ACD 9503

FINAL REPORT
FOR THE
TWIN CMG SYSTEMS

April 1969

Contract No. NAS 9-8181

Contractor:	General Electric Company Avionic Controls Department P.O. Box 5000 Binghamton, New York
Contracting Officer:	National Aeronautics and Space Administration Manned Spacecraft Center Houston, Texas 77058
Prepared by:	G. F. Auclair N.S. Chester

NASA CR 101728

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FOREWORD

This report was prepared by the General Electric Company, Avionic Controls Department, Binghamton, New York, on Contract Number NAS9-8181, "Twin CMG Systems", administered under the direction of the National Aeronautics and Space Administration, Manned Spacecraft Center. Mr. E. L. Tilton was Technical Monitor.

This is the final report, covering the ten-month period July 1968 through April 1969, summarizing the work performed in the design, development, fabrication, and testing of three Twin Control Moment Gyro Systems.

This work was a group effort with the following principle contributors and their field of effort: G. F. Auclair, Project Engineer, R. B. Seminski, Lead Mechanical Design Engineer, R. L. Bichler, Gyro Designer, P. L. Schriebmaier, Mechanical Assembly and Test, D. W. Pepin, Electrical Design Engineer, and N. S. Chester, System Test Engineer. This report was prepared by the Avionic Controls Department of the General Electric Company under publication number ACD 9503.

ABSTRACT

Three Twin Control Moment Gyroscope Systems have been developed, fabricated, tested and delivered to NASA's Manned Spacecraft Center. This work was conducted on contract number NAS9-8181.

Work on this program was directed toward providing a control moment gyro system that is compatible with the NASA/MSC Air-Bearing Space Vehicle Motion Simulator. The hardware supplied includes six (6) single-degree-of-freedom control moment gyroscopes (CMG) mounted in three (3) twin pairs, three (3) electronic packages, and three (3) mounting fixtures for alignment plus the analyses, reports, drawings, and manuals necessary to their description, operation, and maintenance.

Main characteristics of each Twin CMG System are

Momentum Storage (adjustable)	10-40 ft-lb-sec
Maximum Output Torque	150 ft-lb

The three Twin CMG Systems were thoroughly tested and evaluated prior to delivery to NASA. They were all found to meet or exceed all of the specifications.

Section 1

INTRODUCTION AND SUMMARY

This report summarizes the work performed under contract NAS9-8181 concerning the design, fabrication, and acceptance testing of three Twin CMG Systems for NASA/MSC.

A Twin CMG System consists of two single-degree-of-freedom control moment gyros (CMG's) aligned in a mounting frame, and the control electronics (for gimbal control and spin motor power). The CMG's are arranged so that the control torque is always directed about a single-axis, independent of gyro gimbal angle. This allows the use of large gimbal angles so that a major portion of the stored momentum may be transferred to the space vehicle under control without introducing cross-coupling control torques.

The three Twin CMG Systems will be used on the NASA/MSC Space Vehicle Motion Simulator (SVMS) to investigate control schemes for a broad range of space vehicle configurations. The CMG's supplied incorporate variable momentum capabilities, very high output torque, and precision direct-drive gimbal control using electrical rate feedback damping and are well suited for these space vehicle control investigations.

A summary of the nominal characteristics for each single-axis Twin CMG System is given in Table 1. A photograph of the system is shown in Figure 1.

Several other reports that have been issued are in direct support of this final report. (See Appendix A for references.)

TABLE 1

NOMINAL CHARACTERISTICS FOR SINGLE-AXIS TWIN CMG SYSTEM

OVERALL CHARACTERISTICS - SYSTEM

Output Torque, Max.	150	ft-lb
Output Torque Rate, Max.	1200	ft-lb/sec
Momentum Storage Capability, Max.	40	ft-lb-sec
Transfer Function - Gain	15.4	ft-lb/volt
- Time Constant	0.01	sec
Gimbal Slaving Accuracy	10	arc min
Weight (less mounting frame)	68	lbs
Input Power Supply	28	volts dc
Input Power, Peak	160	watts
Input Power, Average	30	watts
Ambient Temperature Range	50-150	°F

CONTROL MOMENT GYRO CHARACTERISTICS - EACH

Momentum, H (adjustable)	5-20	ft-lb-sec
Output Torque, T_o, Max.	75	ft-lb
Spin Motor - Type	Brushless DC	
- Speed (adjustable)	3000-12000	rpm
- Spin-Up Time to Max. H	40	minutes
- Slow Down Time from Max.H	45	minutes
- Power (from 28 vdc)-Peak	23	watts
- Speed Stability	<0.1	%
Torque Motor		
- Type	Inland T-2955D	
- Peak Torque (derated)	0.6	ft-lb
- Peak Input Power	40	watts
- Scale Factor	0.31	ft-lb/amp
Tachometer		
- Type	Inland TG-2139A	
- Scale Factor	1.2	volts/rad/sec
Position Pickoff		
- Type	Film Pot	
- Linearity	0.035	%
- Resolution	Infinite	

TABLE 1 (cont'd)

Gimbal		
- Max. Rate (T_o/H ratio)	3.75	rad/sec
- Inertia	0.011	ft-lb-sec^2
- Output Axis Compliance	40,000	ft-lb/rad
- Friction, Average	0.030	ft-lb
- Angular Freedom		
- - with stops	±45° - ±90°	Adjustable
- - without stops	360°	Continuous
Spin Bearings		
- Type	Ballbearings, size 101	
- Lubrication	Grease	
- Life	> 2000	hours
- Failure Monitor	Thermistors	
Housing Seal		
- Type	"O" Rings	
- Leak Rate, Max.	17	microns/hour
Weight	28.1	lbs

ELECTRONICS

Size	8.5 x 9 x 11	inches
Weight (with cables)	11.8	lbs
Power Losses, Peak	≈ 45	watts
Power Losses, Average	≈ 10	watts
Number of Pluggable Circuit Boards	8	
Number of Components	586	

ALIGNMENT AND MOUNTING FIXTURE

Accuracy	1	arc minute
Weight, Approximate	15.6	lbs

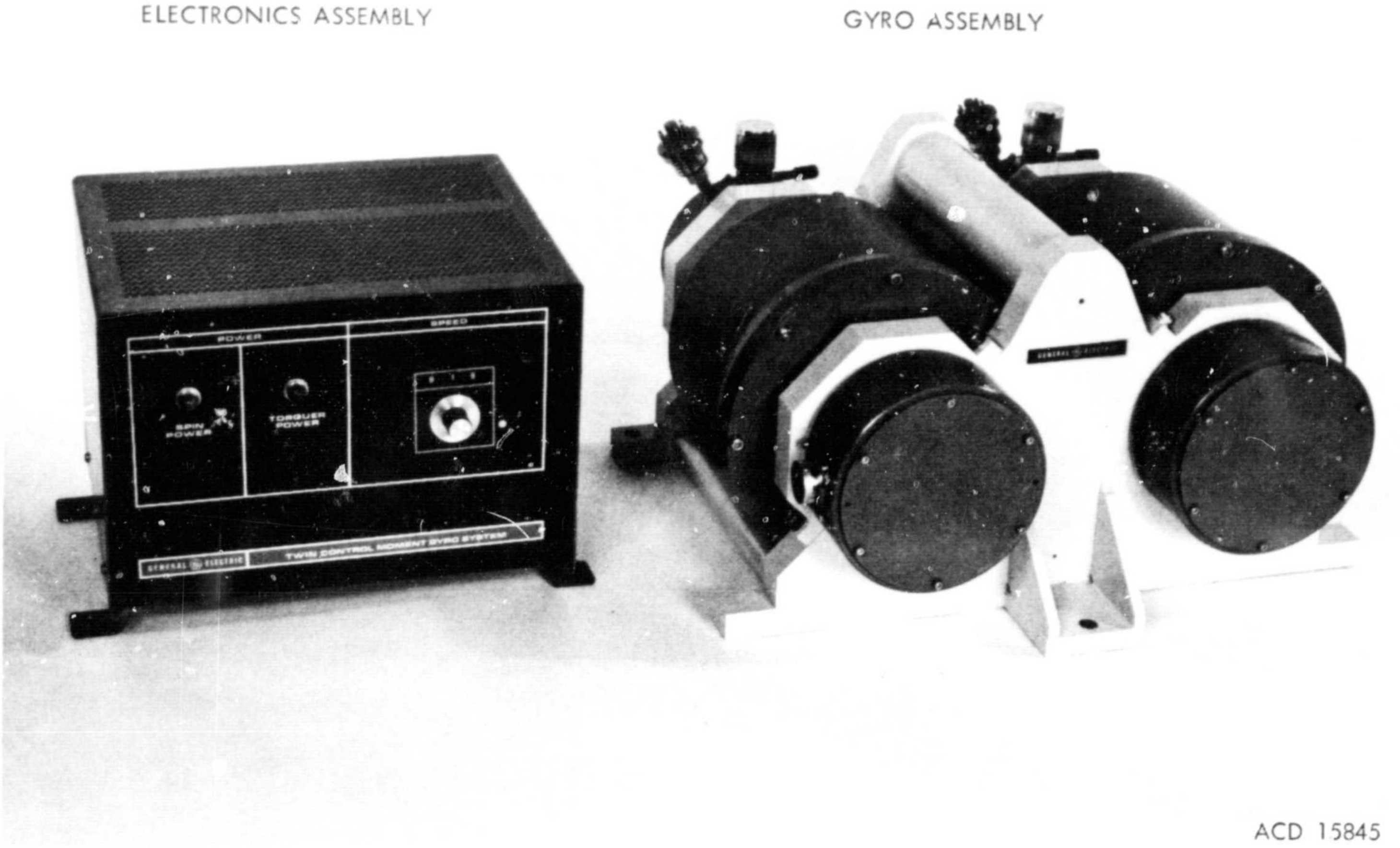


Figure 1. Twin CMG System

Section 2
SUMMARY OF TEST RESULTS

Prior to shipment of the three Twin CMG Systems, the manufacturer has rigorously tested and evaluated each of the systems from the component level through the acceptance system test. They were all found to meet or exceed all of the specifications. The complete acceptance test data and results may be found in the Acceptance Test Reports for each system (dated March 12, 1969). A summary of the acceptance test data is given in Table 2.

TABLE 2

A - ACCEPTANCE TEST DATA SUMMARY

Twin CMG System Serial No. 001
CMG 1 (right) Serial No. 001
CMG 2 (left) Serial No. 002

Test	Test Plan		Test Data			Units
	Paragraph	Specification	(01) CMG 1	(02) CMG 2	System	
Wheel Inertia	7.1.2	.0159 ±.0002	.01592	.01592	-	slug-ft^2
Wheel Dynamic Balance	7.1.3	<40	9	15	-	microinches
Gimbal Static Balance	7.1.4	<.00025	.00013	.00013	-	ft-lb
Gimbal Inertia	7.1.5	<.012	.01091	.01096	-	slug-ft^2
CMG Weight	7.2.2	<30	28.2	28.0	-	pounds
CMG Leak Rate	7.2.3	<60	11.4	12.9	-	micron/hour
Electronics Weight	7.3.5	<15	-	-	11.7	pounds
Mounting Fixture Weight	7.4.1	-	-	-	15.6	pounds
Spin-Up Time	7.5.4	<1	38 minutes	46 minutes	-	hours
Spin-Down Time	7.5.4	<1	47 minutes	40 minutes	-	hours
Running Power	7.5.4	<45	-	-	23	watts
Spin Stability	7.5.5	<0.1%	.044%	.044%	-	percent
Gimbal Friction, Average	7.5.7	<.032	.027	.031	-	ft-lb
Torque Output at H = 20 (10^V input)	7.5.8	154 ±8	-	-	150	ft-lb

TABLE 2

B - ACCEPTANCE TEST DATA SUMMARY

Twin CMG System Serial No. 002
CMG 1 (right) Serial No. 004
CMG 2 (left) Serial No. 003

Test	Test Plan		Test Data			Units
	Paragraph	Specification	(04) CMG 1	(03) CMG 2	System	
Wheel Inertia	7.1.2	.0159 ±.0002	.01592	.01582	-	slug-ft^2
Wheel Dynamic Balance	7.1.3	<40	12.9	14.8	-	microinches
Gimbal Static Balance	7.1.4	<.00025	.00013	.00013	-	ft-lb
Gimbal Inertia	7.1.5	<.012	.01083	.01083	-	slug-ft^2
CMG Weight	7.2.2	<30	28.2	28.0	-	pounds
CMG Leak Rate	7.2.3	<60	19.5	17.5	-	micron/hour
Electronics Weight	7.3.5	<15	-	-	11.8	pounds
Mounting Fixture Weight	7.4.1	-	-	-	15.6	pounds
Spin-Up Time	7.5.4	<1	32 minutes	34 minutes	-	hours
Spin-Down Time	7.5.4	<1	36 minutes	35 minutes	-	hours
Running Power	7.5.4	<45	-	-	29	watts
Spin Stability	7.5.5	<0.1%	.094%	.038%	-	percent
Gimbal Friction, Average	7.5.7	<.032	.030	.027	-	ft-lb
Torque Output at H = 20 (10^V input)	7.5.8	154 ±8	-	-	150	ft-lb

TABLE 2

C - ACCEPTANCE TEST DATA SUMMARY

Twin CMG System Serial No. 003
CMG 1 (right) Serial No. 006
CMG 2 (left) Serial No. 005

Test	Test Plan		Test Data			Units
	Paragraph	Specification	(06) CMG 1	(05) CMG 2	System	
Wheel Inertia	7.1.2	.0159 ±.0002	.01582	.01587	-	slug-ft^2
Wheel Dynamic Balance	7.1.3	<40	16.1	12.9	-	microinches
Gimbal Static Balance	7.1.4	<.00025	.00013	.00013	-	ft-lb
Gimbal Inertia	7.1.5	<.012	.01077	.01057	-	slug-ft^2
CMG Weight	7.2.2	<30	28.0	28.2	-	pounds
CMG Leak Rate	7.2.3	<60	29.1	13.8	-	micron/hour
Electronics Weight	7.3.5	<15	-	-	11.8	pounds
Mounting Fixture Weight	7.4.1	-	-	-	15.6	pounds
Spin-Up Time	7.5.4	<1	34 minutes	36 minutes	-	hours
Spin-Down Time	7.5.4	<1	38 minutes	46 minutes	-	hours
Running Power	7.5.4	<45	-	-	21	watts
Spin Stability	7.5.5	<0.1%	.036%	.040%	-	percent
Gimbal Friction, Average	7.5.7	<.032	.029	.030	-	ft-lb
Torque Output at H = 20 (10^V input)	7.5.8	154 ±8	-	-	150	ft-lb

Section 3

TWIN CMG SYSTEM DESIGN

GENERAL DESCRIPTION

The three-axis Twin CMG Control System consists of three identical (except for mounting orientation) twin CMG systems, each of which consist of:

- Two identical CMG's
- One mounting frame
- One electronic assembly

Each of the gyros contain a single-degree-of-freedom gimbal assembly supporting a momentum rotor and spin motor, torque motor, electronic tach generator, potentiometer, slip ring assembly and gimbal-stop torque shaft. The entire assembly is housed in a canister frame that is end-sealed with O-rings to maintain a low pressure environment (to reduce momentum wheel windage drag). The low-pressure levels can be re-established periodically by an external vacuum pump connected to a manually-controlled throttling valve which is ported to the housing vacuum. A mechanical gimbal stop, equally centered on both sides of the reference zero gimbal position, can be manually adjusted to any of ten discrete 5-degree steps between 45 degrees and 90 degrees. Interconnections made to other equipment are made through hermetically-sealed connectors which channel monitoring signals of gyro performance in addition to operational signal and power leads.

Two main features of the Twin CMG Systems are the variable momentum capabilities (each CMG momentum is variable from 5 to 20 ft-lb-sec) and the precision electrical gimbal slaving. This later feature reduces cross-axis coupling to a minimum.

The mounting frame supports two of the CMG's with their gimbal axes parallel and horizontal to the simulator mounting surface. Since the CMG housing is end-supported by means of trunnion mounts, only rotational positioning is necessary to align to prescribed marks. Levelness is assured by the use of a three-point tie-down to the vehicle structure.

The mounting configuration for three-axis control of the Space Vehicle Motion Simulator (SVMS) is shown in Figure 2. The primary mounting constraint is the availability of only one mounting plane on the SVMS (see Appendix A). Hence, one of the three Twin CMG Systems (System Serial No. 1) is positioned so that the momentum wheel spin axes are horizontal, thereby providing control torque about the vertical axis (axis 1) of the SVMS. The other two Twin CMG Systems have gyro housings which are rotated 90 degrees so that the spin axes are vertical, thereby providing control torques in axes 2 and 3 of the SVMS. By mounting the twin CMG systems as shown in Figure 2, positive control torque is provided in all axes (that is, a plus input signal provides a plus control torque).

The electronics contain all circuitry required for the brushless DC spin motors, the torque motor amplifiers and gimbal rate loop control, slaving and caging circuits, and converters to generate all required voltage levels from the single input supply of 28 VDC. Microminiature circuits, in addition to discrete solid state components, are mounted on individual module boards which can be unplugged and readily serviced. All desired mode switching, output test points, and interface connections are accomplished in this assembly. Power lights and a potentiometer dial selection for momentum speed setting are on the front panel of the assembly.

Complete characteristics for each Twin CMG System were given in Table 1 of Section 1.

SYSTEM DESCRIPTION

Each Twin CMG System provides essentially uncoupled single-axis vehicle control. The small amount of cross coupling that does exist is due to nonperfect gimbal slaving (discussed later) and vehicle cross-axis rates, (i.e., refer to reference 9, page 119).

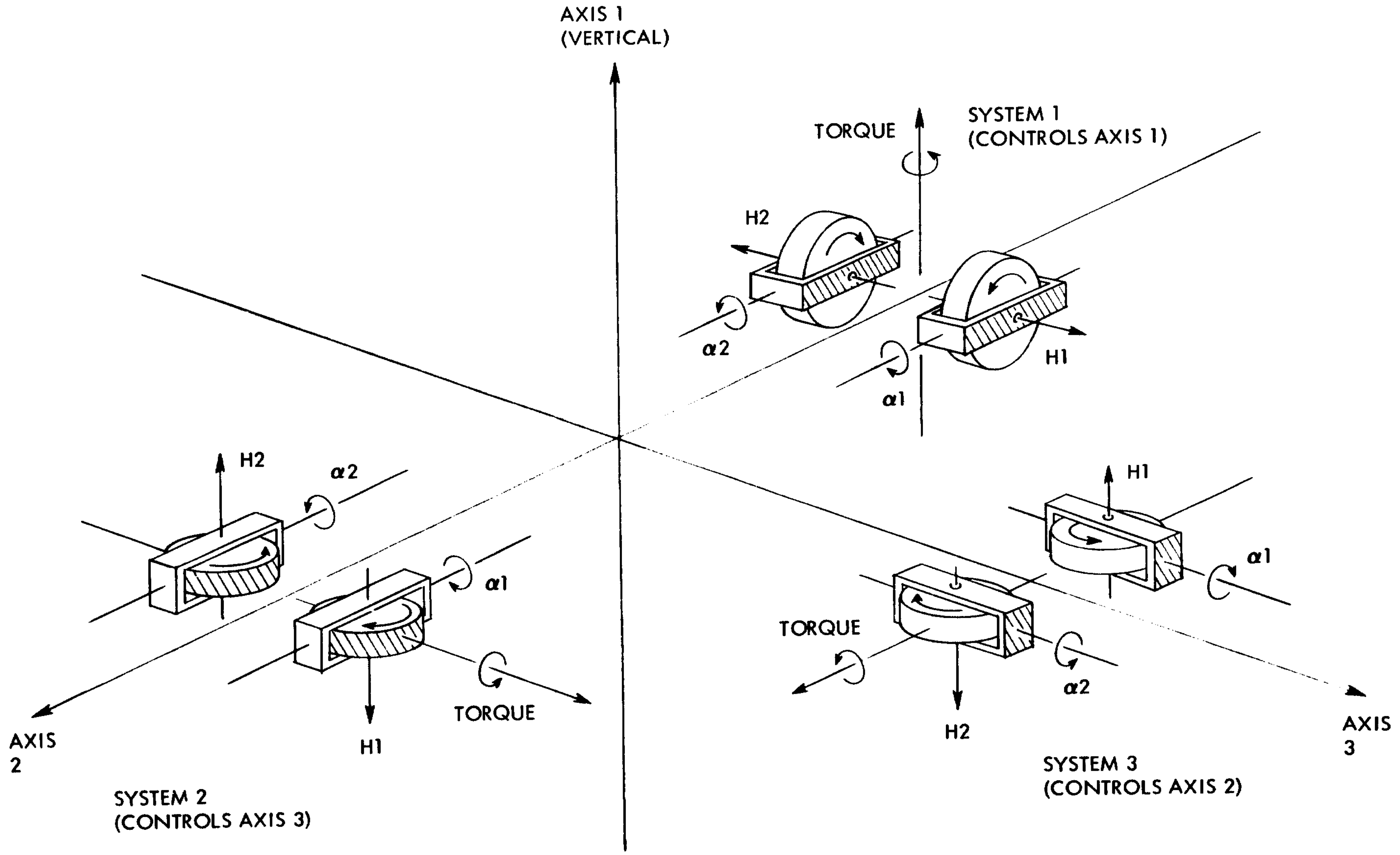


Figure 2. Twin CMG System Three-Axis Configuration

Hence, each Twin CMG System is accurately characterized by the following simple transfer function:

$$\frac{\text{Vehicle Torque}}{\text{Input Command Voltage}} = \frac{T_v}{V_{in}} = \frac{0.77\ H \cos \alpha}{s\ T_1 + 1} \quad \frac{\text{ft-lb}}{\text{v}} \tag{1}$$

Where

H = gyro angular momentum (ft-lb-sec)

α = nominal gyro gimbal angle from zero reference

s = Laplace transform

T_1 = system lag time constant (about 0.01 second; see below)

