SECTION 8.0

NATIONAL RADIO ASTRONOMY OBSERVATORY
POST OFFICE BOX 2
GREEN BANK, WEST VIRGINIA 24944
TELEPHONE ARBOVALE 456-2011

PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE

SUBJECT: DRIVE SYSTEM

8.0 DRIVE SYSTEM

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PREPARED BY ______ APPROVED BY ______ SUBMITTED BY ______

OPERATED BY ASSOCIATED UNIVERSITIES, INC., UNDER CONTRACT WITH THE NATIONAL SCIENCE FOUNDATION

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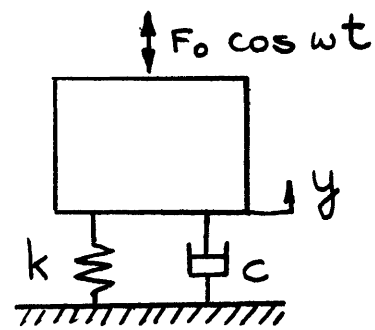
SUBJECT: DRIVE SYSTEM

8.1 EFFECT OF DISTURBANCE FREQUENCY ON SYSTEM STABILITY

THE PHASE LAG INTRODUCED BY THE DISTURBANCE FREQUENCY IS ANALIZED BELOW:



THE FORCE EQUATION OF THE ABOVE DIAGRAM IS:

$$m\ddot{y} = F_o \cos \omega t - c\dot{y} - ky$$

SINGLE DIFFERENTIATION IS EQUIVALENT TO MULTIPLICATION BY $j\omega$, DOUBLE DIFFERENTIATION IS EQUIVALENT TO MULTIPLICATION BY $-\omega^2$

ALSO, $F_o \cos \omega t = F_o e^{j\omega t}$

THUS $(-m\omega^2 + j\omega c + k) y_o e^{j(\omega t + \psi_1)} = F_o e^{j\omega t}$

DIVIDING BY $e^{j\omega t}$

$$\left[(k - m\omega^2) + j\omega c\right] y_o e^{j\psi_1} = F_o$$

MAXIMUM DISPLACEMENT "y_o" AND PHASE ANGLE "ψ_1" CAN BE DETERMINED FROM THE ABOVE RELATIONSHIP.

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THUS,
$$y_0 = \frac{F_0}{\sqrt{(k - m\omega^2)^2 + \omega^2 c^2}}$$

IN THE ABOVE EXPRESSION NUMERATOR AND DENOMINATOR ARE DIVIDED BY k. Ω^2 IS SUBSTITUTED FOR THE RATIO k/m, WHERE Ω IS THE NATURAL FREQUENCY. ALSO, CRITICAL DAMPING $C_c = 2\sqrt{km}$ IS SUBSTITUTED IN THE EQUATION.

GIVING:
$$y_0 = \frac{F_0/k}{\sqrt{\left[1 - \left(\frac{\omega^2}{\Omega^2}\right)\right]^2 + \left[2\left(\frac{\omega}{\Omega}\right)\left(\frac{c}{C_c}\right)\right]^2}}$$

WHERE F_0/k IS THE STATIC DEFLECTION UNDER CONSTANT FORCE F_0.

REARRANGING THE FORCE EQUATION,
$$F_0 = \left[(k - m\omega^2) + j\omega c\right] y_0 e^{j\psi_1}$$

AND SUBSTITUTING $e^{j\psi} = \cos\psi + j\sin\psi$

GIVES:
$$y_0 e^{j\psi_1} = \frac{F_0}{(k - m\omega^2) + j\omega c} = y_0(\cos\psi_1 + j\sin\psi_1)$$

TO CONVERT THE DENOMINATOR INTO A REAL EXPRESSION, NUMERATOR AND DENOMINATOR ARE MULTIPLIED BY $(k - m\omega^2) - j\omega c$.

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THUS,

$$\frac{F_0\left[(k-m\omega^2)-j\omega c\right]}{(k-m\omega^2)^2+\omega^2c^2} = y_0\left(\cos\psi_1 + j\sin\psi_1\right)$$

$$\tan\psi_1 = \frac{\sin\psi_1}{\cos\psi_1}$$

EQUATING THE REAL AND IMAGINARY PARTS IN THE FIRST EQUATION ABOVE GIVES:

$$\sin\psi_1 = \frac{-\omega c}{(k-m\omega^2)^2+\omega^2c^2}$$

$$\cos\psi_1 = \frac{k-m\omega^2}{(k-m\omega^2)^2+\omega^2c^2}$$

THUS, $\tan\psi_1 = \dfrac{-\omega c}{k-m\omega^2}$

SUBSTITUTING $\Omega = \sqrt{\frac{k}{m}}$ AND $c_c = 2\sqrt{km}$ INTO THE ABOVE EXPRESSION GIVES:

$$\tan\psi = \frac{-2\left(\frac{\omega}{\Omega}\right)\left(\frac{c}{c_c}\right)}{1-\left(\frac{\omega^2}{\Omega^2}\right)}$$

IN THE ABOVE EXPRESSIONS

m = MASS

$\ddot{y}$ = ACCELERATION

$\dot{y}$ = VELOCITY

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y = DISPLACEMENT
F_0 = DISTURBANCE FORCE
ω = DISTURBANCE FREQUENCY
K = SPRING CONSTANT
Ω = NATURAL FREQUENCY
C = DAMPING
C_c = CRITICAL DAMPING
C/C_c = DAMPING RATIO (ξ)

NEGATIVE SIGN IN THE NUMERATOR INDICATES PHASE LAG.

CALCULATIONS

PHASE ANGLE IS CALCULATED FOR:

TELESCOPE AXIS NATURAL FREQUENCIES OF:

0.4, 0.5 & 0.7 CPS

DAMPING RATIOS OF: 0.4, 0.5 & 0.6

DISTURBANCE FREQUENCIES OF:
0.03 TO 2.0 RAD PER SEC.

THE RESULTS ARE SHOWN ON TABLE I AND FIGURES NO. 1 & NO. 2

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REPORT NO. H79-8
CONTRACT NO. RAP-79

DATE DEC 20'68

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TABLE I

Ω	c/c_c	ω	$\tan\psi$	ψ
3.1 (.5 CPS)	.4	2	−.87	41°
"	"	0.5	−.13	8°
"	"	0.1	−.02	1°
"	"	0.03	−.002	0°7'
"	.5	2	−.98	44°
"	"	0.5	−.16	9°
"	"	0.1	−.025	1°
"	"	0.03	−.0025	NEGL.
"	.6	2	−1.30	52°
"	"	0.5	−.19	11°
"	"	0.1	−.03	2°
"	"	0.03	−.003	NEGL
4.4 (.7 CPS)	.4	2	−.45	24°
"	"	0.5	−.09	5°
"	"	0.1	−.02	1°
"	"	0.03	−.006	NEGL
"	.6	2	−.67	34°
"	"	0.5	−.14	8°
"	"	0.1	−.03	2°
"	"	0.03	−.009	NEGL
2.5 (.4 CPS)	.4	2	−1.8	61°
"	"	0.5	−.17	9°
"	"	0.1	−.03	2°
"	"	0.03	−.01	0°35'

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TABLE I (CONT.)

Ω	c/c_c	ω	$\tan \psi$	ψ
2.5 (.4 CPS)	.6	2	−2.4	68°
"	"	0.5	−.25	14°
"	"	0.1	−.05	3°
"	"	0.03	−.02	1°

OBSERVATIONS:

INCREASED PHASE ANGLE WILL RESULT IN LESS PHASE MARGIN IN THE DRIVE SERVO BECAUSE IN THE OPEN LOOP ARRANGEMENT THE DISTURBANCE IS PRESENTED IN SERIES; AND THEREFORE, ITS PHASE LAG DIRECTLY ADDS TO THE TOTAL OPEN LOOP PHASE LAG.

FOR A TELESCOPE NATURAL FREQUENCY OF 0.5 CPS ABOUT 40° PHASE LAG WILL RESULT FOR 2 RAD/SEC DISTURBANCE.

THIS CAN BE REDUCED TO APPROXIMATELY 25° IF 0.7 CPS TELESCOPE NATURAL FREQUENCY CAN BE OBTAINED.

FOR DISTURBANCE FREQUENCIES OF 0.5 RAD/SEC THE PHASE LAG IS AROUND 10 TO 14 DEGREES.

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THE TABULATION BELOW IS FOR A STRUCTURAL NATURAL FREQUENCY OF 1.0 CPS WHERE DAMPING RATIOS .4, .5 AND .6 ARE PLOTTED FOR DISTURBANCE FREQUENCIES IN THE RANGE OF .03 TO 2.0 RAD/SEC.

Ω	C/C_c	ω	$\tan \psi$	ψ
6.3 RAD/SEC	0.4	2	.275	15°
"	0.4	0.5	.064	3°
"	0.4	0.1	.013	1°
"	0.4	0.03	.004	NEGL.
"	0.5	2	.345	19°
"	0.5	0.5	.08	4°
"	0.5	0.1	.016	1°
"	0.5	0.03	.005	NEGL.
"	0.6	2	.41	22°
"	0.6	0.5	.096	5°
"	0.6	0.1	.019	1°
"	0.6	0.03	.006	NEGL.

OBSERVATIONS:

A NATURAL FREQUENCY OF 1CPS WILL RESULT IN AN IMPROVED PHASE LAG UNDER OPERATING CONDITIONS, DUE TO DISTURBANCE FREQUENCIES, OF 22°. THIS COMPARES VERY FAVORABLY WITH 34° LAG FOR A NATURAL FREQUENCY OF 0.7 CPS.

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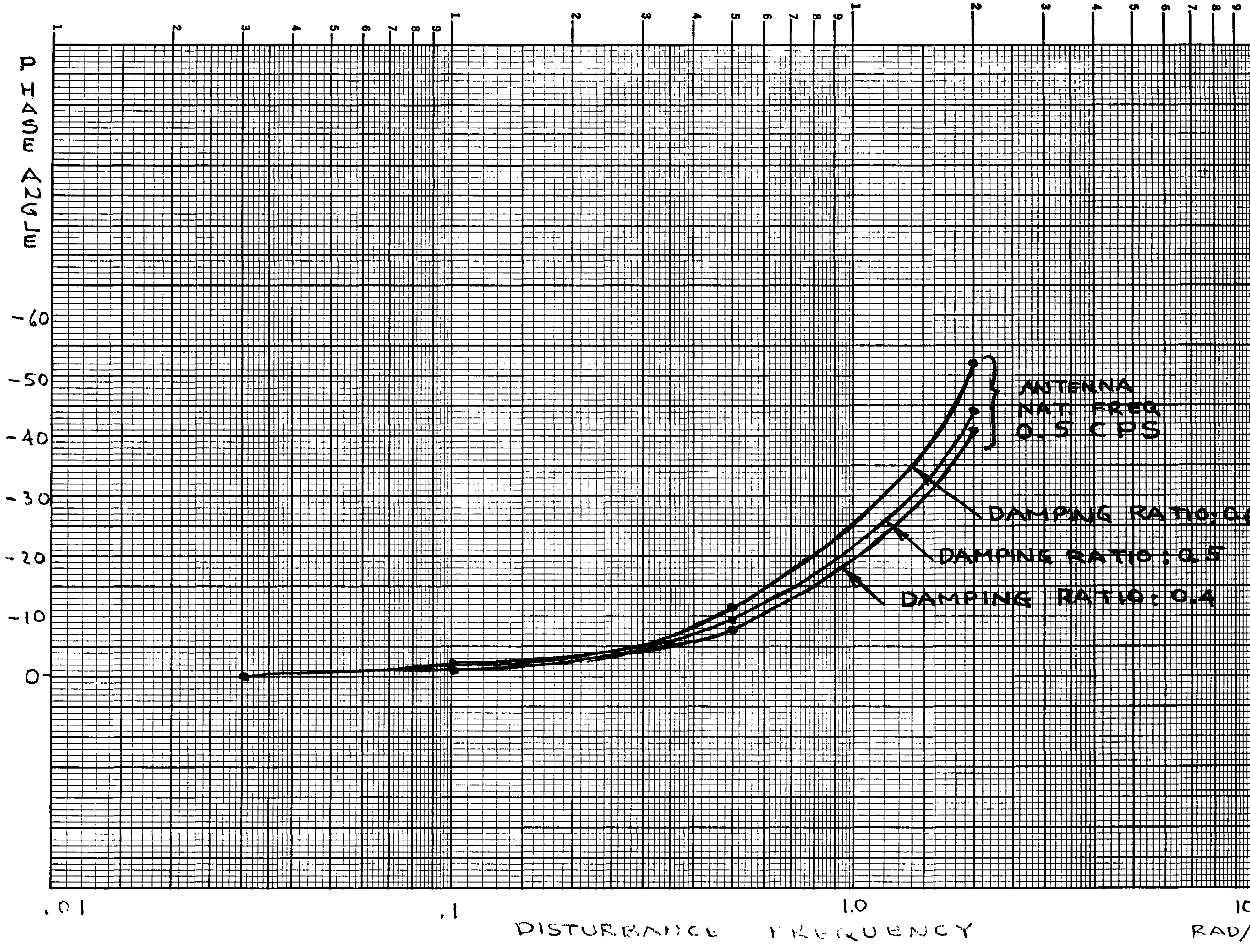

PHASE ANGLE
-60
-50
-40
-30
-20
-10
0
ANTENNA
NAT. FREQ
0.5 CPS
DAMPING RATIO: 0.6
DAMPING RATIO: 0.5
DAMPING RATIO: 0.4
.01
.1
1.0
10.0
DISTURBANCE FREQUENCY
RAD/SEC

