+(F(J,N2)-S7/Z1)**2
      S0=S8-F(J,N2)
      Z0=0.0
      IF(F(J,N2) .EQ. 0.0) GO TO 191
      Z0=S0*100./F(J,N2)
  191 WRITE(3,200) J,F(J,N2),S8,S0,Z0,(ZORIG(J,JJ),JJ=1,NCTL)
      IF(NMOD.EQ.2) WRITE(3,205)ZORIG(J,8),ZORIG(J,9)
  205 FORMAT('+',90X,2F8.2)
  180 Z(J,1)=S0
  200 FORMAT(I10,F20.3,2F15.3,F12.3,3X,9F6.2/)
  210 FORMAT(/////,20X,'ANALYSIS OF RESIDUALS')
      NZERO=NDATPT-1
      DO 250 I=1,NZERO
      M=I
      MM=I+1
      DO 260 J=MM,NDATPT
      IF(Z(M,1)-Z(J,1)) 260,260,270
  270 M=J
  260 CONTINUE
      IF(M .EQ. I) GO TO 250
      PT=Z(M,1)
      Z(M,1)=Z(I,1)
      Z(I,1)=PT
  250 CONTINUE
      S=0.0
      S2=0.0
      DO 280 I=1,NDATPT
      S=S+Z(I,1)
  280 S2=S2+Z(I,1)**2
      MI=S/Z1
      V=(Z1*S2-S*S)/(Z1*(Z1-1.))
      D=SQRT(V)
      WRITE(3,300) S,S2,MI,V,D
  300 FORMAT(20X,'SUM='F15.4/9X,'SUM OF SQUARES='F15.4/13X,'MEAN VALUE='
     1 F15.4,/,15X,'VARIANCE=',F15.4/,5X,'STANDARD DEVIATION=' F15.4/)
      DU=SQRT((MI/B(1))**2)
      IF(DU-.01) 350,360,360
  350 B(1)=B(1)-MI
      CONST1=CONST1-MI
      GO TO 145
  360 IF ((1.-S2/T2) .LE. 0.0) GO TO 371
      R=SQRT(1.-S2/T2)
  370 FORMAT(5X,'MULT CORR COEFF='F6.3/)
      WRITE(3,370) R
  371 WRITE(3,380)
      DO 400 I=1,NDATPT
      RRR=I
      ZEND=(RRR-.5)*100./Z1
  400 WRITE(3,410) Z(I,1),ZEND
  410 FORMAT(2F15.3)
  412 IF(KOUNT-ILEFT) 35,420,420
  380 FORMAT(20X,'CUMULATIVE DISTRIBUTION'/10X,'X',10X,'CUM PERCENT'
     1 /21X,'OF POPULATION'/)
  420 CALL EXIT
```

```
      END
/*
  PHASE SJRGMOD1,*
// EXEC FFORTRAN
      SJBROUTINE MODEL1(     NDATPT,INDEX)
      COMMON /MODATA/ K
      CCMMON/MODELS/F(200,56),Z(200,16)
      GO TO(1,2),INDEX
    1 K=0
    2 DO 10 I=1,NDATPT
      F(I,2)=Z(I,1)
      F(I,3)=Z(I,2)
      F(I,4)=Z(I,3)
      F(I,5)=Z(I,4)
      F(I,6)=Z(I,5)
      F(I,7)=Z(I,6)
      F(I,8)=Z(I,7)
      F(I,9)=Z(I,1)**2
      F(I,10)=Z(I,1)*Z(I,2)
      F(I,11)=Z(I,1)*Z(I,3)
       F(I,12)=Z(I,1)*Z(I,4)
      F(I,13)=Z(I,1)*Z(I,5)
      F(I,14)=Z(I,1)*Z(I,6)
      F(I,15)=Z(I,1)*Z(I,7)
      F(I,16)=Z(I,2)**2
      F(I,17)=Z(I,2)*Z(I,3)
      F(I,18)=Z(I,2)*Z(I,4)
      F(I,19)=Z(I,2)*Z(I,5)
      F(I,20)=Z(I,2)*Z(I,6)
      F(I,21)=Z(I,2)*Z(I,7)
      F(I,22)=Z(I,3)**2
      F(I,23)=Z(I,3)*Z(I,4)
      F(I,24)=Z(I,3)*Z(I,5)
      F(I,25)=Z(I,3)*Z(I,6)
      F(I,26)=Z(I,3)*Z(I,7)
      F(I,27)=Z(I,4)**2
      F(I,28)=Z(I,4)*Z(I,5)
      F(I,29)=Z(I,4)*Z(I,6)
      F(I,30)=Z(I,4)*Z(I,7)
      F(I,31)=Z(I,5)**2
      F(I,32)=Z(I,5)*Z(I,6)
      F(I,33)=Z(I,5)*Z(I,7)
      F(I,34)=Z(I,6)**2
      F(I,35)=Z(I,6)*Z(I,7)
      F(I,36)=Z(I,7)**2

      F(I,37)=Z(I,15)/10000.
      F(I,38)=Z(I,15)*Z(I,1)/10000.
      F(I,39)=Z(I,15)*Z(I,2)/10000.
      F(I,40)=Z(I,15)*Z(I,3)/10000.
      F(I,41)=Z(I,15)*Z(I,4)/10000.