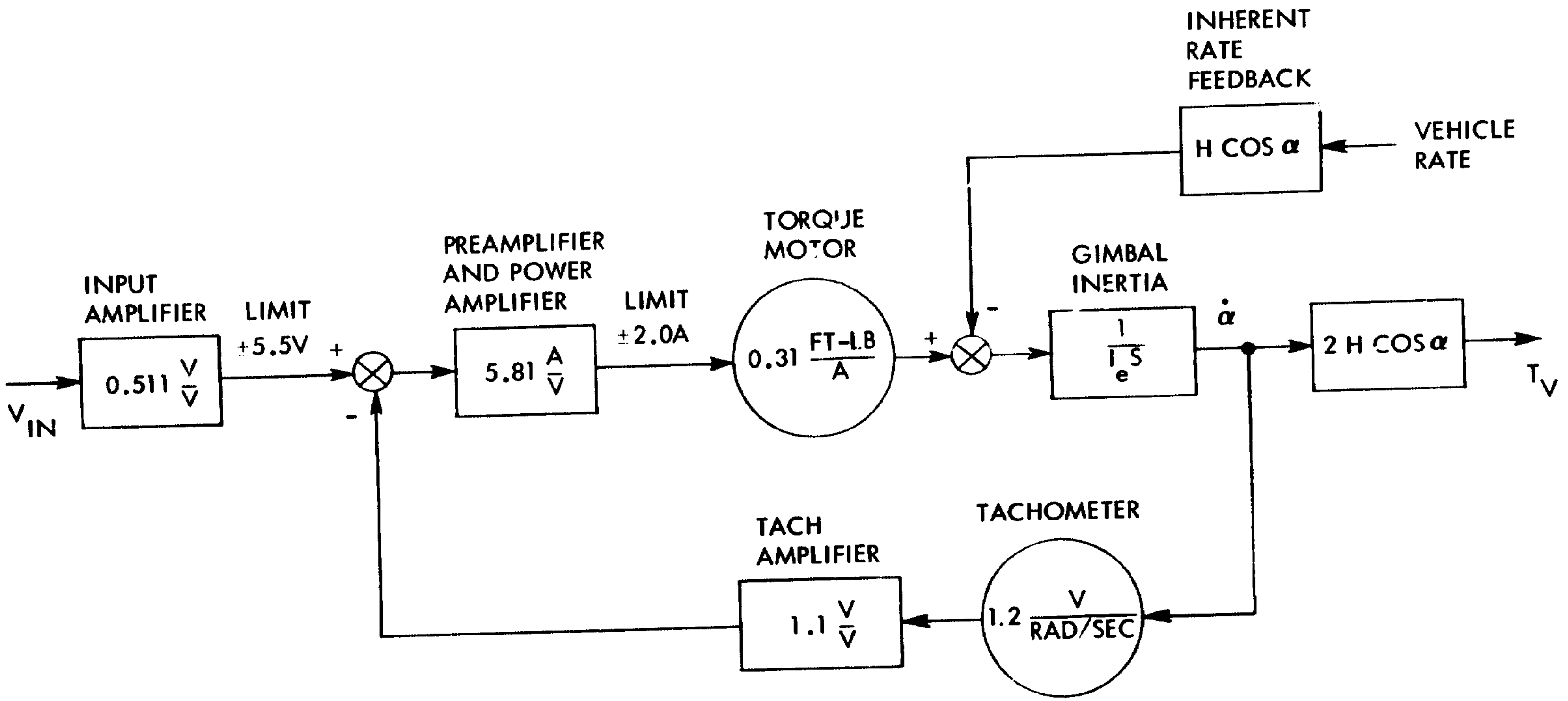
The torque command system block diagram is shown in Figure 3. The gimbal tracking loop is not included in this diagram (see the following section). The block diagram of Figure 3 combines the additive output torque effect of the twin gyro by using the factor of 2 times the term (H cos α). Tachometer feedgack of gimbal rate is employed, and the maximum control torque applied to each gimbal is electronically limited to 0.62 ft-lb. Maximum operating gimbal rate is 3.75 rad/sec, providing a maximum output torque (at H = 20 ft-lb-sec) of 150 ft-lb. The vehicle rate feedback torque is shown as a disturbance input to the system. The effect of the disturbance is minimized through the use of a relatively high tachometer loop gain. This high loop gain also serves to minimize the effects of gimbal friction on the system. The values for respective electronic and mechanical gains are given as nominal values.

The torque gain for the system is easily calculated from Figure 3, by considering the summing point at the preamplifier:

$$0.511\ V_{in} - 1.1 \times 1.2\ \dot{\alpha} = 0 \tag{2}$$

or

$$\frac{\dot{\alpha}}{V_{in}} = \frac{0.511}{1.1 \times 1.2} = \frac{0.511}{1.32} = 0.387\ \frac{\text{rad/sec}}{\text{volt}}\ \text{(nominal)} \tag{3}$$



$I_e = 0.011 + \frac{H^2}{40000}$ SLUG-FT^2

$H = 5$ TO 20 (VARIABLE) FT-LB-SEC

Figure 3. Torque Command, Twin Gyro System Single Axis Block Diagram

Also,

$$\frac{T_v}{V_{in}} = 2\ H \cos\alpha \frac{\dot{\alpha}}{V_{in}} = 0.774\ H \cos\alpha \frac{\text{ft-lb}}{\text{volt}} \qquad (4)$$

At $\alpha = 0^{\circ}$ and H = 20 ft-lb-sec:

$$\frac{T_v}{V_{in}} = 0.774 \times 20 = 15.48 \frac{\text{ft-lb}}{\text{volt}} \text{ (nominal)} \qquad (5)$$

It should be noted that the tachometer amplifier gain (Figure 3) is adjustable. During acceptance testing, the tachometer gain is adjusted to 1.32 v/rad/sec at the test points. The test points have an output impedance of 1000 ohms and were loaded with 50,000 ohms recorder input impedance. Hence, the actual gimbal rate was higher than the indicated rate by the ratio (50,000 + 1000)/50,000 = 1.020; hence the expected torque gain is lower by this ratio, or 15.48/1.020 = 15.16 ft-lb/volt. This calculated value is very close to measured values of 15.0 ft-lb/volt for the three systems. The slightly lower measured gain is due to effective gimbal axis friction at the high gimbal rates, such that a finite error signal, instead of zero as shown in relation (2), is required to maintain a gimbal rate.

The gimbal inertia, I_e, in the block diagram of Figure 3 is an "effective" inertia which is the sum of the real gimbal inertia plus an "apparent" inertia, and is given by

$$I_e = I_g + H^2/K \quad \text{slug-ft}^2 \qquad (6)$$

Where

I_e = effective gimbal inertia

I_g = real gimbal inertia = 0.011 slug-ft^2

H = angular momentum (ft-lb-sec)

K = gyro output axis torsional spring constant = 40,000 ft-lb/rad

The apparent inertia is due to gyro in-plan precession which can occur because the output axis torsional spring constant is not infinite. This is described in detail in references 6 and 10. Hence the effective gimbal inertia varies from 0.011 slug-ft^2 at H = 0, to $0.011 + (20)^2/40{,}000 = 0.011 + 0.010 = 0.021$ slug-ft^2 at H = 20 ft-lb-sec.

The system time constant in relation (1) is calculated by the gimbal loop gain from Figure 3. Hence, the time constant is given by

$$T_1 = \frac{I_e}{5.81 \times 0.31 \times 1.1 \times 1.2} = \frac{I_g + H^2/K}{2.38} \text{ seconds} \tag{7}$$

Thus, this time constant varies from 0.011/2.38 = 0.0046 seconds at H = 0 to 0.021/2.38 = 0.0088 seconds at H = 20 ft-lb-sec. The system time constant has no effect on the available torque from the twin CMG's.

The system transfer function, relation (2), is linear until saturation of an element occurs. One saturation limit is the available gimbal motor torque which occurs because of the power amplifier current limit. This current limit is 2.0 amperes, so the gimbal torque limit is 0.31 x 2.0 = 0.62 ft-lb. This torque thus limits gimbal acceleration, and hence the maximum rate of change of vehicle torque which is given by

$$\dot{T}_v = \frac{T_m}{I_e} (2\,H \cos \alpha) \frac{\text{ft-lb}}{\text{sec}} \tag{8}$$

Where

$\dot{T}_v$ = the rate of change of vehicle torque

T_m = peak gimbal torque (0.62 ft-lb)

I_e = effective gimbal inertia (slug-ft^2)

H = gyro angular momentum (ft-lb-sec)

α = nominal gimbal angle from zero

Thus, at H = 20 ft-lb-sec, the rate of change of vehicle torque for $\alpha = 0^{\circ}$ is $\dot{T}_V$ = (0.62/0.021) 40 = 1180 ft-lb/sec. This agrees well with measured values of about 1200 ft-lb/second.

The output of the input amplifier is limited at approximately ±5.5 volts. Thus, in the event that an excessive input voltage is applied, gimbal rate and, therefore, gyro output torque is limited. This gimbal rate limit is approximately 5.5/1.1 x 1.2 = 4.17 rad/sec, equivalent to a twin system peak output torque of 167 ft-lb (at H = 20 ft-lb-sec).

GIMBAL SLAVING LOOP

An investigation of methods of slaving gyro gimbals in a twin pair configuration (reference 11) showed that the most severe slaving problems were due to:

1. Mismatch in torque motor saturation level
2. Mismatch in tachometer gradients
3. Cross-axis rates

The "direct feed" method was found to be the most effective slaving method, coupled with adjustment of the tachometer gradients of each gyro to better than ±1% of each other. In this method, the torque motor amplifier is set to limit the gyro torque command signal somewhat below the torque motor limit. Thus a small amount of torque capability is available in the torque motor exclusively for gimbal slaving. The gimbal angle difference signal is fed into the torquer power amplifier inside the gimbal rate loop so that gimbal angle compensation can occur even when the torque command signal is in saturation.

A functional block diagram of the complete CMG gimbal control system, showing all gains, is shown in Figure 4. Also shown are all the test point outputs. All electronic lags above 500 rad/sec have been neglected.

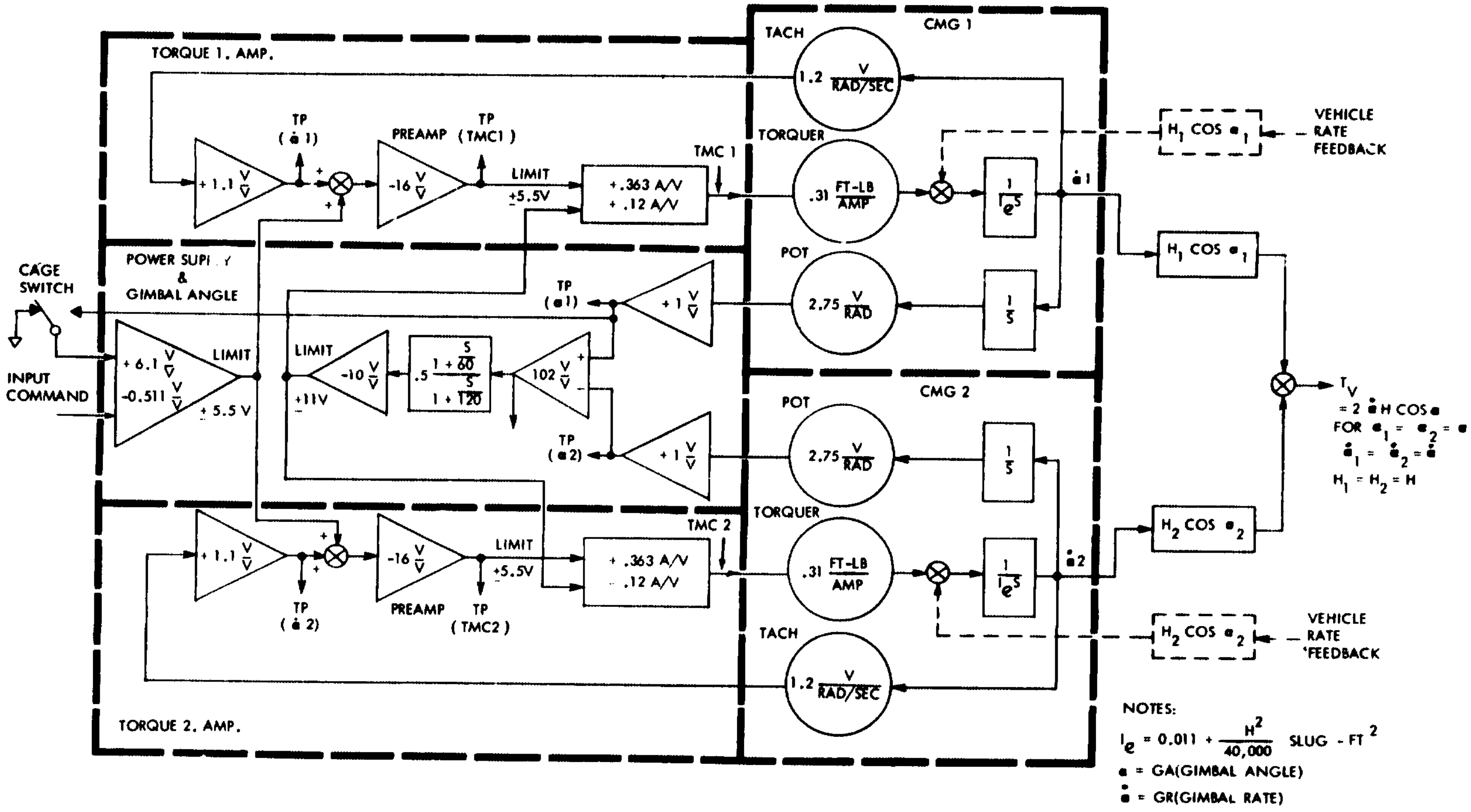


Figure 4. Block Diagram of Twin CMG Gimbal Control System

The slaving loop accuracy is a function of the slaving loop gain K_α. This gain was selected to be about 50 (see reference 11). The actual K_α is calculated as follows (see Figure 4):

$$K_\alpha = 2.75 \times 102 \times 0.5 \times 10 \times 0.12 \times 0.31$$

$$= 52.1 \text{ ft-lb/radians}$$

The gimbal slaving loop crossover frequency, neglecting the compensatory lead-lag, is given by

$$\omega_s = \frac{2 K_\alpha}{I_e} \tag{9}$$

This results in ω_s = 97 rad/sec for H = 0 and ω_s = 70 rad/sec for H = 20 ft-lb-sec. The lead-lag network provides some compensation to stabilize the slaving loop during periods of torque command signal saturation.

Excellent slaving loop accuracy has been obtained in tests. Neglecting the potentiometer linearity accuracy, dynamic errors are under 30 arc minutes during full gimbal acceleration and six arc minutes during full gimbal rate. While static errors are negligible (less than 2 arc minutes) to these values must be added the errors due to the potentiometers of 10.5 arc minutes RSS. (See Design Analyses Report, reference 1.)

CAGING LOOP

The caging loop returns the gimbal angles to their zero position when the cage switch (relay) is energized. The caging loop appears in the CMG System block diagram, Figure 4. When the cage switch is closed, the input command is removed from the input amplifier and replaced with the potentiometer gimbal angle signal for CMG 1, thus closing the gimbal position loop and returning gimbal 1 to its zero position. Gimbal 2 follows gimbal 1 by virtue of the slaving loop.

The gain of the cage loop was chosen to return the gimbals to their zero position with an error well within the requirement of 20 arc minutes. The residual position error is due to the gimbal friction. Assuming a gimbal friction of 0.030 ft-lb, the residual position error is given by (see Figure 4):

$$\alpha_r = \frac{0.030}{0.31 \times 0.363 \times 16 \times 6.1 \times 2.75}$$

$$= 0.00099 \text{ radians} = 3.4 \text{ arc minutes}$$

This is in excellent agreement with measured values. The residual error due to the potentiometers is less than 0.7 arc minutes (through initial alignment procedures).

The gimbal position crossover frequency (when caged) is well below the gimbal rate loop crossover, so the response is approximately a simple time constant when no loop saturation occurs. From Figure 4 the gimbal position crossover frequency is given by

$$\omega_p = \frac{2.75 \times 6.1}{1.2 \times 1.1} = 12.7 \text{ rad/sec}$$

It should be noted that the input amplifier saturates whenever the gimbal angle is greater than $5.5/6.1 \times 2.75 = 0.328$ radians = 18.8 degrees. Hence, the gimbal is rapidly returned to its zero position when the cage switch is closed.

Section 4

CONTROL MOMENT GYRO DESIGN

GENERAL DESCRIPTION

The control moment gyro consists of a sculptured momentum wheel operating at 12,000 rpm and providing a momentum of 20 ft-lb-sec. A pair of deep-groove ball bearings support the wheel which is powered by a brushless DC spin motor. A solid preload arrangement provides the proper ball bearing operating geometry and torsional stiffness over the specified operating temperature. The momentum wheel is supported in a single-degree-of-freedom gimbal which pivots on duplex-pair ball bearings. Components are mounted on the gimbal shaft to provide static and dynamic control of the gimbal. These include a direct-drive torque motor, a tachometer generator, precision potentiometer, and a slip-ring capsule to supply spin motor power and allow unlimited gimbal rotation. If desired, mechanical gimbal stops can be used and manually adjusted to any of ten discrete 5-degree steps between ±45 degrees and ±90 degrees.

The entire gyro assembly is housed in a canister enclosure that is end-sealed with O-rings and evacuated to minimize wheel windage losses. The low-pressure levels can be re-established periodically (30-day intervals) by an external vacuum pump connected to a manually controlled throttling valve which is ported to the housing vacuum. MS-type hermetic connectors are used to provide signal and power into the sealed housing.

The design of the control moment gyro is shown in Figure 5. All major components are also shown. Gyro characteristics were given in Table 1. A photograph of the assembled gyro is shown in Figure 6, and the disassembled gyro in Figure 7.