FIGURE NO. 1

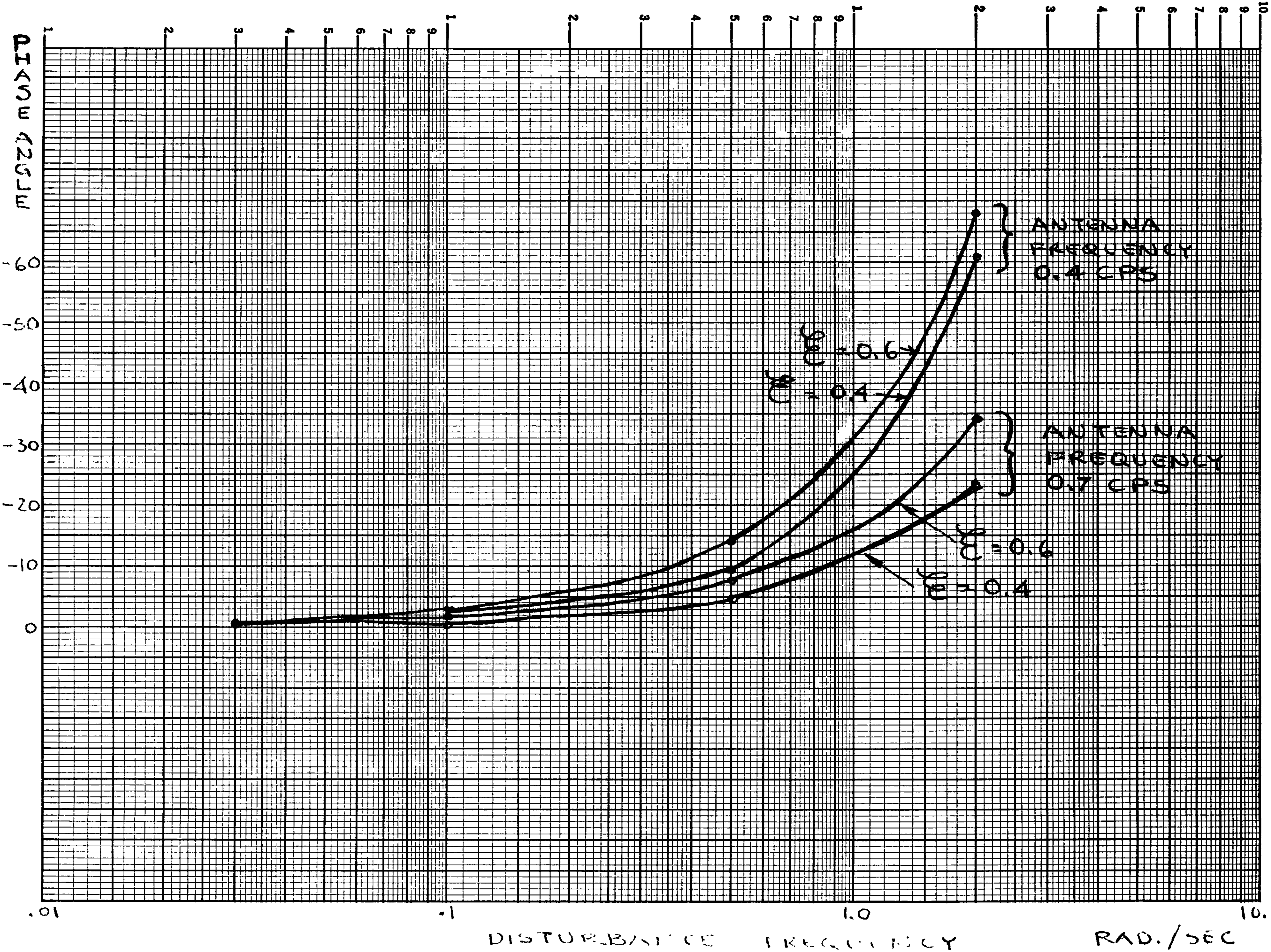
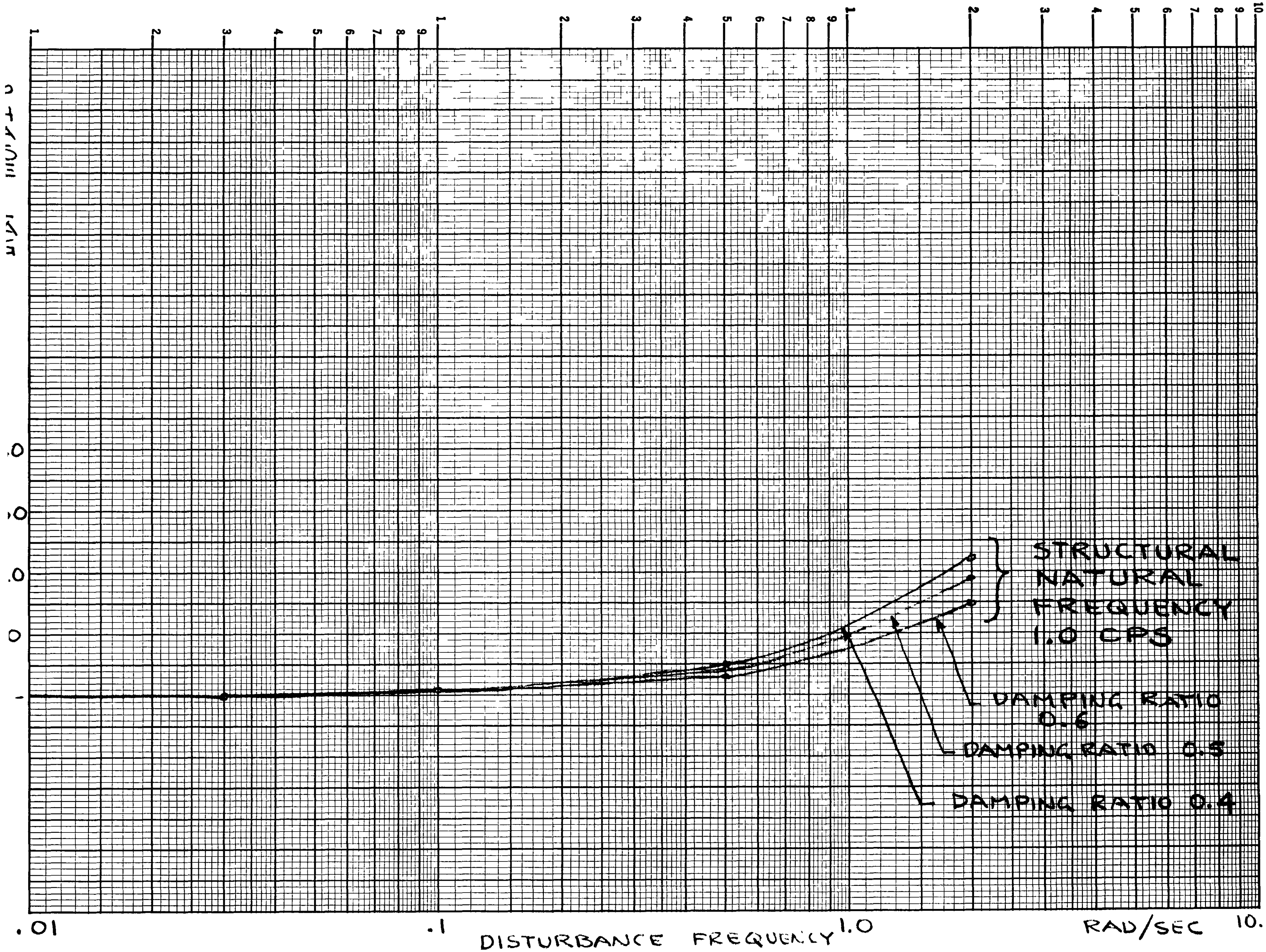

PHASE ANGLE
-60
-50
-40
-30
-20
-10
0
ANTENNA FREQUENCY 0.4 CPS
ANTENNA FREQUENCY 0.7 CPS
ξ = 0.6
ξ = 0.4
ξ = 0.6
ξ = 0.4
.01
.1
1.0
10.0
DISTURBANCE FREQUENCY
RAD./SEC

FIGURE NO. 2



STRUCTURAL NATURAL FREQUENCY 1.0 CPS
DAMPING RATIO 0.6
DAMPING RATIO 0.5
DAMPING RATIO 0.4
.01
.1
1.0
10.0
RAD/SEC
DISTURBANCE FREQUENCY

FIGURE NO. 3

PROJECT: 300 FT DIA. HOMOLOGY RADIO TELESCOPE

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8.2 AZIMUTH AXIS DRIVE SYSTEM

8.2.1. USE OF 16 - 5 HP MOTORS - 8 DRIVING - 8 BUCKING SERVO PERFORMANCE AND ANALYSIS

I - HARDWARE AVAILABLE:

A - GE FRAME 286, 850 RPM, DRIP PROOF SEPARATELY VENTILATED, ROTOR INERTIA 0.087 LB.FT.SEC², OVERLOAD CAPACITY 400% NOT EXCEEDING 0.5 SEC.

B - GE FRAME 286, 850 RPM, DRIP PROOF SEPARATELY VENTILATED, ROTOR INERTIA 0.087 LB.FT.SEC², OVERLOAD CAPACITY 800% NOT EXCEEDING 0.5 SEC.

C - GE FRAME 286, 850 RPM, TOTALLY ENCLOSED, FAN COOLED, 900% MAX. OVERLOAD CAPACITY FOR 0.5 SEC. COMPENSATED FOR LINEAR TORQUE - AMP. CHARACTERISTICS.

ALTERNATE "C" ABOVE WILL BE USED AS IT HAS THE BEST CHARACTERISTICS. WHEN MORE THAN ONE DRIVE IS USED, DRIVES WILL TEND TO GET LOAD FROM EACH OTHER IN TRANSIENT PERIODS. UNDER THESE CONDITIONS OVERLOADING CAPACITY BECOMES IMPORTANT. FOR THE SAME REASON OF UNEQUAL LOADING, LINEAR TORQUE - AMP CHARACTERISTICS ARE IMPORTANT. FINALLY, TOTALLY ENCLOSED CONSTRUCTION WITH INTEGRAL FAN IS SUPERIOR TO DRIP - PROOF CONSTRUCTION WITH SEPARATE VENTILATION.

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THE POWER AMPLIFIER (SERVO AMPLIFIER) TO BE USED IS OF SOLID STATE DESIGN AND NOT ROTARY ELECTRO-MECHANICAL IN NATURE. THIS SELECTION IS MADE BECAUSE OF RESPONSE TIME (BAND WIDTH) IF SOLID STATE AMPLIFIERS ARE NOT USED.

II - TOTAL SYSTEM INERTIA:

WORST CASE LOAD INERTIA IS 2.5×10^9 LB.FT.SEC^2 TO FIND THE INERTIA REFLECTED TO THE MOTOR SHAFTS THIS VALUE IS DIVIDED BY $\frac{1}{N^2}$

$$\frac{I}{N^2} = \frac{2.5 \times 10^9}{48600^2} = 1.06 \text{ LB. FT. SEC}^2$$

THIS IS THE TOTAL INERTIA SEEN BY 8 DRIVING STATIONS. OR, PER STATION INERTIA = 0.13 LB. FT. SEC^2.

TOTAL INERTIA REFLECTED TO EACH MOTOR SHAFT IS:

$$I_T = \underset{\text{(MOTOR)}}{0.09} + \underset{\text{(LOAD)}}{0.13} + \underset{\text{(GEAR BOX)}}{0.01} + \underset{\text{(COUPLING ETC)}}{0.03} = 0.26 \text{ LB.FT.SEC}^2$$

THE ABOVE IS WORST CASE

BEST POSSIBLE (LOWEST INERTIA) COULD BE:

$$I_T = 0.09 + 0.13 + 0.01 + 0.01 = 0.24 \text{ LBFT SEC}^2$$

III GEAR BOX CHARACTERISTICS:

AZIMUTH: GEAR RATIO 444/1

STIFFNESS 62.5 LB-FT/RAD EACH G. BOX, AT MOTOR SHAFT

INERTIA .125 IN LB SEC^2 PER UNIT

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ELEVATION: GEAR RATIO 300/1
STIFFNESS 295 LB.FT/RAD
EACH GEAR BOX, AT MOTOR SHAFT
INERTIA 3.3 LB FT. SEC^2 /UNIT

REQUIRED MINIMUM GEAR BOX NATURAL FREQ.
5.2 RAD/SEC

THUS, THE MAXIMUM ALLOWABLE INERTIA PER GEAR BOX AS REFLECTED TO THE MOTOR SHAFT IS:

$$I = \frac{k}{\omega^2}$$

$$\text{AZIMUTH: } \omega_A = \sqrt{\frac{62.5}{.01}} = 78 \text{ RAD/SEC}$$

$$\text{ELEVATION: } \omega_E = \sqrt{\frac{29.5}{3.3}} = 9.5 \text{ RAD/SEC}$$

FOR THIS REPORT 0.4 LB. FT SEC^2 GEAR BOX INERTIA IS USED FOR EACH GEAR BOX ON EITHER AXIS.

IV <u>TORQUE REQUIRED TO OVERCOME FRICTION</u>

WORST CASE FRICTION TORQUE IS 1.02×10^6 LB.FT AT AZIMUTH AXIS.

TORQUE PER MOTOR IS: $\frac{HP \times 5250}{RPM}$

= 31 LB.FT (RATED TORQUE AT RATED SPEED)

TOTAL RATED TORQUE IS: $8 \times 48{,}600 \times 31 \times \frac{2}{3}$

WHERE 8 IS THE NUMBER OF STATIONS AND 48,600 IS SERVO MOTOR TO ANTENNA AXIS REDUCTION RATIO.

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31 IS TORQUE PER MOTOR AND
2/3 IS USED TO ALLOW FOR THE REVERSE DRIVE (BUCKING) GEAR BOX AND MOTOR (I.E. THE BUCKING POWER IS 1/3 OF THE DRIVING POWER)

THUS, TOTAL RATED TORQUE IS 8×10^6 LB-FT
TORQUE REQUIRED TO OVERCOME FRICTION IS 1.02×10^6 LB-FT
RATED MOTOR EXCITATION FOR RATED OUTPUT IS 240 V DC

EXCITATION REQUIRED TO OVERCOME FRICTION

$$V_E = \frac{1.02 \times 10^6}{8 \times 10^6} \times 240 = 31 \text{ V}$$

WITH 7% MARGIN 33V IS USED FOR THIS REPORT.

V OPEN LOOP GAIN

FROM POSITION REFERENCE PLATFORM 21 BITS OF NATURAL BINARY RESOLUTION DEFINES POSITION WHERE EACH COUNT IS 0.62 ARC SEC (SEE REPORT H79-7 POSITION REFERENCE PLATFORM)

THE DIGITAL TO ANALOG CONVERTER ACCEPTS ± 12 BITS OF NATURAL BINARY AND PROVIDES ± 10 V DC OF OUTPUT WHERE THE INPUT IS DIGITAL DIFFERENCE.

12 BITS = 4096 COUNTS = 10 V DC

1 COUNT = 0.62 ARC SEC $\simeq$ 2.5 mV

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THE OPEN LOOP GAIN DEPENDS ON TWO FACTORS:

1- HOW MUCH SERVO DEAD BAND CAN BE TOLERATED.

2- HOW FAR CAN THE GAIN BE INCREASED, USING FEASIBLE COMPENSATION METHODS BEFORE UNSTABILITY IS CAUSED.

IF WE HAVE ±2 COUNTS AS A DESIGN GOAL, THE REQUIRED GAIN IS:

$$A = \frac{33}{5.0 \times 10^{-3}} = 6600 \text{ VOLTS/VOLT}$$

OR 4400 VOLTS/VOLT FOR 1.9 ARC SEC. HYSTERESIS. WHERE 33 VOLTS REPRESENTS THE EXCITATION REQUIRED AT EACH SERVO MOTOR SO THAT ALL 8 OF THEM ACTING TOGETHER CAN OVERCOME FRICTION. A GAIN OF 4400 = 73 Db IS USED IN THIS REPORT.

VI - TRANSFER FUNCTION

THE TRANSFER FUNCTION IS EXPRESSED BY:

$$\frac{\theta_0}{\varepsilon_i} = \frac{1/K_B}{s\left[1 + \frac{J_T}{\left(\frac{K_B K_T}{R_T}\right)} s\right]\left(1 + \frac{L_M}{R_T} s\right)}$$

WHERE

J_T IS TOTAL WORST CASE INERTIA REFLECTED TO THE MOTOR SHAFT

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ON PER GEAR BOX BASIS.

$J_T = 0.26$ LB FT SEC^2

K_B IS BACK ELECTROMOTIVE FORCE FOR THE SELECTED MOTOR.

$K_B = 2.69$ VOLTS / RAD / SEC

K_T IS MOTOR TORQUE CONSTANT

$K_B = 1.73$ LB FT / AMP

R_T IS TOTAL LOOP RESISTANCE INCLUDING MOTOR ARMATURE RESISTANCE, AMPLIFIER OUTPUT RESISTANCE AND CABLING. THE MOTOR ARMATURE RESISTANCE IS TAKEN AT 120°F.

$R_T = 2.0$ OHMS

L_M IS TOTAL LOOP IMPEDANCE

$L_M = 0.012$ HENRIES

$$G_S = \frac{1/2.69}{s\left[1 + \frac{.26}{\frac{2.69 \times 1.79}{2}}\right]\left(1 + \frac{.012}{2.0}s\right)} = \frac{.37}{s(1+.11s)(1+.006s)}$$

FROM THE ABOVE, MECHANICAL TIME CONSTANT IS 0.11 SEC. ELECTRICAL TIME CONSTANT IS 0.006 SEC.

TO IMPROVE THE ABOVE, TACHOMETER FEED-BACK IS CONSIDERED NEXT.

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$$G_s = \frac{G}{1 + GH}$$

WHERE $H = K_G S$ IS THE TACHOMETER FEED BACK. G IS MOTOR PLUS LOAD TRANSFER FUNCTION.