      F(I,42)=Z(I,15)*Z(I,5)/10000.
      F(I,43)=Z(I,15)*Z(I,6)/10000.
   10 F(I,44)=Z(I,15)*Z(I,7)/10000.
      INDEX=2
      K=K+1
```

```
C       SE... IS THE NO. OF CONTROLS OF SERVC FLAP
        N=K+7
        DO 20  I=1,NDATPT
   20   F(I,45)=Z(I,N)
        RETURN
        END
/*
   PHASE SURGMATX,SURGMOD1
// EXEC FFORTRAN
        SUBROUTINE MATINV (A,B,. NG,NRA)
        DIMENSION A(56,56),IROW(56),ICOL(56),B(56,56)              ,F(56)
        NG=0
        N=NRA
        M=N+1
        DO 7  I=1,N
        IROW(I)=I
        ICOL(I)=I
        DO 7  J=1,N
    7   B(I,J)=A(I,J)
        DO 20  K=1,N
        AMAX=B(K,K)
        DO 10  I=K,N
        DO 10  J=K,N
        IF(ABS(B(I,J))-ABS(AMAX))10,9,9
    9   AMAX=B(I,J)
        IC=I
        JC=J
   10   CONTINUE
        KI=ICOL(K)
        ICOL(K)=ICOL(IC)
        ICOL(IC)=KI
        KI  =  IROW(K)
        IROW(K)=IROW(JC)
        IROW(JC)=KI
        IF(AMAX)11,12,11
   12   NG=9
        GO TO 30
   11   DO 14  J=1,N
        E=B(K,J)
        B(K,J)=B(IC,J)
   14   B(IC,J)=E
        DO 15  I=1,N
        E=B(I,K)
        B(I,K)=B(I,JC)
   15   B(I,JC)=E
        DO 16  I=1,N
        IF(I-K)18,17,18
   17   F(I)=1
        GO TO 16
   18   F(I)=0
   16   CONTINUE
        PVT=B(K,K)
        DO 8  J=1,N
    8   B(K,J)=B(K,J)/PVT
        F(K)=F(K)/PVT
        DO 19  I=1,N
```

```
      IF(I-K)21,19,21
   21 AMULT=B(I,K)
      DO 22 J=1,N
   22 B(I,J)=B(I,J)-AMULT*B(K,J)
      F(I)=F(I)-AMULT*F(K)
   19 CONTINUE
      DO 20 I=1,N
   20 B(I,K)=F(I)
      DO 25 I=1,N
      DO 24 L=1,N
      IF(IROW(I)-L)24,23,24
   24 CONTINUE
   23 DO 25 J=1,N
   25 A(L,J)=B(I,J)
      DO 26 J=1,N
      DO 28 L=1,N
      IF(ICOL(J)-L)28,29,28
   28 CONTINUE
   29 DO 26 I=1,N
   26 B(I,L)=A(I,J)
   30 RETURN
      END
      SUBROUTINE MTRXMP(NRA,NCA,NCB,A,B,C,NDIAG)
      DIMENSION A(56,56),B(56,1),C(56,1)
      IF(NDIAG)100,120,140
  100 DO 110 I=1,NRA
      DO 110 J=1,NCA
  110 A(I,J)=-A(I,J)
      RETURN
  120 DO 130 I=1,NRA
      DO 130 J=1,NCB
      C(I,J)=0
      DO 130 K=1,NCA
  130 C(I,J)=C(I,J)+A(I,K)*B(K,J)
      RETURN
  140 DO 150 I=1,NRA
      DO 150 J=1,NCB
  150 C(I,J)=A(I,I)*B(I,J)
      RETURN
      END

PHASE SURGMOD2,SURGMOD1
 EXEC FFORTRAN
      SUBROUTINE MODEL2(     NDATPT,INDEX)
      COMMON/MODELS/F(200,56),Z(200,16)
      COMMON /MODATA/ K
      COMMON/TWO/N
      GO TO(1,2),INDEX
    1 K=0
    2 DO 10 I=1,NDATPT
      F(I,2)=Z(I,1)
      F(I,3)=Z(I,2)
      F(I,4)=Z(I,3)
      F(I,5)=Z(I,8)
      F(I,6)=Z(I,1)**2
      F(I,7)=Z(I,2)**2
```

```
      F(I,8)=Z(I,3)**2
      F(I,9)=Z(I,8)**2