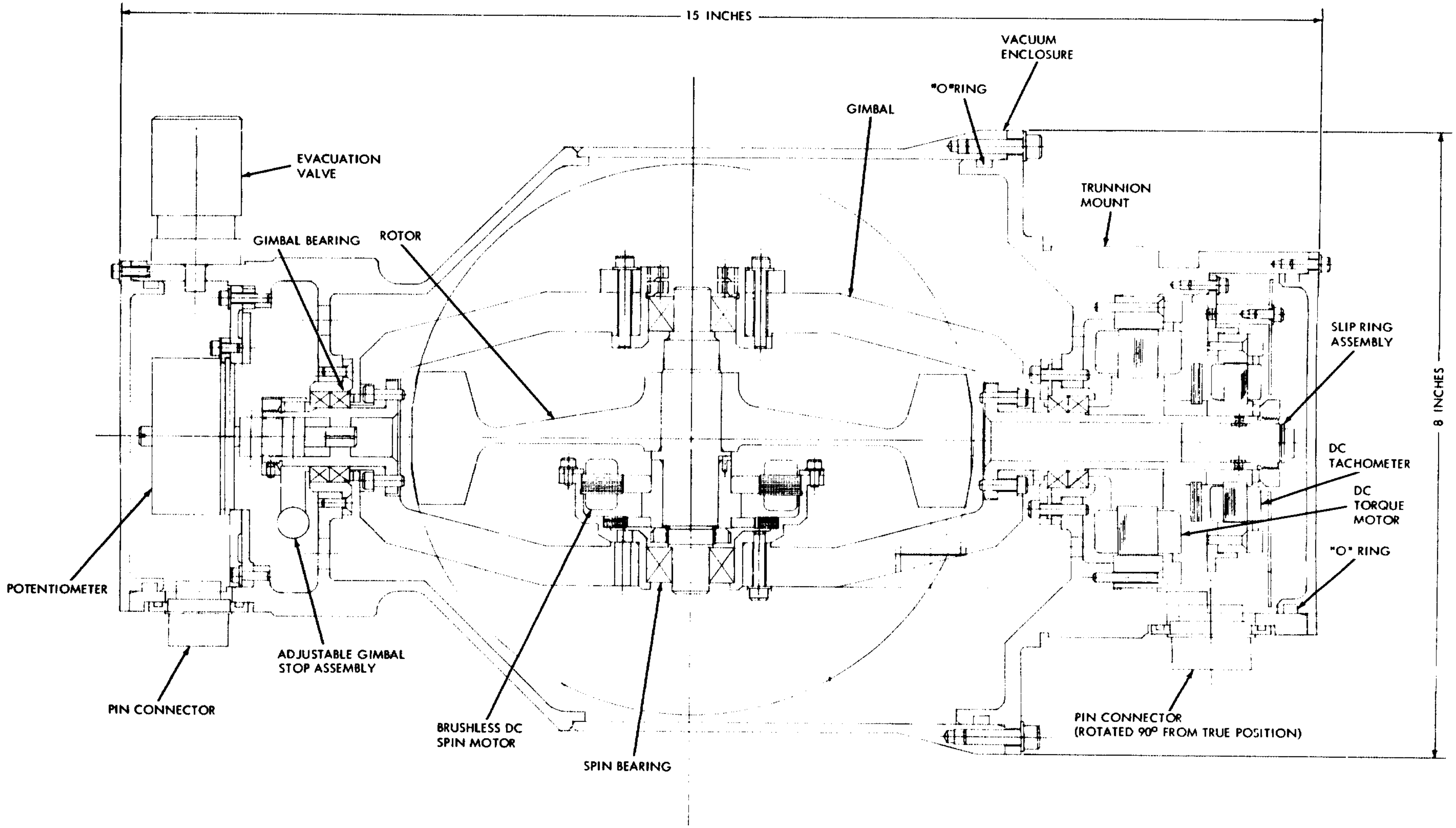


Figure 5. Outline Drawing of Control Moment Gyro

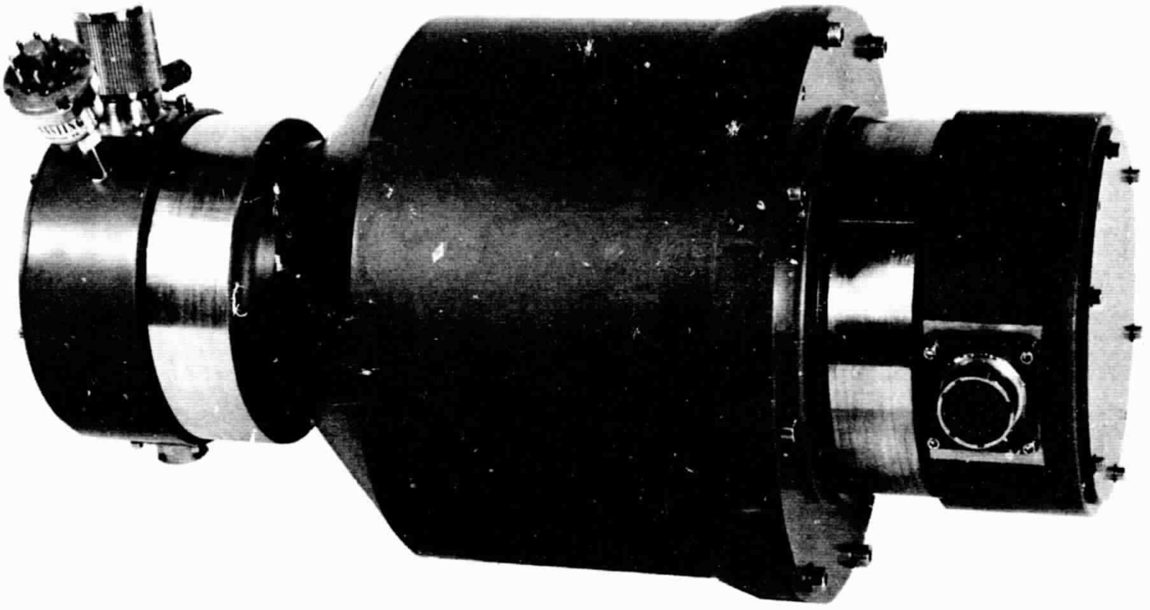


Figure 6. Assembled Control Moment Gyro

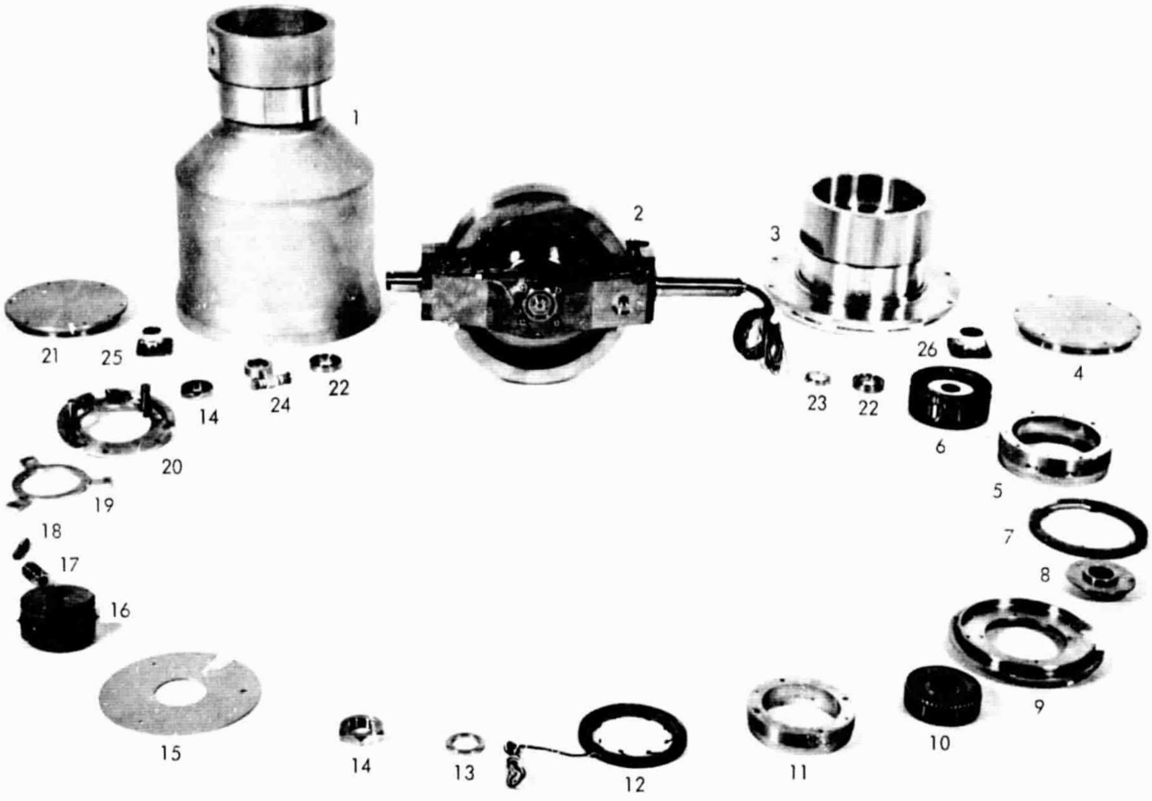


Figure 7. Disassembled Gyroscope, Control Moment

LEGEND:

1 GYROSCOPE HOUSING
2 SPIN ASSEMBLY
3 TORQUE MOTOR HOUSING
4 TORQUER END COVER
5 TORQUE MOTOR STATOR
6 TORQUE MOTOR ROTOR
7 TORQUE MOTOR BRUSH ASSEMBLY
8 MAGNETIC SHIELD
9 TACHOMETER RING ADAPTER
10 TACHOMETER ROTOR
11 TACHOMETER STATOR
12 TACHOMETER BRUSH ASSEMBLY
13 WASHER
14 GIMBAL NUT
15 WIRE SHIELD
16 POTENTIOMETER
17 POTENTIOMETER COUPLER
18 POTENTIOMETER ADAPTER SHAFT
19 POTENTIOMETER HOUSING
20 GIMBAL STOPS AND RING ASSEMBLY
21 POTENTIOMETER END COVER
22 GIMBAL BEARING
23 GIMBAL SPACER BEARING
24 GIMBAL STOP ARM ASSEMBLY
25 PIN CONNECTOR
26 PIN CONNECTOR

This control moment gyro has been designed with a very high-output torque capability. The gyro can safely produce an output torque of 75 ft-lb, equivalent to a torque to momentum ratio of 3.75. At the same time, the use of a direct-drive torque motor and tachometer feedback allows precision gimbal rate and, hence, output torque control.

A mounting frame is used to support two CMG's with their gimbal axes parallel and horizontal to the Space Vehicle Motion Simulator (SVMS) mount surface. The CMG housing is end-supported by means of trunnion mounts, so that only rotational positioning is necessary to align the CMG's in the mounting frame. Levelness of the mounting frame to the SVMS mounting surface is assured by the use of a three-point tie-down. Two sets of alignment marks are provided on the mounting frame to allow precise positioning on the SVMS. A photograph of two CMG's in a mounting frame is shown in Figure 8.

DISCUSSION OF DESIGN

A discussion of the various design areas follows:

MOMENTUM WHEEL (ROTOR)

The momentum wheel is the same basic sculptured design that had previously been employed on an 18.5 ft-lb-sec CMG. The angular momentum has been increased to 20 ft-lb-sec (at 12,000 rpm) by increasing the rim thickness. In addition, a tapered web design has been employed for high torsional rigidity.

The rotor outline and dimensions are shown in Figure 9. For more detail, see GE drawing 931C420, Spin Rotor, Gyro. The rotor is made from stainless steel, type 17-4 PH; characteristics of this material are given in Table 3.

The results of computer runs to determine stress are shown in Table 4 and the stress distribution plots of Figures 10, 11 and 12 (corresponding to zero speed, full speed and 50 percent overspeed, respectively). The stress calculation techniques are detailed in the Design Analyses Report (reference 1). Also shown in Table 4 are the

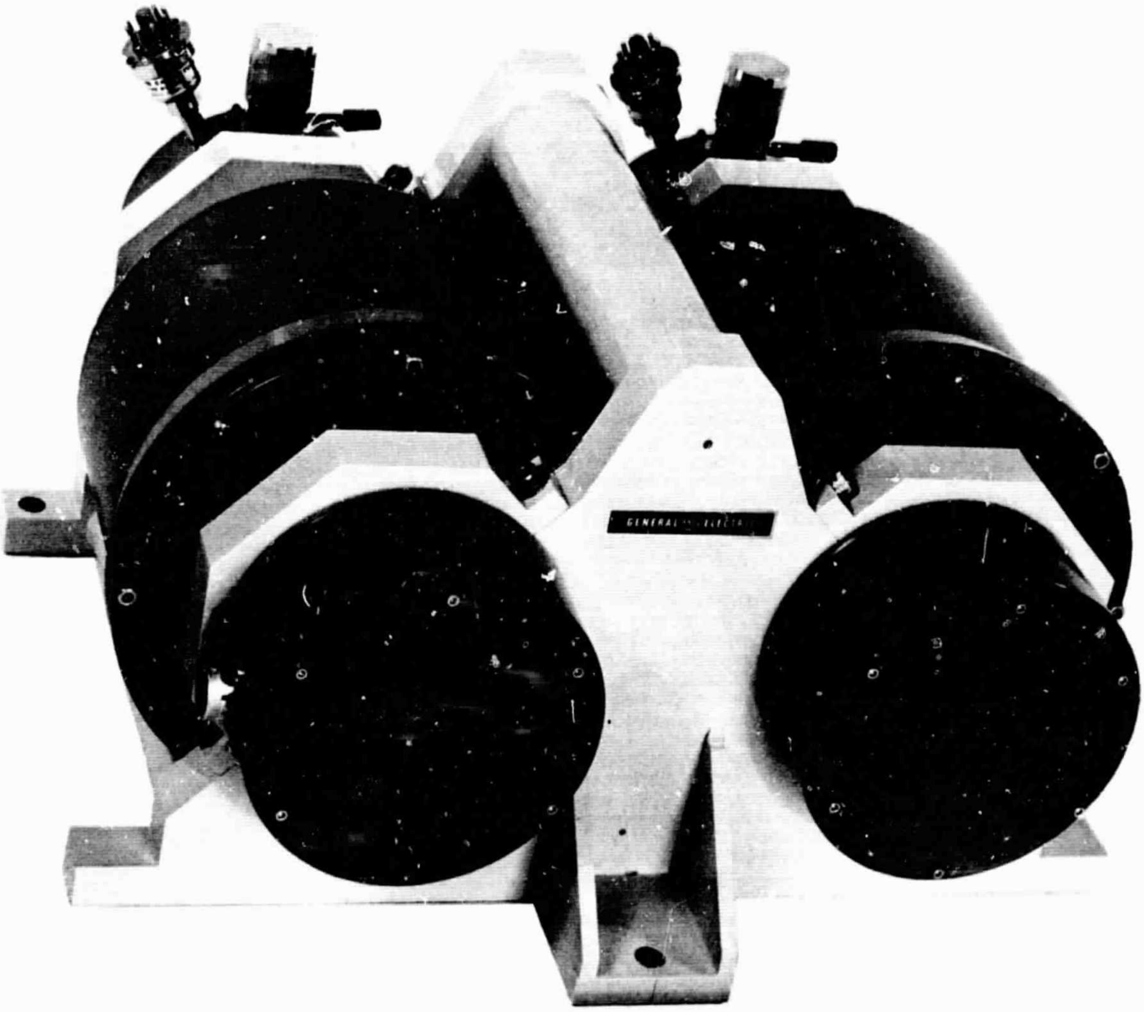
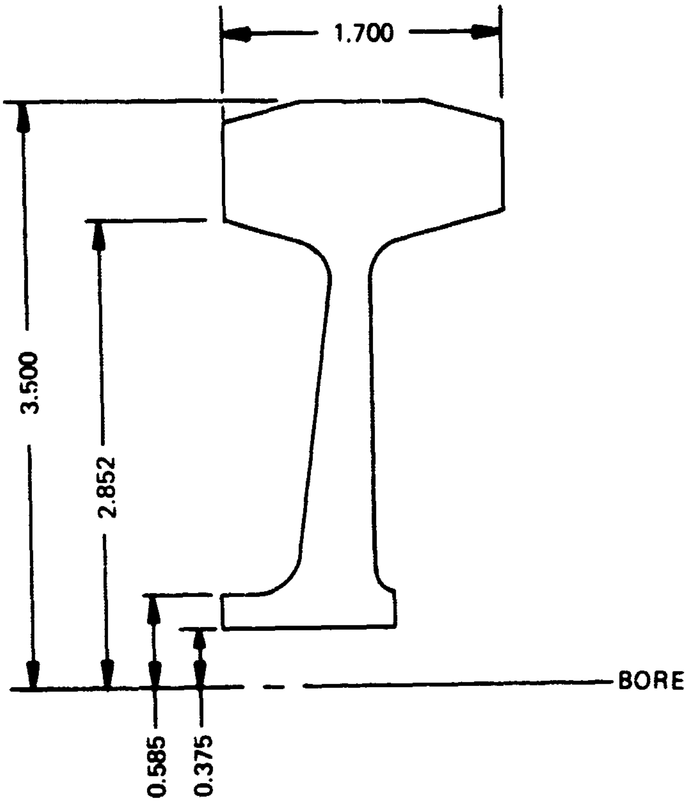


Figure 8. Twin Control Moment Gyro Assembly

results of inertia and weight calculations using another computer program. These calculations are in excellent agreement with measured values.

As can be seen from the data in Table 4 and the stress distribution plots, the largest stress in the rotor is the tangential stress at the bore. This stress is totally due to the shrink-fit, and has a value of 40,000 psi. The peak stress in the rotor rim is only about 10,500 psi at full wheel speed (12,000 rpm), and 24,000 psi at 50 percent wheel overspeed (18,000 rpm).

Using the specified stress safety factor of 4:1, the allowable maximum stress is 185,000/4 = 46,250 psi. The stress data presented shows that this safety factor is conformed to in the rotor, even at 50 percent overspeed.



ALL DIMENSIONS IN INCHES
MATERIAL: 17-4 PH STEEL

Figure 9. Gyro Rotor

TABLE 3
ROTOR MATERIAL CHARACTERISTICS

Material	Stainless Steel, type 17-4PH, condition H-900
Modulus of Elasticity	28.5×10^6 psi
Density	0.282 lb/in^3
Poisson's Ratio	0.272
Yield Strength, 0.2% offset	185,000 psi

TABLE 4
CALCULATED ROTOR PHYSICAL CHARACTERISTICS

Outside Diameter	7.00 inches
Weight	9.055 pounds
Inertia about Spin Axis	0.1601 slug-ft^2
Inertia about Gimbal Axis	0.0833 slug-ft^2
Nominal Full Operating Speed	12,000 rpm
Momentum at 12,000 rpm	20.12 ft-lb-sec^2
Shrink-Fit (on diameter)	0.00080 inch
Stresses at 12,000 rpm	
Radial stress at bore	19,600 psi
Tangential stress at bore	40,000 psi
Radial stress at rim (peak)	10,385 psi
Tangential stress at rim (peak)	10,500 psi
Allowable Stress for 4:1 Safety Factor	46,250