SUBSTITUTING $K_G = 20$ VOLTS / RAD/SEC GIVES IMAGINARY ROOTS.

SUBSTITUTING $K_G = 10$ V/RAD/SEC

$$G_s = \frac{.079}{S(1 + .025S + .00014S^2)}$$

$$= \frac{.079}{S(1 + .0165S)(1 + .0085S)}$$

$$\omega_n = \sqrt{\frac{1}{.00014}} = 84.5 \text{ RAD/SEC}$$

$$\xi = \frac{.025}{.00014 \times 2 \times 84.5} = 1.05 \text{ DAMPING RATIO}$$

SUBSTITUTING $K_G = 1$ V/RAD/SEC

$$G_s = \frac{.27}{S(1 + .085S + .00048S^2)}$$

$$= \frac{.27}{S(1 + .079S)(1 + .006S)}$$

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$$\omega_n = \sqrt{\frac{1}{.00048}} = 45.6 \text{ RAD/SEC}$$

$$\xi = \frac{.085}{.00048 \times 2 \times 45.6} = 1.95 \text{ DAMPING RATIO}$$

THUS, K_G = 10V/RAD/SEC GIVES GOOD RESULTS AND REPRESENTS THE ZONE OF FEEDBACK REQUIRED.

OVER ALL LOOP TRANSFER FUNCTION IS:

$$G(s) = \frac{73 \text{ Db}}{\underbrace{(1+.02s)}_{\text{PLATFORM}}\underbrace{(1+.16s)}_{\text{STRUCTURE}}\underbrace{(1+.013s)}_{\text{GEAR BOX AZIMUTH}}\underbrace{s(1+.016s)(1+.0085s)}_{\text{MOTOR + LOAD + TACH.}}}$$

AS THE ABOVE EXPRESSION CROSSES THE 0 Db AXIS WITH APPX. 80 Db/DECADE SLOPE, STRONG COMPENSATION IS REQUIRED.

COMPENSATION NETWORK #1
FROM BODE PLOT,

$$T_{LAG} = \frac{1}{.025} = 40$$

$$T_{LEAD} = \frac{1}{.8} = 1.25$$

$$G(s) = \frac{(1+1.25s)^2}{(1+40s)^2}$$

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$$\text{PHASE SHIFT} = \frac{73^\circ + 73^\circ}{\underbrace{90^\circ + 90^\circ}_{\text{COMP NETWORK}} + \underbrace{3^\circ}_{\text{PLATFORM}} + \underbrace{22^\circ}_{\text{STRUCT.}} + \underbrace{2^\circ}_{\text{GEAR BOX}} + \underbrace{90^\circ + 2^\circ + 1^\circ}_{\text{MOTOR LOAD TACH}}}$$

$$= \frac{146}{300} \rightarrow 154 \text{ LAG}$$

PHASE MARGIN = 180 − 154 = 26°

COMPENSATION NETWORK # 2

$$T_{LAG} = \frac{1}{.016} = 62$$

$$T_{LEAD} = \frac{1}{.5} = 2$$

$$G(s) = \frac{(1 + 2s)^2}{(1 + 62s)^2}$$

PHASE SHIFT = 142° LAG
PHASE MARGIN = 38°

NETWORK NO. 2 IS MORE ADEQUATE; AS, BECAUSE OF DISTURBANCE FREQUENCIES UP TO 22° PHASE MARGIN MAY BE LOST.

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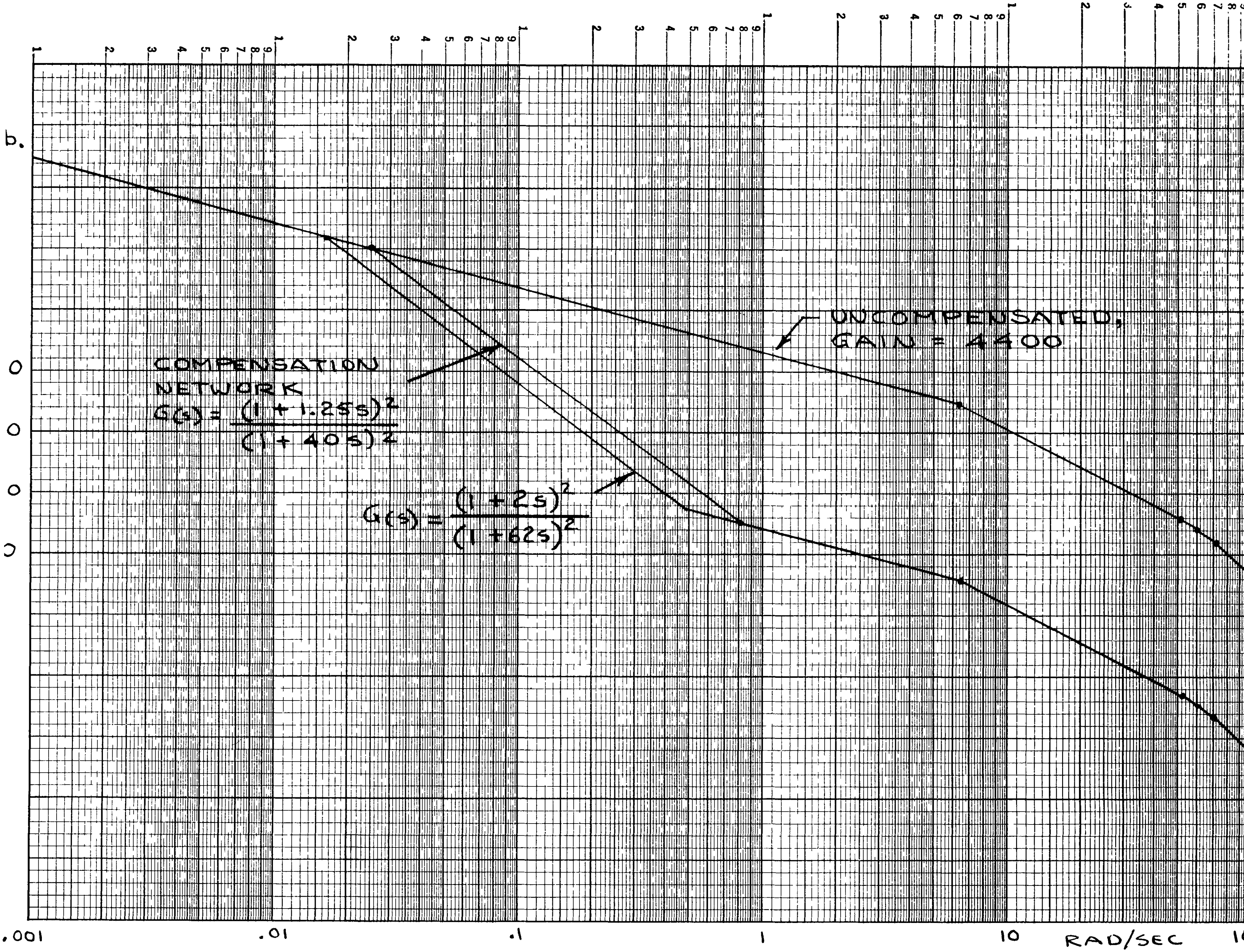

UNCOMPENSATED,
GAIN = 4400
COMPENSATION
NETWORK
G(s) = (1 + 1.25s)^2 / (1 + 40s)^2
G(s) = (1 + 2s)^2 / (1 + 62s)^2
.001
.01
.1
1
10
RAD/SEC
100

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PROJECT: 300 FT. DIA. HOMOLOGY TELESCOPE

SUBJECT: DRIVE SYSTEM

RESULTS FOR 5 HP SERVO MOTOR

1- 16 MOTORS ARE USED. 8 DRIVING 8 BUCKING

2- DC MOTOR WITH FRAME 286, 850 RPM TOTALLY ENCLOSED, FAN COOLED, 900% MAXIMUM OVERLOAD CAPACITY COMPENSATED FOR LINEAR TORQUE - AMPERE CHARACTERISTICS IS USED.

3- SOLID STATE POWER AMPLIFIER IS NEEDED.

4- TACHOMETER FEEDBACK IS NEEDED.

5- SIXTEEN IDENTICAL GEAR BOXES ARE USED FOR EACH AXIS, EACH WITH THE FOLLOWING CHARACTERISTICS:

AXIS	STIFFNESS	INERTIA	RATIO
AZ	62.5 LB-FT/RAD	.01 LB.FT.SEC^2	444/1
EL	295 "	3.3 "	300/1

AZ GEAR BOX CHARACTERISTICS ARE ADEQUATE. ELEVATION GEAR BOX CHARACTERISTICS WILL BE DISCUSSED UNDER 20 HP DRIVES.

6- 1.02×10^6 LB FT OF TORQUE REQUIREMENT FOR THE AZIMUTH AXIS DIRECTLY INFLUENCES SERVO DEAD BAND AND GAIN REQUIREMENTS. GAIN REQUIREMENTS IN TURN INFLUENCE DRIVE STABILITY. THUS, REDUCING THE TORQUE BY 30% WILL IMPROVE DEAD BAND BY THE SAME AMOUNT.

7- THE STRUCTURAL CHARACTERISTICS USED ARE: 1.0 CPS FOR AZIMUTH AND ELEVATION. AS SEEN FROM THE BODE PLOT, THE ANTENNA DRIVE AND STRUCTURE COMBINATION WILL HAVE A CLOSED LOOP BAND WIDTH OF APPROXIMATELY 0.4 CPS. THIS FREQUENCY IS ONE OCTAVE ABOVE THE UPPER LIMITS OF THE DISTURBANCE FREQUENCIES, AND THE RESULTING OPERATION AS SHOWN, IS SATISFACTORY.

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PROJECT: 300 FT DIA. HOMOLOGY RADIO TELESCOPE

SUBJECT: DRIVE SYSTEM

8.2.2 HIGHER SLEW RATE AZIMUTH DRIVES

IN THIS REPORT THE POSSIBILITIES OF USING 16 UNITS OF 10 HP, 1750 RPM, # 286 FRAME MOTORS FOR OBTAINING UP TO .2°/SEC SLEW RATE; 16 UNITS OF 15 HP, 2500 RPM, # 365 FRAME MOTORS FOR .3°/SEC; AND 16 UNITS OF 20 HP, 3500 RPM, # 365 FRAME MOTORS FOR .4°/SEC SLEW RATE ARE INVESTIGATED.

THE 16 UNITS ARE USED AS 8 DRIVING AND 8 BUCKING UNDER NORMAL OPERATION. FOR SLEWING, ALL 16 UNITS ARE DRIVING.

THE MECHANICAL TIME CONSTANT (T_M) OF THE DRIVE MOTORS AND LOAD CHARACTERISTICS AS REFLECTED TO THE MOTOR SHAFT INFLUENCING THE VALUE OF T_M ARE THE ONLY LIMITING FACTORS DUE TO THE CHANGE OF DRIVING MOTORS.

THEREFORE, T_Ms FOR THE NEW 10 HP, 15 HP AND 20 HP MOTORS ARE CALCULATED BELOW:

$$T_M = \frac{J_T}{\left(\frac{K_B K_T}{R_T}\right)}$$

WHERE,

J_T IS TOTAL WORST CASE LOAD INERTIA REFLECTED TO THE MOTOR SHAFT IN LB-FT-SEC^2

K_B IS BACK-ELECTROMOTIVE FORCE FOR THE SELECTED MOTOR IN VOLTS/RAD/SEC

K_T IS MOTOR TORQUE CONSTANT IN LB-FT/AMP

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R_T IS TOTAL ARMATURE LOOP RESISTANCE INCLUDING AMPLIFIER OUTPUT AND POWER CABLING.

DATA

HP	RPM	FRAME	J_T	K_B	K_T	R_T
5	850	286	.24	2.69	1.73	2
10	1750	286	.24	1.31	.84	1
15	2 500	365	.37	.88	.59	.7
20	3 500	365	.37	.63	.42	.5

THE CALCULATED MECHANICAL TIME CONSTANTS FROM THE ABOVE DATA ARE:

FOR	THE	5 HP	UNIT	T_M	= .11
"	"	10 "	"	"	= .22
"	"	15 "	"	"	= .49
"	"	20 "	"	"	= .68

AS SECTION 8.2 SHOWS THE ANALYSIS OF THE 5 HP UNIT IN DETAIL, HAD THE OTHER VALUES BEEN BELOW .11 SEC, THEIR SATISFACTORY OPERATION COULD HAVE BEEN ASSUMED WITHOUT FURTHER CALCULATIONS.

IN THIS PARTICULAR CASE, AS THE 20 HP UNIT WITH $T_M = .68$ REPRESENTS WORST CASE, CALCULATIONS WILL BE LIMITED TO THIS UNIT.

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SUBJECT: DRIVE SYSTEM

IF BY TACHOMETER FEED BACK COMPENSATION THE NATURAL FREQUENCY OF THE DRIVE CAN BE INCREASED TO 50 RAD/SEC OR HIGHER, WITHOUT CAUSING THE INNER LOOP (VELOCITY FEEDBACK LOOP) TO OSCILLATE, THE USE OF THE 20 HP MOTOR (AND ALSO 15 HP OR 10 HP MOTORS) SHOULD NOT PRESENT ANY ADDITIONAL PROBLEMS COMPARED TO THE 5 HP UNIT.

THE TRANSFER FUNCTION OF THE 20 HP MOTOR IS:

$$\frac{\theta_o}{E_i} = \frac{1.59}{s(1+.68s)(1+.0011s)}$$

IF TACHOMETER FEED BACK IS USED WITH K_G = 10V/RAD/SEC, THE DRIVE TRANSFER FUNCTION INCLUDING MOTOR, LOAD AND TACHOMETER BECOMES:

$$G_s = \frac{.094}{s(1+.04s+.000029s^2)}$$

THE ROOTS OF THE DENOMINATOR ARE −.040 AND −.0005, THUS,

$$G_s = \frac{.094}{s(1+.04s)(1+.0005s)}$$

THE NEAREST ROLL-OFF FREQUENCY IS $\omega_n = \frac{1}{.04} = 25$ RAD/SEC COMPARED TO 50 RAD/SEC OBTAINED FOR THE 5 HP UNIT, THIS IS NOT ADEQUATE. A K_G VALUE OF 20V/RAD/SEC WILL BE TRIED NEXT.

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SUBJECT: DRIVE SYSTEM

IF BY TACHOMETER FEED BACK COMPENSATION THE NATURAL FREQUENCY OF THE DRIVE CAN BE INCREASED TO 50 RAD/SEC OR HIGHER, WITHOUT CAUSING THE INNER LOOP (VELOCITY FEEDBACK LOOP) TO OSCILLATE, THE USE OF THE 20 HP MOTOR (AND ALSO 15 HP OR 10 HP MOTORS) SHOULD NOT PRESENT ANY ADDITIONAL PROBLEMS COMPARED TO THE 5 HP UNIT.

THE TRANSFER FUNCTION OF THE 20 HP MOTOR IS:

$$\frac{\theta_o}{E_i} = \frac{1.59}{s(1+.68s)(1+.0011s)}$$

IF TACHOMETER FEED BACK IS USED WITH $K_G = 10V/RAD/SEC$, THE DRIVE TRANSFER FUNCTION INCLUDING MOTOR, LOAD AND TACHOMETER BECOMES:

$$G_s = \frac{.094}{s(1+.04s+.000029s^2)}$$

THE ROOTS OF THE DENOMINATOR ARE −.040 AND −.0005, THUS,

$$G_s = \frac{.094}{s(1+.04s)(1+.0005s)}$$

THE NEAREST ROLL-OFF FREQUENCY IS $W_n = \frac{1}{.04} = 25$ RAD/SEC COMPARED TO 50 RAD/SEC OBTAINED FOR THE 5 HP UNIT, THIS IS NOT ADEQUATE. A K_G VALUE OF 20V/RAD/SEC WILL BE TRIED NEXT.