      F(I,10)=Z(I,1)*Z(I,2)
      F(I,11)=Z(I,1)*Z(I,3)
       F(I,12)=Z(I,2)*Z(I,3)
      F(I,14)=Z(I,9)
      F(I,15)=Z(I,9)**2
   10 F(I,13)=Z(I,1)*Z(I,2)*Z(I,3)
      INDEX=2
      K=K+1
C     THREE IS THE NO. OF CONTROLS OF SERVO FLAP
      N=K+3
      IF(N.EQ.8) RETURN
      DO 20 I=1,NDATPT
   20 F(I,16)=Z(I,N)
      RETURN
      END
/*
  PHASE SURGMOD3,SURGMOD1
// EXEC FFORTRAN
      SUBROUTINE MODEL3(     NDATPT,INDEX)
      COMMON/MODELS/F(200,56),Z(200,16)
      COMMON /MODATA/ K
      GO TO(1,2),INDEX
    1 K=0
    2 DO 10 I=1,NDATPT
      F(I,2)=Z(I,1)
      F(I,3)=Z(I,2)
      F(I,4)=Z(I,3)
      F(I,5)=Z(I,4)
      F(I,6)=Z(I,5)
      F(I,7)=Z(I,6)
      F(I,8)=Z(I,1)**2
      F(I,9)=Z(I,1)*Z(I,2)
      F(I,10)=Z(I,1)*Z(I,3)
      F(I,11)=Z(I,1)*Z(I,4)
      F(I,12)=Z(I,1)*Z(I,5)
      F(I,13)=Z(I,1)*Z(I,6)
      F(I,14)=Z(I,2)**2
      F(I,15)=Z(I,2)*Z(I,3)
      F(I,16)=Z(I,2)*Z(I,4)
      F(I,17)=Z(I,2)*Z(I,5)
      F(I,18)=Z(I,2)*Z(I,6)
      F(I,19)=Z(I,3)**2
      F(I,20)=Z(I,3)*Z(I,4)
      F(I,21)=Z(I,3)*Z(I,5)
      F(I,22)=Z(I,3)*Z(I,6)
      F(I,23)=Z(I,4)**2
      F(I,24)=Z(I,4)*Z(I,5)
      F(I,25)=Z(I,4)*Z(I,6)
      F(I,26)=Z(I,5)**2
      F(I,27)=Z(I,5)*Z(I,6)
   10 F(I,28)=Z(I,6)**2
      INDEX=2
      K=K+1
C           SIX IS NUMBER OF SERVO FLAP CONTROLS
```

```
      N = K+6
      DO 20 I=1,NDATPT
   20 F(I,29) = Z(I,N)
      RETURN
      END
/*
   PHASE SURGMOD4,SURGMOD1
// EXEC FFORTRAN
      SUBROUTINE MODEL4(NDATPT,INDEX)
      COMMON/MODELS/F(200,56),Z(200,16)
      COMMON/MODATA/K
      GO TO(1,2),INDEX
    1 K=0
    2 DO 10 I=1,NDATPT
      F(I,2)=Z(I,1)
      F(I,3)=Z(I,2)
      F(I,4)=Z(I,3)
      F(I,5)=Z(I,4)
      F(I,6)=Z(I,5)
      F(I,7)=Z(I,6)
      F(I,8)=Z(I,7)
      F(I,9 )=Z(I,4)**2
      F(I,10)=Z(I,4)*Z(I,5)
      F(I,11)=Z(I,4)*Z(I,6)
      F(I,12)=Z(I,4)*Z(I,7)
      F(I,13)=Z(I,5)**2
      F(I,14)=Z(I,5)*Z(I,6)
      F(I,15)=Z(I,5)*Z(I,7)
      F(I,16)=Z(I,6)**2
      F(I,17)=Z(I,6)*Z(I,7)
      F(I,18)=Z(I,7)**2
      F(I,19)=Z(I,8)**2
      F(I,20)=Z(I,9)**2
      F(I,21)=Z(I,8)*Z(I,9)
      F(I,22)=Z(I,4)*Z(I,8)
      F(I,23)=Z(I,4)*Z(I,9)
      F(I,24)=Z(I,5)*Z(I,8)
      F(I,25)=Z(I,5)*Z(I,9)
      F(I,26)=Z(I,6)*Z(I,8)
      F(I,27)=Z(I,6)*Z(I,9)
      F(I,28)=Z(I,7)*Z(I,8)
      F(I,29)=Z(I,7)*Z(I,9)
      F(I,30)=Z(I,8)
   10 F(I,31)=Z(I,9)
      INDEX = 2
      K = K+1
C             NINE IS THE NUMBER OF SERVO FLAP CONTROLS
      N = K+9
      DO 20 I = 1,NDATPT
   20 F(I,32) = Z(I,N)
      RETURN
      END
```

APPENDIX B

BASIC PROGRAM

MCMOD1

MCNOJ:

```
1   RESTORE 600
13  READ A0,A1,A2,A3,A4,A5,A6,A7,A8,A9
20  READ B0,B1,B2,B3,B4,B5,B6,B7,B8,B9
30  READ C0,C1,C2,C3,C4,C5,C6,C7
40  PRINT "DID YOU CHECK STATEMENT 1 FOR CORRECT PPRAMETER DATA";
60  INPUT V$
62  PRINT "INPUT THE LIMITING VALUE OF PARAMETER DESIRED";
63  INPUT V
64  PRINT LIN(2)
65  PRINT "D2S D2C D3S D3C D4S D4C"
66  PRINT
70  FOR I=-4 TO 4
80  FOR J=-4 TO 4
90  FOR K=-4 TO 4
100  FOR L=-4 TO 4
110  FOR M=-4 TO 4
120  FOR N=-4 TO 4
130  S1=SQR(I*I+J*J)+SQR(K*K+L*L)+SQR(M*M+N*N)
140  IF S1>8 THEN 240
150  Z=A0+A1*I+A2*J+A3*K+A4*L+A5*M+A6*N+A7*I*I+A8*I*J+A9*I*K
160  Z=Z+B0*I*L+B1*I*M+B2*I*N+B3*J*J+B4*J*K+B5*J*L+B6*J*M+B7*J*N
170  Z=Z+B8*K*K+B9*K*L+C0*K*M+C1*K*N+C2*L*L+C3*L*M+C4*L*N
180  Z=Z+C5*M*M+C6*M*N+C7*N*N
210  IF ABS(Z)>=V THEN 240
220  PRINT  USING 230;I,J,K,L,M,N,Z
230  IMAGE 6(2D,2X),6D.2D
240  NEXT N
250  NEXT M
260  NEXT L
270  NEXT K
280  NEXT J
290  NEXT I
300  PRINT LIN(2)
310  GOTO 1000
320  REM   HP EQUN.
321  DATA 744.939,1.3963,-1.2542,-2.9213,-1.2528,-.2653,.4265,1.5997,1.1209
322  DATA .173,.0714,-.5684,.175,1.495,-.0591,-.019,-.082,-.5694,.7783
323  DATA .2484,-.0333,-.3934,.7101,-.0531,.3603,1.3596,-.0295,1.1858
380  REM   ALPHA MAX EQUN.
381  DATA 11.053,.1962,.5943,-.0678,-.0093,-.0316,-.1302,.0792,-.0274
382  DATA -.082,.0303,-.03,-.0149,.1249,-.0613,-.0871,.019,-.0569,.0412
383  DATA -.0031,-.0536,.0629,.0472,-.0862,-.0594,.0708,-.0061,.0587
390  REM   BM EQUN.
391  DATA 4410.59,-142.223,-206.073,32.5693,52.894,-10.4327
392  DATA 53.9868,37.9401,3.6878,-20.5406,-12.9403,-25.7651,-22.4228
393  DATA 29.9141,-12.5554,-49.3425,-5.0432,35.0723,60.6177,16.3783
394  DATA -13.5574,-98.5754,16.2727,55.9666,-12.5085,68.8309,30.8389
395  DATA 87.3327
400  REM   RV EQUN.
401  DATA 297.001,-17.5886,9.3449,27.1376,1.6159,48.9879,-15.7595,2.1711
402  DATA 8.8384,2.4898,-2.769,.414,-7.723,12.5843,2.5764,1.3008,-1.425,-14.4104
403  DATA 6.075,3.6815,16.3866,-6.9432,11.0551,13.1069,24.1043,15.1314,5.6591
404  DATA 19.6047
500  REM    RV OP
501  DATA 287.321,-18.5093,12.5886,25.1653,.0665,48.8584,-14.4661,2.6408
502  DATA 7.9244,2.6801,-2.7284,1.065,-7.9199,12.3808,2.7869,3.0317,-.6995
503  DATA -13.8191,6.3857,4.2497,16.1808,-6.9566,11.0812,10.8276,21.4394
504  DATA 14.7582,6.1214,19.1995
600  REM      RV IP
601  DATA 79.2904,-5.8321,-6.1315,8.8073,-.3534,3.7171,-13.5148,.5852,1.4527
602  DATA .0237,.4007,-.5386,3.0076,2.6987,1.3308,-6.2942,-4.4798,-2.5551
603  DATA 1.8996,-.4598,1.1636,-.9397,3.7933,8.4988,9.0936,3.1029
604  DATA -1.5203,3.1471
1000  END
```

APPENDIX C

MAXIMUM SLOPE

APPENDIX C

MAXIMUM SLOPE

A flow diagram of the computer program used to investigate the maximum slope search characteristics is shown in Figure C-1, and the listing is given in Table C-1. The first step is to set the initial values of the independent variables. These values are usually taken to correspond to no multicyclic control. The increment of the independent variable to be used in the search is also set.

The first step in the actual processing loop is to calculate the controlled variables (y's) using the coefficients in Table 11. Next, the value of the optimization parameter, P, and the derivatives of this function with respect to each of the controlled variables are calculated for the particular optimization function being investigated.

The decision on whether or not P has increased is bypassed during the first pass so that the next step is to calculate the derivatives of the controlled variables with respect to each independent variable using the coefficients of Table 13. The derivative of the optimization function with respect to each independent variable is then calculated as indicated in paragraph 3.1. If, at this point, the maximum derivative of the optimization function with respect to each of the independent variables is 0, the system has arrived at the "best" operating point and the process is stopped. If this condition is not true, the independent variable providing the maximum derivative of the optimization function is incremented and the process repeats from the step where the values of y were calculated.

If the value of P does not decrease as a result of a particular iteration, it means that the operation has stepped across a valley of the surface describing the optimization parameter in terms of each of the independent variables. Therefore, the increment that caused that step is removed; the derivative of the optimization function with respect to that independent variable is set equal to 0; and the process is tried again using the independent variable with the next largest derivative. Note that if another independent variable causes a decrease in P, the whole process is repeated and a new derivative is calculated for that which was previously set to 0.

This process continues until an operating point is reached wherein increments of each independent variable causes the value of P to increase. At that point the process stops. However, the value of the increment can be changed and the operation continued from the operating point just found.