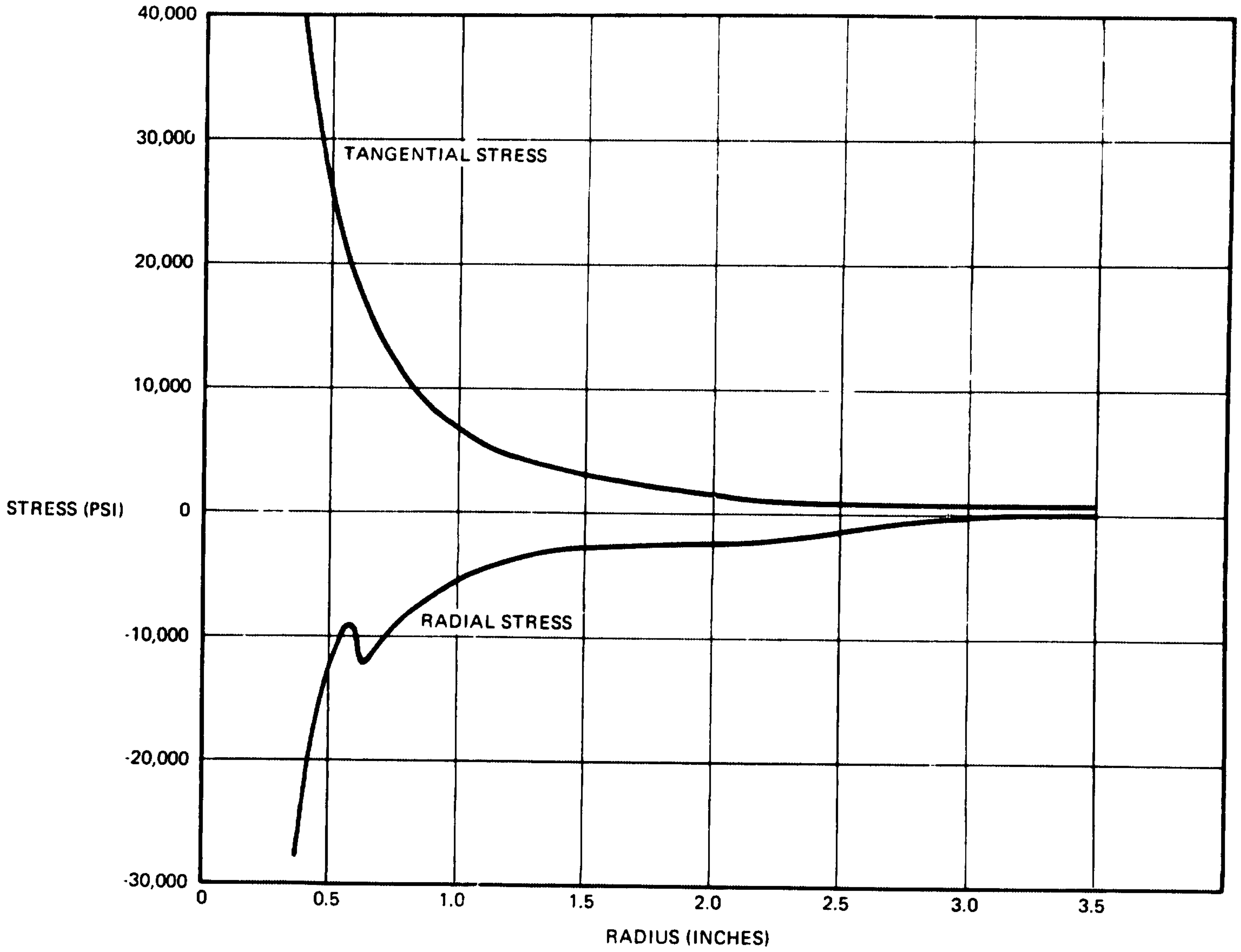


Figure 10. Stress Distribution at Zero Speed

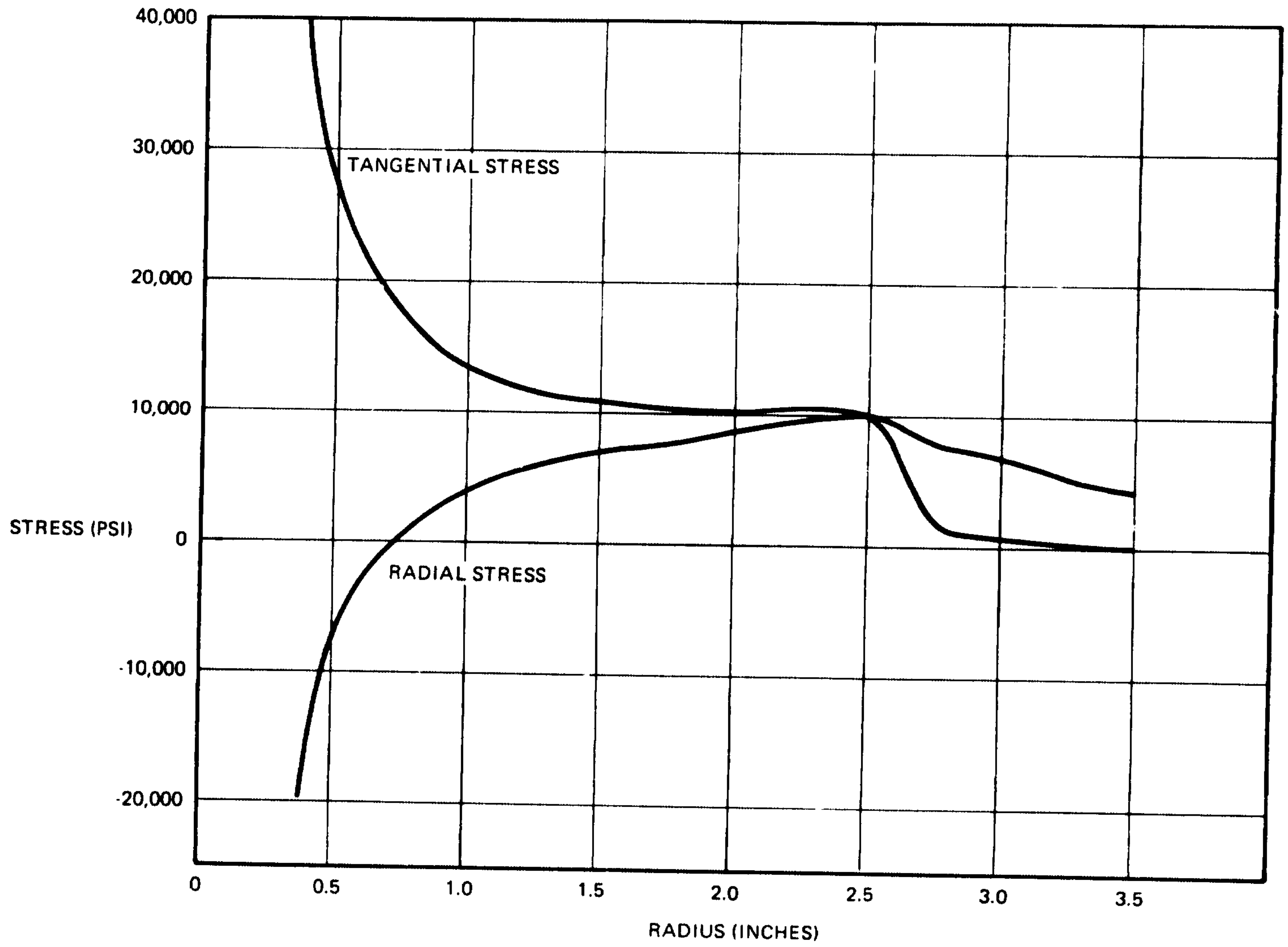


Figure 11. Stress Distribution at 12,000 rpm

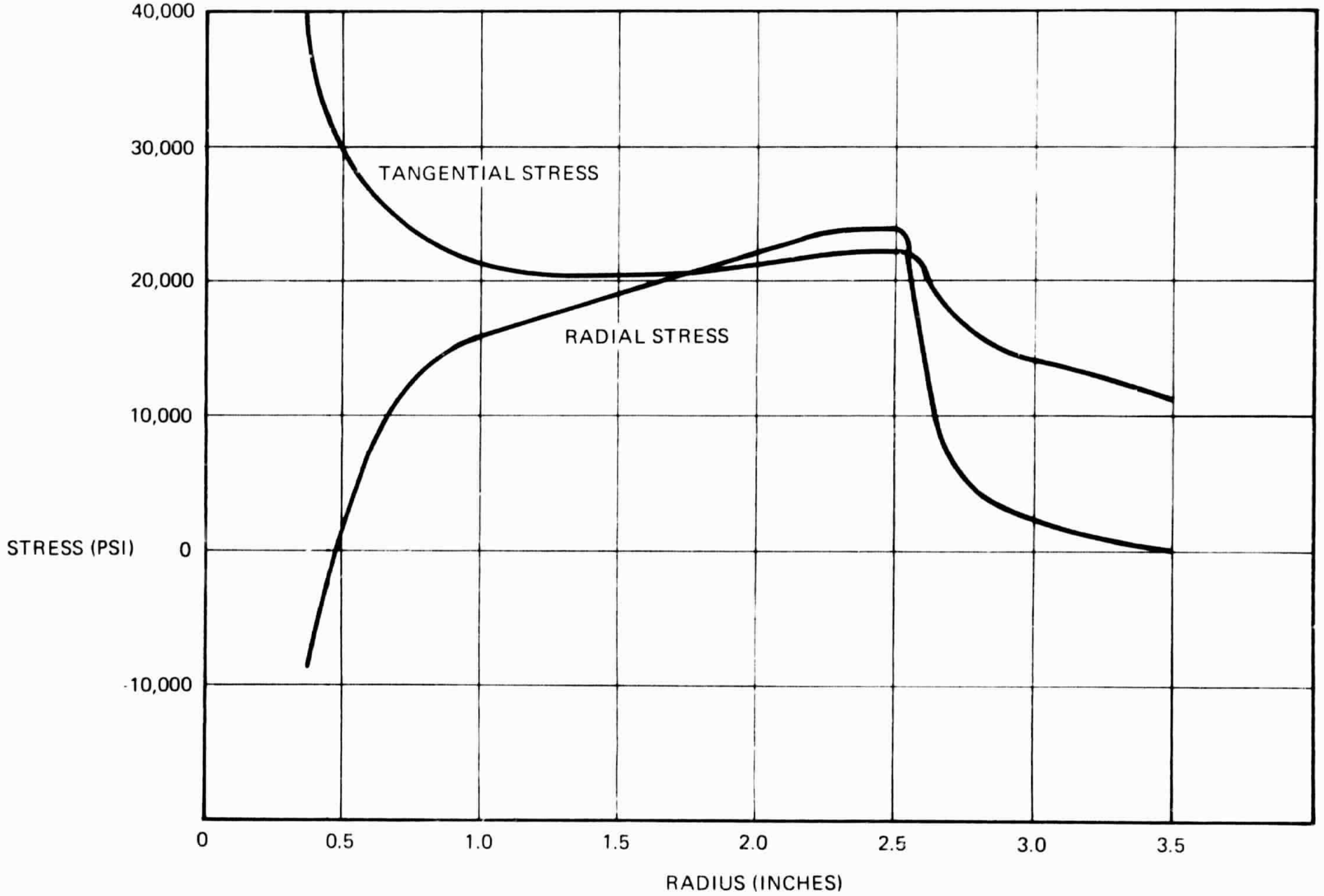


Figure 12. Stress Distribution at 18,000 rpm

SPIN BEARING REQUIREMENTS AND SELECTION

The main spin bearing requirements are as follows:

- Minimum life - 2000 hours
- Maximum running speed - 12,000 rpm (at H = 20 ft-lb-sec)
- Peak gyro output torque load - 75 ft-lb
- Reliability and duty cycle - not specified
- Bearing drag torque to be minimized so that running power is low
- Laboratory environment temperature of $50^{\circ}F$ to $140^{\circ}F$
- Vacuum enclosure with nominal pressure of 0.1 to 10 torr

The following bearing load duty cycle has been assumed for life determination over the 2000 hour life period:

Time	Gyro Output Torque	Spin Bearing Radial Load
20 hours	75.0 ft-lb (maximum torque)	278 pounds
200 hours	18.8 ft-lb (25% maximum torque)	69.5 pounds
500 hours	7.5 ft-lb (10% maximum torque)	27.8 pounds
1280 hours	3.8 ft-lb (5% maximum torque)	13.8 pounds

Based on the maximum radial loads, the life requirements, and the drag torque requirements, a Barden deep-groove type 101 bearing was chosen. The main characteristics of this bearing are:

Type	101SSTXK5G-6
Static load rating - radial, C_o	570 pounds
- thrust, T_o	1880 pounds
Dynamic radial load rating, C_s (12,000 rpm)	130 pounds

The fatigue life for this bearing was calculated in the Design Analyses Report (reference 1) with the following results:

L_{10} = 12,000 hours life at 0.90 reliability

Using standard life-reliability curves gives

Reliability = 0.9915 for 2000 hours life

Hence, there is a probability of 0.9915 that one bearing will operate without fatiguing for 2000 hours, or a reliability of 0.983 for two bearings.

The spin bearing lubrication is provided for by grease. Andok C grease has been chosen for its low-lub drag properties. Life of the lubricant is assured by employing bearing shields to minimize evaporation and utilizing a cartridge width bearing providing a large lubricant reservoir. Experience with previous designs indicates adequate lubrication should be provided for a minimum of 5000 hours.

The calculated bearing losses (for both bearings) at 12,000 rpm are as follows:

Torque due to 8.5 lb wheel radial load	-	0.025 in-oz
Torque due to 10 lb thrust load (preload)	-	0.190 in-oz
Torque due to retainer drag	-	0.08 in-oz
Torque due to lubricant drag	-	0.418 in-oz
		0.713 in-oz

This is approximately 6.3 watts power at 12,000 rpm dissipated in the bearings. The calculated losses are in good agreement with measured values.

Thermistors are provided near each spin bearing to permit monitoring of the bearing temperature as a measure of imminent bearing failure. These thermistors typically read 110^{o}F to 140^{o}F (44^{o}C to 60^{o}C) when running at 12,000 rpm at a room temperature environment.

SPIN BEARING PRELOAD

It had originally been proposed that an aluminum gimbal be employed with a preload rod arrangement for controlling the bearing preload under temperature variations. Since this method permits one bearing outer race to float in the gimbal under temperature excursions, the center of gravity of the wheel shifts. This causes gimbal unbalance which exceeds the specification of 0.0005 ft-lb.

The design was changed to a solid preload. The temperature problem was resolved by employing a titanium gimbal, thus providing closely matched gimbal and shaft thermal coefficients. Gimbal inertia was increased but is within specifications. Stiffness of the gimbal was improved by a factor of 1.65 over aluminum.

A preload of 8 to 10 pounds was selected for good stiffness at reasonable friction torque. Fine preload adjustment is obtained with a preload nut.

WHEEL SPEED MAGNETIC PICKUP

A digital wheel speed signal (one pulse per revolution) is provided by a magnetic pickup (Electro Products Lab, Inc., Model 3015-HTB) mounted near the inner radius of the wheel rim. The first wheel balance hole is drilled at the inner radius to provide the required pulse (the other balance holes are at the wheel outer radius). During assembly, the pickup is adjusted to provide an output pulse of 2.0 volts peak-peak per 1000 rpm.

BRUSHLESS DC SPIN MOTOR

The General Electric brushless DC motor was selected to accelerate and decelerate the momentum wheel because of the following advantages:

1. Very high efficiency
2. Precision speed control

3. Proven design and available hardware
4. Versatile capability - adjustable speed, adjustable torque, simple despin technique

The motor that is used was originally developed for NASA/MSFC (see reference 8) as a 20 in-oz torque motor. As a spin motor, it is used at 2-3 in-oz so that I^2R losses are reduced and very high efficiency obtained.

A detailed description of the motor operation can be found in references 6 and 8 and will not be repeated here. The motor consists of a permanent magnet rotor and a two-phase wound stator. A Hall effect probe resolver is used to commutate motor rotor position and to provide signals that are amplified to drive the two stator windings. Hall effect probes, being four-quadrant multipliers, provide a convenient method of controlling motor torque.

The motor that is used is identical to the NASA/MSFC motor (reference 8) except for new windings constants, thinner punchings (to reduce core losses), improved Hall effect probes and no magnet keeper. The motor characteristics are given in Table 5.

TABLE 5

BRUSHLESS DC SPIN MOTOR CHARACTERISTICS

Torque Constant	2.4	in-oz/amp
Generator Constant	0.0018	volts peak/rpm
Resistance (per phase)	1.1	ohms
Inductance (per phase)	0.6	millihenry
Number of Poles	6	---
Core losses at 12,000 rpm	0.5	watts
Efficiency at 12,000 rpm		
- at 2.4 in-oz	93	%
- at 1.0 in-oz	93	%
Weight	12	oz
Turns per phase	144	---
Hall Effect Probes	SV210	---

A summary of the characteristics of the complete spin motor system is given in Table 6. The spin-up and spin-down times are based on bearing plus windage drag which varies from 0.4 in-oz at stall to 1.0 in-oz at 12,000 rpm. Spin-down is obtained by decoupling the electronics and placing a 15-ohm resistor across each motor phase. Motor back emf plus bearing drag thus produce the spin-down in a very simple and reliable manner. Both the spin-up and the spin-down times are well within the one hour specification. Note that, during spin-up, the total motor and electronics losses are only 8 watts and that, at full speed (12,000 rpm), are only 3.3 watts. The total running power is only 12 watts. Actual measured data on the gyros is in good agreement with these calculations.

TABLE 6

NOMINAL CHARACTERISTICS OF BRUSHLESS DC
SPIN MOTOR DRIVE SYSTEM

1. General		
Motor Torque	2.4	in-oz
Motor Efficiency	93	%
Electronics Efficiency	80	%
Overall Efficiency	74	%
2. Accelerating Wheel to H = 20 ft-lb-sec at 12,000 rpm		
Spin-Up Time	38	minutes
Spin-Down Time	45	minutes
Total Spin-Up Energy	700	watt-minutes
Total Input Power - Stall	8	watts
Total Input Power - Peak	29	watts
Power Summary at Peak Power:		
Output (Shaft) Power	21.3	watts
Motor Losses	1.6	watts
Electronics Losses	5.9	watts
3. Running 12,000 rpm		
Total Drag Torque (bearings and windage)	1.0	in-oz
Total Input Power	12	watts
Speed Stability	<0.1	%
Power Summary:		
Drag Torque Power	8.0	watts
Motor Losses	0.7	watts
Electronics Losses	2.6	watts

A speed-torque curve for the spin motor system is shown in Figure 13 to further illustrate system operation. The torque is essentially flat from zero speed to operating speed, at which point, the speed control maintains speed within 0.1 percent accuracy from any output torque from zero to maximum rated value.

A complete description of all spin motor electronics is given in Section 5, Electronics Design.

ROTOR WINDAGE

Detailed calculations of rotor windage are presented in the Design Analyses Report (reference 1). It was shown that rotor speed can be maintained at 12,000 rpm with a zero pressure as high as 50 torr (mm Hg). However, to maintain top system performance, it is recommended that the gyro be re-evacuated whenever the gyro pressure exceeds 10 torr.

GIMBAL DESIGN

A titanium gimbal was selected in order to provide a good thermal match with the wheel and wheel shaft to allow a solid preload method to be applied. Titanium is nonmagnetic and provides a high stiffness and low inertia.

The gimbal is made of titanium alloy with these characteristics:

Material	Ti 6A1 4V
Modulus of Elasticity	16.5×10^6 psi
Modulus of Rigidity	6.6×10^6 psi
Yield Strength, 0.2% offset	120,000 psi

A computer program was written, using numerical integration, to determine the gimbal stiffness and maximum stress. The program is fully described in the Design Analyses Report (reference 1). The results were:

Torsional spring constant	230,000 ft-lb/rad
Maximum stress (at 75 ft-lb gyro output torque)	2140 psi

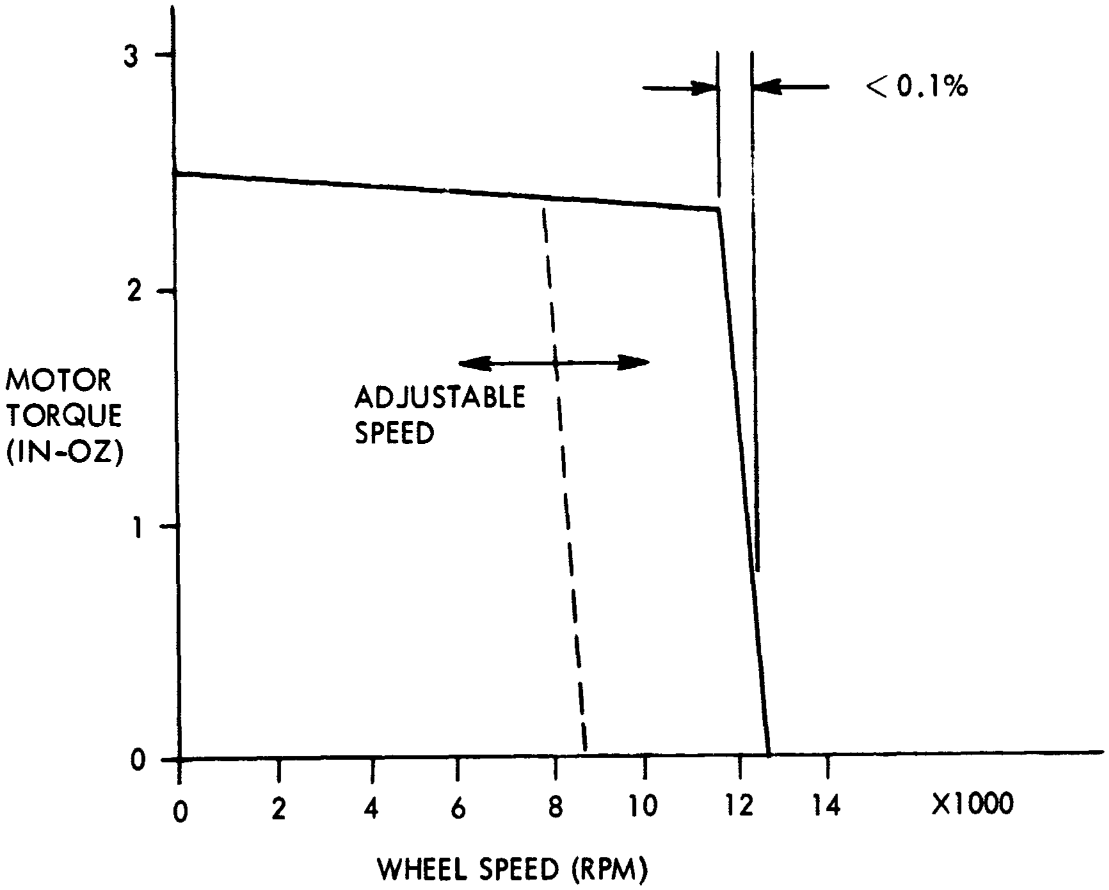


Figure 13. Brushless DC Spin Motor System Speed-Torque Curve

The gimbal is split along the gimbal axis into two parts to permit assembly of the rotor and shaft with it. Care must be taken in the precision machining to ensure the shafts, when assembled to the gimbal, have a maximum wobble of 0.001 TIR.

OUTPUT AXIS COMPLIANCE

The output axis compliance must be minimized to reduce the effective inertia due to the torsional spring rate. For this system, a stiffness of 50,000 ft-lb/rad was desired. The following are the component parts contributing to the total compliance:

Item	Calculated Spring Constant
Wheel Web	800,000 ft-lb/rad
Spin Bearing	145,000 ft-lb/rad
Gimbal Bearing	623,000 ft-lb/rad
Gimbal	230,000 ft-lb/rad
Shaft (Wheel)	360,000 ft-lb/rad

The total calculated torsional spring constant (all springs in series) is 59,000 ft-lb/rad. The measured spring constant was approximately 40,000 ft-lb/rad, which is completely acceptable, but somewhat below the calculated value. However, the calculations are only approximate and, in the case of the bearings, based on nominal manufacture supplied data. Thus, the agreement between the calculated and measured values is satisfactory.

GIMBAL BEARINGS

Size A539TX80DF10G-6 bearings were chosen principally for their physical configuration. The thin axial length with a large bore is desirable for this gimbal application. The static load capacity of 380 pounds exceeds the peak anticipated load of 48 pounds. The bearings have phenolic retainers and are lubricated with Andok "C" grease.

A duplex pair is employed at each gimbal shaft, preloaded to 10 pounds. One bearing is free floating to prevent loading due to thermal effects. Bearing friction is calculated to be 0.0026 ft-lb.

GIMBAL INERTIA

A list of the significant parts contributing to the gimbal axis inertia is:

Gimbal	0.00144 ft-lb-sec^2
Wheel	0.00834 ft-lb-sec^2
Torque Motor Rotor	0.00002 ft-lb-sec^2
Spin Motor Weight	0.00065 ft-lb-sec^2
Balance Weight	0.00022 ft-lb-sec^2
	0.01067 ft-lb-sec^2

This is within the maximum of 0.012 ft-lb-sec^2 specified and in excellent agreement with measured values.

GIMBAL BALANCE

The requirement of 0.0005 ft-lb unbalance means that special care must be taken in the design, machining and balancing procedure to meet the specification.

The gimbal was statically balanced by placing the shafts on parallel knife edges and shifting the c.g. with balance weights until there is no preferred angular position. Errors introduced into the balancing procedure are as follows:

1. Shift of rotor c.g. (at 45°) due to compliance of bearings = 0.000075 ft-lb
2. Shift of rotor c.g. (at 45°) due to gimbal flexing = negligible
3. Inner race eccentricity of gimbal bearings = 0.000133 ft-lb
4. Eccentricity of gimbal shaft = negligible. Static balance of the gimbal shaft on knife edge and tight inner race fit eliminates this error.
5. Torquer eccentricity due to removal and replacement after balancing = 0.0000333 ft-lb
6. Tachometer eccentricity due to removal and replacement after balancing = 0.0000125 ft-lb
7. Shift of wiring harness in wiring after balancing = 0.0000286 ft-lb

The RSS value of these errors is 0.000125 ft-lb. Errors in balancing due to the procedure (knife edge level, waviness, etc.) from previous experience is 0.00032 ft-lb. Total error is 0.00045 ft-lb versus the allowable 0.0005 ft-lb.

GIMBAL AXIS FRICTION

The primary gimbal axis friction estimates are given below.

Slip Ring Assembly	0.0015
Gimbal Bearings	0.0026
Tachometer	0.0063
Torque Motor	0.0130
Potentiometer	0.0020
Total	0.0254

Actual measured values varied from 0.027 to 0.031 ft-lb, apparently due to high torque motor friction.

TORQUE MOTOR

An Inland T-2955D brush-type DC torque motor is employed on the gimbal axis. The major torque motor characteristics are given in Table 7.

TABLE 7

TORQUE MOTOR CHARACTERISTICS

Model	Inland T-2955D
Rated Torque	0.85 ft-lb
Motor Friction Torque	0.013 ft-lb
Ripple Torque	5%
Ripple cycles per revolution	41
Ultimate Temperature Rise	5°C/watt
Rotor Inertia	0.00023 slug-ft^2
Motor Weight	1.5 lbs
Brush Life	10^7 revolutions
Winding Constants:	
DC Resistance (25°C)	10.3 ohms
Torque Constant	0.31 ft-lb/amp
Back emf Constant	0.42 volts/rad/sec
Inductance	17 millihenries

TACHOMETER GENERATOR

An Inland TG-2139A brush type DC tachometer is mounted adjacent to the torquer for measuring gimbal rate. The tach windings are 0.375 inch away from the torquer to minimize magnetic influence of the two. Mu metal shielding prevents noise pickup on the tachometer signal. Tachometer characteristics are listed in Table 8.

TABLE 8

TACHOMETER CHARACTERISTICS

Model	Inland TG-2139A	
Voltage Sensitivity	1.20	volts/rad/sec
DC Resistance	1130	ohms
Inductance	0.60	henries
Friction Torque	0.0063	ft-lb
Ripple Voltage	2	%
Ripple Cycles per Revolution	49	
Rotor Moment of Inertia	0.000037	slug-ft^2
Weight	0.56	lb

SLIP RING ASSEMBLY

A 17092C36-0 slip ring assembly manufactured by the Electro Tech Corporation provides the electrical coupling to the rotating gimbal. This is a proven unit produced in quantities in excess of 50 for a Bendix Stable Platform.

GIMBAL POTENTIOMETER

A Model 205 rotary linear film potentiometer made by CIC Corporation is used for indicating gimbal position. This potentiometer is specified by General Electric Drawing Number 854D239, Resistor-Variable, Linear Precision. Potentiometer characteristics are listed in Table 9.

TABLE 9
LINEAR POTENTIOMETER CHARACTERISTICS

Model	205 Rotary Linear Film Potentiometer, CIC Corp
Electrical Characteristics:	
Resistance range	20K ohms
Resistance tolerance	±10%
Resolution	Virtually infinite
Electrical function angle	$350^{\circ} \pm 3^{\circ}$
Electrical contact angle	$356^{\circ} +2^{\circ} -3^{\circ}$
Three zero width taps:	
one center tap	
one at $+90^{\circ}$ from center tap	$\pm 0.1^{\circ}$
one at -90° from center tap	$\pm 0.1^{\circ}$
Independent Linearity (no wiper load)	0.035%
Temperature coefficient	-300 ppm maximum
Power rating	4 watts
Mechanical Characteristics:	
Single-turn with 360° continuous rotation	
Starting torque	0.3 in-oz maximum
Operating temperature	$-55^{\circ}C$ to $+150^{\circ}C$
Clockwise rotation	viewed from servo mount end
Weight	4 oz

GIMBAL STOPS

Gimbal motion limits are adjustable from $\pm 45^{\circ}$ to $\pm 90^{\circ}$ in 5° increments. The stops consist of a compression spring mounted on the gimbal which makes contact with an adjustable pin in the case. The spring rate is selected to decelerate the gimbal in 8° from a velocity of 3.75 rad/sec.