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SUBJECT: DRIVE SYSTEM

$$G_S = \frac{.049}{S(1 + .021S + .000015S^2)}$$

$$= \frac{.049}{S(1 + .020S)(1 + .0008S)}$$

FROM THE ABOVE EXPRESSION, THE NEAREST ROLL-OFF FREQUENCY IS

$\omega_n = \frac{1}{.020} = 50$ RAD/SEC, THIS IS SATISFACTORY.

THE INNER LOOP DAMPING RATIO IS:

$$\xi = \frac{.021}{.000015 \times 2 \times 50} = 14$$

THIS IS MORE THAN ADEQUATE, INDICATING HIGHER VALUES OF K_G FOR HIGHER VALUES OF W_n ARE A POSSIBILITY.

CONCLUSION

SIXTEEN UNITS OF 10, 15, OR 20 HP MOTORS CAN BE USED ON AZIMUTH AXIS FOR HIGHER SLEW RATES WITHOUT CAUSING PERFORMANCE DEGRADATION.

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PROJECT: 300 FT DIA HOMOLOGY RADIO TELESCOPE

SUBJECT: DRIVE SYSTEM

8.3 ELEVATION AXIS DRIVE SYSTEM

8.3.1 USE OF 20 HP MOTORS WITH 2 DRIVING 2 BUCKING GEAR BOXES

I - HARDWARE:

THE SAME CLASS OF GE DC-MOTOR IS USED WHICH NOW BECOMES FRAME 368

THE POWER AMPLIFIER REMAINS SOLID STATE

II - TOTAL SYSTEM INERTIA:

MOTOR INERTIA	0.41	LB. FT SEC^2
GEARBOX INERTIA AZ REFLECTED TO MOTOR SHAFT	3.30	"
LOAD INERTIA PER DRIVING STATION	0.24	"
MARGIN	0.25	"
TOTAL	4.20	" PER GEAR BOX

III - GEAR BOX CHARACTERISTICS:

RATIO: 300/1

STIFFNESS: 295 LB FT/RAD

INERTIA: 3.3 LB FT SEC^2

IV - MOTOR EXCITATION REQUIRED TO OVERCOME STATIC FRICTION AND THE GAIN DERIVED FROM THIS RELATIONSHIP IS EXPECTED TO BE IN THE AREA OF GAIN = 2400 VOLTS/VOLT AS DISCUSSED IN SECTION 8.2, BASED ON A FRICTION TORQUE OF 560,000 LB FT.

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SUBJECT: DRIVE SYSTEM

V - STABILITY ANALYSIS

THE NEW MOTOR CHARACTERISTICS ARE

J_M = 0.41 LB. FT. SEC^2

K_B = 2.60 V/RAD/SEC

K_T = 1.79 LB-FT/AMP

R_M = .153 OHMS

L_M = .0036 HENRIES

SEE PAGE NO 8.16 – 8.17 FOR THE EXPLANATION OF THE ABOVE SYMBOLS.

TOTAL LOAD INERTIA USED IS 4.2 LB. FT. SEC^2
TOTAL LOOP RESISTANCE USED IS 0.5 OHMS INCLUDING AMPLIFIER OUTPUT IMPEDANCE AND CABLING.

THUS, MOTOR PLUS LOAD TRANSFER FUNCTION IS:

$$\frac{\theta_o}{\varepsilon_1} = \frac{1/K_B}{s\left[1 + \frac{J_T}{\left(\frac{K_B K_T}{R_T}\right)} s\right]\left(1 + \frac{L_M}{R_T} s\right)}$$

$$= \frac{1/2.60}{s\left(1 + \frac{4.2}{\frac{2.60 \times 1.79}{.5}} s\right)\left(1 + \frac{.0036}{.5} s\right)}$$

$$= \frac{.38}{s(1 + .5s)(1 + .0072s)}$$

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THE TIME CONSTANTS ARE:

MECHANICAL TIME CONSTANT .5
ELECTRICAL TIME CONSTANT .0072

USING TACHOMETER GENERATOR FEEDBACK TO IMPROVE THESE GIVES THE RESULTS SHOWN ON TABLE I BELOW FOR VARIOUS VALUES OF K_G IN VOLTS/RAD/SEC FOR THE TACHOMETER FEED BACK.

K_G V/RAD/SEC	T_M MECH. TIME CONST.	T_E ELEC. TIME CONST	ω_n NAT. FREQ	ξ DAMPING RATIO
2	.28	.008	22	3.2
10	.067	.039	37	1.9
30	.032	.009	59	1.2

THUS, K_G = 30 V/RAD/SEC IS ADEQUATE

THE RESULTING TRANSFER FUNCTION FOR MOTOR, LOAD AND TACHOMETER IS:

$$G_S = \frac{0.031}{s(1+.032s)(1+.009s)}$$

THE CONTRIBUTION OF THIS FUNCTION TO OVERALL PHASE LAG IS DUE TO

T_M = .032 2 DEG. LAG VS. 1° FOR THE 5 HP
T_E = .009 1 " " " 1° " " "
T_G = .105 6 " " " 1° " AZ. GEAR BOX

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OPEN LOOP GAIN OF 2400 = 67.6 Db

OVERALL LOOP TRANSFER FUNCTION IS:

$$G(s) = \frac{67.6\,\text{Db}}{\underbrace{(1+.02s)}_{\text{PLATFORM}}\underbrace{(1+.16s)}_{\text{STRUCTURE}}\underbrace{(1+.105s)}_{\text{GEAR BOX}}\underbrace{s(1+.032s)(1+.009s)}_{\text{MOTOR+LOAD+TACH.}}}$$

AS THIS EXPRESSION CROSSES THE ZERO Db AXIS ON THE BODE PLOT WITH 80 Db/DECADE SLOPE, COMPENSATION NETWORKS ARE NEEDED.

USING $G(s) = \frac{(1+2s)^2}{(1+59s)^2}$ AS COMPENSATION

NETWORK PROVIDES A PHASE LAG OF 155° AND A PHASE MARGIN OF 25°. THIS IS MARGINAL UNDER DISTURBANCES.

USING $G(s) = \frac{(1+3.3s)^2}{(1+91s)^2}$ GIVES A

PHASE LAG OF 147° AND A PHASE MARGIN OF 33°.

THUS, WITHIN THE AREA OUTLINED BY THESE NETWORKS IT IS FEASIBLE TO OBTAIN 30° – 40° PHASE SHIFT FOR ADEQUATE PERFORMANCE.

THE ANALYSIS IS ALSO BASED ON 1.9 ARC SEC HYSTERESIS AND 560,000 LB-FT OF FRICTIONAL TORQUE

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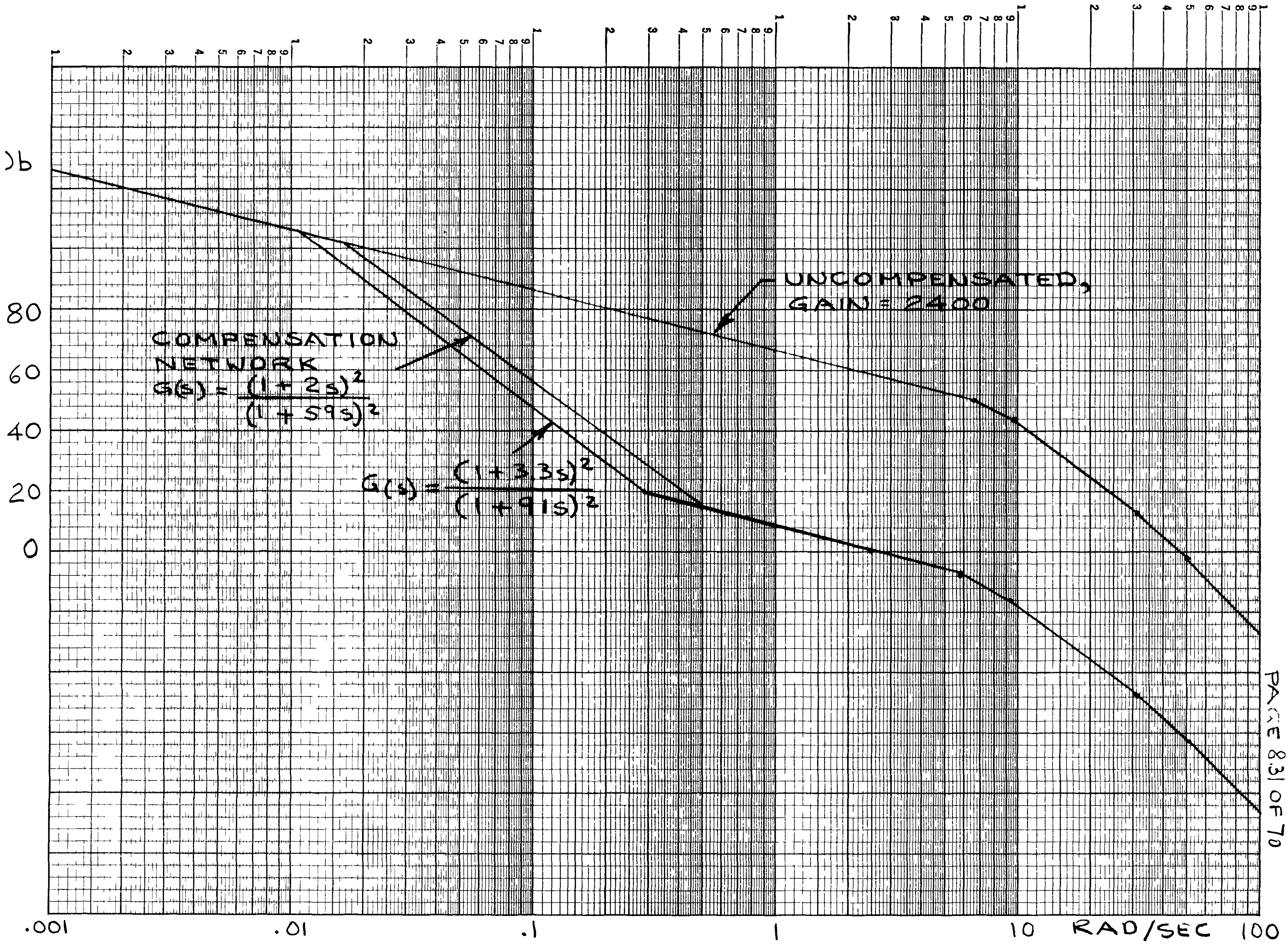
db
80
60
40
20
0
UNCOMPENSATED,
GAIN = 2400
COMPENSATION
NETWORK
G(s) = (1 + 2s)^2 / (1 + 59s)^2
G(s) = (1 + 3.3s)^2 / (1 + 91s)^2
.001
.01
.1
1
10
RAD/SEC
100

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THUS, USING 20 HP MOTORS WILL CAUSE A PHASE MARGIN DEGRADATION OF APPX 5° LOOKING AT PAGE 8.19

THIS IS NOT PROHIBITIVE.
THE ANTENNA STRUCTURAL NATURAL FREQUENCY OF 1.0 CPS IS INFLUENCING THE PERFORMANCE MORE SEVERALLY THAN THE GEAR BOX, INDICATING THAT PRESENT GEAR BOX CHARACTERISTICS (SEE PARA III THIS REPORT) ARE SATISFACTORY

CONCLUSIONS

1- FOUR MOTORS ARE USED. TWO DRIVING TWO BUCKING.
2- EACH MOTOR IS 20 HP, DC EXCITATION FRAME 368, 850 RPM, 900% MAXIMUM OVERLOAD CAPACITY, LINEAR TORQUE-AMP CHARACTERISTICS,
3- SOLID STATE POWER AMPLIFIER AND TACHOMETER FEED BACK ARE USED.
4- NO CHANGE IN GEAR BOX RATIO, INERTIA OR STIFFNESS IS NEEDED.
REDUCING GEAR BOX INERTIAS FROM 3.3 TO 0.5 LB.FT.SEC² WILL IMPROVE PERFORMANCE BUT IS NOT ABSOLUTELY NEEDED. (PHASE MARGIN IMPROVEMENT OF ABOUT 5°.
5- 1.0 CPS OF STRUCTURAL BAND WIDTH WILL RESULT IN APPX .4 CPS OVERALL ANTENNA BAND WIDTH. THIS IS ALMOST ONE OCTAVE ABOVE THE WORST CASE DISTURBANCE FREQUENCY. AS ANALIZED ABOVE, SATISFACTORY OPERATION IS EXPECTED.

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8.3.2. DOUBLING OF THE ELEVATION AXIS SLEW SPEED FROM 6°/MIN. TO 12°/MIN.

THE DRVING UNITS USED IN THE ANALYSIS CONTAINED IN SECTION 8.3.1 HAVE THE FOLLOWING OVERLOAD CHARACTERISTICS:

OVERLOAD	SAFE TIME SPAN
25%	INDEFINITELY
35%	5 MINUTES
100%	1 MINUTE

AS THE REQUIRED DOUBLING THE SPEED REPRESENTS 100% OVERLOAD FOR TIME SPANS CONSIDERABLY IN EXCESS OF ONE MINUTE, DIFFERENT HARDWARE OR TECHNOLOGY IS NEEDED. FOUR OF THESE ARE DISCUSSED BELOW WITH THEIR RELATIVE MERITS.

I - IN THE ORIGINAL SET-UP THERE WERE TWO DRIVING TWO BUCKING UNITS, EACH 20 HP. IN THE SLEW MODE ALL UNITS ARE DRIVING, THUS 80 HP IS USED. TO DOUBLE THE SPEED, A TOTAL OF 160 HP WILL BE NEEDED.
IN APPROACH NO. 1, AS DISCUSSED IN THIS PARAGRAPH, AN EIGHTY HORSEPOWER MOTOR IS ADDED TO EACH DRIVING UNIT. THE ADDITION CAN BE EITHER PARALLEL BY TAPPING FROM ANOTHER POINT IN THE GEAR BOX, OR SERIES WHERE THE NEW MOTORS ARE MOUNTED IN TANDEM WITH THE OLD SERVO MOTORS ON THE SAME SHAFT. IN THIS CASE,

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IT IS MANDATORY TO BREAK-UP THE 80 HP UNIT TO TWO 40 HP UNITS AND USE ONE ON THE BUCKING UNIT AND ONE ON THE DRIVING UNIT; THUS, THE TWO UNITS WILL BE IDENTICAL AND FORWARD-REVERSE DRIVE CHARACTERISTICS OF THE AXIS WILL BE SIMILAR.

IF THIS METHOD IS USED, THE 40 HP MOTOR SHOULD BE BETWEEN THE GEAR BOX AND THE SERVO MOTOR. THIS APPROACH WILL PROVIDE MAXIMUM SHAFT STIFFNESS BETWEEN SERVO MOTOR AND TACHOMETER AS WELL AS SERVO MOTOR AND GEAR BOX BECAUSE DURING NORMAL OPERATION THE GEAR BOX WILL BE ROTATED THROUGH THE HEAVIER SLEW MOTOR SHAFT AND THE SLEW MOTOR ARMATURE WILL NOT ACT AS A TORSION PENDULUM BETWEEN THE SERVO MOTOR AND THE TACHOMETER.

ANOTHER CONSIDERATION FOR METHOD NO. I IS TO INTERLOCK THE SERVO MOTOR AND TACHOMETER CONNECTIONS SUCH THAT DURING THE SLEW MODE ALL THESE ARE OPEN, PREVENTING ANY VOLTAGE LEVELS, TWICE THE NORMAL LEVEL, FROM BEING FED INTO THE ELECTRONICS.

II - A SECOND METHOD TO SOLVE THIS PROBLEM IS TO REPLACE THE 850 RPM, FRAME SIZE 368, 20 HP MOTORS WITH 1750 RPM SAME FRAME SIZE, 40 HP UNITS.