The following outputs are printed for each iteration of the actual processing loop:

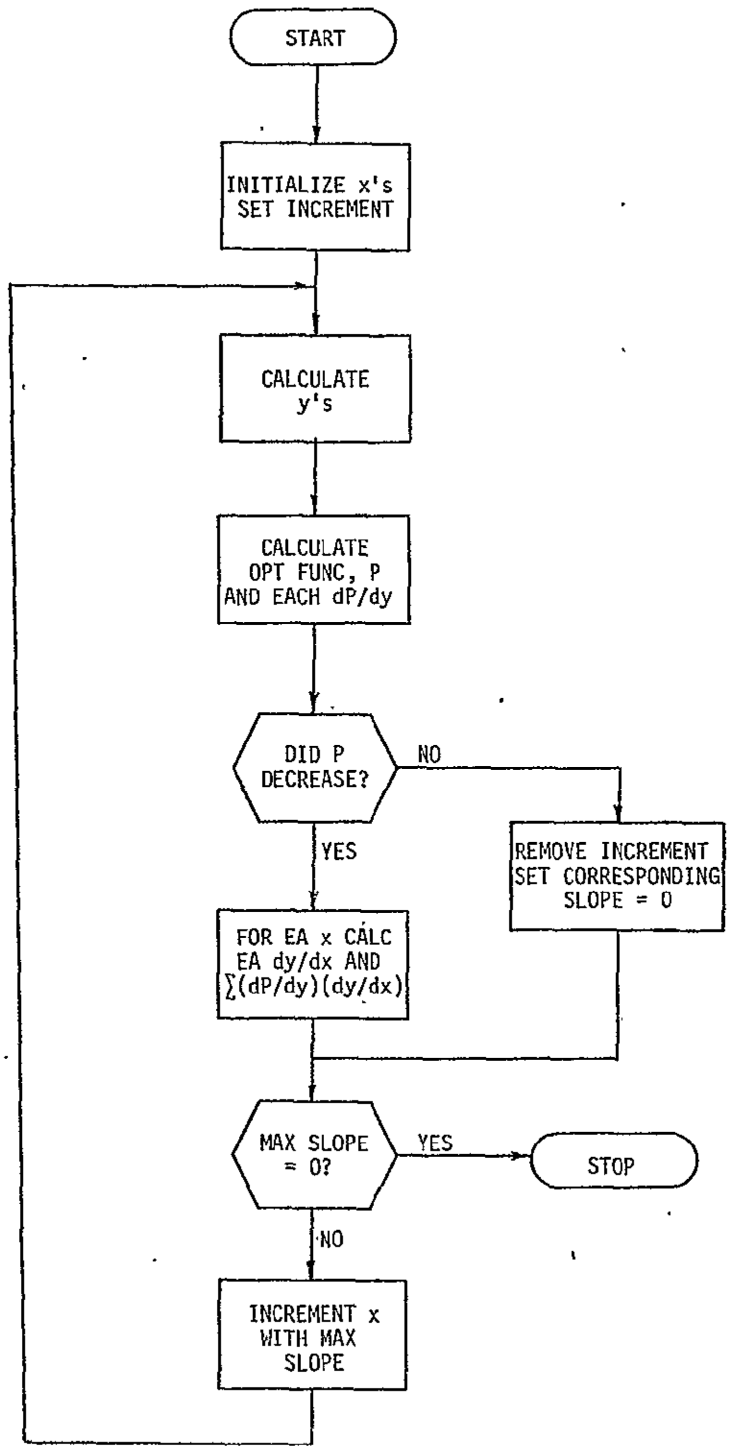

Figure C-1. Shortest Path Model.

TABLE C-1. MAXIMUM SLOPE MODEL

```
LOR4

1  COM X[6],S[6]
2  W=0
6  DATA 0,0,0,0,0,0
7  MAT  READ X
10  FILES COEFF
13  A1=-.5
14  P2=1000
15  DIM Z[4],Y[4]
16  DATA 7000,750,12,300
17  MAT  READ Z
22  DIM R[6]
23  DATA 6,10,13,15,16,16
24  MAT  READ R
25  DIM M[4,32]
26  MAT  READ #1;M
31  IMAGE #,3D
32  IMAGE #,X4D
33  IMAGE #,4D
39  GOTO 48
40  PRINT "CHANGE ";
41  INPUT X1,X2
42  IF X1=0 THEN 48
43  IF X1>6 THEN 47
44  X[X1]=X2
46  GOTO 40
47  INPUT X[1],X[2],X[3],X[4],X[5],X[6]
48  REM
50  FOR I=1 TO 6
52  PRINT  USING 31;2*X[I]
54  NEXT I
60  GOSUB 500
70  FOR I=1 TO 4
72  PRINT  USING 32;Y[I]+Y[I]*9*(I=3)
74  NEXT I
76  GOSUB 620
78  PRINT  USING 32;10*P1
80  IF P1<P2 THEN 90
82  X[N3]=X[N3]-A2
84  S[N3]=0
86  PRINT  USING "#,24X"
88  GOTO 252
90  P2=P1
100  FOR I=1 TO 6
102  S[I]=0
110  FOR K=1 TO 4
112  S1=M[K,I+1]
114  FOR J=1 TO 6
116  A=M[K,I+J+R[I MIN J]]
118  A=A*X[J]*(1+(I=J))
120  S1=S1+A
122  NEXT J
124  S[I]=S[I]+S1*Q[K]/Z[K]
130  NEXT K
132  PRINT  USING 33;10*S[I]
140  NEXT I
252  N3=T1=0
```

TABLE C-1. MAXIMUM SLOPE MODEL (continued)

```
254  FOR I=1 TO 6
256  IF ABS(S[I]) <= T1 THEN 262
258  T1=ABS(S[I])
259  N3=I
262  NEXT I
270  IF N3=0 THEN 999
290  A2=A1*SGN(S[N3])
296  PRINT  USING "2XSD";N3*SGN(A2)
300  X[N3]=X[N3]+A2
320  GOTO 50
500  REM CALC Y'S
504  FOR K=1 TO 4
508  Y[K]=M[K,1]
512  FOR I=1 TO 6
516  Y[K]=Y[K]+M[K,1+I]*X[I]
520  FOR J=I TO 6
524  Y[K]=Y[K]+M[K,I+J+R[I]]*X[I]*X[J]
528  NEXT J
532  NEXT I
544  NEXT K
548  RETURN
620  REM CALC P1 & DERIVATIVES
621  IF W=4 THEN 661
623  P1=100*(Y[4]/Z[4])↑2
624  Q[4]=200*Y[4]/Z[4]
629  IF W=3 THEN 665
632  Q[3]=0
634  IF Y[3]<Z[3] THEN 639
636  P1=P1+10*(12*(Y[3]/Z[3]-1))↑4
638  Q[3]=Q[3]+480*(12*(Y[3]/Z[3]-1))↑3
639  IF W=2 THEN 670
640  P1=P1+20*(Y[2]/Z[2]-1)
642  Q[2]=20
644  IF Y[2]<Z[2] THEN 649
646  P1=P1+10*(30*(Y[2]/Z[2]-1))↑4
648  Q[2]=Q[2]+1200*(30*(Y[2]/Z[2]-1))↑3
649  IF W=1 THEN 675
650  P1=P1+36.99+100*(Y[1]/Z[1]-1)
652  Q[1]=100
654  IF Y[1]<Z[1] THEN 660
656  P1=P1+10*(7*(Y[1]/Z[1]-1))↑4
658  Q[1]=Q[1]+280*(7*(Y[1]/Z[1]-1))↑3
660  RETURN
661  P1=100*Y[4]/Z[4]
662  Q[4]=100
665  P1=P1+100*(Y[3]-11.1)/Z[3]
666  Q[3]=100
670  P1=P1+100*(Y[2]-745)/Z[2]
671  Q[2]=100
675  P1=P1+100*(Y[1]-4411)/Z[1]
676  Q[1]=100
680  RETURN
999  END
```

Each independent variable

Each controlled variable

Optimization parameter

Derivative of the optimization parameter with respect to each controlled variable

Independent variable selected to be incremented and the direction.

APPENDIX D

SEQUENTIAL SEARCH MODEL

APPENDIX D

SEQUENTIAL SEARCH MODEL