GYRO HOUSING

The gyro housing acts mainly as a vacuum enclosure. The gyro reaction loads are carried by the trunnion mounts which produce negligible stresses in the housing.

The housing is made from 6061-T6 aluminum which has a yield strength of 40,000 psi. It is shown in the Design Analyses Report (reference 1) that the maximum stress occurs in the end cover (potentiometer end) and has a value of 6200 psi. This is well within the specified stress safety factor of four.

Rubber O-rings are used to seal the CMG housing at several locations. They provide adequate sealing and ease of assembly. The vacuum valve is a Hoke, Inc., Model 4561 Q4M, and the vacuum gage tube is a Hastings-Rag Dist., Inc., Model DV-4D (range: 0-20 torr).

MOUNTING FIXTURE

The mounting (and alignment) fixture is a dip-brazed aluminum structure designed to allow trunnion mounting of the gyros. The locations of the mounting points are such that a direct path is provided for the gyroscopic forces to be transferred to the vehicle. A three point mounting technique is employed to assure levelness and minimum stress in the mounting fixture and vehicle mounting surface. Both a scribe line and a reference surface is provided for alignment of the mounting fixture on the Space Vehicle Motion Simulator Mounting surface.

The mounting frame is precision machined to allow the gimbal axes to be aligned to the scribe lines on the vehicle to well within the specified accuracy of two arc minutes. This is achieved by machining the trunnion bores, mounting feet, scribe marks and reference surface all in one machining operation to an accuracy of 0.0001 inch/inch (0.344 arc minutes).

SYSTEM ALIGNMENT ERRORS

A detailed alignment tolerance analysis was performed for the Design Analyses Report (reference 1) which showed that all specified alignment tolerances could be met. The results are briefly summarized below.

- Alignment of momentum vector to gimbal axis.

  The RSS static alignment error is 0.58 arc minute compared to a specified value of 1 arc minute.

  The dynamic alignment error is due to gyro output axis compliance. Using the measured output axis torsional spring gradient at the maximum output torque of 75 ft-lb, gives a dynamic alignment error of

  $$\frac{75}{40{,}000} = 0.00188 \text{ radian} = 6.45 \text{ arc minute}$$

  The specified allowable value is 10 arc minutes.

- Alignment of gimbal axes to each other.

  The RSS alignment error is 0.59 arc minute compared to a specified value of 2 arc minutes.

- Alignment of gimbal axis to mounting fixture axis.

  The RSS static alignment error is 0.48 arc minute. The required accuracy of 2 arc minutes (with a goal of 1 arc minute) must be maintained at full torque output (150 ft-lb). A conservative estimate of the mounting fixture stiffness is 10^6 ft-lb/rad, which results in an additional error of

  $$\frac{150}{10^6} = 0.00015 \text{ radian} = 0.52 \text{ arc minute.}$$

  Thus, the total alignment error at full output torque is less than 0.48 + 0.52 = 1.0 arc minute.

Section 5

ELECTRONICS DESIGN

GENERAL DESCRIPTION

The electronics assembly contains all the circuitry required for the brushless DC spin motors, the torque motor amplifiers and gimbal rate loop control, slaving and caging circuits, and converters to generate all required voltage levels from the single-input supply of 28 VDC. All desired mode switching, output test points, and interface connections are accomplished in this assembly. Power lights and a potentiometer dial selection for momentum speed setting are on the front panel of the assembly. (See Figures 14 and 15.) A summary of the overall electronics assembly characteristics was given in Table 1.

The electronics assemblies have all been packaged to provide maximum convenience and accessibility for laboratory operation. All of the electronic parts, with the exception of EMI filters, relays, and four high-power resistors which dissipate the back emf in the spin motors, are mounted on eight unpluggable circuit board assemblies in each electronic assembly. Sufficient clearance has been provided between the chassis bottom surface and Space Vehicle Motion Simulator mounting surface and between board assemblies to insure adequate cooling of parts by natural convection without introducing appreciable heat into the Space Vehicle Motion Simulator mounting surface. Figure 16 shows an internal view of the Electronics Assembly.

There are four different types of the eight unpluggable circuit boards used. One type, of which one board is used, is a power supply and speed control board which contains the two-speed control circuits, one for each gyro of the pair, and a DC-DC converter which furnishes the supply voltages and triangular waves. Another type, of which only one board is used, is the power supply and gimbal board which contains a DC-DC converter, a potentiometer drive circuit, slave circuits, a caging circuit, and an input amplifier. The third type, of which two boards are used, is the torque motor amplifier board which contain gimbal control circuits, torquer amplifiers, and rate loop

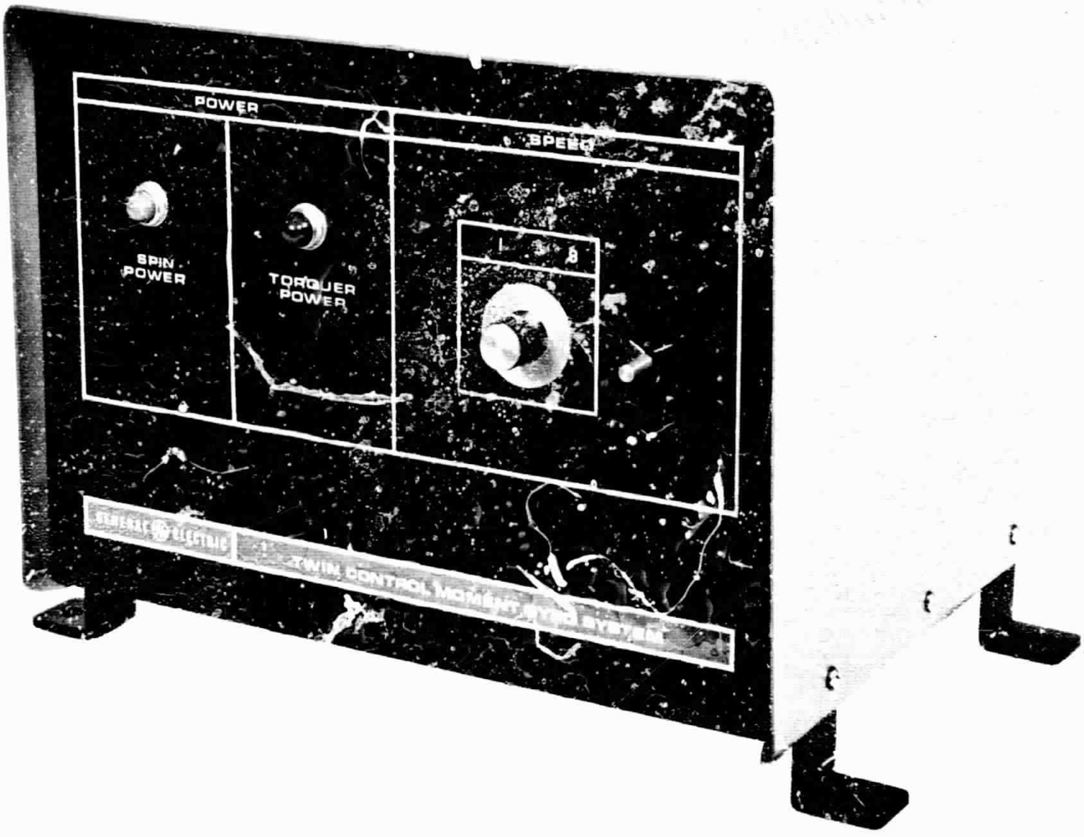


Figure 14. Twin CMG Electronics Assembly

Figure 15. Electronics Input and Output Connectors

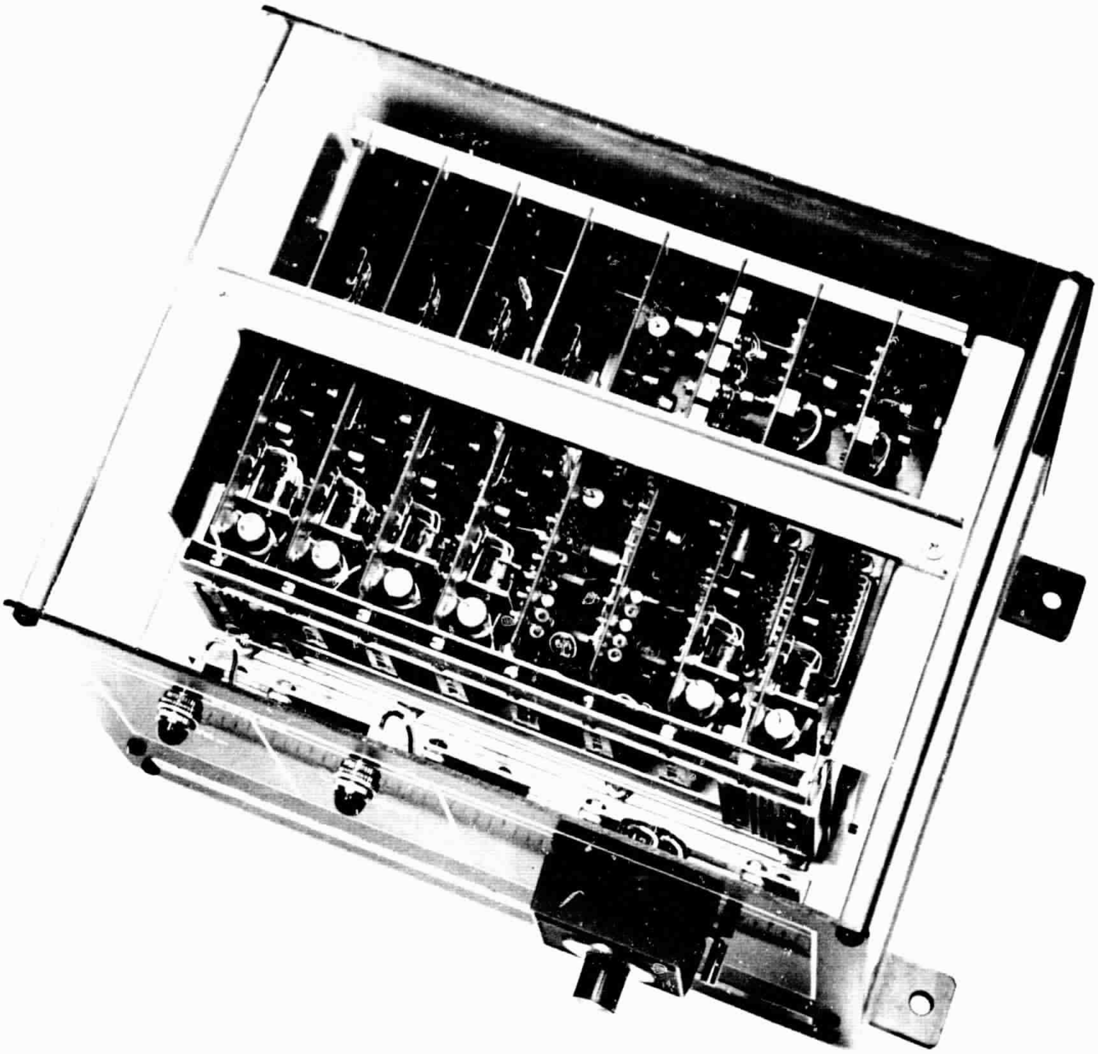


Figure 16. Electronics Assembly with Top Cover Removed

circuits. The fourth type, of which there are four used, is the spin motor amplifier board, phase A and phase B for each of the two gyro's spin motors. Figure 17 shows a block diagram of the breakdown of the electronics assembly. The eight unpluggable boards are shown in Figure 16. Figure 18 is an example of a typical unpluggable circuit board. The GE drawings for the actual schematics of the four types of circuit boards are shown in Figures 19, 20, 21 and 22. They should be referred to in conjunction with the discussion that follows in the design of the individual circuits.

DESIGN OF GIMBAL CIRCUITS

DC-DC CONVERTER (Figure 19)

A DC-DC converter is a circuit which changes the magnitude of an available DC voltage to another desired magnitude. The type used is a standard two transistor and two transformer converter that has been tested and evaluated under previous contracts. With this configuration converter the saturable base-drive transformer T_1 controls the switching operation at the base circuit power levels. The linearly operating output transformer transfers the output power to the load. Because the output transformer T_2 is not allowed to saturate, the peak collector current of each transistor is determined principally by the value of the load impedance. This feature provides high efficiency.

The converter circuit provides an overall power output of about 2 watts. The rectified square wave converter output is passed through two microcircuit regulators, an NC511 and an NC513 which regulate the voltage to plus and minus 12 volts DC. The squared wave outputs of the converter circuits are also integrated using a simple RC circuit to provide triangular waves, ±2 volts p-p, at a frequency of 4700 Hz. These power supply voltages are necessary to properly operate the gimbal control circuits.

PULSE WIDTH MODULATED POWER AMPLIFIER

Switching mode power amplifiers, using pulse width modulation (PWM), are used in the torque motor electronics. Pulse width modulated amplifiers achieve very high efficiency since the transistors are used as switches. This high efficiency is obtained at all output voltage levels.

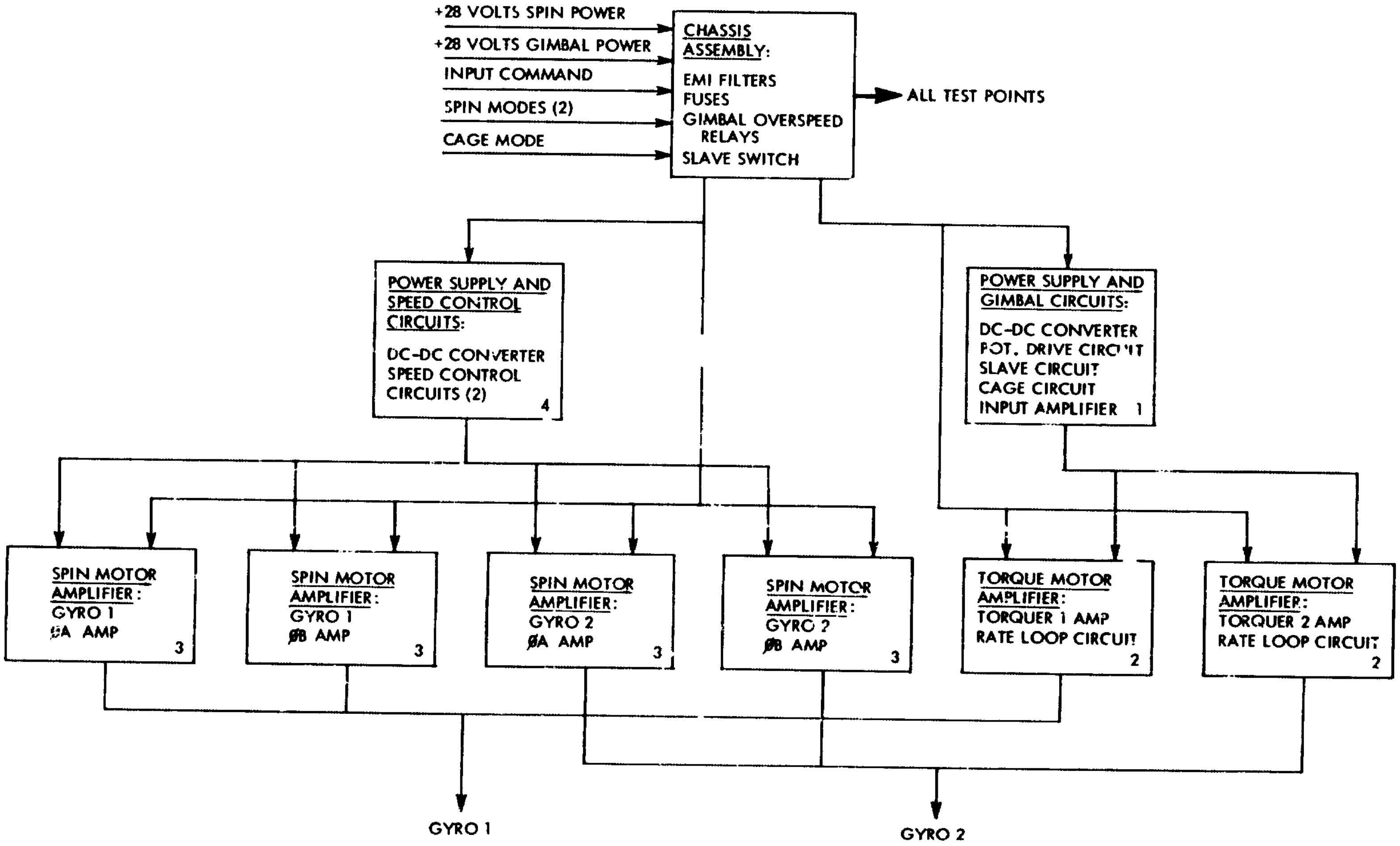


Figure 17. Block Diagram of Twin CMG Electronics Assembly

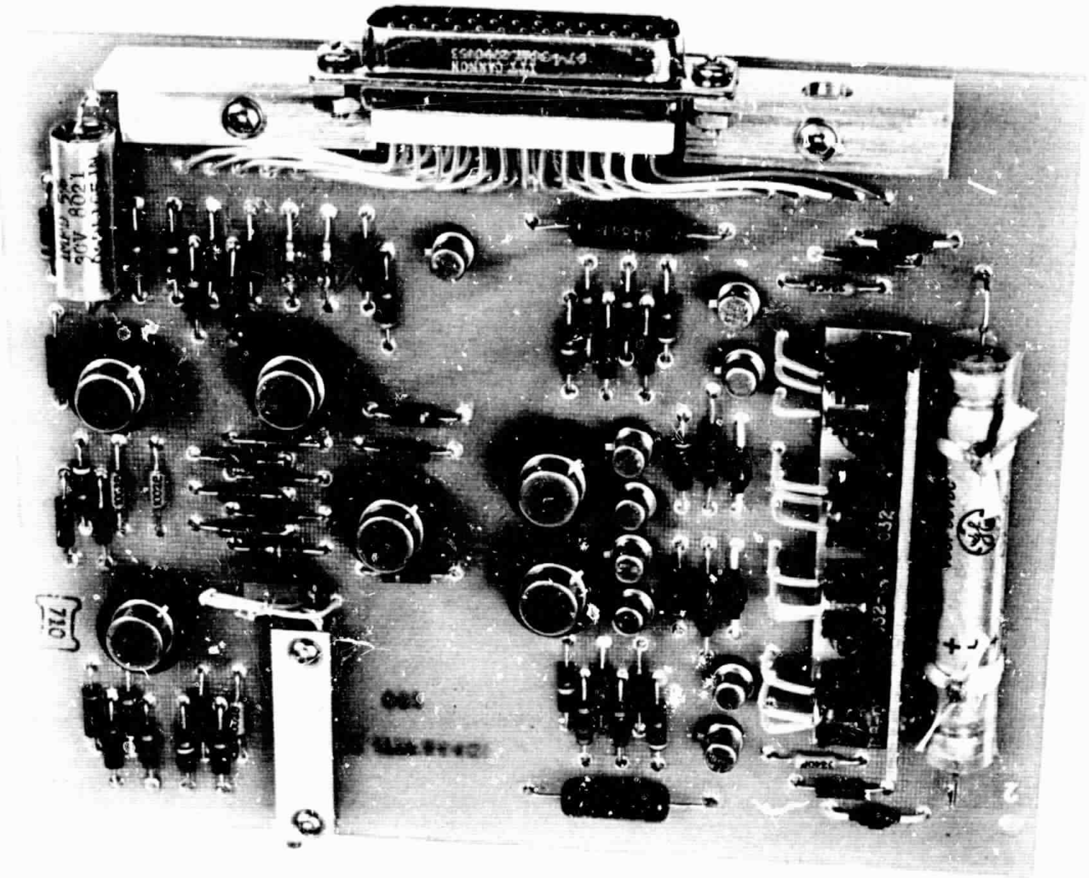


Figure 18. Typical Circuit Board Layout (Torque Motor Amplifier)