III - THE SAME RESULTS CAN BE OBTAINED BY RETAINING THE PRESENT 20 HP DRIVE 20 HP BUCKING UNIT DESIGN BUT DOUBLING THE NUMBER OF UNITS.

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IN THIS CASE, THE 850 RPM UNITS SHOULD BE CHANGED TO 1750 RPM, 20 HP, FRAME SIZE 366 UNITS.

IV- ANOTHER POSSIBILITY IS TO USE EDDY CURRENT COUPLINGS IN CONJUNCTION WITH ADDED ON SLEW MOTORS.
THIS METHOD HAS LITTLE CHANCE OF SUCCESS BECAUSE THE EDDY CURRENT COUPLING RATINGS DO NOT GO ABOVE 20 HP. THUS, FOR 160 HP 8 UNITS ARE NEEDED. ARRANGING THEM AROUND GEAR BOXES WILL NOT BE SIMPLE, I.E., TWO UNITS AROUND EACH DRIVING OR BUCKING SERVO MOTOR OF METHOD I, OR ONE UNIT WITH EACH SERVO MOTOR OF METHOD III
IN ADDITION TO THE ABOVE, THE EDDY CURRENT COUPLINGS NEED SEPARATE VENTILATION.
THEIR MAIN ADVANTAGE IS .26 $LB-FT-SEC^2$ INERTIA PER 20 HP UNIT COMPARED TO 4X THAT MUCH FOR A 40 HP SLEW MOTOR.

THE VARIOUS APPROACHES DESCRIBED ABOVE ARE COMPARED IN TABULATED FORM ON THE FOLLOWING PAGE.

CONCLUSION

FROM TABLE I IT CAN BE CONCLUDED THAT, ALTHOUGH IT IS NOT THE LEAST EXPENSIVE APPROACH, USING FOUR 40 HP SERVO MOTORS INSTEAD OF THE 20 HP UNITS PROVIDE THE HIGHEST SERVO PERFORMANCE AND RELIABILITY. MOREOVER, IF ONE UNIT FAILS, THE REMAINING UNITS CAN CARRY ALL TRACKING AND SLEW OPERATIONS AS THEY CAN WITHSTAND 35% OVERLOAD FOR UP TO 5 MIN.

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TABLE OF COMPARISON

METHOD	SERVO PERFORMANCE	MEAN TIME TO FAILURE (RELIABILITY)	SPARES PERFORMANCE	COST PERFORMANCE
1	LOWEST	BEST	LOWEST	BEST
2	BEST	BEST	BEST	MEDIUM
3	BEST	MEDIUM	BEST	LOWEST
4	MEDIUM	BEST	LOWEST	MEDIUM

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8.3.3 SERVO DRIVE PERFORMANCE ANALYSIS FOR 40 HP DRIVE UNITS

THE HARDWARE USED IS GE FRAME 368, 40HP, 1750 RPM, TOTALLY ENCLOSED, FAN COOLED UNITS WITH COMPENSATED WINDINGS FOR LINEAR TORQUE-AMPERE CHARACTERISTICS.

GEAR BOX CHARACTERISTICS ARE GIVEN BELOW:

RATIO: 300/1
STIFFNESS: 295 LB FT/RAD
INERTIA: 3.3 LB-FT SEC^2

LOAD CHARACTERISTICS ARE:

MOTOR INERTIA:	0.41 LB-FT-SEC^2
GEAR BOX INERTIA REFLECTED TO MOTOR SHAFT	3.30 "
LOAD INERTIA REFLECTED TO MOTOR SHAFT	0.24 "
MARGIN	0.25 "
TOTAL	4.20 LB-FT-SEC^2 PER GEAR BOX

REQUIRED SYSTEM OPEN LOOP GAIN TO OVERCOME FRICTION AND CAUSE NO MORE HYSTERESIS THAN ALLOWED IN THE ERROR ANALYSIS IS GAIN = 2400 VOLTS/VOLT = 68 Db

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FOUR UNIT OF DRIVING MOTORS ARE USED. UNDER NORMAL OPERATING CONDITIONS TWO UNITS ARE DRIVING AND TWO UNITS ARE BUCKING.

STABILITY ANALYSIS:
THE CHARACTERISTICS OF THE SELECTED UNIT ARE AS FOLLOWS:

J_M = .42 LB-FT. SEC^2
K_B = 1.26 V/RAD/SEC
K_T = .87 LB-FT/AMP
R_M = .04 OHMS
L_M = .00085 HENRIES

THE ABOVE SYMBOLS ARE EXPLAINED ON PAGE 8.16.

TOTAL LOAD INERTIA USED IS 4.2 LB-FT SEC^2 AS SHOWN ON PAGE NO. 37 TOTAL LOOP RESISTANCE USED IS 0.5 OHMS, THIS VALUE INCLUDES ARMATURE RESISTANCE, POWER AMPLIFIER OUTPUT RESISTANCE AND AMPLIFIER - MOTOR POWER CABLING RESISTANCE.

THE MOTOR PLUS LOAD TRANSFER FUNCTION IS:

$$\frac{\theta_o}{\varepsilon} = \frac{1/K_B}{s\left[1 + \frac{J_T}{\left(\frac{K_B K_T}{R_T}\right)} s\right]\left(1 + \frac{L_M}{R_T} s\right)}$$

$$= \frac{1/1.26}{s\left(1 + \frac{4.2\,s}{\frac{1.26 \times .87}{.5}}\right)\left(1 + \frac{.0085}{.5} s\right)}$$

$$= \frac{.8}{s(1 + 1.9s)(1 + .0017s)}$$

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USING VARIOUS LEVELS OF TACHOMETER FEED BACK GIVES THE ELECTRICAL AND MECHANICAL TIME CONSTANTS TABULATED BELOW:

TACHOMETER FEEDBACK K_G = V/RAD/SEC	MECHANICAL TIME CONST. τ_M	ELECTRICAL TIME CONST. τ_E
10	.21	.002
20	.087	.022
30	.073	.0015
40	.056	.0015
50	.045	.0015
70	.032	.0015

FOR $K_G = 40$ $\quad G_s = \dfrac{.024}{s(1+.056s)(1+.0015s)}$

THE INNER LOOP CHARACTERISTICS ARE

$$\omega_n = \frac{1}{.058} = 17 \text{ RAD/SEC}$$

$$\xi = \frac{.058}{2 \times .0001 \times 17} = 17 \text{ DAMPING RATIO}$$

FOR $K_G = 70$ $\quad G_s = \dfrac{.014}{s(1+.032s)(1+.0015s)}$

THE INNER LOOP CHARACTERISTICS ARE

$$\omega_n = \frac{1}{.033} = 30 \text{ RAD/SEC}$$

$$\xi = \frac{.033}{2 \times .000056 \times 30} = 10 \text{ DAMPING RATIO}$$

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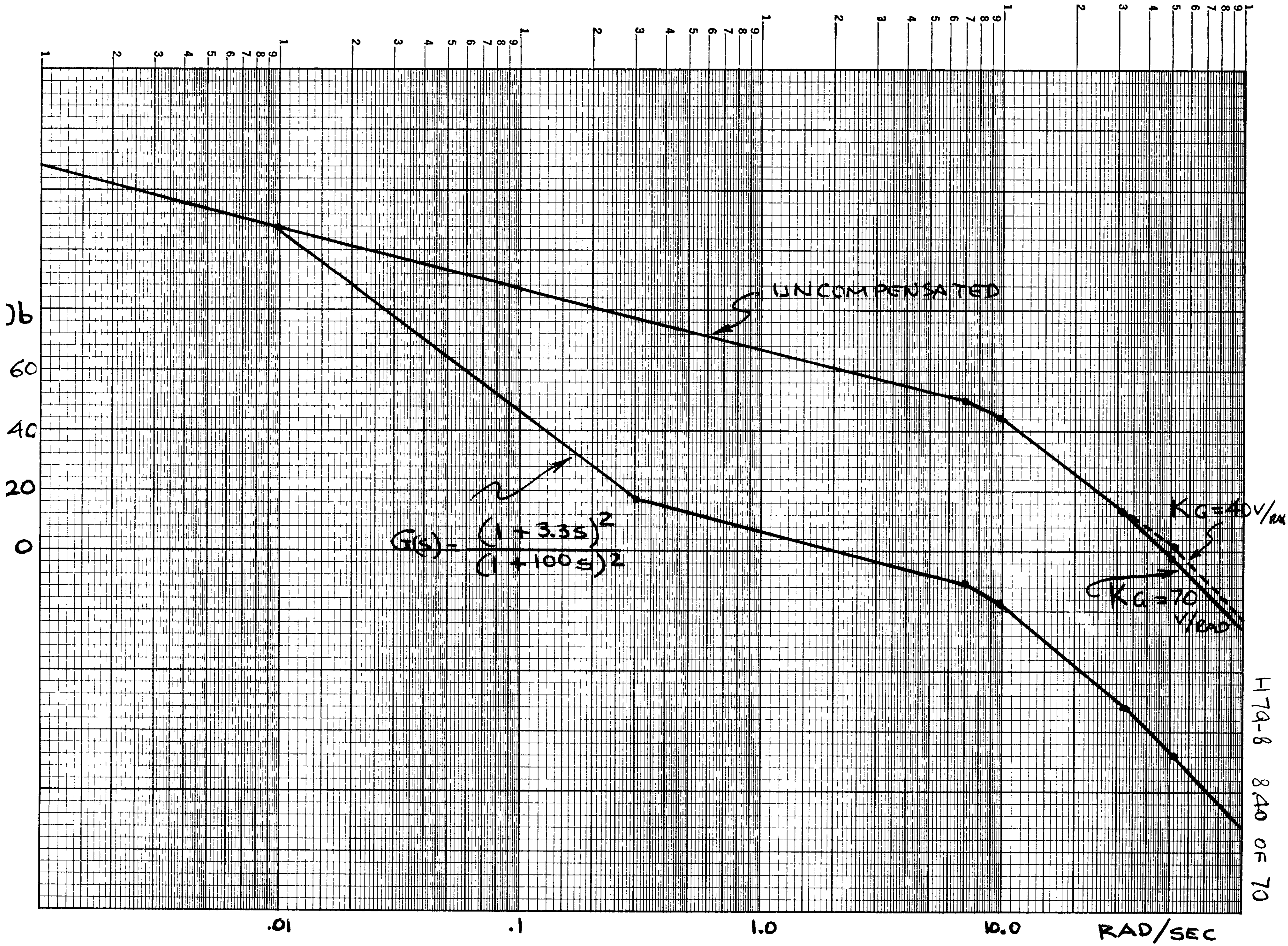
db
60
40
20
0
.01
.1
1.0
10.0
RAD/SEC
UNCOMPENSATED
G(s) = (1 + 3.3s)^2 / (1 + 100s)^2
KG = 40 V/RAD
KG = 70 V/RAD

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ON THE BODE PLOT $K_G = 40$ AND $K_G = 70$ ARE SHOWN. INNER LOOP PERFORMANCE WISE THERE IS LITTLE DIFFERENCE BETWEEN THE TWO LEVELS. THE INFLUENCE OF THIS SPAN ON PHASE MARGIN IS APPROXIMATELY 3° OUT OF 39° AS SHOWN BELOW:

$$G_S = \underbrace{\frac{(1+3.3s)^2}{(1+100s)^2}}_{\text{COMPENSATION NETWORK}} \times \frac{68\ \text{Db}}{\underbrace{(1+.02s)}_{\text{REF. PLATFORM}}\underbrace{(1+.16s)}_{\text{STRUCTURE}}\underbrace{(1+.105s)}_{\text{GEAR BOX}}\underbrace{s(1+.032s)(1+.0015s)}_{\text{MOTOR + LOAD + TACHOMETER}}}$$

SINCE THE ZERO Db CROSSING OF THE COMPENSATED BODE PLOT IS AT 2 RAD/SEC FOR $s = j\omega = j2$ THE PHASE ANGLE IS:

$$\varphi = \frac{82° + 82°}{90° + 90° + 2° + 17° + 12° + 90° + 3° + 1°} = 305° - 164°$$

$$= 141°$$

THE PHASE MARGIN IS: 180 − 141 = 39°

<u>CONCLUSION:</u>

FOUR 40 HP, 1750 RPM, 368 FRAME MOTORS ARE USED WITH SOLID STATE POWER AMPLIFIERS. NO CHANGES ARE REQUIRED IN THE GEAR BOX RATIO, STIFFNESS AND INERTIA CHARACTERISTICS. TO OBTAIN THE NECESSARY PERFORMANCE TACHOMETER COMPENSATION AND LEAD-LAG COMPENSATION ARE NEEDED.
THE ANTENNA CLOSED LOOP BAND WIDTH IS CLOSE TO THE SYSTEM WITH 20 HP UNITS. FOR THIS RANGE OF BAND WIDTH PERTURBANCE ERRORS ARE WITHIN THE ERROR BUDGET.

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8.4 ALTERNATE DRIVE CONCEPTS

8.4.1 DC TORQUER FOR ANTENNA DRIVE AZIMUTH ONLY

IF A TORQUE MOTOR IS USED DIRECTLY COUPLED TO THE WHEELS, THE GEAR BOX WITH A RATIO OF 444/1 FOR EACH ONE OF THE 16 DRIVING UNITS CAN BE ELIMINATED. THUS, THE NEW ANTENNA AXIS TO MOTOR SHAFT RATIO INSTEAD OF 48,600 IS

$$AZ = \frac{48\,600}{444} = 109 = N_1$$

THE LOAD INERTIA REFLECTED TO THE MOTOR SHAFT IS

$$I_{AZ} = \frac{2.5 \times 10^9}{109^2} = 2.1 \times 10^5 \text{ LB FT SEC}^2$$

FOR ALL 16 DRIVING UNITS.

USING SIXTEEN DRIVING UNITS, TORQUE REQUIRED FROM EACH UNIT IS;

$$Tq = \frac{8 \times 10^6}{16 \times 109} = 4,600 \text{ LB FT}$$

OR TOTAL TORQUE AT MOTOR SHAFTS

= 73 000 LB FT

ALTHOUGH TORQUERS WITH UP TO 16,000 LB FT ARE AVAILABLE, THIS WILL REQUIRE 5 DRIVING UNITS VS. 16

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PREVIOUSLY USED 5 HP MOTORS AND GEAR BOXES. 5000 LB FT WOULD BE MORE ADEQUATE FOR SIZE AND POWER AMPLIFIER.

THE DATA CAN BE SUMMED UP AS FOLLOWS:

1 - 16 DRIVING TORQUERS NEEDED DIRECTLY COUPLED TO THE WHEELS

2 - MOTOR SHAFT TO ANTENNA REDUCTION RATIO IS 109/1

3 - LOAD INERTIA REFLECTED TO EACH MOTOR SHAFT IS 13,000 LB FT SEC^2

4 - TORQUE OF EACH UNIT IS 5000 LB FT MAXIMUM (STALL)

5 - TORQUE REQUIRED TO OVERCOME MAX. STATIC FRICTION AS PER CENT OF TOTAL AVAILABLE TORQUE:

$$\frac{1.02 \times 10^6}{8 \times 10^6} \times 100 = 13\ \%$$

MIN. STATIC FRICTION EXPECTED: 5×10^5 LB FT.