A flow diagram of the computer program used to investigate the sequential search characteristics is shown in Figure D-1, and the listing is given in Table D-1. The first step is to set the initial values of the independent variables and the slopes of the optimization function with respect to these variables. The independent variables are usually taken to correspond to no multicyclic pitch, and the initial slopes set to zero. The size of the increment, the degree of lag and the amount of noise are also set as part of the initialization process.

The first step in the actual processing loop is to calculate the controlled variables (y's) using the coefficients in Table 11. Next, the effect of lag is introduced on the basis of the calculated values of the y's, the previous values of the y's, and the lag parameter set as part of the initialization process. These new values of y are stored for use in the next lag calculation. Next, the noise amplitude is generated for each of the y's and the values of y with lag and noise are used to calculate the optimization parameter, P, from the functions of Figure 3. It is the optimization parameter, affected by noise and lag, that is used in the subsequent control action.

The decisions on whether or not P decreased and the basis for selecting the next independent variable to be incremented are bypassed during the first pass so that the next step is to increment the first independent variable in the sequence. During subsequent passes, when P decreases, the change in P is used to calculate the slope of P to be associated with the most recently incremented independent variable. The basis for selecting the next independent variable to be incremented can then be alternated between a fixed sequence and the independent variable with the maximum slope. However, the maximum slope criterion is not used if the maximum slope is less than .01.

If P did not decrease and if an increment of the opposite sign has already been tried, the increment is removed and a "restart" flag is set so that a new baseline value of P is determined prior to incrementing another independent variable. In addition, the sign of the slope associated with the most recently incremented independent variable is set equal to the smaller of the signs of the slopes determined with positive and negative increments. This aids the search process when the most recently incremented independent variable next comes up in this fixed search sequence. However, the magnitude of the slope is set less than .01, so that it does not become a candidate for incrementing in accordance with the maximum slope criterion. If the reverse increment has not been tried, and if the search strategy being investigated requires that it be done, the change in P is used to calculate and store a slope associated with the most recently incremented independent variable, the increment is removed, and one of opposite sign is applied.