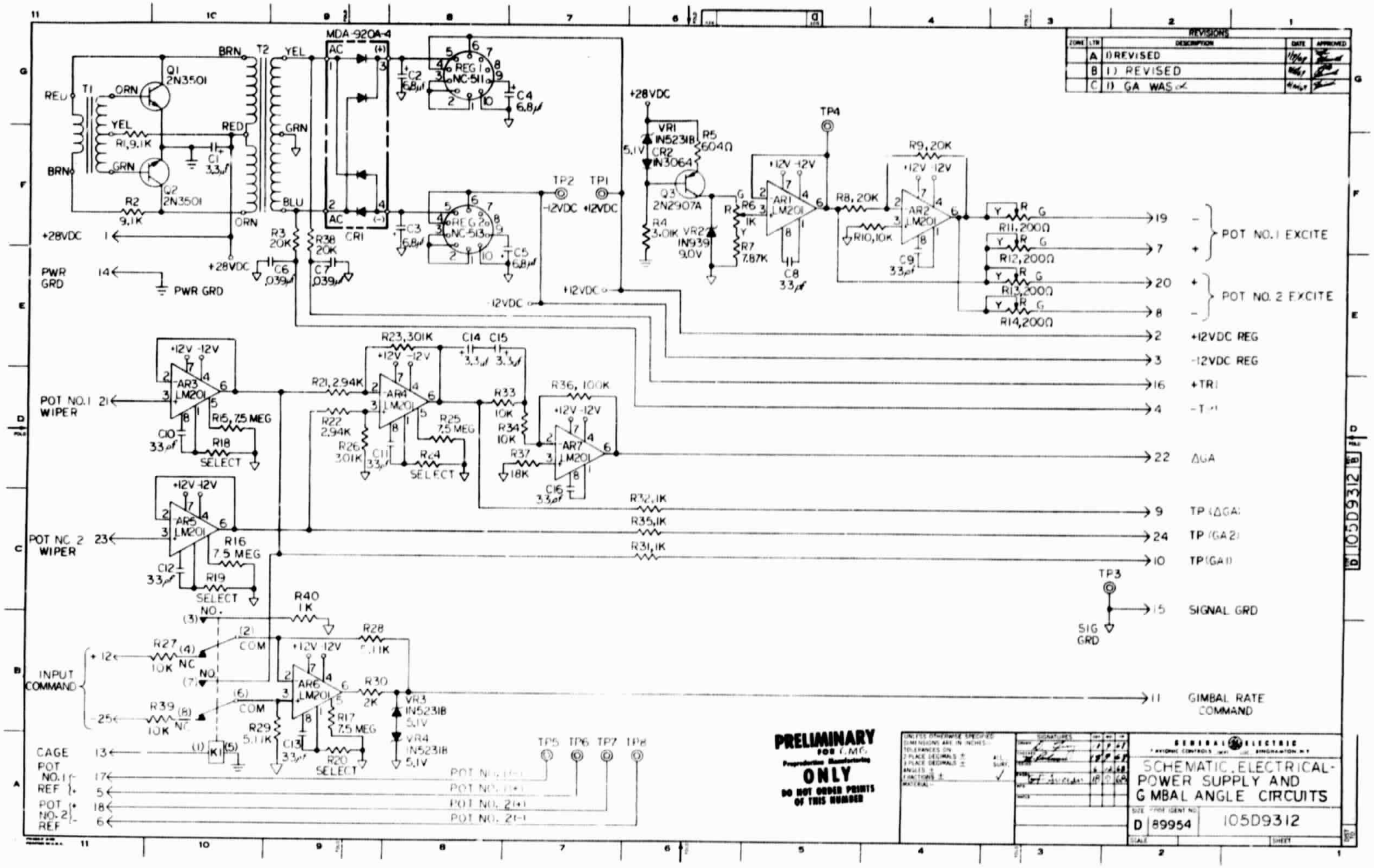


Figure 19. Power Supply and Gimbal Angle Circuits

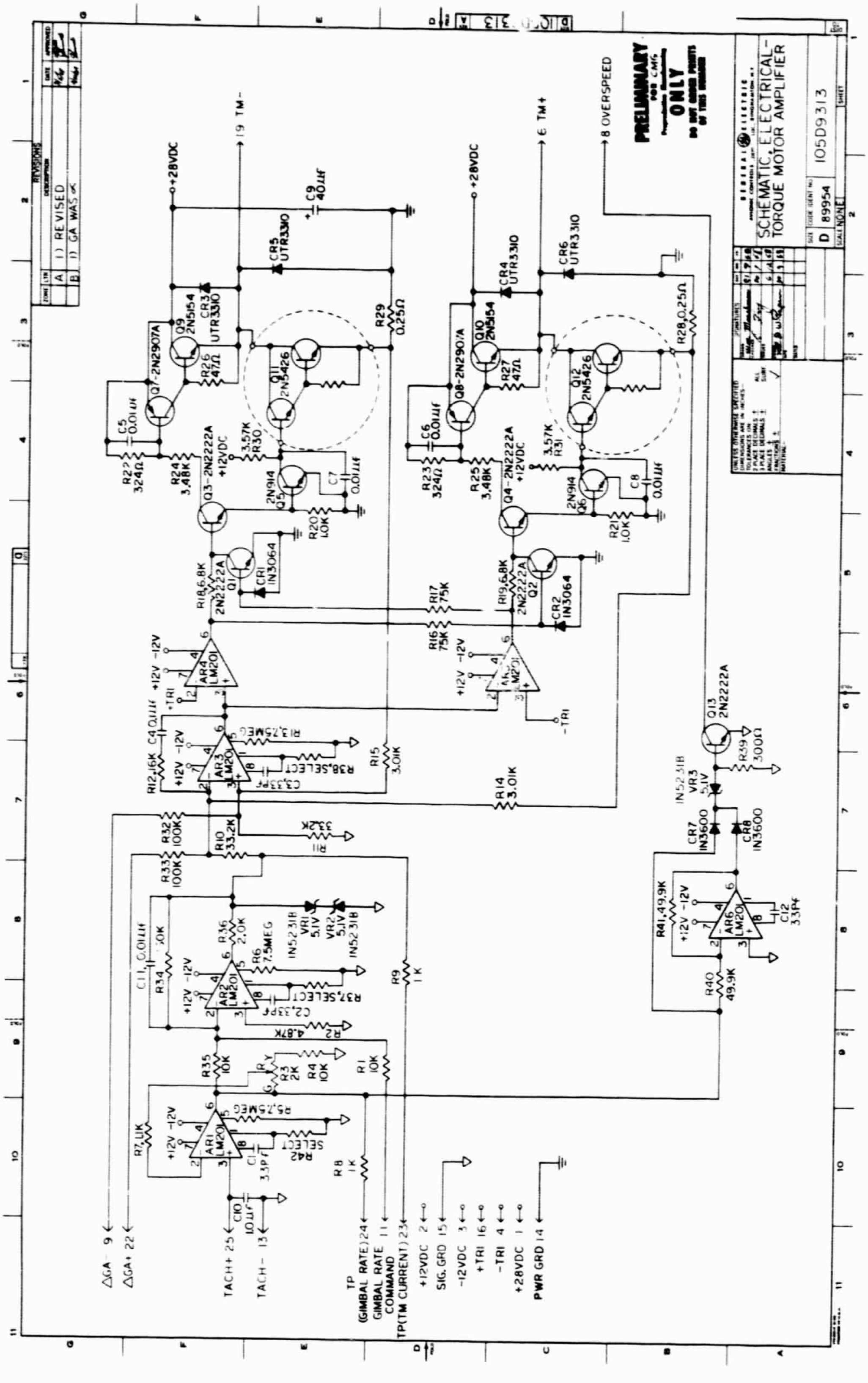


Figure 20. Torque Motor Amplifier

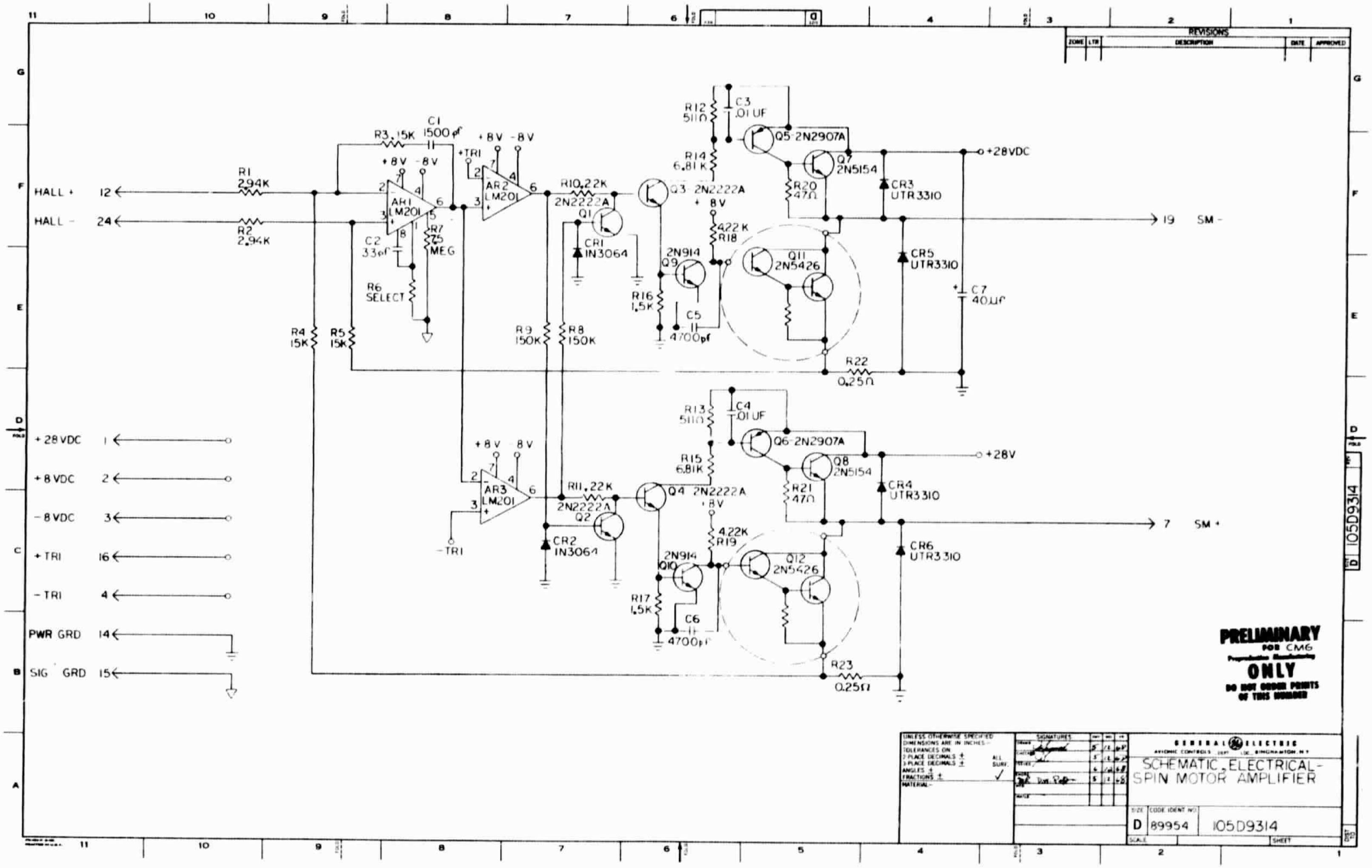


Figure 21. Spin Motor Amplifier

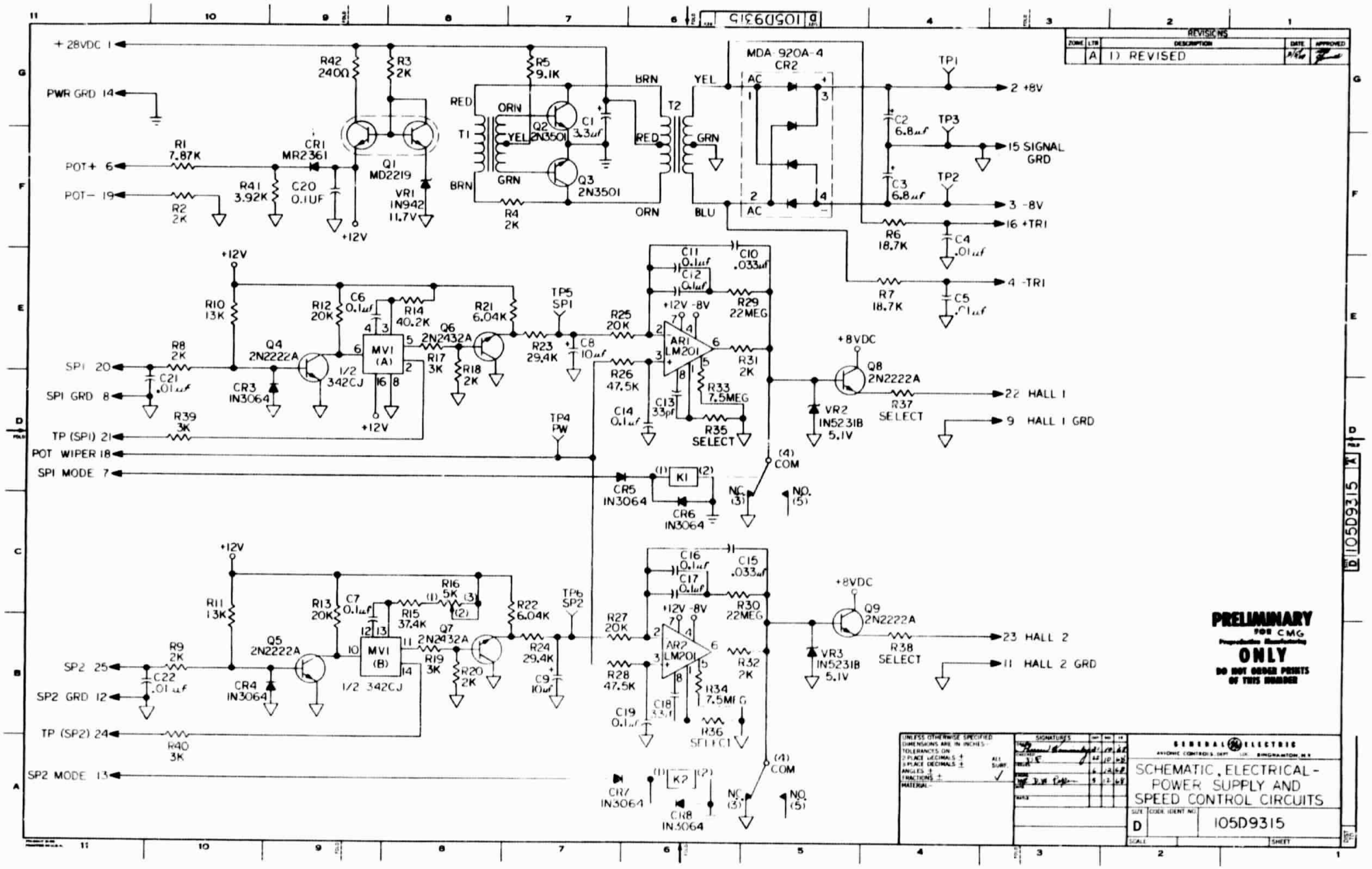


Figure 22. Power Supply and Speed Control Circuits

Reference 6 contains a short explanation of the operation of the Pulse Width Modulation and Power Amplification as applied to the Twin CMG Systems. Reference 7, Chapter 4, "Electromechanical Control Systems", explains this operation in greater depth. In particular, the section on servo signal conversion and compensation accurately covers the theory of operation of the Pulse Width Modulation and Power Bridges used in the Twin CMG System electronics.

A block diagram of a pulse width modulated power amplifier using current feedback is shown in Figure 23. Current feedback is used to maintain constant current in the presence of varying motor back emf. Current feedback also linearizes amplifier gain and eliminates inherent deadband in the power bridge output stage. This makes the amplifier well suited for servo loop torque motor drives.

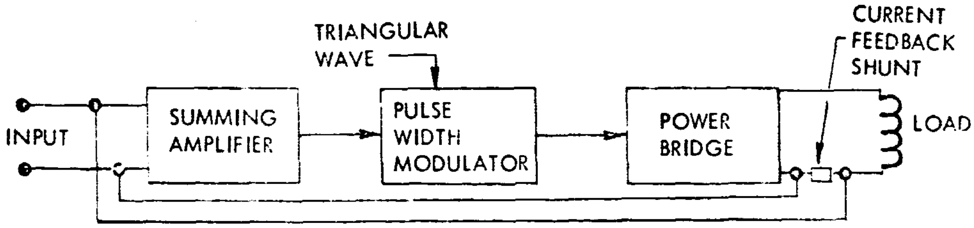


Figure 23. PWM Power Amplifier with Current Feedback

The output stage of the power amplifier consists of a bridge configuration of power transistors so that bi-directional drive capability can be provided from a single power supply voltage. The basic power bridge configuration is shown in Figure 24. Operation of the bridge, to achieve positive current as shown in Figure 24, is as follows:

1. Q_4 is turned on and Q_3 is turned off
2. Q_1 and Q_2 are driven push-pull at the PWM rate, with the duty cycle determined by the PWM to produce the desired output current.
3. With Q_1 on, the current path is through Q_1, the load, and Q_4.
4. With Q_1 off, the current free-wheels through diode D2, the load and Q_4. Q_2 is on during this time but no current flows through it.

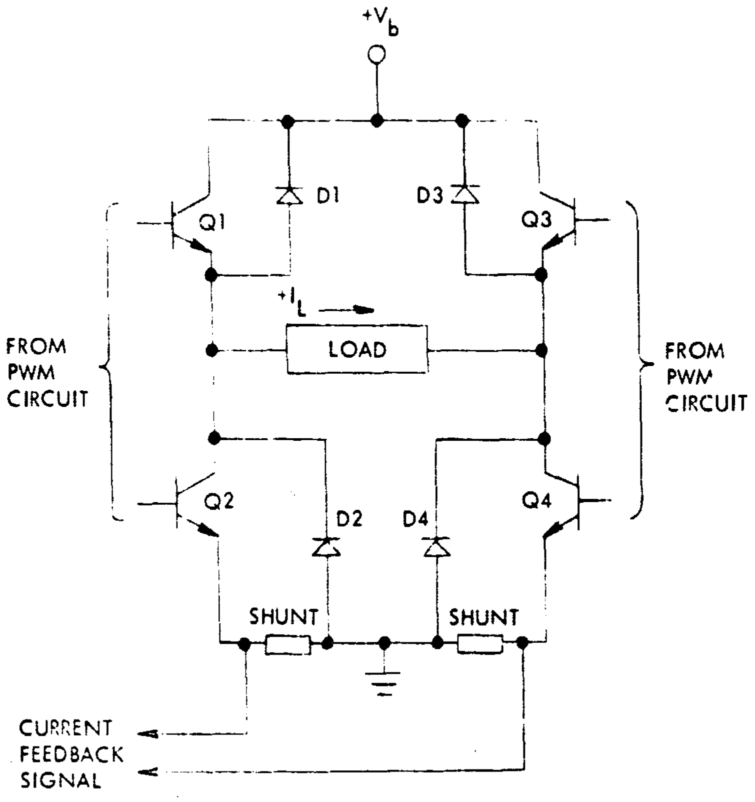


Figure 24. Power Bridge Circuit

The PWM circuit receives DC from the summing amplifier and provides pulses on one of two output lines depending on polarity. The output pulses are time-ratio modulated, with duty cycle (T_1/T) proportional to input signal. The period of the PWM is one-half that of the sawtooth, or

$$T = \frac{1}{2} T \text{ saw}$$

The sawtooth frequency is 4800 Hz so $T_{saw} = 208.3\ \mu\text{sec}$ and $T = 104.2\ \mu\text{sec}$. The sawtooth waveform is 1.0 volts peak, so that 100% pulse width modulation occurs at an input voltage (V_{in}) of 1.0 volts. The gain of the PWM is

$$\frac{T_1}{V_{in}} = \frac{10.42\ \mu\text{sec}}{1.0 \text{ volts}} = \frac{104.2\ \mu\text{sec}}{\text{volt}}$$

The gain of the power bridge can be expressed as an output voltage V_o for a PWM input time (T_1). For 28 volts power supply with 2 volts drop across the semiconductors, this gain is approximately

$$\frac{V_o}{T_1} = \frac{28-2}{104.2}\,\frac{\text{volts}}{\mu\text{sec}} = \frac{26}{104.2}\,\frac{\text{volts}}{\mu\text{sec}} = 0.25\,\frac{\text{volts}}{\mu\text{sec}}$$

The load current is given by

$$I_L = \frac{V_b \frac{T_1}{T} - 2V_D}{R + R_s}$$

where I_L is the instantaneous load current; V_b is the power supply voltage; R is the load resistance; R_s is the current feedback shunt resistance; T is the PWM period, T_1 is the time Q_1 is on; and V_D is the "on" voltage drop across transistors and diodes.

The PWM power amplifier for the torque motor is shown in the right-hand side of Figure 20. The following components make up the power amplifier:

■ Power Bridge	
a. Output Stage	Q9, Q11, Q10, Q12
b. Drivers	Q3, Q5, Q7, Q4, Q6, Q8
■ Pulse Width Modulator	AR4, AR5, Q1, Q2
■ Summing Amplifier	AR3

The output stage power transistors have a current rating of 5 amps. For the torque motor amplifier, they are used at a maximum current of about 2.5 amps.

The current feedback resistors determine the closed loop amplifier gain. This is given by

$$\frac{I_o}{V_{in}} = \frac{1}{R_s} \frac{R_f}{R_i} \frac{\text{amps}}{\text{volt}} \tag{10}$$

where

I_o = output current

V_{in} = input voltage

R_s = shunt resistor (R28, R29) = 0.25 ohms

R_f = feedback resistor (R14, R15) = 3.01 K ohms

R_i = input resistor (R10) = 33.2 K

thus the power amplifier gain is

$$\frac{I_o}{V_{in}} = \frac{1}{0.25} \frac{3.01}{33.2} = 0.363 \frac{\text{amps}}{\text{volt}}$$

The gimbal slaving loop error signals are fed into the power amplifier through 100 K ohm resistors (R32, R33). For these slaving loop inputs, the power amplifier gain is

$$\frac{I_o}{V_{in}} = \frac{1}{0.25} \frac{3.01}{100} = 0.12 \frac{\text{amps}}{\text{volt}}$$

The current feedback loop gain is adjusted in the summing amplifier. The loop crossover is adjusted to provide a simple break at approximately 300 Hz (1900 rad/sec).