6 - RATED MOTOR VOLTAGE

I^2R IS GIVEN AS 23,200 (STALL)

R GIVEN AS 1.6; THUS

$$I = \sqrt{\frac{23200}{1.6}} = 122 \text{ AMPS MAX}$$

RATED VOLTAGE IR = 195 VOLTS

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7- GAIN REQUIRED

13% OF 195 = 27 VOLTS

FOR 1.8 ARC SECOND DEAD BAND AT 2.5 mV / .6 ARC SEC

OPEN LOOP GAIN $\frac{27\,000}{7.5} = 3600$ VOLTS/VOLT

8 - TRANSFER FUNCTION OF MOTOR AND LOAD

$$\frac{\theta_o}{\varepsilon_i} = \frac{1/K_B}{s\left[1 + \frac{J_T}{\left(\frac{K_B K_T}{R_T}\right)} s\right]\left(1 + \frac{L_M}{R_T} s\right)}$$

K_B = 57 V/RAD/SEC

J_M = 36 LB FT SEC^2 MOTOR ONLY

J_T = 36 + 13,000 $\simeq$ 13000 LB FT-SEC^2

K_T = 41.5 LB-FT/AMP

R_T = 1.6 OHMS INCLUDING CABLES, AMPLIFIER OUTPUT, ETC

L_M = .014 HENRIES

L_M/R_T GIVEN AS T_E = .022

$$T_M = \frac{13000}{\frac{57 \times 41.5}{1.6}} = 8.8$$

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TRANSFER FUNCTION:

$$G_s = \frac{.0175}{s(1+8.8s)(1+.022s)}$$

THE MECHANICAL TIME CONSTANT IS EXCESSIVE.

9 – USING TACHOMETER FEED BACK AND TRYING TO FIND OPTIMIZED RANGE OF OPERATION, THE MOTOR PLUS LOAD PLUS TACHOMETER TRANSFER FUNCTION IS:

$$G(s) = \frac{.0175}{s(1+8.8s)(1+.022s)+.0175K_G s} = \frac{G'}{1+G'H}$$

WHERE G' = MOTOR + LOAD TRANSFER FUNCT.
H = TACHOMETER TRANSFER FUNCT.

A – FOR $K_G = 100$ V/RAD/SEC

$$G(s) = \frac{.0064}{s(1+3.2s+.07s^2)}$$

$$= \frac{.0064}{s(1+3.2s)(1+.02s)}$$

$$\omega_n = \sqrt{\frac{1}{.07}} = 3.8 \text{ RAD/SEC}$$

$$\zeta = \frac{3.2}{.07 \times 2 \times 3.8} = 6 \text{ (DAMPING RATIO)}$$

B – TRY $K_G = 1.000$ V/RAD/SEC

$$G_s = \frac{.0095}{s(1+.450s)(1+.025s)}$$

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$\omega_n = 10$ RAD/SEC

$\zeta = 2.3$

C - FOR KG = 4000 V/RAD/SEC

$$G(s) = \frac{246 \times 10^{-6}}{s(1 + .096s)(1 + .028s)}$$

$\omega_n = 19.2$ RAD/SEC $\zeta = 1.2$

ALTHOUGH A VALUE OF KG = 4000 SEEMS HEIGH, IF WE CONSIDER THAT MAXIMUM ANTENNA SPEED IS .105°/SEC RESULTING IN MOTOR SHAFT SPEED OF 11.5°/SEC = .2 RAD/SEC. THUS THE MAXIMUM VOLTAGE IS 800 VOLTS.
FOR SIDEREAL SPEED TACH FEED BACK IS .29 VOLTS AT MINIMUM SPEED ($\frac{1}{10}$ SIDEREAL) TACH FEEDBACK IS 29 MILLIVOLTS. IT IS SUGGESTED THAT FOR SLEWING CONDITIONS ABOVE 33 X SIDEREAL THE TACH. LOOP BE AUTOMATICALLY DISCONNECTED.

THE TRANSFER FUNCTION FOR TRIAL "C" IS SELECTED FOR FURTHER ANALYSIS.

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10- THE OVERALL OPEN LOOP TRANSFER FUNCTION IS GIVEN BELOW:

$$G(s) = \frac{3600}{\underbrace{(1+.02s)}_{\text{REFERENCE PLATFORM}}\underbrace{(1+.16s)}_{\text{STRUKTURE}}\underbrace{s(1+.096s)(1+.028s)}_{\text{TORQUER + LOAD + TACH.}}}$$

GAIN = 3600 = 20 × LOG 3600 = 71.2 Db

THERE IS NO GEAR BOX TRANSFER FUNCTION IN THE ABOVE EXPRESSION.

SINCE THE BODE PLOT CROSSES THE 0 Db AXIS WITH A SLOPE OF 100 Db PER DECADE, COMPENSATION IS REQUIRED.

$$T_{LAG} = \frac{1}{.015} = 67$$

$$T_{LEAD} = \frac{1}{.5} = 2$$

COMPENSATION NETWORK TRANSFER FUNCTION IS:

$$G(s) = \frac{(1+2s)^2}{(1+67s)^2}$$

THE COMPENSATED BODE PLOT CROSSES THE 0 Db AXIS AT 2.5 RAD/SEC.

PHASE SHIFT FOR 2.5 RAD/SEC IS:

$$\phi = \frac{(1+j5)^2}{(1+j167)^2} \times \frac{K}{(1+j.05)(1+j.4)j(1+j.24)(1+j.07)}$$

$= 312°$ LAG $- 158°$ LEAD $= 154°$ LAG

PHASE MARGIN $180° - 154° = 26°$

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TRYING A SECOND COMPENSATION NETWORK,

$$T_{LAG} = \frac{1}{.009} = 110$$

$$T_{LEAD} = \frac{1}{.3} = 3.3$$

$$G(s) = \frac{(1 + 3.3s)^2}{(1 + 110s)^2}$$

PHASE SHIFT = 146° LAG
PHASE MARGIN = 34°

BECAUSE OF THE DISTURBANCE FREQUENCIES, THIS SECOND COMPENSATION NETWORK IS MORE ADEQUATE.

11- CONCLUSION

a - 16 TORQUE MOTORS CAN BE USED TO DRIVE THE AZIMUTH AXIS.

b - IF DIRECT MOUNTED, ALL GEAR BOXES CAN BE ELIMINATED.

c - REDESIGNING OF THESE UNITS MAY BE REQUIRED TO REDUCE DIAMETER AND TO ADD TO THE HEIGHT FOR DIRECT COUPLING.

d - THE RATED TORQUE PER UNIT IS 5000 LB. FT. THE HOUSED UNIT IS 1800 TO 2400 LB EACH.

e - A PHASE MARGIN OF APPX. 34° CAN BE OBTAINED USING PROPER

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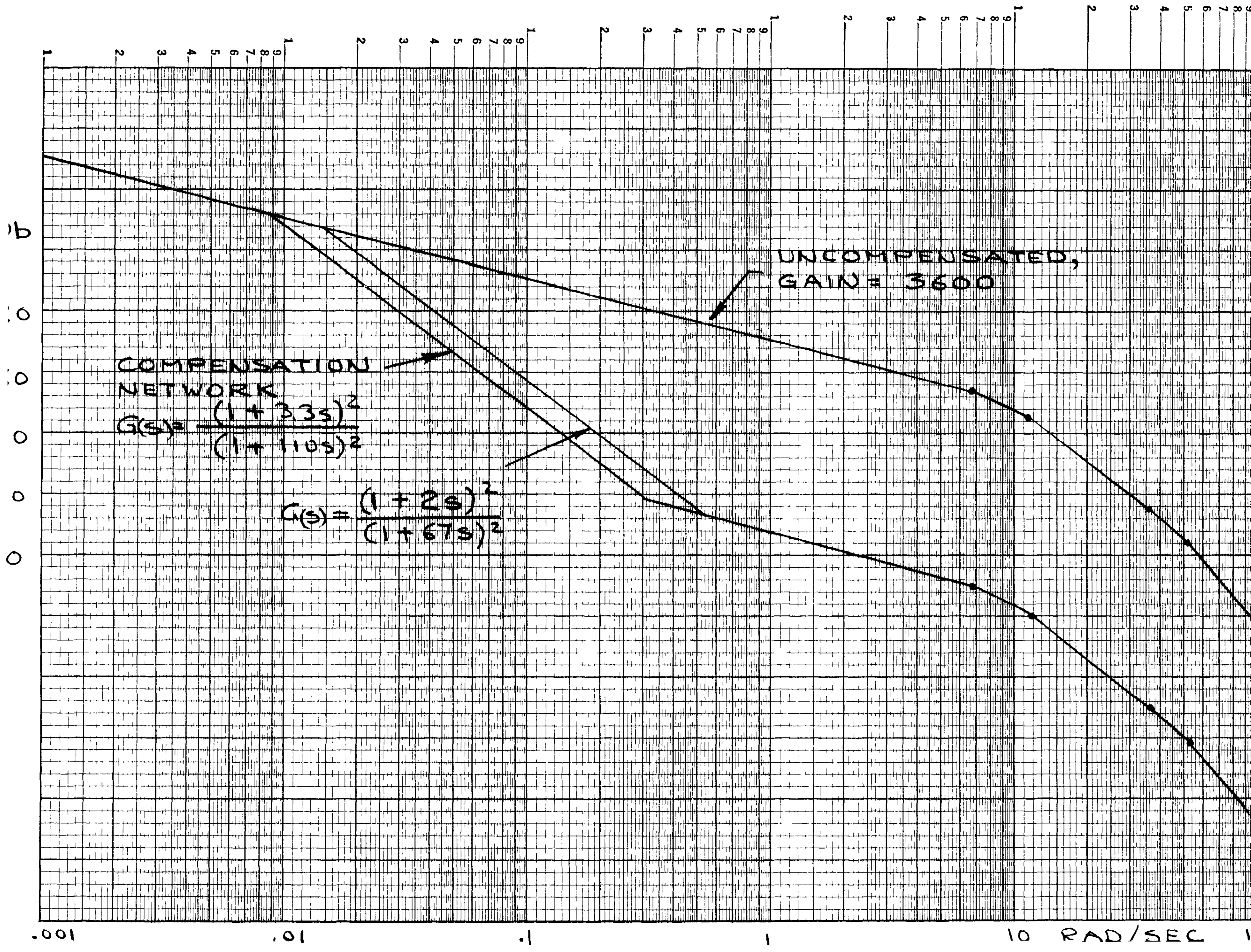

UNCOMPENSATED,
GAIN = 3600
COMPENSATION
NETWORK
G(s) = (1 + 3.3s)^2 / (1 + 110s)^2
G(s) = (1 + 2s)^2 / (1 + 67s)^2
.001
.01
.1
1
10
RAD/SEC
100

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TACHOMETER COMPENSATION AND COMPENSATION NETWORKS.

f – APPX. 0.4 CPS CLOSED LOOP BAND WIDTH SEEMS FEASIBLE IF THE ANTENNA STRUCTURAL RESONANT FREQUENCY IS AROUND 1.0 CPS. THIS FREQUENCY IS APPROXIMATELY ONE OCTAVE HIGHER THAN WORST CASE DISTURBANCE FREQUENCY. THIS, AND THE CALCULATED 34° PHASE MARGIN IS EXPECTED TO PROVIDE SATISFACTORY PERFORMANCE.

g – THE UNIT USED IS GE FRAME NO. 30229 WITH 39 1/4" HOUSING DIAMETER AND 11 INCHES HEIGHT.

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8.4.2 EDDY CURRENT COUPLINGS FOR DRIVE TORQUE AND SPEED MODULATION

THESE COUPLINGS ARE USED IN CONJUCTION WITH AC OR DC MOTORS RUNNING AT CONSTANT SPEED. THEORETICALLY THE MOTOR RESPONSE CAN BE ELIMINATED FROM THE TRANSFER FUNCTION IF WE ASSUME HIGH INERTIA MOTOR ARMATURE. AS AC MOTORS ARE MORE ECONOMICAL AND THERE IS NO DIFFERENCE BETWEEN AC AND DC PERFORMANCE, AC IS USED IN MOST CASES.

OTHER NOTES:

a - THE BEST OPERATIONAL RANGE OF A 20 HP UNIT IS 300 TO 600 RPM AS SLIP CAUSES HEAT; YET, IT IS NEEDED FOR CONTROL ANTENNA SPEED REQUIREMENTS ARE .0175 RPM TO 1/10 SIDEREAL OR A RATIO OF 250 TO 1. THIS RANGE IS NOT DESIRABLE FOR EDDY CURRENT COUPLINGS.

b - THE MOTORS ARE RUNNING AT FULL SPEED ALTHOUGH MOST OF THE TIME ANTENNA MOVEMENT IS VERY SLOW.

c - EACH UNIT NEEDS 1100 CFM COOLING AIR.

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d - THE WEIGHT OF EACH UNIT IS 1800 LBS

e - TACHOMETER COMPENSATION IS NOT POSSIBLE FOR THIS APPLICATION.

f - THE SIMPLIFIED TRANSFER FUNCTION IS $G(s) = \frac{1}{(1+.2s)}$

WITH 70% OVER EXCITATION THE TIME CONSTANT IS .2. ACTUAL TIME CONSTANT IS .34.

COMPARED TO THE OTHER APPROACHES

.016 FOR THE 5 HP MOTOR + TACH
.032 " " 20 " " "
.096 " TORQUER + TACH

IT REPRESENTS A VALUE 3X WORSE EVEN IF IT IS COMPARED TO THE TORQUER IT IS ALSO LOWER THAN THE ANTENNA STRUCTURAL NATURAL FREQUENCY INDICATING THAT IT WILL REDUCE THE PHASE MARGIN BY APPX 15° DOWN TO 25°. WHICH IS MARGINAL COMPARED TO 40°.

g - <u>OVERLOAD CAPACITY</u>:
IF DC MOTORS (5HP OR 20 HP) ARE USED, UP TO 900 %

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INSTANTANEOUS OVERLOAD CAPACITY IS AVAILABLE
IN CASE OF COUPLINGS, THIS IS POSSIBLE ONLY IF COUPLING AND MOTOR ARE OVERSIZED.

h - A TIME CONSTANT OF .34 MEANS A ROLL OF FREQUENCY OF 3 RAD/SEC COMPARED TO 3.8 RAD/SEC OF THE ANTENNA STRUCTURE, NOW THE DRIVE IS LIMITING THE ANTENNA PERFORMANCE RATHER THAN THE STRUCTURE. THIS WILL FURTHER REDUCE THE OPERATIONAL ANTENNA BAND WIDTH AND INCREASE ITS VULNERABILITY TO DISTURBANCE FREQUENCIES ABOVE 0.5 RAD PER SEC.

i - <u>CONCLUSIONS:</u>
BECAUSE OF PERFORMANCE REQUIREMENTS, THE EDDY CURRENT APPROACH IS CONSIDERED TO BE INFERIOR TO DC MOTORS OR TORQUERS.

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8.5 REFINEMENTS OF SERVO STABILITY AND LOOP COMPENSATION

IN SECTIONS 8.2 AND 8.3 IT WAS SHOWN THAT STABLE OPERATION IS POSSIBLE BY USING TACHOMETER FEEDBACK COMPENSATION AND DOUBLE LEAD-LAG COMPENSATION FOR EACH AXIS DRIVE.

THE ANALYSIS IN THE ABOVE REPORTS INDICATES THAT THE CLOSED LOOP BAND WIDTH WILL BE AROUND 2.5 RAD/SEC.

IT WAS SHOWN IN SECTIONS 8.1 THAT INCREASING THE CLOSED LOOP SERVO DRIVE BAND WIDTH WILL REDUCE THE DISTURBANCE FREQUENCY EFFECTS AND THUS WILL REDUCE THE PHASE MARGIN REQUIREMENTS TO COUNTERACT THE WIND GUST DISTURBANCES.