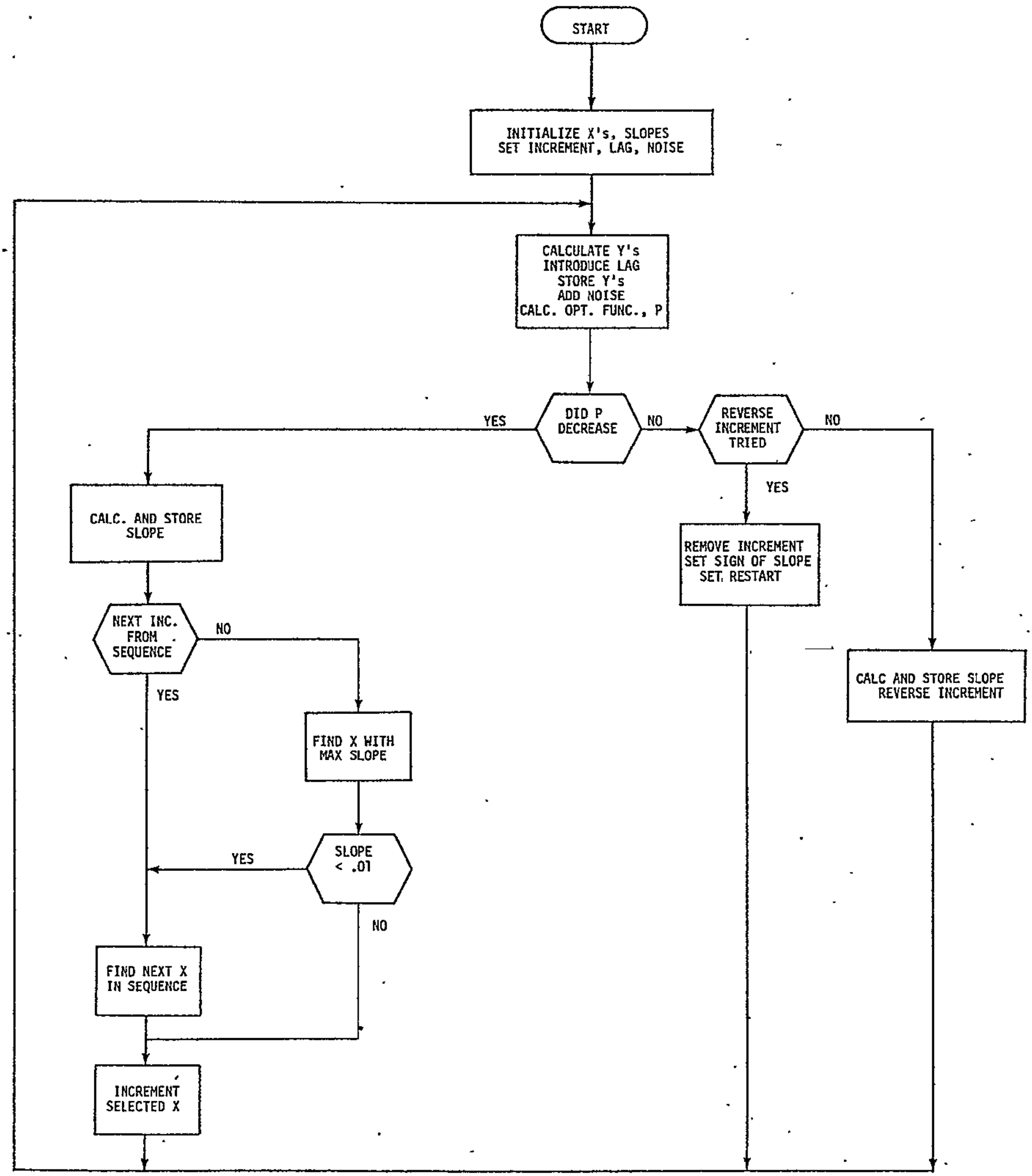

Figure D-1. Sequential Search Model.

C:P3

TABLE D-1. SEQUENTIAL SEARCH MODEL

```
1  COM X[6],S[6]
6  DATA 0,0,0,0,0,0
7  MAT  READ X
8  DATA 0,0,0,0,0,0
9  MAT  READ S
10  FILES COEFF
11  F1=0
12  F2=N1=N2=1
13  A1=-.5
14  RESTORE 16
15  DIM Z[4],Y[4],H[4],B[4],D[4]
16  DATA 7000,750,12,300
17  MAT  READ Z
18  U=.0025
19  T=.393
20  REM PRINT F1: 0 ONE P1, 1 NORMAL, 2 ALL Y'S, 3 THREE P1'S
21  REM F2: 0 RESTART, 1 1ST PASS, 2 SEQ, 3 MAX SLOPE, 4 -INCREMENT
40  P2=999
41  DIM R[6]
42  DATA 6,10,13,15,16,16
43  MAT  READ R
44  DIM M[4,32]
45  MAT  READ #1;M
46  DIM A$[11],B$[11]
47  IMAGE #,3D
48  IMAGE #,X4D
49  IMAGE #,4D
50  GOTO 58
51  PRINT "CHANGE ";
52  INPUT X1,X2
53  IF X1=0 THEN 58
54  IF X1>6 THEN 57
55  X[X1]=X2
56  GOTO 51
57  INPUT X[1],X[2],X[3],X[4],X[5],X[6]
58  IF F1=0 THEN 63
59  PRINT " 2S 2C 3S 3C 4S 4C";
60  PRINT "  OPT   BM   HP 10AM   RU";
61  PRINT " OPTN";
62  PRINT " S2S S2C S3S S3C S4S S4C"
63  C1=C2=C3=0
64  C4=C5=0
65  IF F1=0 THEN 100
66  FOR I=1 TO 6
67  PRINT  USING 47;2*X[I]
68  NEXT I
100  REM
101  IF F2>0 THEN 110
103  MAT Y=B
105  GOTO 121
110  FOR K=1 TO 4
111  Y[K]=M[K,1]
112  FOR I=1 TO 6
113  Y[K]=Y[K]+M[K,1+I]*X[I]
114  FOR J=I TO 6
115  Y[K]=Y[K]+M[K,I+J+R[I]]*X[I]*X[J]
```

TABLE D-1. SEQUENTIAL SEARCH MODEL (continued)

```
116  NEXT J
117  NEXT I
120  NEXT K
121  MAT V=Y
122  IF F1=0 THEN 128
123  GOSUB 600
124  PRINT  USING 48;P1
125  IF F1<2 THEN 128
126  PRINT  USING "5D";Y[1],Y[2],10*Y[3],Y[4]
127  PRINT  USING "#,23X"
128  REM TIME LAG
130  IF F2=1 THEN 134
131  MAT H=(1-T)*H
132  MAT Y=(T)*Y
133  MAT Y=Y+H
134  MAT H=Y
136  IF F1=0 THEN 140
138  PRINT  USING 48;Y[1],Y[2],10*Y[3],Y[4]
140  GOSUB 600
146  C1=C1+Y[4]
147  C2=C2+Y[4]↑2
148  C3=C3+1
149  C4=C4+P1
150  C5=C5+P1↑2
165  REM GENERATES AND PRINTS NOISY DATA
168  GOSUB 500
169  IF F1<2 THEN 180
170  IF F1#3 THEN 172
171  PRINT  USING "#,4DX";P1
172  PRINT
174  PRINT  USING "#,23X"
176  PRINT  USING 48;Y[1],Y[2],10*Y[3],Y[4]
180  GOSUB 600
182  IF F1=0 THEN 184
183  PRINT " ";
184  PRINT  USING "#,3D";P1
200  IF F2<2 THEN 221
201  S1=(P1-P2)/A2
202  IF P1<P2 THEN 218
203  PRINT " ";
204  IF F2=4 THEN 210
205  F2=4