POTENTIOMETER EXCITATION CIRCUIT

This circuit is shown in the upper right-hand corner of Figure 19, and is redrawn in Figure 25 for explanation purposes. This circuit functions to provide voltage excitation

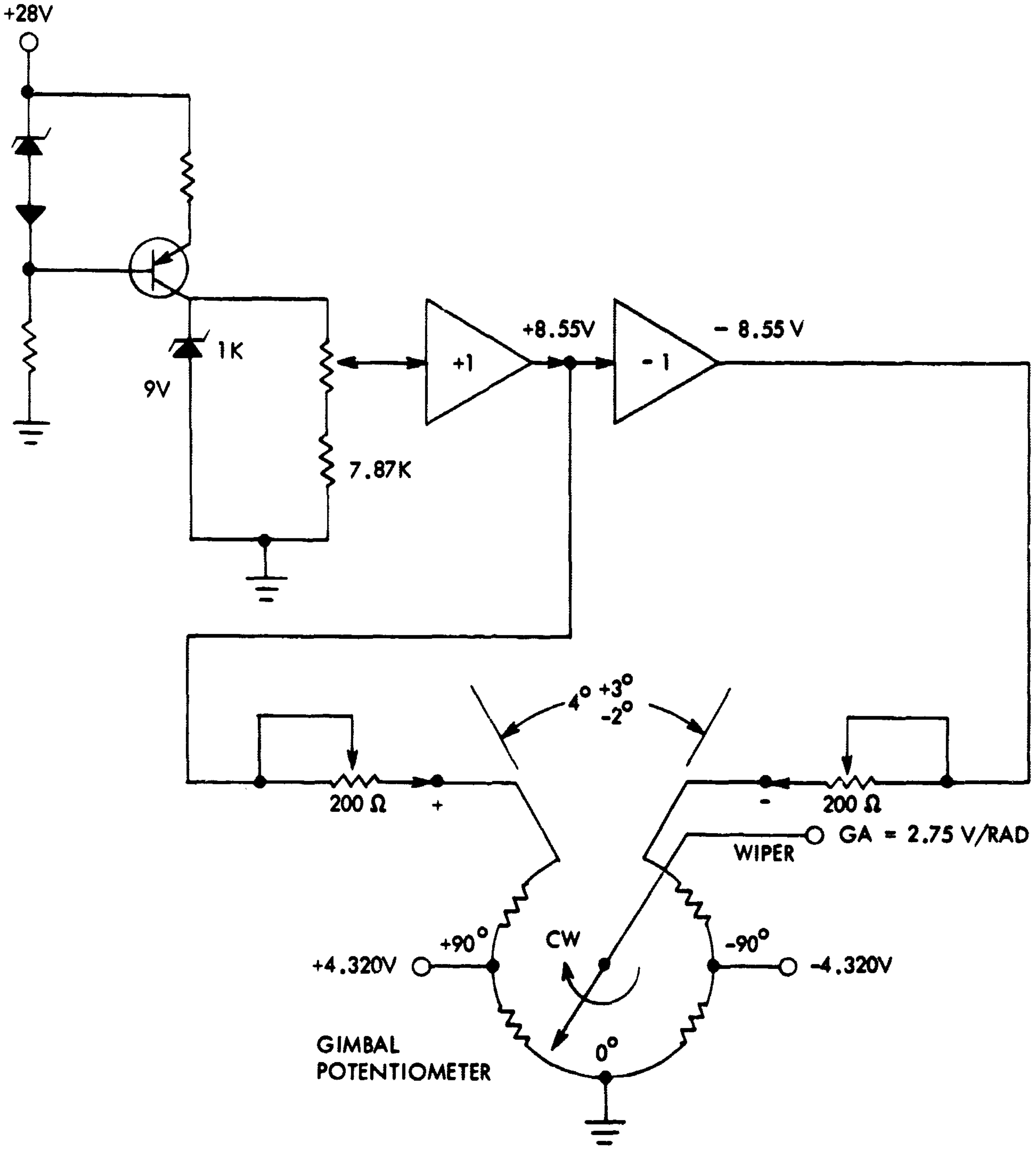


Figure 25. Potentiometer Excitation Circuit

to the gimbal potentiometers. A voltage divider network, using an adjustable trim potentiometer, at the zenered output of a transistor, makes it possible to select the excitation voltage level between 8 and 9 volts DC. Sending this voltage excitation level through an inverting amplifier makes it possible to provide plus and minus excitation voltage levels to the potentiometer. (See Figure 25 and Figure 4 of Section 3.)

The 200-ohm trim potentiometers set the gimbal angle transfer function at 2.75 volts per radian by setting a specific linear voltage drop about the potentiometer as a function of the potentiometer angle. Since the potentiometer shaft or wiper is mechanically connected to the gimbal shaft and set up so that zero degree is zero volts out, an accurate voltage representation of gimbal angle can be obtained. It is the difference of the gimbal angle voltages of the two gyros of the twin pair that is used to electronically slave together the two gyro gimbal angles.

GIMBAL SLAVING CIRCUIT

A gimbal slaving loop or tracking loop is employed to insure that the angular difference between gimbals of each pair of gyros is minimized. Gimbal slaving involves the feedback of relative gimbal angle error to both gyros of the twin pair. The major error sources are those which lead to gimbal shaft torque differences between the two gyros. The worst error sources are those due to non-identical limits (or saturations) in the gimbal command electronics and tachometer gradient errors. Figure 4 of Section 3 shows a block diagram of the slaving circuit. The actual circuit is shown in Figure 19, consisting of operational amplifiers AR3, AR4, AR5 and AR7.

The slaving loop circuits are set up such that the two outputs from the twin CMG gimbal potentiometers are fed into a summing amplifier to obtain a gimbal angle difference voltage. This difference signal is then looped back into the power amplifiers of the torque motor drive circuits of both gyros in the twin pair. The result is that the current in the torque motor of leading gimbal angle is decreased and the current in the torque motor of lagging gimbal angle is increased. This causes the leading gimbal to slow down and the lagging gimbal to speed up in such a way that the two gimbals track each other. Limiting factors in maintaining gimbal tracking are the accuracy of the gimbal position transducer and the relative differences between the command electronics and mechanical elements for each gyro in the twin set.

GIMBAL OVERSPEED

Gimbal overspeed can occur if there is a full-on failure in the torque motor amplifier, tachometer and input preamplifiers, or DC-DC converters, as well as broken or shorted cable leads, that is, any failure that would put full current in the torque motor. Such a failure could cause a gimbal rate of almost 15 rad/sec before the gimbal hits the stops if the stops are at the maximum angle of ±90°. This rate is four times the maximum gimbal rate (3.75 rad/sec or 75 ft-lb output torque) and would cause permanent spin bearing damage. To protect against such damage, a relay has been placed in series with each torque motor. Figure 26 shows a block diagram of the Gimbal Overspeed Circuit. The actual circuit is on the torque motor amplifier circuit board (trip circuit consisting of AR6 and Q13 of Figure 20) and on the chassis (relays).

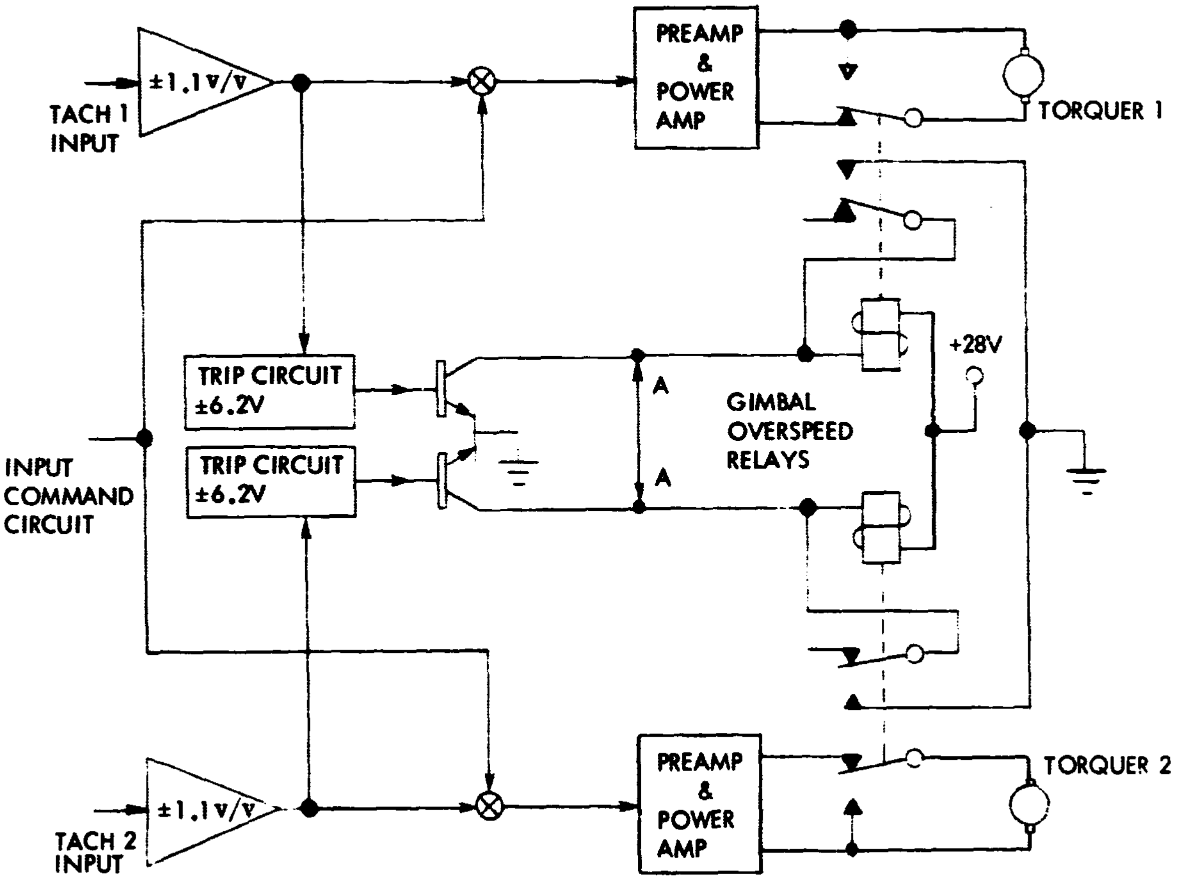


Figure 26. Block Diagram of Gimbal Overspeed Circuit

Gimbal overspeed is sensed by monitoring tachometer voltage. If either gyro gimbal rate increases about 4.7 rad/sec, which is equivalent to having 6.2 volts applied to the trip circuit from the output of the tachometer gain amplifier, transistors turn on and cause the overspeed relays to energize. Relay contacts then open, removing power from the torque motor and at the same time short the torque motor leads together so that the back emf produced will cause the torque motor to slow down, thus slowing the gimbal rate. Because of a latching system used in conjunction with the overspeed relay, torque motor power must be momentarily shut off in order that the overspeed relays may be de-energized and gimbal rate may be again controlled.

CAGE MODE

A cage mode circuit is employed in the gimbal command circuit for the purpose of driving and maintaining the gyro gimbal angles at zero degrees. Figure 4 of Section 3 shows a block diagram of the caging electronics. This mode of operation would be desired when spinning up or spinning down the gyros, or when the gyros are running idly with no torque outputs demanded from the system. Gimbal caging may be initiated by exciting the gimbal caging relays (relay K1 of Figure 19). With the relays excited, relay contacts disconnect the input command from the gimbal rate command circuits, and simultaneously connects the gimbal angle voltage from the gyro potentiometer to the gimbal rate command in such a fashion that the gimbals are driven in the reverse direction to zero degrees, at which point the gimbal angle voltage is zero volts. With this voltage at zero volts there is no torque motor current, hence the gyro gimbals remain stationary. In this manner the gyro gimbals may be maintained at a gimbal angle of zero degrees.

DESIGN OF SPIN CIRCUITS

DC-DC CONVERTER (Figure 22)

The design of the converter circuit for the spin electronics (top of Figure 22) is similar to the design of the converter circuit in the torquer electronics. However, no regulators are used in the spin electronics converter, which provides an output of ±7.5 volts DC at a capability of 1.8 watts power. The same ±2 volts p-p triangular waves are produced; however, the frequency is 12 KHz. This higher frequency is used to allow a higher crossover frequency of the spin motor current feedback loop.

Since the speed control operational amplifiers require a precision +12 volt DC for there operation in addition to the ±7.5 volts provided by the converter, a dual transistor (Q1 of Figure 22) is used in conjunction with a zener diode to provide a stable +12 volt DC power input.

PULSE WIDTH MODULATED POWER AMPLIFIER (Figure 21)

The design of the pulse width modulated spin motor power amplifier is identical to that of the torquer electronics except that several resistor and capacitor values are changed. The gain of this amplifier is

$$\frac{I_o}{V_{in}} = \frac{1}{0.25}\,\frac{15}{2.94} = 20.4\ \frac{\text{amps}}{\text{volt}}$$

The crossover frequency of the current feedback loop is set at approximately 2000 Hz. This high crossover frequency is required to obtain satisfactorily high loop gain at the motor operating frequency of 600 Hz (three times the 200 Hz wheel speed for the six pole spin motor).

SPEED CONTROL CIRCUIT

The speed control circuit (Figure 27) is basically an analog circuit. The wheel speed signal, digital pulses, obtained from a magnetic pickup on the gimbal, is converted to an analog DC signal proportional to speed by means of a precision single-shot and a chopping transistor. This DC speed signal is compared to a DC reference voltage which determines final wheel speed. When below final speed, the comparator output is in controlled saturation and provides constant Hall-effect probe current, and hence constant motor acceleration torque.

When the DC speed signal reaches the reference voltage, the comparator begins to turn off the Hall current, and hence motor torque. The comparator gain is selected

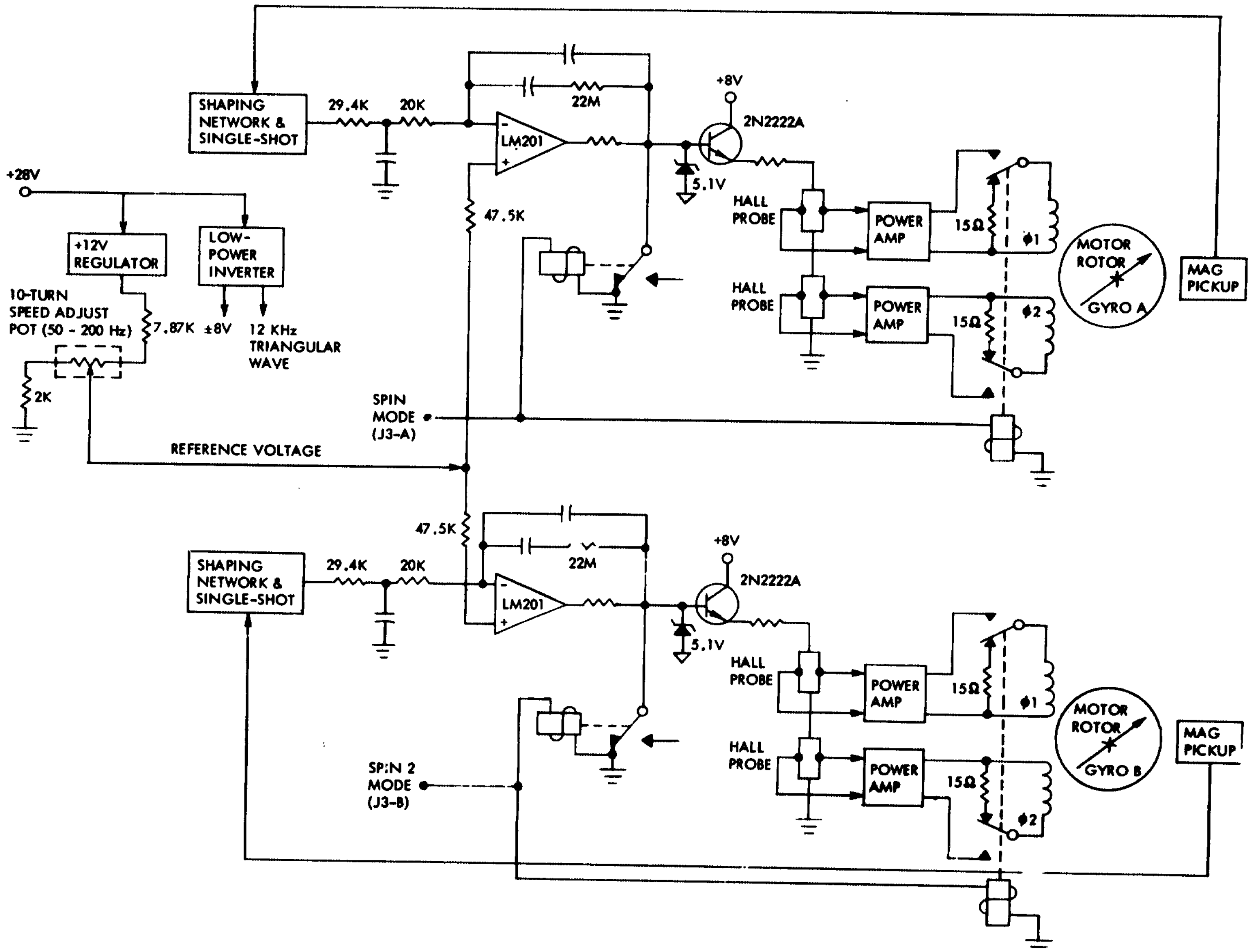


Figure 27. Brushless DC Spin Motor Electronics for Single-Axis Twin CMG System with Speed Control Circuits

so that Hall current is decreased to zero for less than a 0.1 percent change in wheel speed. The net result is a precise control of wheel speed, which can be varied simply by changing the reference voltage.

The speed control circuit for each gyro is controlled by a spin-mode relay. When excited, spin current flows through the motor windings causing the spin motor and thus the gyro wheel to accelerate as described on the preceding page. In the unexcited mode, spin current is removed from the motor windings, and a 15 ohm resistor is placed across each motor winding such that the back emf of the motor windings causes the wheels to decelerate. Since the reference speed control voltage is generated by a precision 10 turn potentiometer, mounted on the electronics front panel, wheel speed is varied simply by adjusting this potentiometer.

The complete speed control circuit is shown in Figure 22. It is repeated twice (two CMG's) once in the middle and once at the bottom of Figure 22. The single shots (or monostable multivibrator, MV1(A) and MV1(B)) are the Amelco dual one shot, type 342CJ, consisting of two integrated circuit single shots in one package. These single-shots have good temperature stability; combined with precision metal film resistors and polycarbonate capacitors, the pulse width temperature coefficient is approximately +0.03%/°C. To compensate for this temperature variance, speed control reference voltage is dropped through a 1.3 V reference diode (CR1 of Figure 22) with a temperature coefficient of -4mv/°C, resulting in a percent temperature variation of $+0.004/(12-1.3)/100 = +0.037\%/^{\circ}C$. This results in a very low drift of wheel speed with temperature. All six speed control circuits were checked for speed control drift with temperature, and all were better than ±0.2% over the full operating range of 10°C to 60°C.

Wheel overspeed can occur only if there is a full-on failure in the speed control circuit. In the remote case of such a failure, the wheel speed will be limited to approximately 40 percent overspeed by the spin motor back emf. At this speed, the wheel stresses are still four-to-one below the tensile strength of the 17-4 PH steel wheel material. This represents a more than adequate safety margin.

Section 6

TWIN CMG SYSTEM RELIABILITY

A predicted MTBF of 14,880 hours for each Twin CMG System has been calculated. The details of these calculations are given in the Design Analyses Report (reference 1), and are summarized in Table 10. The predicted MTBF is strictly valid only for a mission time of 2000 hours, but can be used for other mission lengths with small mathematical error.

TABLE 10

MTBF - TWIN CMG SYSTEMS

Assembly	Failure Rate $F/10^6$ Hours	Quantity per System	Total Failure Rate $F/10^6$ Hours
Control Moment Gyro	17.735	2	35.470
Electronic Assembly (excluding lamps and elapsed time meter)	31.659	1	31.732
Total Failure Rate			67.202

Twin CMG System MTBF = $10^6/67.202$ = 14,880 hours

Section 7
CONCLUSIONS AND RECOMMENDATIONS

The Twin CMG Systems, which have been designed and fabricated to investigate CMG control schemes on the NASA/MSC Space Vehicle Motion Simulator, have demonstrated excellent performance characteristics in thorough acceptance testing. All three systems have met or exceeded the specifications.

The Twin CMG System incorporates several design features which make them well suited for their intended use of experimental investigation of space vehicle control using control moment gyros. Special features include:

- Variable momentum capability
- Brushless DC spin motor
- Very high torque/momentum ratio
- Directed drive torque motor
- Tachometer rate feedback
- Trunnion mounting

The Twin CMG System provides both high output torque (because of high structural stiffness design) and precise vehicle control (through the use of direct torquer drive and electrical rate feedback).

Although the Twin CMG Systems have been designed for laboratory use, few design changes are required to make them flightworthy. The control moment gyros themselves are presently capable of meeting typical space equipment environmental requirements; the electronics require repackaging.

Future control moment gyro efforts, in addition to the NASA simulator investigations, should concentrate on configuration and control law investigations, CMG mission optimization, and CMG flightworthy readiness.

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APPENDIX A

STATEMENT OF WORK

(from Contract NAS9-8181)

1.0 PURPOSE

The purpose of this Statement of Work (SOW) is to specify the procurement of six (6) single-degree-of-freedom Control Moment Gyroscopes (CMG's) mounted in three (3) twin pairs, three (3) electronic packages, and three (3) mounting fixtures for alinement plus the analyses, reports, drawings, and manuals necessary to their description, operation, and maintenance.

2.0 SCOPE

The contractor shall furnish all engineering services, labor, materials, and personnel necessary to provide the services and equipment hereinafter called for:

a. Design and fabrication of three twin CMG systems in accordance with the technical requirements listed in section 4.0 of this Statement of Work.

b. Assembly, testing, and demonstration of the twin CMG systems at the contractor's plant prior to delivery.

c. Preparation of manuals, drawings, diagrams, and spare parts lists to illustrate assembly, adjustment, operation, and maintenance of the equipment.

d. Documentation as described in sections 5.0, 6.0, and 7.0.

3.0 GENERAL REQUIREMENTS

The requirements of this SOW call for six (6) single-degree-of-freedom gyros mounted in three (3) pairs on mounting fixtures so as to comprise a zero (0) momentum configuration when caged. The gimbals of each pair shall be electrically slaved together. Each pair is to be arranged such that it can be mounted on an air-bearing supported space vehicle motion simulator and give an output torque about one of three orthogonal axes on the simulator as shown in figure 1. Each pair of gyros shall be supplied with an electronics package. The package shall supply the power interface for the gyro pair, the input and output signal interface connectors for the gyro pair, the spin motor control electronics, caging electronics and gimbal slaving electronics for the gyro pair.

The intent of this procurement is to obtain a laboratory set of twin gyros to be used on an air-bearing supported simulator for investigation of twin gyro control schemes and twin gyro control systems for spacecraft pointing and maneuvering. The variable momentum capability of the gyros described by this SOW together with the variable inertia capability of the air-bearing supported simulator will allow investigations of control schemes for a broad range of space vehicle configurations.