THE DOUBLE LEAD-LAG COMPENSATION NETWORKS IN SECTIONS 8.2 AND 8.3 ARE EXPRESSED BY THE FOLLOWING RELATIONSHIPS:

$$G_s = \frac{(1+2s)^2}{(1+62s)^2} \quad \text{AND} \quad G_s = \frac{(1+3.3s)^2}{(1+91s)^2}$$

IMPLEMENTATION OF A TIME CONSTANT ABOVE 5 USUALY IS AVOIDED IN THE INDUSTRY, SINCE RESISTOR VALUES ABOVE 1 MEG OHM ARE NOT CONSIDERED ADEQUATELY SELECTED BECAUSE DUST, MOISTURE ETC. COLLECTED ON THE RESISTOR OR ABSORBED BY THE RESISTOR ELEMENT CAN CAUSE DRIFT AND AGEING. SIMILARLY, CAPACITORS ABOVE 5 MF ARE NOT WELCOME IN COMPENSATION CIRCUITS. IF CAPACITORS ABOVE 5 MF ARE USED, THEY BECOME PROPORTIONALLY BULKY. TANTALUM OR

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ELECTROLYTIC CAPACITORS CANNOT BE USED BECAUSE OF SEVERAL DISADVANTAGES, I.E. HIGH LEAKAGE, RAPID AGEING, SELF-GENERATED DC POTENTIAL BETWEEN THE TERMINALS AND WIDE TOLERANCE LIMITS.

THUS, IMPLEMENTATION OF A TIME CONSTANT $\tau = 62$ WILL REQUIRE AS AN EXAMPLE, 5 MF OF CAPACITANCE AND 12.4 MEG OHMS OF RESISTANCE OR 1 MEG OHM OF RESISTANCE BUT 62 MF CAPACITANCE, DEPENDING WHICH PARAMETER IS CONTROLLED OR LIMITED.

HOWEVER, 5 MF AND 1MEG OR $\tau = 5$ WOULD BE MORE DESIRABLE.

IF THE BODE PLOT ON PAGE 8.20 IS RECONSIDERED AND TWO OTHER TECHNIQUES ARE USED, THE RESULTING TIME CONSTANTS CAN BE LIMITED NOT TO EXCEED 5 SEC. AND THE CLOSED LOOP BAND WIDTH (ZERO DB CROSSING OF THE BODE PLOT) CAN BE IMPROVED.

FIRST, TRIPLE LEAD-LAG NETWORKS ARE USED. THESE ARE RC NETWORKS AROUND OPERATIONAL AMPLIFIERS. THESE NETWORKS DO NOT HAVE EXACTLY THE SAME ROLL-OFF FREQUENCIES BECAUSE OF COMPONENT TOLERANCES SUCH A REQUIREMENT DOES NOT EXIST. IT IS EXPECTED THAT THE INDIVIDUAL ROLL-OFF FREQUENCIES WILL BE WITHIN ±15% TO EACH OTHER.

SECOND, THE EFFECTS OF INSERTING A "POLE" NEAR THE STRUCTURAL FREQUENCY AND A "ZERO" APPROXIMATELY 3 OCTAVES AWAY ARE DEMONSTRATED.

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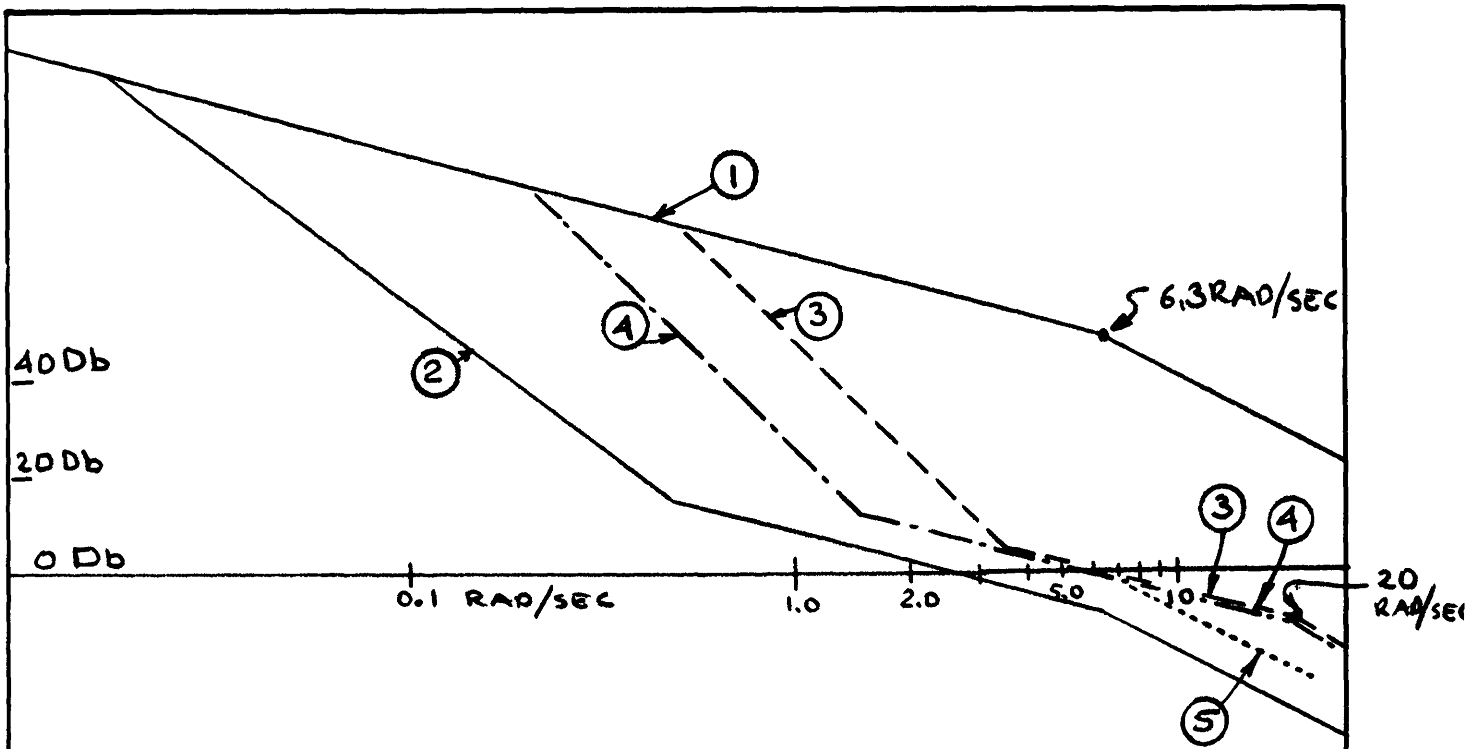

① UNCOMPENSATED BODE PLOT (PAGE 8.20)

② COMPENSATION NETWORK $\frac{(1+2s)^2}{(1+62s)^2}$ USED

③ COMPENSATION NETWORK $\frac{(1+.28s)^3}{(1+2s)^3}$ USED ALSO "POLE" IS INSERTED AT 6.3 RAD/SEC AND "ZERO" IS INSERTED AT 20 RAD/SEC

④ COMPENSATION NETWORK $\frac{(1+.67s)^3}{(1+5s)^3}$ WITH "POLE" AND "ZERO" INSERTION AS ABOVE UNDER ITEM #3.

⑤ COMPENSATION NETWORK AS SHOWN UNDER ITEM NO. 4 LESS "POLE" AND ZERO INSERTION.

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THE TRANSFER FUNCTION OF THE DRIVE SYSTEM EXCLUDING THE LEAD-LAG COMPENSATION NETWORK IS:

$$G_s = \frac{K}{\underbrace{(1+.02s)}_{\text{PLATFORM}}\underbrace{(1+.16s)}_{\text{STRUCTURE}}\underbrace{(1+.013s)}_{\text{GEAR BOX}}\underbrace{s(1+.016s)(1+.0085s)}_{\text{MOTOR, TACHOMETER, LOAD}}}$$

FOR PLOTS NO. 3 TO NO. 5 THE ZERO Db CROSSING IS AT 6 RAD/SEC.

REPLACING "s" BY jW AND SUBSTITUTING W = 6 RAD/SEC GIVES THE FOLLOWING RESULTS FOR THE COMPENSATION NETWORKS TABULATED ON PAGE NO. 3 OF THIS REPORT:

PLOT ③
PHASE LAG = 212°
PHASE MARGIN = −32°
PERFORMANCE = UNSTABLE

PLOT ④
PHASE LAG = 158°
PHASE MARGIN = +22°
PERFORMANCE = STABLE

PLOT ⑤
PHASE LAG = 186°
PHASE MARGIN = −6°
PERFORMANCE = UNSTABLE

CONCLUSION

1- REFINEMENTS ARE POSSIBLE ON THE COMPENSATION NETWORKS USED IN REPORTS NO. 2 AND NO. 3. AN EXAMPLE IS SHOWN ABOVE. THE BENEFITS ARE:

a- INCREASED BAND WIDTH, RESULTING IN BETTER OVERALL DYNAMIC PERFORMANCE, IN GENERAL, PERTURBANCE ERROR REDUCTION IN PARTICULAR.

b- REDUCTION OF NETWORK TIME CONSTANTS; THUS, PROVIDING EASE OF IMPLEMENTATION.

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8.6 SERVO DRIVE INTERLOCKS

THE FOLLOWING INTERLOCKS REQUIREMENTS HAVE TO BE CONSIDERED:

1- THE POSITIONING SERVO UNITS ALL HAVE A COMMON REFERENCE INPUT DERIVED FROM THE REFERENCE PLATFORM. THUS, IF ONE DRIVING UNIT GETS AHEAD OF THE OTHERS DUE TO TOLERANCES IN HARDWARE OR DISTURBANCE, THERE SHOULD BE A FEEDBACK SIGNAL CORRECTING THE INDIVIDUAL UNIT.

2- THE SAME UNIT WILL PERFORM AS A DRIVING UNIT AS WELL AS A BUCKING UNIT WHERE THE BUCKING UNIT ALWAYS HAS A FIXED RATIO OF OUTPUT TORQUE COMPARED TO THE DRIVING UNIT. BECAUSE OF VARIATIONS IN THE HARDWARE, THE BUCKING RATIO SHOULD BE ADJUSTABLE.

3- THE SELECTED SERVO MOTORS CAN HAVE UP TO 900% OVERLOAD FOR UP TO 0.5 SECONDS. HOWEVER, TO PERFORM UNDER THESE CONDITIONS, THE POWER AMPLIFIER SHOULD HAVE SIMILAR OVERLOAD CAPABILITIES. THIS AFTER A CERTAIN LIMIT BECOMES PROHIBITIVE. THEREFORE, OVERLOAD CONTROL IS NEEDED IN THE INDIVIDUAL UNITS.

FIGURE NO. 1 ON THE FOLLWG. PAGE REPRESENTS THE DRIVE SERVO INTERFACE WITH THE REFERENCE PLATFORM, GENERATION OF THE POSITION ERROR SIGNAL AND THE MECHANICAL FEED-BACK PATH.

FIGURE NO. 2 SHOWS A BLOCK DIAGRAM FOR DRIVE-BUCK RATIO SELECTION AND UNIT TORQUE CONTROL.

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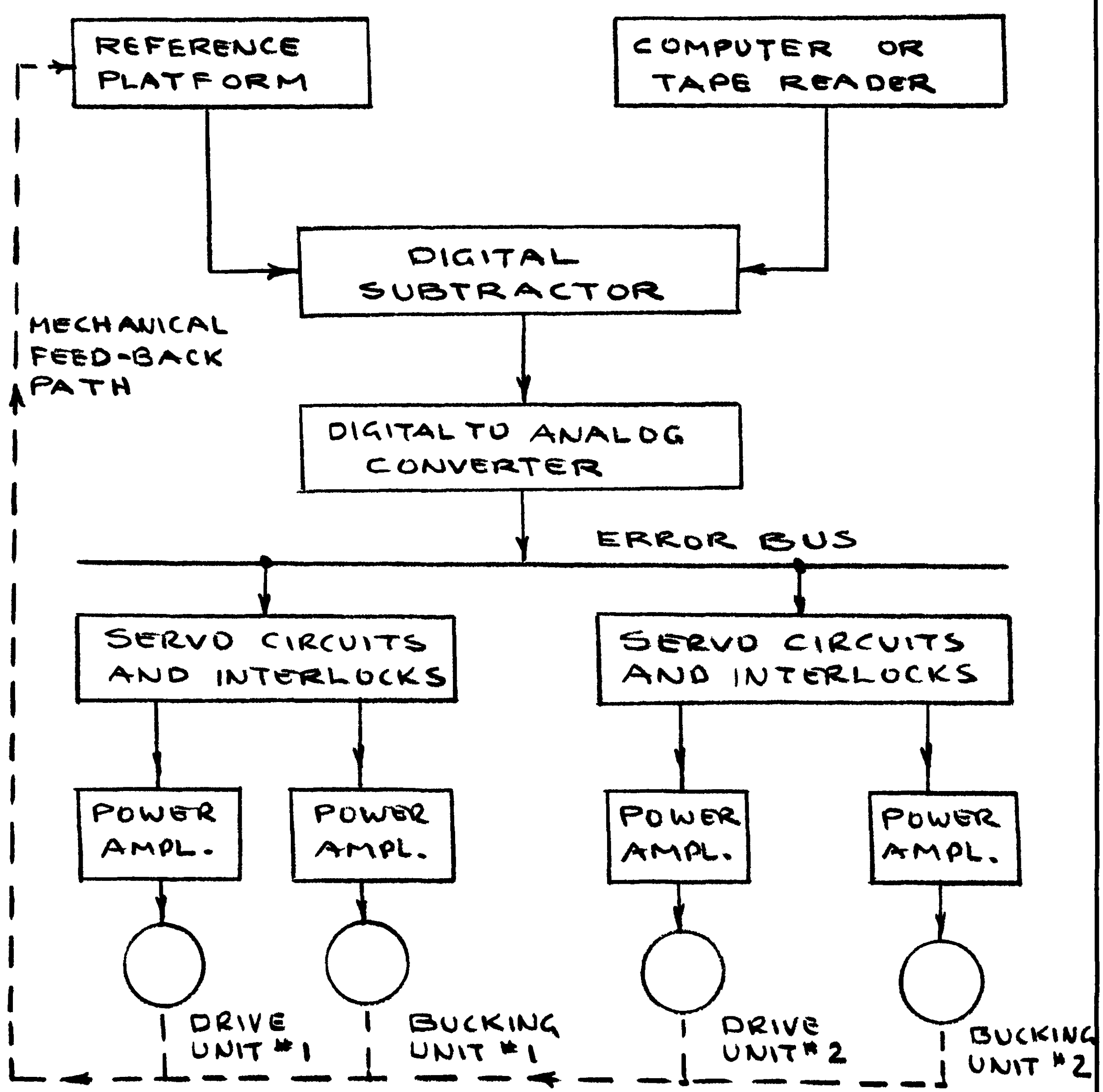

FIGURE NO. 1

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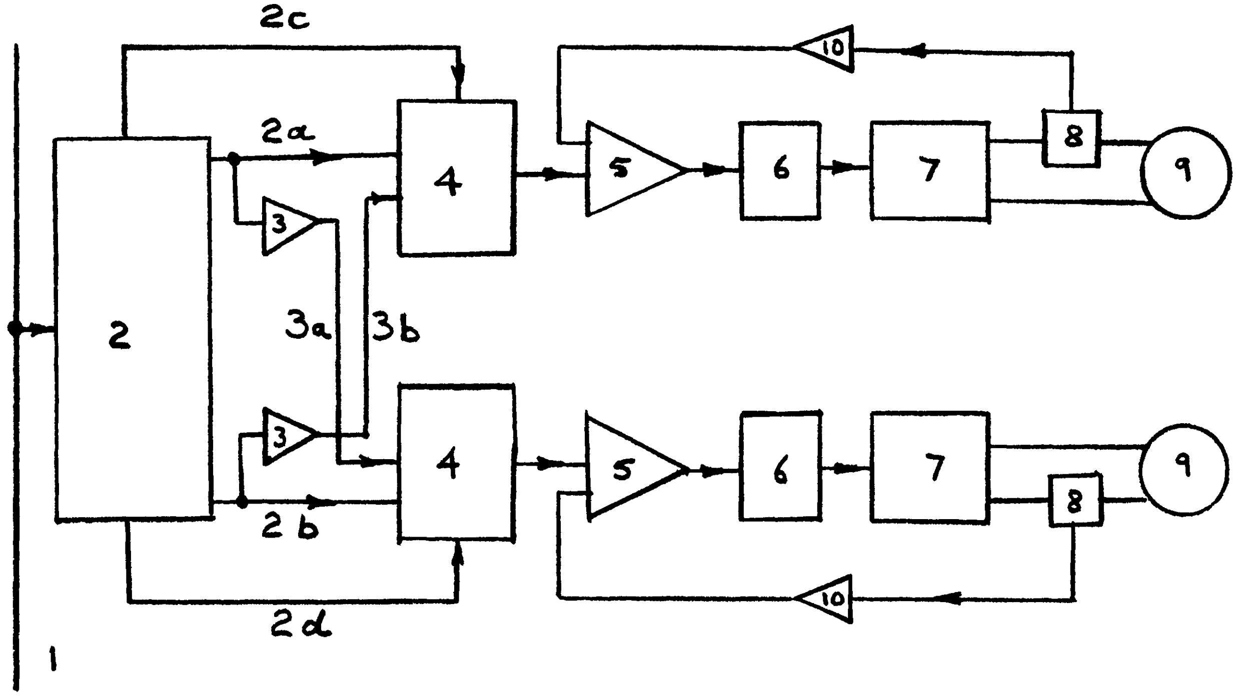