206  S[N3]=S1
207  X[N3]=X[N3]-2*A2
208  A2=-A2
209  GOTO 300
210  F2=0
212  S[N3]=.001*SGN(ABS(S[N3]) MIN ABS(S1))
213  X[N3]=X[N3]-A2
214  IF F1=0 THEN 316
215  PRINT
216  GOTO 316
218  S[N3]=S1
219  PRINT "M";
220  GOTO 222
221  PRINT "B";
222  P2=P1
223  MAT S=D
```

TABLE D-1. SEQUENTIAL SEARCH MODEL (continued)

```
240  IF N2=1 THEN 270
250  N2=1
251  F2=3
252  N3=T1=0
254  FOR I=1 TO 6
256  IF ABS(S[I])<T1 THEN 262
258  T1=ABS(S[I])
259  N3=I
262  NEXT I
263  IF T1<.01 THEN 270
264  GOTO 290
270  N2=2
271  F2=2
272  N1=N1+1-6*(N1=6)
274  N3=N1
290  A2=A1*(SGN(S[N3])+(S[N3]=0))
291  X[N3]=X[N3]+A2
300  IF F1=0 THEN 316
304  PRINT  USING 49;S[1],S[2],S[3],S[4],S[5],S[6]
308  PRINT  USING "#,3D";F2
312  PRINT  USING "XDS";N3*SGN(A2)
316  IF C3<18 THEN 65
320  IF F1#0 THEN 328
324  PRINT
325  PRINT  USING "3D.D";X[1],X[2],X[3],X[4],X[5],X[6]
328  PRINT  USING "4D";C1/C3,SQR(C2/C3-(C1/C3)↑2)
332  PRINT  USING "4D";C4/C3,SQR(C5/C3-(C4/C3)↑2)
336  GOTO 63
500  REM ADD NOISE
505  FOR K=1 TO 4
510  V1=1
512  V2=RND(1)+.0002
514  IF V2<.5002 THEN 520
516  V2=V2-.5
518  V1=-1
520  V3=1.6231*SQR(LOG(1/V2)-.3)-1.017
522  V3=V3*V1
524  Y[K]=Y[K]+V3*Z[K]*U
526  NEXT K
530  RETURN
600  REM CALC OPT FUNCTION
623  P1=100*(Y[4]/Z[4])↑2
634  IF Y[3]<Z[3] THEN 640
636  P1=P1+10*(12*(Y[3]/Z[3]-1))↑4
640  P1=P1+20*(Y[2]/Z[2]-1)
644  IF Y[2]<Z[2] THEN 650
646  P1=P1+10*(30*(Y[2]/Z[2]-1))↑4
650  P1=P1+36.99+100*(Y[1]/Z[1]-1)
654  IF Y[1]<Z[1] THEN 660
656  P1=P1+10*(7*(Y[1]/Z[1]-1))↑4
660  RETURN
999  END
```

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Once started, the model is allowed to run for a sufficient number of iterations to characterize its operation. Provisions are made for printing the following information on each iteration cycle:

Each independent variable

Each controlled variable as calculated, with lag, with lag and noise

Optimization parameter from calculated controlled variables, with lag and with lag and noise

The slope of the optimization parameter associated with each independent variable

Independent variable selected to be incremented and the direction

Mean and standard deviation about the mean for P and R_V over a number of iterations, usually 18.