The primary simulator to be used in the investigations is the Space Vehicle Motion Simulator (SVMS). A photograph of this air-bearing table (SVMS) is shown in figure 2 and general dimensions of the mounting surface are defined in figure 1. The following is a description of the pertinent characteristics of the SVMS.

a. The component mounting area is a normally horizontal surface with 40 square feet of area as shown in figure 1.

b. The mounting surface is alined within one arc minute of the geometrical axes of the air-bearing table and has two orthogonal scribe marks parallel, within the same accuracy, to the two lateral geometrical axes.

c. The maximum loading allowed on the mounting surface is 75 $\mathrm{lbs/ft^2}$.

d. The surface has a grid of tapped holes (1/4 - 28 UN) two inches on center over the mounting area as shown in figure 1.

e. 28 volts d.c. at a maximum of 30 amperes is available at the mounting surface from an offboard regulated power source.

f. Fifty-five (55) hardwire data and signal channels are available across the air-bearing interface.

g. The SVMS has three-degrees-of-freedom, $\pm 30^{\circ}$ about the lateral axes, and continuous freedom about the vertical axis.

h. The range of inertia for each axis of the SVMS is from 3,000 to 13,000 slug $\mathrm{ft^2}$.

The fidelity of the SVMS balance is adversely affected by the presence of heat sources on its mounting surface. This factor should be kept in mind during the design of items called for in this SOW. Of particular importance is the minimization of fluctuating heat leads on the SVMS mounting surface.

In general, the specified items in this SOW can be broken down into three main categories and the categories subdivided as follows:

3.1 Each gyro assembly shall include the following as a minimum:

1. Gyro housing
2. Rotor
3. Gimbal
4. Spin motor and bearings
5. Torquer motor and bearings
6. Gimbal position transducer
7. Gimbal rate transducer
8. Slip rings
9. Adjustable gimbal stops
10. Bearing monitor
11. Cable connections
12. Evacuation valve
13. Mounting brackets
14. Alinement provisions

3.2 Three (3) electronic packages are required. Each package shall contain independent electronics for each of the gyro pairs and shall include the following subassemblies packaged for easy accessibility and modifications.

1. Chassis
2. Spin motor power supply and speed control electronics
3. Torquer motor amplifier and electronics
4. Caging electronics
5. Slaving electronics
6. Necessary power supplies
7. Cables
8. Cable connections

9. Power connector

10. Input and output connectors

11. Necessary heat sinks

12. Indicator lights

13. Mounting provisions compatible with SVMS

3.3 Three (3) mounting fixtures are to be provided for the three gyro pairs. The fixtures are to be compatible with the SVMS and must satisfy the alinement requirements of this SOW.

4.0 TECHNICAL REQUIREMENTS

4.1 Gyro

1. Momentum

Three twin CMG systems are required with a variable momentum capability of 5 ±1/2 to 20 ±1/2 ft. lb. sec. per CMG. (10 to 40 ft. lb. sec. per axis). A capability of 5 to 25 ft. lb. sec. per CMG may be considered. It is desirable to have the momentum continuously variable.

2. Gimbal freedom

Continuous gyro gimbal rotation (greater than 360°) is required with the capability of adding adjustable mechanical stops. The stops will be adjustable from $\pm 45^\circ$ to $\pm 90^\circ$ from gimbal center position in 5° increments and will also be removable. It is desirable to accomplish these adjustments with a minimum of gyro disassembly.

3. Torque output

The peak output torque shall not be less than 75 ft. lbs. per gyro.

4. Gimbal inertia and stiffness

It is required that the gimbal inertia be kept low (<0.012 ft. lb. sec^2) and the gimbal stiffness high ($>$ 25,000 lbs/inch).

5. Gimbal damping

The gimbal damping shall be minimized to improve open-loop response.

6. Gimbal friction

The gimbal axis friction shall be less than 0.032 ft-lb. for each gyro.

7. Rotor and gyro housing safety factor

A safety factor of 4 on yield is required for the stress levels of the rotor at maximum speed and for the gyro housing when evacuated. If feasible, a pressure interlock should be incorporated that prevents operation of the spin motor above the safe housing pressure level.

8. Life

The rotor bearings and gimbal bearings and lubrication system shall be designed to have a minimum operational life of 2000 hours under continuous operation after delivery, i.e., development or acceptance testing shall not be included in the 2000 hours.

9. Weight

The total weight of two CMG's and associated electronics for each axis excluding the mounting fixture shall not exceed 75 lbs. The rotor weight shall not exceed 20 lbs. for each CMG.

10. Housing evacuation

A vacuum valve is required to evacuate the housing of the rotor by means of a vacuum pump. A manual throttling type valve with plastic seat (seat of Kynar or Teflon preferred) shall be used. The leak rate of the housing shall be such that evacuation is not required in less than one-week intervals. "O" ring type seals will be used for the housing to permit easy access to the adjustable gimbal stops.

11. The overall dimensions of each CMG excluding mounting fixture and associated electronics shall not exceed 8" x 8" x 15".

12. Disturbance torques

The maximum disturbance torque doe to unbalance of each gyro gimbal assembly shall be less than 0.0005 ft. lbs. in any gyro gimbal position, i.e., each gyro shall not contribute more than 0.0005 ft. lbs. of unbalance torque due to gimbal position changes after it is statically balanced at its zero momentum position. Such unbalance could be caused by non-symmetries in the gimbals, torquers, slip rings, tachometers, and potentiometers by bearing plan or by gimbal flexibility.

13. Orthogonality

Each gyro momentum vector shall be perpendicular to its gimbal axis within one arc minute under static conditions and within 10 ARC minutes under all dynamic operating conditions implied by this SOW. It shall be possible to aline (parallel) the gimbal axes of each gyro pair to within two arc minutes of each other. This shall be done by means of a mounting fixture. The procedure for obtaining such alinement shall be given in the operating manual and demonstrated at the contractor's facility prior to delivery.

14. Spin motor

Any type motor may be used to meet the following conditions:

a. Reasonable efficiency at all speeds within the angular momentum requirements.

b. Power:

accelerating: 30 watts maximum
running : 18 watts maximum

c. Speed stability ±0.1% at all required momentum levels.

d. Spin up time : <1 hour

e. Spin down time : <1 hour

f. Operating speed not to exceed 24050 rpm under any conditions.

15. Torquer motor

a. Type : d.c.

b. Peak output torque : > 0.5 ft. lb

c. Peak input at stall : <80 watts

16. Gimbal position transducer

a. Linear potentiometer

b. Accuracy - ±0.1% of 180° required, ±0.01% of 180° design goal.

c. Friction level - Less than 1.0 inch ounces.

17. Gimbal rate transducer

    a. Tachometer generator

    b. Voltage sensitivity: greater than 1 volt/rad/sec.

    c. Resolution - 0.001°/sec or better for rates less than 0.2°/sec.

    d. Linearity: better than 1%.

18. Bearing failure monitor

A thermistor shall be located on both spin bearing housings of each gimbal, and electrical leads brought out to a connector for the purpose of indicating the onset of bearing failure by means of monitoring bearing temperature.

4.2 Electronics

1. General

    a. The electronic packages shall contain all solid state components to minimize power requirements and heat dissipation.

    b. The primary voltage source to the electronics package shall be 28V d.c.

    c. The electronics package shall be designed so as to minimize heat dissipation into and around the SVMS mounting surface. The use of fans or blowers is prohibited.

    d. Cables and connectors

    The size and type of cables and connectors required shall be determined during the contract period to the mutual agreement of the government and the contractor. The contractor shall provide the necessary cables between the electronics package and the gyro to be compatible with the SVMS mounting positions of the electronic and gyro packages.

    e. Indicator lights

    A red indicator light (visible from 40 ft. in a normally lighted room) shall be installed on each of the three electronic packages to indicate the application of power to the gyro spin motors.

2. Peak Power

The maximum peak power for the six gyros plus electronics shall not exceed 525 watts under any combination of operating conditions.

3. Spin motor electronics

The contractor shall design the spin motor electronics to maintain the required speed stability (0.1%). The method of changing momentum level shall be by resistance adjustment (i.e., potentiometer) and shall be easily accomplished without replacing electrical or mechanical components. A signal proportional to wheel speed shall be provided for external monitoring.

4. Torquer motor electronics

   a. The contractor shall design the torquer motor electronics to include all amplifiers necessary to meet the requirements of this SOW.

   b. The gimbal torquer amplifier shall accept analog inputs. Peak torque shall be obtained at an input of ±10V d.c. to the torquer amplifier. The input impedance to the torquer amplifier shall be at least 1,000 ohms.

5. Caging electronics

The contractor shall design the caging electronics so that the gyro gimbals can be driven to and maintained at their zero position to within 20 arc minutes.

6. Slaving electronics

The contractor shall design the slaving electronics so that the gimbal angles of each pair of gyros track to within 20 arc minutes of each other under static conditions and within one degree under all dynamic conditions required by this Statement of Work. However, the accuracy of the slaving servo is dependent on the accuracy of the gimbal position transducers.

The slaving electronics shall include all of the electronic circuitry necessary to slaving each gimbal pair when a torquer command is applied to that gimbal pair at a single electrical input point.

7. Input signals required per axis

The input signals to the electronics are:

   a. Torque command to ±10V d.c. maximum (10 ma max. current).

   - b. Caging command - to be initiated by a discrete 28V d.c. signal to each gyro pair.

8. Output signals per gyro
   - a. Gimbal angles
   - b. Gimbal rates
   - c. Wheel speed
   - d. Bearing monitor

4.3 Mounting fixtures

Three mounting fixtures are required (one for each axis). Each fixture shall be compatible with mounting and alignment provisions of the SVMS and be designed to hold and align either gimbal axis of the gyro pair to within 2 arc minute of the scribe marks on the mounting surface of the SVMS, with a design goal of 1 arc min., and to satisfy the requirements of paragraph 4.1.13. The stiffness of the fixture shall be such that the alignment requirements are satisfied under all static and dynamic operating conditions up to 150 ft lbs output torque. The procedure for obtaining such alignment shall be given in the operating manual and demonstrated on one of the twin CMG systems at the contractor's facility prior to delivery.

4.4 Environment

a. Pressure - atmospheric, sea level

b. Ambient temperature range: $50^{\circ}F$ to $140^{\circ}F$

c. Humidity - 95% R.H. maximum

4.5 Materials

Because of the use of these devices on air-bearing tables, it is required that maximum use be made of non-magnetic corrosion-resistant materials. Such use will include mounting fixtures, gyro case, gyro gimbal mounting brackets, screws, bolts, nuts, and electronic chasses. Exceptions will be made in the case of commercially purchased off-the-shelf items such as the tachometers and potentiometers to reduce cost.

4.6 Standards

MIL standard designs are preferred where applicable. Good quality workmanship consistent with design requirements should be used.

5.0 DETAIL SCHEDULES TO BE PREPARED BY CONTRACTOR

For each Work Statement deliverable end item, the contractor shall prepare a master summary phasing schedule to depict significant milestones from contract award through end item delivery that denotes piece parts logistics, detailed manufacturing activity flow chart, decision points, test constraints, and similar information. Five (5) copies of this schedule shall be forwarded to the NASA contracting officer within ten days after contract award.

6.0 DOCUMENTATION

6.1 A complete set of each of the following items shall be submitted (one reproducible plus four (4) copies).

1. Schematics and diagrammic drawings
2. Wiring diagrams including component internal wiring diagrams
3. Assembly drawings
4. Subassembly drawings
5. Part drawings
6. Complete drawings for supplier-procured components are desirable, but not required.
7. Operation and maintenance manuals to illustrate and describe assembly, adjustments, calibration, alinements, trouble-shooting procedures, and operation of the gyros and electronics.
8. Complete list of parts used giving part manufacturers and that manufacturer's part number. Special items shall be fully described including name and location of supplier. Commercially available parts shall be adequately identified to enable the government to replace these parts through normal procurement.
9. Recommended spares list.

6.2 Design or development reports

1. Prior to manufacture the contractor shall submit his electrical and mechanical manufacturing drawings to the contracting officer for information.
2. Prior to manufacture the contractor shall submit the following analyses:
    a. Stress analysis on rotor and gyro housing to show conformance to the specified safety factor.

b. Gimbal and bearing load analysis.

c. Rotor windage analysis.

d. An analysis giving alinement tolerances and error sources indicating that the specification for alinement of the momentum vector to the gimbal axis has been met.

e. Meantime between failure (MTBF) or other predictions of life expectancy of the hardware.

6.3 Preliminary testing and demonstration at contractor's facility

The contractor shall submit the proposed acceptance test program including schedule and acceptance test procedures to the contracting officer for approval at least 45 days prior to the start of the testing. The contractor shall notify the contracting officer five calendar days before the date of test. Proposed individual tests and demonstrations on the gyros and electronics shall include at a minimum:

1. Wheel and gimbal balance
2. Spin up and spin down time measurement
3. Gimbal damping and inertia measurement
4. Gimbal friction measurement
5. Spin up and constant speed power measurement
6. Gain, thresholds, limit levels and maximum outputs of electronic circuits
7. Gimbal frequency response to sinusoidal torquer amplifier inputs
8. Power conversion efficiency measurements
9. Response and accuracy of the caging loop
10. Response and accuracy of the gimbal slaving loop
11. Accuracy measurements on the tachometer and potentiometer
12. Torque profile tests (gyro output)
13. Spin wheel speed stability measurement at minimum, intermediate and maximum speeds
14. Mounting and alinement procedures

The contractor shall submit an acceptance test report covering the above tests and demonstrations within 15 calendar days after delivery of hardware. This report shall include failure reports and analyses to assure definition and resolution of problems noted during acceptance testing and demonstration. The contracting officer's representative will witness the preliminary testing and demonstration at contractor's plant. Final acceptance test will be made at destination.

7.0 REPORTS

7.1 Monthly progress reports

The contractor shall prepare and submit to the contracting officer five copies of a monthly progress report, describing in detail for each Work Statement deliverable end item, the status of piece part logistics, the status of progress on the detailed manufacturing activity flow chart, problem areas, and the status of design or test operations towards completion.

The monthly progress report shall also describe any situation which could have adverse effect upon the completion date, together with a revised estimate of the completion date. Due by the 10th of the month following the report period.

7.2 Final Reports

A final report giving sufficient detail to comprehensively explain the results achieved under this contract shall be submitted within 30 days after delivery of all the equipment.

8.0 QUALITY ASSURANCE PROVISIONS

The contractor shall establish and maintain an inspection system which uses the requirements of NASA Quality Publication NPC-200-3 as a guide and shall include the following:

1. A drawing for each part, subassembly and assembly. Drawing changes may be made during the program, but will not necessarily be updated until all changes are finalized prior to shipment of equipment. The final drawings will reflect the shipped equipment.

2. The Contractor's Reliability and Quality Assurance personnel will inspect major electronic assemblies for workmanship. In addition, all machined parts will be inspected after fabrication. An inspection flow plan will be submitted to NASA/MSC.

3. Any failures affecting redesign of equipment will be reported in the monthly status reports.

4. All purchased items will be controlled by Engineering personnel, with complete records of parts inventory.

5. All instruments are calibrated on an established schedule within the Department.

6. Records will be maintained by documentation on standard Departmental forms and in engineering log books. No new forms are planned to be generated.

SVMS MOUNTING SURFACE

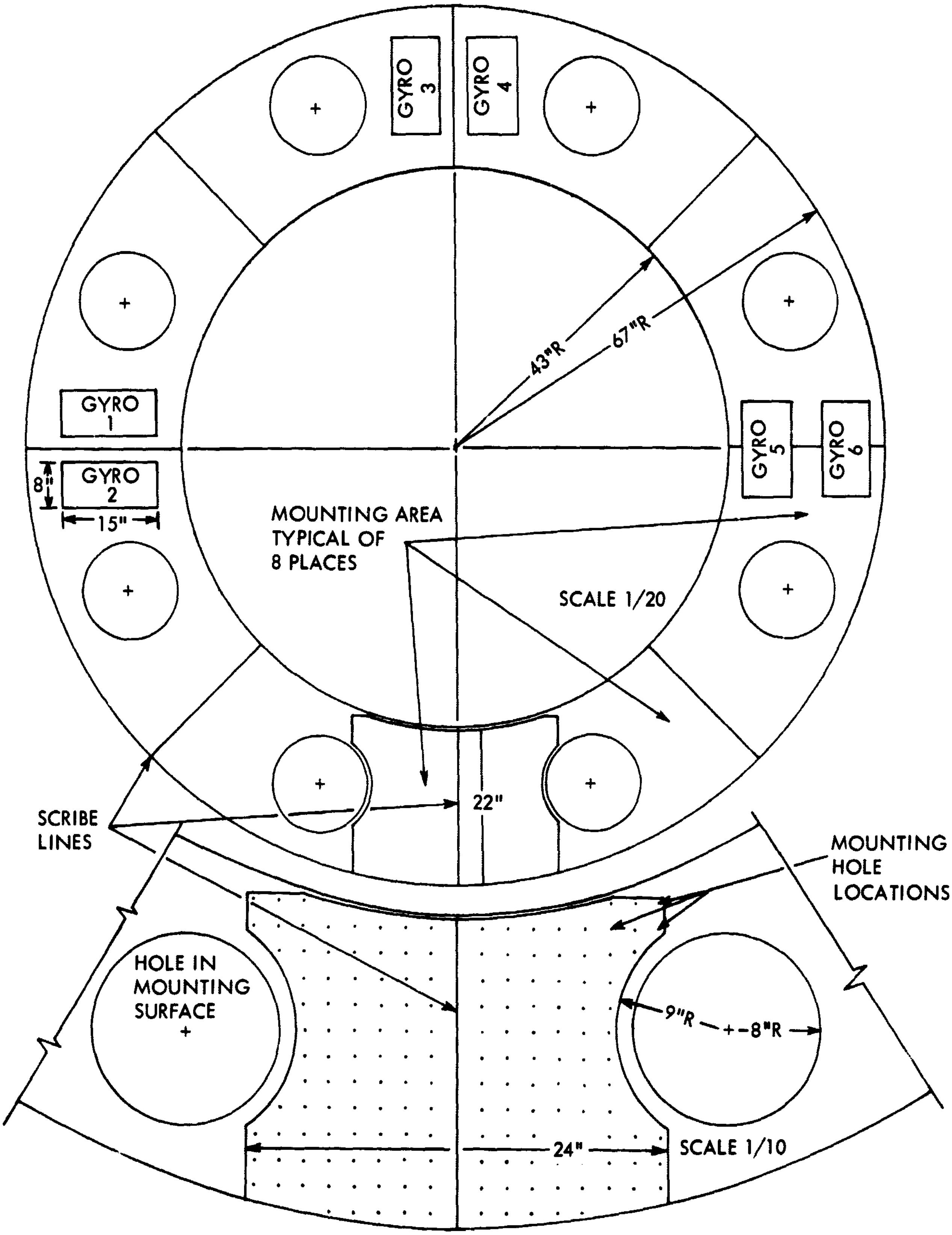

FIGURE 1

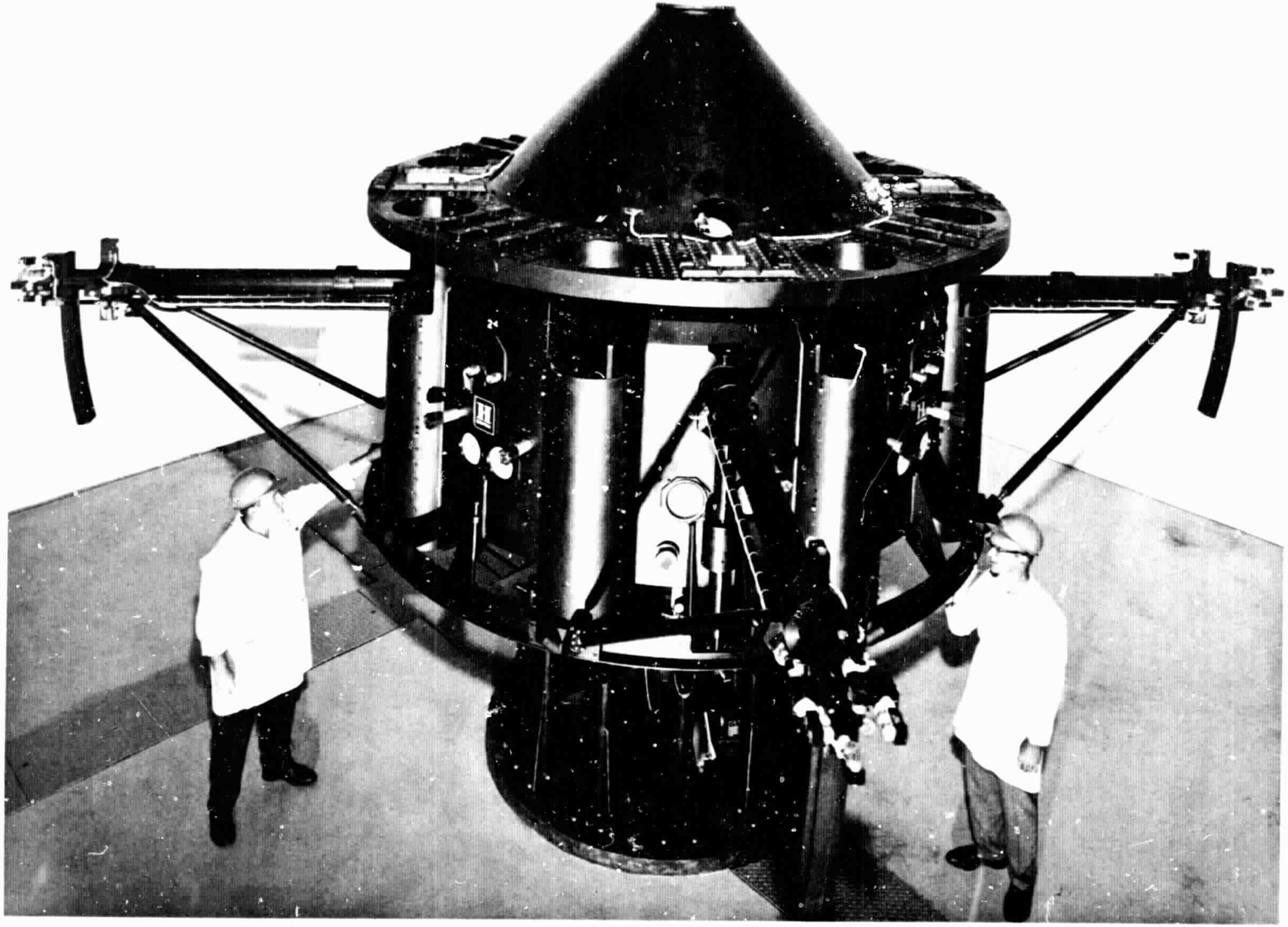

FIGURE 2