FIGURE NO. 2

1 - ERROR BUS, SEE FIG. NO. 1
2 - ERROR POLARITY DISCRIMINATOR.
2a - ANALOG DRIVING SIGNAL, POSITIVE ERROR.
2b - ANALOG DRIVING SIGNAL, NEGATIVE ERROR.
2c - LOGIC SIGNAL, POSITIVE ERROR.
2d - LOGIC SIGNAL, NEGATIVE ERROR.
3 - BUCKING TORQUE RATIO SETTING.
3a - BUCKING SIGNAL, POSITIVE ERROR.
3b - BUCKING SIGNAL, NEGATIVE ERROR.
4 - DRIVE OR BUCKING ANALOG SIGNAL SWITCHING
5 - COMPARATOR, ERROR VS. TORQUE OUTPUT
6 - SERVO COMPENSATION CIRCUITS
7 - POWER AMPLIFIER
8 - TORQUE SENSOR
9 - SERVO MOTOR
10 - TORQUE LIMIT SETTING

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FIGURE NO. 2 REPRESENTS SOME OF THE FUNCTIONS IN THE "SERVO CIRCUITS AND INTERLOCKS" BLOCK OF FIGURE NO. 1

THE OPERATION OF FIG. NO. 2 IS DESCRIBED BELOW:

THE ERROR SIGNAL FROM THE ERROR BUS IS FED TO THE ERROR POLARITY DISCRIMINATOR. THIS CIRCUITRY HAS TWO FUNCTIONS:

a- PROVIDE POSITIVE AND NEGATIVE ANALOG ERROR SIGNALS ON SEPARATE TERMINALS.

b- PROVIDE SWITCHING SIGNALS (LOGIC SIGNALS) INDICATIVE OF POSITIVE AND NEGATIVE ERROR.

THE BLOCKS #3 ON FIG. NO. 2 PROVIDE ADJUSTIBLE BUCKING SIGNALS TO ANALOG SIGNAL SWITCHING CIRCUITS (#4) WHERE, THE CORRECT SIGNAL IS SELECTED BY LOGIC SIGNALS 2c AND 2d.

THE COMPARATOR RECEIVES TWO VOLTAGE SIGNALS OF WHICH ONE IS PROPORTIONAL TO ERROR AND THE SECOND PROPORTIONAL TO UNIT TORQUE, THESE TWO VARIABLES CAN BE COMPARED BECAUSE THEY BOTH CAN BE SCALED IN TERMS OF SERVO STIFFNESS.

THE SIGNAL THUS GENERATED IS FED THROUGH THE SERVO COMPENSATION CIRCUITS AND POWER AMPLIFIER TO ENERGIZE THE SERVO MOTOR, THE TORQUE SENSOR HAS ISOLATED FLOATING INPUT BUT REFERENCED OUTPUT CONVERTING MOTOR TORQUE TO A VOLTAGE SIGNAL. ITEM NO. 10 ON FIG. NO. 2 IS AN ADJUSTABLE SCALER AND LIMIT SETTER FOR THE TORQUE SIGNAL.

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8.7 ERROR CALCULATIONS

THE OVER ALL SYSTEM ERROR CONSISTS OF THREE MAIN COMPONENTS:

REFERENCE PLATFORM ERROR
DRIVE SERVO HYSTERESIS ERROR
WIND GUST DISTURBANCE ERROR

THE REFERENCE PLATFORM ERROR WAS CALCULATED AS APPX 4.0 ARC SEC. ROOT SUM SQUARE COMBINATION OF ALL INDEPENDENT ERRORS.

DRIVE SERVO HYSTERESIS ERROR HAS BEEN LIMITED TO 1.9 ARC SEC AS SHOWN IN REPORTS NO. 2 AND NO. 3 FOR THE 5HP AND 20 HP DRIVE SERVO ANALYSIS.

THE WIND GUST DISTURBANCE ERRORS ARE CALCULATED BELOW USING TWO METHODS.

METHOD NO. 1

THIS METHOD IS A WORST CASE APPROACH. IT DOES NOT TAKE THE ANTENNA STRUCTURE (DISH) FILTERING EFFECT INTO ACCOUNT.

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FROM REPORT NO. 1

$$y_0 = \frac{F_0/k}{\sqrt{\left[1+\left(\frac{\omega^2}{\Omega^2}\right)\right]^2 + \left[2\left(\frac{\omega}{\Omega}\right)\left(\frac{c}{c_c}\right)\right]^2}}$$

WHERE

y_0 = MAXIMUM DISPLACEMENT IN RADIANS

F_0 = DISTURBANCE FORCE 2.8×10^6 LB-FT

ω = DISTURBANCE FREQUENCY, 2 RAD/SEC

k = COMBINED EFFECT OF SERVO AND STRUCTURAL STIFFNESS
AZ. STRUCTURE : 1.9×10^{12} LB FT/RAD
AZ. SERVO : 1.11×10^{11} "
EL. STRUCTURE : 3.0×10^{12} "
EL. SERVO : $.61 \times 10^{11}$ "
SINCE IN EACH CASE THE STRUCTURAL STIFFNESS IS BY AT LEAST ONE ORDER OF MAGNITUDE HIGHER THAN SERVO STIFFNESS, ONLY THESE LAST VALUES ARE USED.

Ω = BAND WIDTH, STRUCTURE PLUS DRIVE = 2.5 RAD/SEC

α = GUST FACTOR. THE NUMERATOR IN THE ABOVE EXPRESSION IS

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MULTIPLIED BY $\alpha = .20$ BECAUSE, IT IS THE GUST COMPONENT IN THE WIND WHICH WILL CAUSE A DISTURBANCE ERROR.
A STATIC WIND LOAD WILL BE CORRECTED BY THE REFERANCE PLATFORM AND WILL NOT ENTER THE ERROR BUDGET.

$$y_0 = \frac{9.2}{1.17} \times 10^{-6} \text{ RAD}$$
$$= 1.6 \text{ ARC SEC}$$

METHOD NO. 2

THIS METHOD USES A STATISTICAL APPROACH OF WIND TORQUE AND TAKES THE DISH FILTER EFFECT INTO ACCOUNT, I.E THE GUST FRONT PROGRESSING OVER THE ENTIRE DIAMETER OF THE DISH.

DATA

ω_0 = WIND VELOCITY SPECTRAL DENSITY = 2 RAD/SEC

ω_1 = STRUCTURAL FILTER EFFECT = $\frac{1}{\tau}$ WHERE τ IS THE TIME REQUIRED FOR THE WIND STEP FRONT TO PASS ALONG THE MAXIMUM STRUCTURAL DIMENSION.

$$\tau = \frac{300 \text{ FT}}{18 \text{ MI/HR}} = 11.4 \text{ SEC}$$

$$\omega_1 = \frac{1}{11.4} = 0.088 \text{ RAD/SEC}$$

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T_0 = WIND TURQUE INPUT, 2.8×10^6 LB-FT

α = GUST FACTOR, RMS VELOCITY VARIATION AS COMPARED TO AVERAGE WIND VELOCITY.

C_1 = WORST CASE ADMITTANCE OF SERVO PLUS STRUCTURE COMBINATION

$C_1 = \frac{1}{K}$, ELEVATION IS WORST WITH 560 000 LB-FT FOR 1.9 ARC SEC WHICH CORRESPONDS TO

$K = 6.1 \times 10^{10}$ LB-FT / RAD OR

$C_1 = .16 \times 10^{-10}$ RAD / LB-FT

THE RMS ERROR IS GIVEN BY EXPRESSION

$$\mathcal{E}_{rms} = \frac{4 \alpha T_0 C_1}{\sqrt{2 \pi w_0}} \times \left[\sum \text{POWER SPECTRUM INTEGRANT} \right]^{\frac{1}{2}}$$

TO BE ABLE TO COMPARE METHOD NO. 1 AND METHOD NO. 2 RESULTS, METHOD NO. 2 WILL BE CALCULATED WITHOUT THE BENEFIT OF THE POWER SPECTRUM INTEGRANT.

$$\mathcal{E}_{rms} = \frac{4 \times .2 \times 2.8 \times 10^6 \times .16 \times 10^{-10}}{\sqrt{6.28 \times 2}}$$

$$= 10.2 \times 10^{-6} \text{ RAD} = 2.1 \text{ ARC SEC}$$

THIS COMPARES FAVORABLY WITH 1.6 ARC SEC

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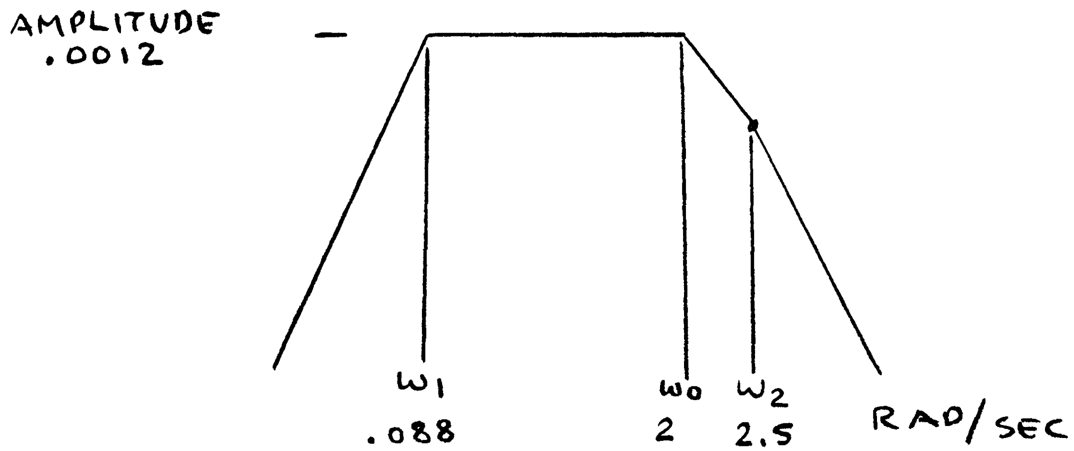
OF METHOD NO. 1.

CORRECTING THE 2.1 ARC SEC FOR THE POWER SPECTRUM:



THE ABOVE DIAGRAM REPRESENTS THE POWER SPECTRUM ON LOG-LOG SCALE.

THE AMPLITUDE RATIO IS DETERMINED BY $A = \left(\frac{W_1}{W_2}\right)^2$ WHERE W_2 IS THE ANTENNA DRIVE CLOSED LOOP RESPONSE AT 2.5 RAD/SEC AND W_1 IS .088 RAD/SEC AS SHOWN ON PAGE 3.

$$A = \left(\frac{.088}{2.5}\right)^2 = .0012$$

THE AREAS BELOW .088 AND ABOVE 2.5 RAD/SEC ARE NEGLIGIBLE.
THE INTEGRANT FROM .088 TO 2 IS $.0012(2 - .088)$. SIMILARLY FROM 2 TO 2.5 THE INTEGRANT IS $.0012\left(\frac{2.5-2}{2.5 \times 2}\right)$

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THUS, THE SQUARE ROOT OF THE SUM OF THE POWER SPECTRUM INTEGRANT BECOMES:

$$\sqrt{\Sigma \phi} = \sqrt{.0023 + .0001} = .05$$

THUS, 2.1 x .05 = .1 ARC SEC RMS WIND GUST PERTURBANCE ERROR IS OBTAINED.

CONCLUSION

THE RSS (ROOT SUM SQUARE) COMBINATION OF PLATFORM, DRIVE SERVO HYSTERESIS AND WIND GUST ERRORS WILL BE IN THE RANGE:

4.5 TO 4.9 ARC SEC
WORST CASE

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8.8 COST-ESTIMATE

THE COST FIGURES LISTED IN THE FOLLOWING PAGE APPLY TO ELEVATION- AND AZIMUTH DRIVE-SYSTEMS HAVING SLEW RATES OF 12°/MIN. AND 18°/MIN. RESPECTIVELY (4-40 HP, 16-15 HP. UNITS)

HARDWARE DESCRIPTION:

ELEVATION - FOUR UNITS OF 40 HP, 1750 RPM NO. 368 FRAME SIZE DC SERVO MOTORS.

FOUR INDUSTRIAL TYPE PERMANENT MAGNET TACHOMETERS

FOUR SCR TYPE SOLID STATE POWER AMPLIFIERS

FOUR ANALOG SERVO CIRCUITRY AND INTERLOCKS

FOUR SETS OF AC POWER SWITCH-GEAR AND DELTA-DELTA POWER TRANSFORMERS

POWER AND CONTROL CABLING.

AZIMUTH - SIXTEEN UNITS OF 15 HP, 2500 RPM NO 365 FRAME DC SERVO MOTORS

SIXTEEN SETS OF COMPATIBLE HARDWARE AS LISTED ABOVE FOR ELEVATION.

SUPPLIERS ARE AS FOLLOWS :

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SUBJECT: DRIVE SYSTEM

LIST OF SUPPLIERS:

1. - GENERAL ELECTRIC CO. — DC-MOTORS
212 N. VIGNES ST.
LOS ANGELES, CALIF. 90012
TEL. - 213-625-7381
MR. MICHALSKY
MR. A. UWE
MR. J.F. MILLER

2. - RELIANCE ELECTRIC & ENG'G CO. — DC-MOTORS & CONTROL EQUIPMENT
24710 EUCLID DRIVE
CLEVELAND, OHIO 44117 OR
980 MONTEREY PASS ROAD
MONTEREY PARK, CALIF. 91754
TEL 213-262-2121

3. - SWEO-ASSOCIATES, INC. — CONTROLS & SERVO
365 CONVENTION WAY
REDWOOD CITY, CALIF 94063
TEL. - 415-369-2555

4. - WESTAMP
1542, 15th ST.
SANTA MONICA, CALIF. 90404
TEL - 213-393-0401

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COST SUMMARY:

A) AZIMUTH SYSTEM:

MOTORS	:	$ 45,000.-
POWER AMPLIFIERS	:	72,000.-
AC-POWER EQUIPMENT	:	13,000.-
CONTROLS	:	40,000.-
MISCALL. HARDWARE	:	12,000.-

TOTAL COST OF EQUIPMENT: $ 182,000.-

B) ELEVATION SYSTEM:

MOTORS	:	$ 32,000.-
POWER AMPLIFIERS	:	48,000.-
AC-POWER EQUIPMENT	:	6,000.-
CONTROLS	:	4,000.-
MISCALL. HARDWARE	:	4,000.-

TOTAL COST OF EQUIPMENT: $ 94,000.-

TOTAL COST OF DRIVE SYSTEMS: $ 276,000.-

USE $ 300,000.- IN ESTIMATE!

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